Reconnection Process in the Sun and Heliosphere

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Abstract Solar flare, coronal mass ejection and many other interesting plasma and magnetic field structures in the heliosphere are believed to be generated by a powerful plasma process widely known as reconnection of magnetic field lines. The basic understanding of this reconnection process is described by considering a simple model suggested by Dungey that contains a kind of consistent flow of plasma around an x-type neutral point. There are, however, several comprehensive MHD models, some of which are also discussed in this article. Spontaneous reconnection based on tearing mode instability is described very briefly for completeness. The crucial role played by magnetic reconnection in violent energy conversion occurring in solar flare, coronal mass ejection and other related phenomena like hard x-ray and soft x-ray emissions is highlighted. Several convincing observational evidences that support reconnection model are presented. Numerical simulation is seen to be an essential part of this study that enhances our understanding of the evolution of plasmoid and multiple shocks due to reconnection of field lines. Some challenges are mentioned towards the end of the presentation.

1 Introduction

We are all aware of the magnetosphere of our planet, Earth. It is a cavity formed as a result of the interaction between the solar wind and the magnetic field of Earth. Similarly the heliosphere is like a huge bubble in space generated by the interaction of the solar wind and the interstellar medium. It may be called the magnetosphere of the Sun. The solar wind travels at supersonic speed within the solar system and it becomes subsonic at a point called the termination shock. The point where the interstellar medium and the solar wind pressure balance is called the heliopause. A bow

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N. Gopalswamy et al. (eds.), *Heliophysical Processes*, Astrophysics and Space Science Proceedings, DOI 10.1007/978-3-642-11341-3_7,

shock is formed where the interstellar medium moving in the opposite direction becomes subsonic as it collides with the heliopause.

The solar wind, solar flares and coronal mass ejections send material, mostly ionized particles, and magnetic fields out into the heliosphere. This flow of mass and magnetic fields creates and fills the heliopshere, which is a volume inside the local interstellar medium and contains the solar system. Another important structure is the heliospheric current sheet, which looks like a ripple in the heliosphere, created by the Sun's rotating magnetic field. It extends throughout the heliosphere and is considered to be the largest structure in the solar system. Many interesting phenomena are seen to be associated with this current sheet.

Solar flares, coronal mass ejections and the closed magnetic loop structures in the heliospheric current sheet are believed to be generated by a very powerful plasma process known as reconnection of magnetic field lines. Therefore, we would like to concentrate first on the basic understanding of this reconnection process. This idea actually started with Giovanelli's suggestion of the importance of null points based on the observation of solar flares. Later this has been developed by Dungey (1961) in the physics of magnetosphere with great success. The role of magnetic reconnection in solar flares has been described quite well in a review paper by Lakhina (2000). Following Dungey's concept, we will describe later on the general development of the process of reconnection. It may be useful to introduce first some basic understanding of plasma motions and magnetic field structures and their evolution in the solar wind plasma. The general motion of plasma and the behaviour of the magnetic field are governed by the following equations: Equation of the motion of plasma

$$\rho \frac{d\upsilon}{dt} = -\nabla p + \frac{1}{c}\ J \wedge B, \tag{1}$$

Maxwell's equation

$$\text{c Curl B} = 4\,\pi\,\text{J}, \tag{2}$$

$$\frac{\partial B}{\partial t} = -c\,Curl\;\;E, \tag{3}$$

and Ohm's law

$$J = \sigma \left(E + \frac{1}{c}\ \upsilon \wedge B \right) \tag{4}$$

Using (2), (3) and (4), it is readily obtained the following equation:

$$\frac{\partial B}{\partial t} = \xi \nabla^2 B + \nabla \wedge (\upsilon \wedge B)\,, \tag{5}$$

where $\xi = \frac{c^2}{4\pi\sigma}$, σ represents conductivity and ξ is the magnetic diffusivity. In the above equations $\rho, \upsilon, p, J, B, E, c$ denote the charge density, plasma velocity, scalar pressure, current density, magnetic (field) induction, electric field, and the velocity of light respectively.

The equation of motion (1) represents how the plasma is accelerated because of the gradient of pressure and the magnetic force while the induction equation (5) describes the changes in the magnetic field due to plasma motion and magnetic diffusion. Nonlinear terms indicate how the plasma and the magnetic field are coupled. In absence of plasma velocity, the ordinary electric current is governed by the Ohm's law $J = \sigma E$, where the magnetic field is secondary and can be calculated from Ampere's law c Curl B $= 4\pi J$. In the magnetohydrodynamic (MHD) theory, velocity v and the magnetic field B are primary and J and E can be calculated from

$$Curl\ B = \frac{4\pi}{c}\ J$$

and

$$E = \frac{J}{\sigma} - \frac{\upsilon \wedge B}{c}. \quad (6)$$

Now for large σ, J/σ can be neglected and the electric field is then driven by the velocity and magnetic field. Ratio of the 2nd term to the first term on the right hand side of (5) defines the magnetic Reynolds number given by

$$R_m = \frac{\upsilon B}{L} \Big/ \left(\xi \frac{B}{L^2}\right) = \frac{\upsilon L}{\xi}. \quad (7)$$

R_m is extremely large ($\sim 10^{10}$) in the solar atmosphere and therefore the magnetic field lines are frozen in. However in a thin sheet of current or in a filament in the solar atmosphere, where L is very small (in the order of a km or so), the R_m could be very small (~ 1) so the magnetic field is not frozen in and can slip through the plasma while the magnetic energy is converted into heat in the time scale $T \sim L^2/\xi$.

1.1 Basic Reconnection Process

The basic process of reconnection depends on (1) the topology of the magnetic field, and (2) the motion of plasma near the neutral point. Dungey (1958) developed this model of reconnection to describe the interaction of the solar wind with the magnetosphere of Earth. A simple model for the magnetic field and the plasma motion around the neutral point is shown in Fig. 1.

Basically the magnetic field lines are anti-parallel to each other such that there is just one neutral point N with limiting field lines called separatrix. Two limiting lines are going into N while two are coming out. This is the magnetic topology. Now let us consider the plasma flow around such a neutral point. This holds an important key for the process of reconnection. It is very difficult to describe the plasma motion in the presence of a pressure tensor and different conductivities. However, in the absence of pressure and with an infinite conductivity, the Ohm's law that can provide velocity is given by $E + (\upsilon \wedge \mathbf{B})/c = 0$. The above equation also defines an electric

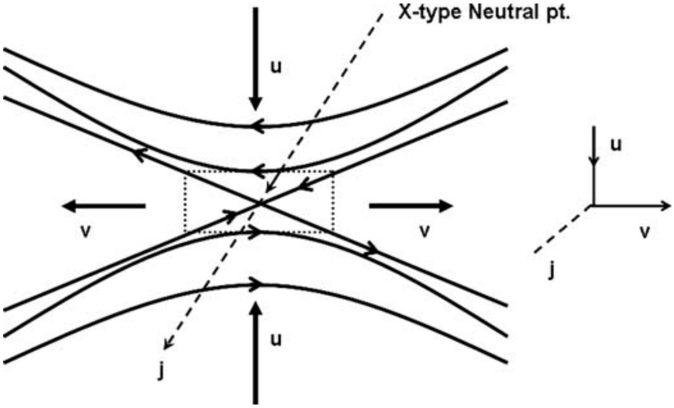

Fig. 1 Magnetic field topology and flow pattern around the neutral point (see Dungey 1961)

field. Suppose that the field lines are moving from both sides towards the neutral point as shown in Fig. 1. According to frozen-in-field approximation, they remain as unbroken field lines and still they can go to N or can go out from N. The direction of electric field associated with the motion of field lines is the same as that in above, below or at the neutral point. This kind of motion tends to increase current density at N. However, this is not reconnection.

The reconnection is the consequence of the breakdown of frozen-in-field approximation, which may be caused because of a high current density. It occurs when there is resistivity or anomalous resistivity. In this case the scenario becomes different. If one allows that these field lines do not remain as the same field line as before, then at some instant of time a pair of inflowing field lines actually becomes the limiting field lines and immediately after that they form an outflowing pair of field lines. This permits the limiting field lines to get cut at the neutral point and then reconnect to form a different set of field lines. This is possible because the frozen-in-field approximation is violated. This process is described as the reconnection of the field lines as they pass through N. This is the pictorial description of the reconnection of field lines.

We can probably proceed further with the MHD theory to describe the above process in the solar atmosphere. We have already seen that in many regions the Reynolds number R_m is usually very large and therefore, the diffusion of the magnetic field is negligible and as a result the plasma motion can be described by the equation, $E + (\upsilon \wedge B)/c = 0$, where E, B, υ are already defined earlier. The nature of the plasma flow can be virtually obtained from this equation. Hence the transport of magnetic flux near the separatrix is always associated with the plasma in such a region. However, in a thin current sheet or in a filament, Reynolds number becomes small and the frozen-in-field approximation is not valid. In such a region, the above equation is not valid. Dungey pointed out that in such a region, a large current is generated without being opposed by an electromagnetic force. The equation governing the plasma motion and the current are Maxwell's equation, the equation of

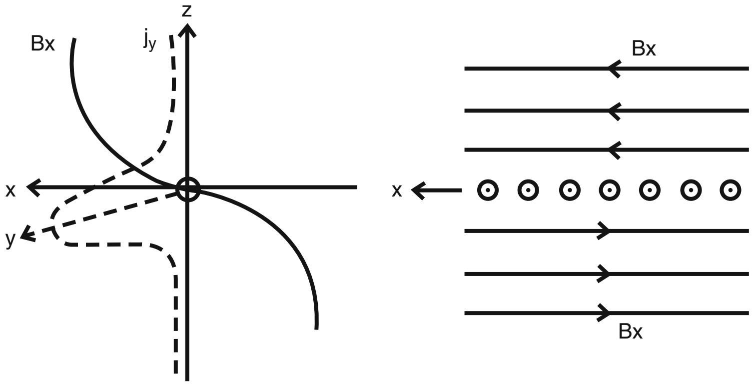

Fig. 2 Magnetic field strength and current density across the current sheet obtained from the diffusion equation. The current flows along y-direction. (Reproduced from Das 2004, copyright 2004)

motion and the Ohm's law given by

$$E + \frac{1}{c}\, \upsilon \wedge B = J/\sigma. \tag{8}$$

In thin region, near the neutral point, the diffusion term is substantial and therefore it may be useful to examine the evolution of the current and the magnetic field at the separatrix without the effect of a plasma flow. The magnetic induction (5) becomes a simple diffusion equation represented by

$$\frac{\partial B}{\partial t} = \xi\, \nabla^2 B. \tag{9}$$

In one dimension, $\dfrac{\partial B_x}{\partial t} = \xi\, \dfrac{\partial^2 B_x}{\partial z^2}$,where B_x is the magnetic field along x-direction and z is the vertical direction as shown in Fig. 2.

The solution can be obtained in terms of the error integral showing a large current flowing along the y-direction and the magnetic field lines are in the opposite direction around $z = 0$. In fact B_x varies with z and changes sign at $z = 0$. The magnetic flux diffuses from above as well as from below and gets dumped at the separatrix feeding the current. This reduces the gradient in the magnetic field and thus reducing the diffusion rate and slowing down the whole process. So the process becomes unproductive in a steady state. In order to maintain this process in a steady state, it becomes necessary to introduce a plasma flow from both sides for transporting the magnetic flux towards the neutral point at a rate at which they annihilate. The large magnetic flux through the diffusion region can maintain large current in the neutral sheet. However, this is also unphysical unless there is an outflow for these fluxes. The pictorial model suggested by Dungey (1961) contains a kind of a consistent flow of plasma around an x-type neutral point as shown in Fig. 1.

The existence of the diffusion region due to the finite resistivity is an essential requirement of the model to support the large current density. The resistivity has the classical value when it is entirely due to particle scattering by Coulomb collisions and it is shown how the Reynolds number can become appropriate in a thin sheet or a filament in the solar atmosphere for violating the frozen-in-field condition. In the magnetosphere, Coulomb collisions are extremely small and even in the neutral sheet region R_m cannot be made small. In such a plasma, an anomalous resistivity, which could be a few orders of magnitude larger, can occur due to scattering by many microscopic processes including plasma instabilities, Landau damping and so on.

This can also be understood in terms of electric field scenario suggested by Dungey (1958). Near the neutral point, some electric field is needed to drive the current, which is given by $E = \eta J$, where η is the resistivity, and J is in the y-direction and therefore the electric field also is in the same direction. Far away from the neutral point, the frozen-in-field approximation is valid and therefore there exists an electric field both above and below the neutral point bringing a flux of magnetic energy, equal to $c\,(E \wedge B)/4\pi$, towards the reversal region from both sides. However, this process of transport falls on the region where the magnetic field is zero and therefore the diffusion discussed earlier must play the role in bringing the magnetic energy into the neutral plane. This is the simplest picture of reconnection under the assumption that there exists resistivity in the region and the sheet is very thin. There exist, however, several comprehensive models, some of which will be discussed in the next lecture.

2 Reconnection Models

2.1 Sweet–Parker Model

It is assumed that the magnetic field lines are anti-parallel with a neutral sheet rather than a neutral line in between the field lines. The configuration of the magnetic field lines and the direction of flow are shown in Fig. 3.

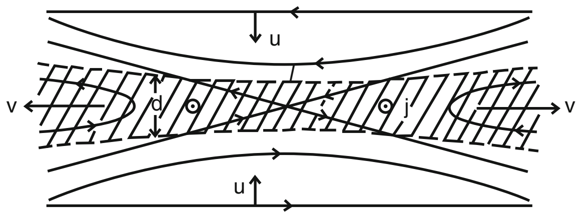

Fig. 3 Sweet–Parker model of reconnection (reproduced from Das 2004, copyright 2004)

Plasma flows with a normal velocity u from both sides into a diffusion region of the current sheet. The length of the diffusion is l while the width is denoted by d. It is further assumed that the plasma is flowing out with a velocity υ. A steady-state reconnection is maintained by the balance between the plasma flowing into the diffusion region and the equal amount of plasma out flowing in the current sheet. From conservation of mass, we get

$$ul = \upsilon d, \tag{10}$$

(a consequence of $\nabla \cdot \upsilon = 0$).

From the momentum balance equation, it is seen that $p = p_o + B^2/8\pi$, where p is the plasma pressure on the central plane where the magnetic field is assumed to be negligible or almost zero, and p_o is the pressure outside the diffusion region where the magnetic field is B. The pressure difference $(p - p_o)$ drives the plasma flow out of the diffusion region with a velocity v determined by

$$p - p_o = B^2/8\pi = \frac{1}{2}\rho\upsilon^2, \tag{11}$$

or,

$$\upsilon = \left(\frac{B^2}{4\pi\rho}\right)^{\frac{1}{2}} = \upsilon_A, \tag{12}$$

where, υ_A is the Alfven velocity.

Now the magnetic field is carried by the fluid towards the diffusion region which is controlled by the magnetic induction equation (5). The balance between the convecting flux and the flux annihilation due to the diffusion within it determines the width of the diffusion region. In a steady state, the velocity u is then given by

$$u = \xi/d \tag{13}$$

where $\xi = \eta c^2/4\pi$ and η is the resistivity. Then from (10), (12) and (13), we get $u = \upsilon \frac{d}{l} = \upsilon_A\, \xi/lu$, or, $u^2 = \upsilon_A \frac{\eta c^2}{4\pi l} = \upsilon_A^2 \frac{\eta c^2}{4\pi l \upsilon_A} = \upsilon_A^2 \frac{1}{R_m}$, where the magnetic Reynolds number R_m is given by

$$R_m = \frac{\upsilon_A l}{\eta c^2/4\pi}. \tag{14}$$

Thus the reconnection rate is given by

$$u = \frac{1}{\sqrt{R_m}}\upsilon_A. \tag{15}$$

R_m is a function of the Alfven velocity which is in this case is the outflow velocity from the diffusion region as the result of reconnection and l is the diffusion length which in this particular case is the overall system length. If there were no reconnection, the ordinary diffusion rate would have been given by $\upsilon_d = \xi/l = \upsilon_A/R_m$, where $\xi = \eta c^2/4\pi$. Thus it is seen that the reconnection rate is larger than the ordinary diffusion by a factor of $\sqrt{R_m}$ and since R_m is very large in interplanetary space, the reconnection is enhanced by a large factor. However, it is seen that the rate of reconnection or the inflow velocity is still very small compared to the Alfven velocity. Thus the Sweet-Parker model (Sweet 1957; Parker 1957) remains inefficient in producing a fast reconnection and thus the conversion of magnetic energy to plasma energy takes place at a slow rate.

2.2 Petschek Model

Sweet–Parker model cannot produce a large rate of reconnection because the length of diffusion region l, which is also the scale length of the system can be very large compared to the width of the region. This can be verified easily from the relation $u = (d/l)\upsilon_A$, which is much less than one and therefore the low rate of reconnection. Petschek realized this and suggested that if the size of diffusion can be limited to a smaller dimension, then the rate can be enhanced substantially because $u > \upsilon_A$ if $d > l$. Petschek (1964) pointed out that in the MHD flow in the outer region, it is possible that two standing MHD wave fronts can be maintained and these fronts are slow shocks. The diffusion region can be matched to a region of standing waves which deflect and accelerate the incoming plasma into two jets sustained between the shocks. The diffusion region is still important in the sense that the actual reconnection takes place there. A schematic view of the magnetic field and plasma flow configuration is shown in Fig. 4. A small diffusion region at the center around the neutral line still exists between the two standing waves.

Suppose α is the half angle of the exit flow or the angle of the slow shock such that it remains stationary in the flow. Now the plasma flow normal to the plane of the shock must be equal to the Alfven shock speed normal to the shock front in the frame of the out-flowing plasma shown in Fig. 4. The laws of flux conservation give

$$uB = \upsilon B_o, \tag{15}$$

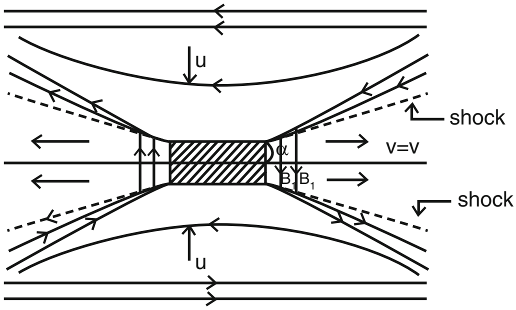

Fig. 4 Petschek model of reconnection (reproduced from Das 2004, copyright 2004)

where the magnetic field B is associated with the inflow, while B_o denotes the field in the outflow. The conservation of tangential stress gives

$$\rho u \upsilon = \frac{BB_o}{4\pi}. \tag{16}$$

Combining the above two equations, we get $\upsilon = \upsilon_A$, which is parallel to the x-axis shown in Fig. 4, similar to Sweet–Parker model.

The flow speed normal to the shock is denoted by $\upsilon_n$and is given by

$$\upsilon_n = \upsilon_A \sin\alpha, \tag{17}$$

and the normal component of the magnetic field

$$B_n = B_o Cos\alpha. \tag{18}$$

In order to keep the shock stationary with respect to the outflow of the plasma, the velocity perpendicular to the shock front must be balanced by the normal component of the Alfven wave velocity, i.e.

$$\upsilon_n = \frac{B_n}{(4\pi\rho)^{1/2}}.$$

Now using (18) and (19) we get

$$\upsilon_A \sin\alpha = \frac{B_o Cos\alpha}{(4\pi\rho)^{1/2}} = \frac{uB}{\upsilon_A}\frac{Cos\alpha}{(4\pi\rho)^{1/2}},$$

or,

$$\tan\alpha = \frac{uB}{\upsilon_A^2}\frac{1}{(4\pi\rho)^{1/2}} = \frac{u}{\upsilon_A} \tag{19}$$

For $u << \upsilon_A$, the angle α is quite small. As u increases, α will increase to accommodate the incoming flow. If $u = \upsilon A$, α becomes $\pi/4$ and the reconnection rate is enhanced considerably. It is possible because the outflow is not confined to the narrow width of the diffusion region like in the Sweet–Parker model. The outflow occurs in an expanding wedge whose angle would change according to the inflow rate. There is, however, an upper limit to the reconnection rate in the Petschek model. Equation (19) has been derived by assuming that u and B are constant throughout the inflow region starting from $x = \pm\infty$ and extending up to the diffusion region. Now that the electric field is also uniform in the steady state, the velocity and the magnetic field at infinity can be related by the relation $uB = u_\infty B_\infty$, where u and B are the velocity and the magnetic field at the diffusion region and u_∞ and B_∞ represent the velocity and the magnetic field at ∞. When α is small for $u << \upsilon_A$, the flow velocity u remain uniform throughout the inflow region with $u = u_\infty$. As α increases, u has to increase and then B decreases in the diffusion region and becomes less than B_∞. This is achieved by rotating the magnetic field vector towards the normal. Since the plasma flow is weakly perturbed in the region outside the diffusion region, it is assumed that the currents in these regions can be neglected (Petschek 1964). Magnetic field can be assumed to be potential and Vasyliunas (1975) has obtained the upper limit of the reconnection which is given as

$$u = (\pi/4)\upsilon_{A\infty}/\ln R_m,$$

where R_m is defined with respect to the speed $\upsilon_{A\infty}$. Thus it is possible to reach a fairly high reconnection rate with an appropriate boundary condition.

2.3 Spontaneous Reconnection or Patchy Reconnection

This is believed to occur when an original stable system moves to a new one with an onset of instability because of gradual changes of the stable system by an external force. The tearing mode instability is one of the most favourite candidates that can be triggered in a current sheet described earlier in a stable equilibrium (Fig. 5). If the electric field is generated consistently by a small disturbance, and not imposed by an external force, then it is called a spontaneous reconnection. The generation of these instabilities requires some kind of dissipation near the neutral point. For dissipation due to collisions, it is called a resistive instability and for dissipation due to the anomalous resistivity caused by wave turbulence or some other sources in a collisionless plasma then it is called a collisionless tearing mode.

Consider a current sheet near the neutral line in the magnetic field configuration shown in Fig. 5 wherein there exists magnetic fields with opposite directions. If the current is disturbed by a small perturbation, then some type of bunching in the current sheet occurs because of the self-generated magnetic field. The instability occurs because of the violation of frozen-in-field condition. It occurs in the region where the current is enhanced as a result of diffusion. The equation that controls the perturbation in fields and currents is given by

$$E^{(1)} + \frac{1}{c}\upsilon^{(1)} \wedge B = \frac{J^{(1)}}{\sigma},$$

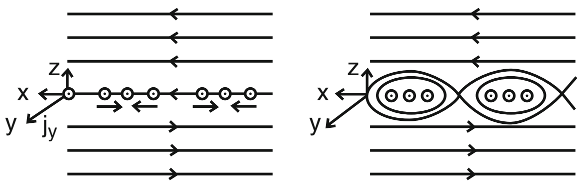

Fig. 5 Magnetic field configuration and tearing model instability

where $E^{(1)}, v^{(1)}$ and $J^{(1)}$ are the first order perturbations. At the center, where $B = 0$, the electric field and currents are governed by the conductivity in the current sheet. Then the magnetic perturbation is given by the induction equation

$$\frac{\partial b^{(1)}}{\partial t} = \frac{c^2}{4\pi\sigma}\nabla^2 b^{(1)}$$

The induction equation outside the resistive region is given by

$$\frac{\partial b^{(1)}}{\partial t} = \nabla \wedge \left(\upsilon^{(1)} \wedge B\right).$$

Usually the parameters that determine this tearing mode instability are obtained by solving these equations outside and inside the region and matching the solution at the boundary. However, one can estimate the growth of this tearing instability by examining the induction equation near the neutral line. The growth rate is given by

$$\gamma_T = \frac{c^2}{\pi\sigma d^2},$$

where length in the x direction is much longer than d, i.e. $k_x < \frac{1}{d}$ can be neglected. It depends upon the width of the current sheet. The narrower the width, the larger is the growth rate. Furthermore, the growth rate increases if the conductivity decreases. Both these results have very important impact on the growth of a solar flare or a coronal mass ejection. As a consequence, this instability is seen to produce magnetic islands or plasmoids in the current-sheet that can be blown away from the region of the neutral point.

2.4 Collisionless Tearing Mode

The tearing mode instability in a current sheet in a collision dominated plasma has been discussed already in the previous section. In a collisionless plasma this can be described adequately in the framework of Vlasov equation where the wave-particle interaction can provide the necessary dissipation in a generalized sense due to electron and/or ion Landau damping. Therefore, there will be a diffusive layer as in the case of the fluid theory and the plasma and field configurations are the same as before containing a neutral layer with a current sheet. Following the general description (see e.g., Laval et al. 1966; Galeev and Zelenyi 1976) the general expression for the growth rate can be obtained. It is seen to produce substantial growth for a very thin current sheet. One of the significant results is the generation of a magnetic island or a plasmoid. However, a finite component of the magnetic field normal to the current sheet, which magnetizes the electron in a neutral layer, stabilizes the electron tearing mode and as a result, no reconnection can take place.

Ion-tearing mode can still exist (Schindler 1974; Galeev and Zelenyi 1976). This, however, is limited to only a small range of magnetic field. In the case of a reconnection in the tail of the magnetosphere, Buchner and Zelenyi (1987) have suggested that ion-tearing can be sustained if the electron orbits become chaotic (Chen and Palmadesso 1986). However, more recent numerical simulation indicates that even the chaotic motion of electrons cannot prevent stabilization of the tearing mode. Therefore the possibility of the influence of external sources in the generation of the instability has been explored by several researchers. One of such sources considered by Sundaram et al. (1979) and Das (1992) was the effect of the background of lower hybrid/ion-cyclotron waves. It was shown that in such cases the tearing mode instability can be sustained with higher growth rate. In another approach, Lakhina (1992) considered a small perturbation at the boundary of the magnetospheric tail, as an external source to develop a theory of driven reconnection in the Earth's magneto tail. Recent work on numerical simulations has enhanced our understanding of reconnection enormously.

3 Role of Magnetic Reconnection in Solar Flares

Solar flares are believed to be generated by magnetic reconnection. Flares are generally classified into two types: compact and two ribbon flares. The two ribbon flares appear as long-lived, slowly developing large loops. During the preflare phase, a large flux tube with an overlying arcade of magnetic field lines rises slowly upward into the corona because of several possible reasons. For example, it may be due to a spontaneous eruptive MHD instability or due to a magnetic non-equilibrium state when the separation of footpoints or the twist in the field or the pressure becomes too large. As the field lines form inverted Y-shaped structure and relax, the reconnection of the field lines takes place below the filament leading to shocks generated by the process described by Petschek and to impulsive bursty regions. This is also known as emerging flux or interacting flux models. A general scenario on the basis of simulations and observations is presented in Fig. 6.

A slightly different mechanism was thought to be required to produce short-lived impulsive flares known as compact flares. However, observations made with Yohkoh Hard-X-ray Telescope (HXT) and Soft X-ray Telescope (SXT) show a compact flare with a geometry similar to that of a two ribbon flares. The reconnection region is identified as the site of particle acceleration suggesting that the basic physics of the reconnection process may be common to both the types of flares. A schematic view of this process is shown in Fig. 7.

Now we would like to elaborate the present status of our understanding from the point of view of observations.

1. Cusp-shaped loop structure in long duration events (LDE) is one of the most important discoveries of Yohkoh (SXT). An example of this kind of flare is shown at the left of the Fig. 6. This was reported to be seen within a few hours after a large-scale coronal eruption, which created a helmet streamer-like configuration,

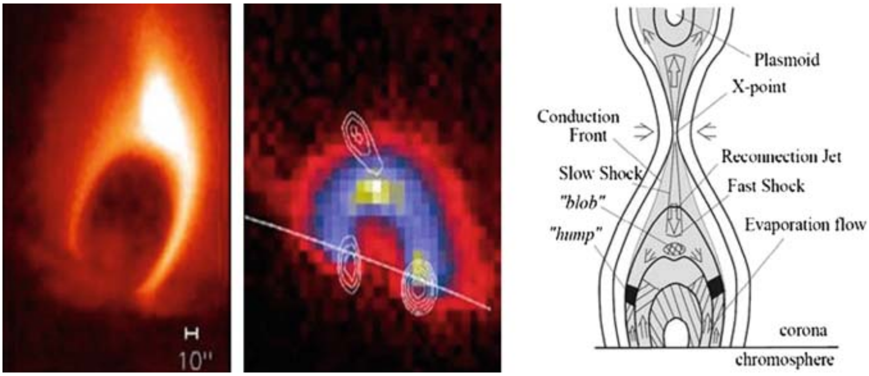

Fig. 6 Observational evidence and illustration of simulation results for the magnetic reconnection in solar flares – a general scenario. (*left*) Illustration of LDE (long duration event) flares; (*middle*) Observation of loop-top hard X-ray source, (reprinted with permission from Elsevier, K. Shibata 1996); (*right*) A schematic illustration of the reconnection model of a solar flare on the basis of simulation results.(reproduced by permission of AAS, Yokoyama and Shibata 2001)

which in turn suggests the formation of a current sheet as a result of some MHD instability. The apparent height of the loop and the distance between the footpoints of the loop are also seen to increase gradually. This actually inferred the successive magnetic field reconnection in the current sheet above the loop, which is supported by the theoretical studies. Most recent observations of flares and other related phenomena with SXT onboard Yohkoh have also shown the soft X-ray (SXR) emissions association with the reconnection. In fact these are considered to be the evidence of reconnection. With a closer examination of the observations, it is reported that a small magnetic island (or plasmoid) is ejected during the rise phase of a flare. It is likely that the ejection of the plasmoid triggered the flare. Similarly the observations by HXT, also on Yohkoh, have brought out the major discovery of a hard X-ray (HXR) loop top source above a soft X-ray bright loop during the impulsive phase. This is shown in the middle of the Fig. 6. Furthermore, long duration event (LDE), large-scale arcade formation and impulsive flares show many common features such as plasmoid/filaments ejection in the Yohkoh data. All these phenomena have led to a model for flares based on reconnection as shown in Fig. 7.

2. Cusp-shaped loops or arcades have also been found in a scale much larger than that for LDEs although the evolution of the features are similar. A large helmet streamer, which may occur due to a coronal mass ejection, has been conjectured as another view of a large-scale arcade. Yohkoh/SXT has revealed that these large-scale arcades are very similar to LDE flares from various points of view apart from the size and magnetic field strength. The formation of a magnetically closed helmet structure observed as a bright feature with the SXT on the Yohkoh spacecraft is interpreted as a consequence of magnetic reconnection that proceeded along a vertical magnetic neutral sheet formed by a mass ejection.

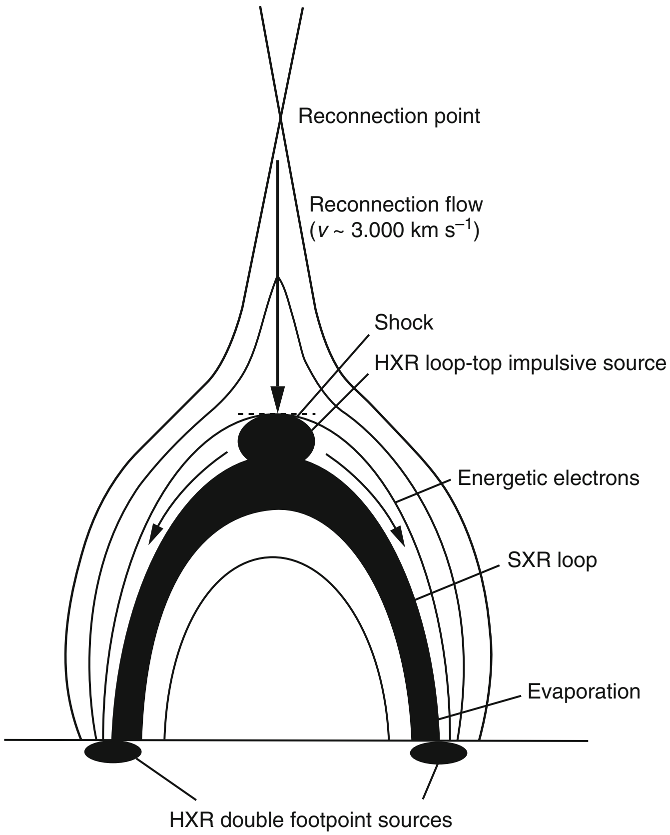

Fig. 7 A schematic view of the site of particle acceleration as a result of reconnection (Masuda et al. 1994; reproduced by permission from Macmillan Publisher Ltd., Nature 371, 1994)

3. The detection of a reconnection inflow as well as an outflow has been an important aspect to our understanding of reconnection in solar flares. In fact, this is considered to be a very important signature of reconnection near the neutral point or line.
4. *Impulsive flare*: We have already mentioned that this is the second type of flares, which does not show a cusp-shaped structure. These are bright in hard X-rays and show an impulsive phase whose duration is short. Masuda et al. (1994) have observed a loop-top hard X-ray source appearing well above a soft X-ray bright loop. This is a distinct indication that an impulsive energy release did not occur within the soft X-ray loop but above the loop. One possible physical mechanism to produce such a loop-top hard X-ray source is a magnetic reconnection occurring near the X-type neutral point much above the loop as shown in Fig. 6. It is shown by Soward and Priest (1982) that the outflow from the reconnection process produced by the Petschek mechanism is supermagnetosonic with respect to fast-mode magnetosonic wave speed and so anything that obstructs the flow will

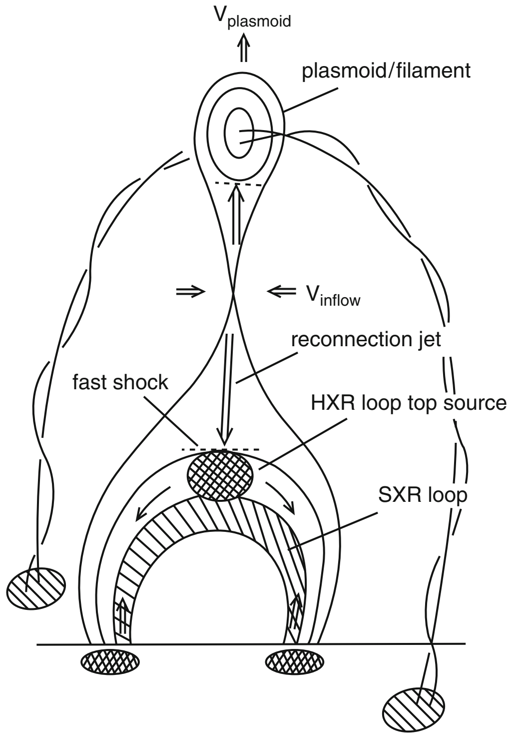

Fig. 8 A unified model on the basis of plasmoid-driven reconnection (reprinted with permission from Elsevier, Shibata 1996)

create a fast shock, which produces superhot plasma and/or high energy electrons emitting hard X-rays. A schematic view is shown in Fig. 7. The discovery of the loop-top HXR source has made it possible to think of unifying two classes of flare, LDE flare and impulsive flare by a single mechanism of magnetic reconnection. If these impulsive flares are also generated by the reconnection process, then these must be associated with a plasmoid or a filament ejection. Interestingly many such flares are found to be associated with a plasmoid ejection (Masuda et al. 1994). Using all these findings, Shibata (1996) has proposed a model based on a plasmoid ejection, which is shown in Fig. 8.

In this model the impulsive phase corresponds to the initial phase of the plasmoid injection. The ejection of the plasmoid produces a strong inflow into the x-point which drives the fast reconnection. The inflow velocity is estimated by using the conservation of mass and assuming that the density does not change appreciably. The Alfven Mach number of the inflow becomes comparable to the inflow speed expected from the Petschek model. Furthermore, according to the reconnection theory, two high speed jets from the neutral point move in opposite direction at a velocity $\upsilon_O \sim \upsilon_A$. However, in the fast reconnection process the jet can exceed

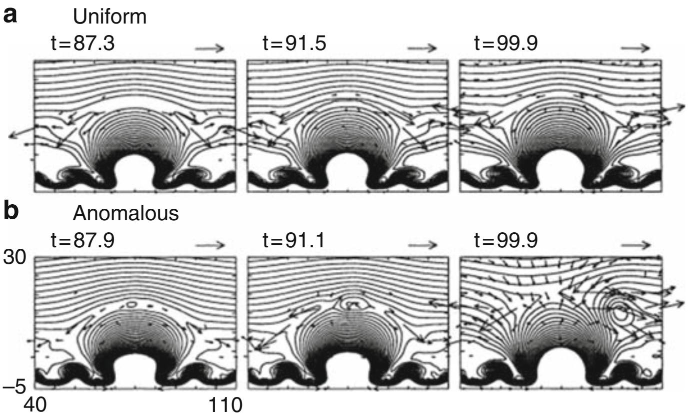

Fig. 9 Recent MHD simulation of reconnection between emerging flux and coronal field (reproduced by permission of AAS, Yokoyama and Shibata 1994)

fast-mode wave speed, and when it collides with the top of the SXR loop it generates fast shocks producing high energy electrons at the loop top which are observed as HXR. This seems to support the observation on temperature.

3.1 Reconnection Between Emerging Flux and Coronal Field

When an emerging flux interacts with the quiet coronal field, two horizontal jets or loops are seen in both sides of the emerging flux regions. Recent MHD simulation of the above physical situation has shown the formation of magnetic islands that are ejected out of the current sheet. This is shown in Fig. 9. The simulation seems to explain the above features very well by the magnetic reconnection model suggested by Yokoyama and Shibata (1994).

A localized resistivity seems to be essential for the fast reconnection. If the current sheet is long enough, the tearing mode instability with anomalous resistivity may produce such a reconnection and island formation. The plasmoid produced in this situation appears to be similar to the plasmoid ejected in larger flares shown in Fig. 6.

3.2 Recent Simulation and Present Status of Theoretical Understanding

More realistic simulation of a flare has been done by Yokoyama and Shibata (2001) by including thermal processes that are important for quantitative comparison with observations. Both the temperature and density evolution leading to the reconnection and island formation are shown in Fig. 10. The regions of X-ray emissions are

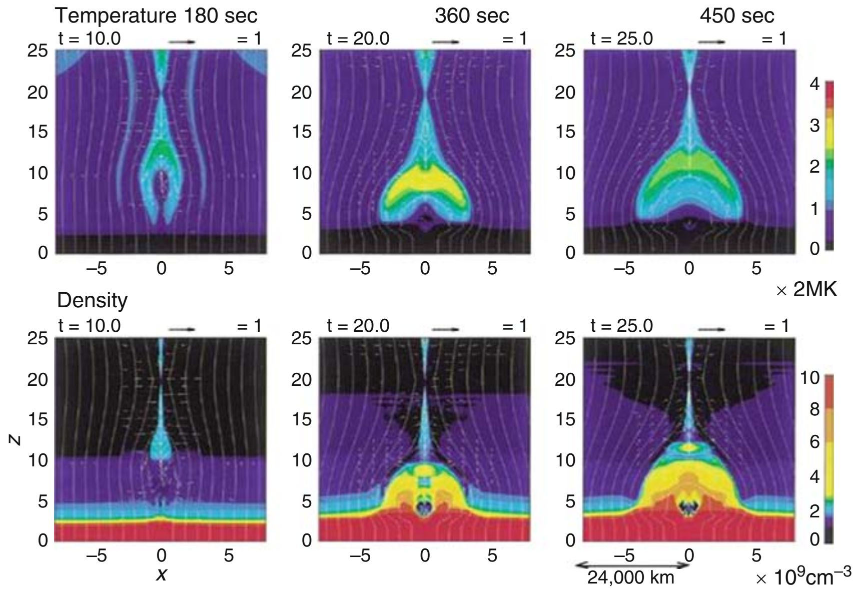

Fig. 10 A more realistic simulation model leading to reconnection and island formation (reproduced by permission of AAS, Yokoyama and Shibata 2001)

also seen in Fig. 10. The localized resistivity appears to be necessary for the fast reconnection (Ugai 1999a,b; Yokoyama and Shibata 2001).

3.3 Scale-Matching Between Macro and the Micro Features or Scales

This is an important aspect of reconnection which remains unanswered. For example, there is an enormous gap of scale sizes between the region of anomalous resistivity and a solar flare. The scale size of the anomalous resistivity d can be approximated by $d = \rho_i \sim 10\,\text{m}$, where d is the thickness of the current sheet and ρ_i represents the ion Larmour radius. The scale size of a flare $\approx 10^4$ km. Therefore there is a gap of seven orders of magnitude between the small scale size and the large scale size. The MHD turbulence or the stochastic magnetic reconnection may have an answer to this problem.

3.4 Turbulent Structure in the Magnetic Reconnection Jet

Tanuma and Shibata (2005) have shown a very interesting turbulent structure containing internal shocks in the magnetic reconnection jet in solar flares. They have

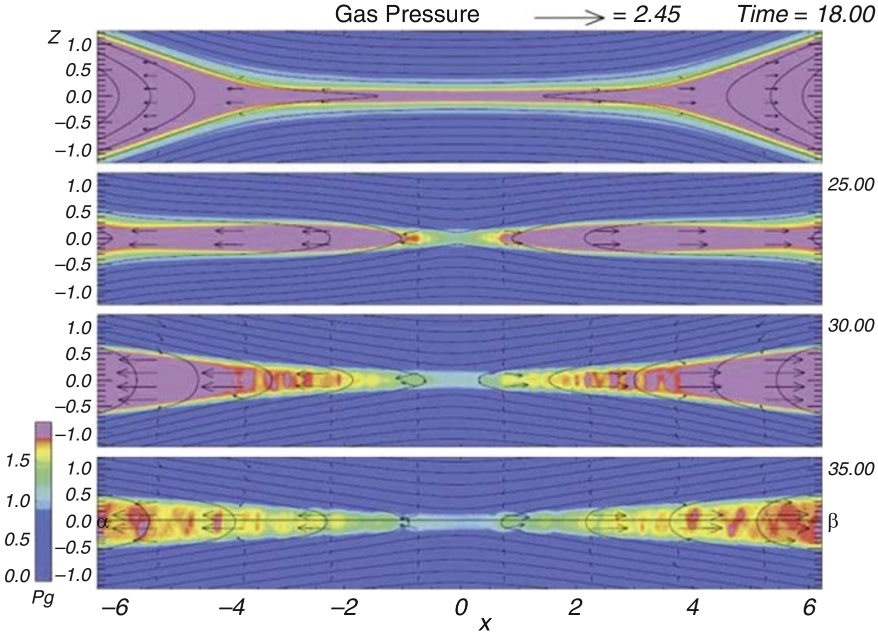

Fig. 11 Turbulent structure in the outflow. The Petschek-like reconnection is seen in the top panel while the development of multiple island-like structures are shown in other panels (reproduced by permission of AAS, Tanuma and Shibata 2005)

examined how magnetic reconnection creates multiple shocks by performing a 2-D resistive MHD simulation. This is shown in Fig. 11. Certain amount of energy is seen to be continuously transferred into the system. A secondary tearing mode instability plays a crucial role.

3.5 *Reconnection in Heliospheric Current Sheet*

There exist a large number of satellite observations giving evidence for the reconnection in the planetary space and around the heliospheric current sheet. During the solar maximum mission, a few probable coronal disconnection events appearing as the pinching of a helmet stream followed by the release and outward acceleration of U- and V-shaped structures are observed. The sequence of events is such that it indicates reconnection across the heliospheric current sheet between previously open field region and the creation of detached magnetic structure. This process then sends back the open field lines towards the Sun as closed field arches. There also exist observations of an internal magnetic reconnection within a flux rope. As the flux rope field lines at the interface of the two-speed solar wind are sheared, oppositely directed field lines are generated which press together and get reconnected

(Schmidt and Cargil 2001). Magnetic reconnection caused by resistive tearing mode in a non-periodic multiple current sheets has been investigated by using two dimensional simulations. The result shows that it produces unsteady complex reconnection which is supported by two observations of very complex structure with directional discontinuities in magnetic field current system. These discontinuities observed at the sector boundary crossing in the heliosphere may be associated with magnetic islands and plasmoids due to reconnection (Wong et al. 1997).

4 Summary

- Magnetic reconnection is the underlying driver of giant explosive releases of magnetic energy in the Sun's atmosphere that are observed as solar flare or CMEs.
- Several compelling observational evidence for reconnection which support reconnection model of solar flares are presented.
- Numerical simulation suggests that the localized resistivity is necessary for magnetic reconnection.
- There is still an enormous gap between the microscale of anomalous resistivity and the size of solar flares.
- The MHD turbulence model of reconnection shows interesting features in various cases and may play an interesting role in solving the scale-matching problem.

Acknowledgements The author would like to thank Mr. Hitesh Macwan for his help in preparing this manuscript.

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