Magnetic Reconnection in Solar Flares and CMEs

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Keywords: Solar flares, CME, Magnetic reconnection

Abstract: Magnetic reconnection has been believed as a major cause of energy-releasing in solar flares. This work first discusses the basic 2-D models, the Sweet-Parker Model and the Petschek Model. Then, we investigate some existing models explaining the effect of magnetic reconnection on solar flares and coronal mass ejections (CMEs). In the passage, Solar flare models like the emerging-flux, Sheared Arcade, and High-temperature turbulent current sheet models are listed. CME models have been discussed in both 2-D and 3-D.

1. Introduction

Magnetic fields can be found in the Earth's dipolar magnetic field, the magnetosphere, the solar chromosphere and corona, and a broader from the interstellar medium to galaxy clusters. The topological rearrangement of magnetic field lines, known as magnetic reconnection, rearranges magnetic field-line configurations in magnetized astrophysical and laboratory plasmas and also restructures macroscopic quantities of plasmas, including flow and thermal energy.

With the development of technology, astronomical observations, theory and numerical simulations, and laboratory investigations, much progress has been made in recent decades to study the physical characteristics of magnetic reconnection. It plays a crucial role in naturally occurring plasmas, as evidenced by space and astrophysical studies, and this has sparked a strong interest in the preliminary study. Theory and numerical models can help disassemble the complicated reconnection phenomena into a collection of less complicated processes, allowing for a better physical explanation of each approach.

2. Plasma Physics Background

In plasma physics, the generalized form of Ohm's Law is expressed as

$$\mathrm{E}+\frac{\mathrm{V}\times\mathrm{B}}{c}=\eta\mathrm{J}+\frac{\mathrm{J}\times\mathrm{B}}{en_e c}-\frac{\nabla\cdot\mathrm{P}_e}{n_e ec}+\frac{m_e}{n_e e^2}\frac{\mathrm{dJ}}{\mathrm{d}t}\cdots \tag{1}$$

J represents the current density, n is the particle number density, $\mathrm{P_e}$ is the electron stress tensor. $\frac{\mathrm{J}\times\mathrm{B}}{en_e c}$ is the Hall term. $-\frac{\nabla\cdot\mathrm{P}_e}{n_e ec}$ is the electron pressure and $\frac{m_e}{n_e e^2}\frac{\mathrm{dJ}}{\mathrm{d}t}$ is the electron inertia.

3. Existing 2-d Mr Model

Sweet and Parker proposed the first quantitative model for a reconnection process in a current layer, explaining how energy is released in solar flares. In their theory, in a current sheet with half-length L and half-width δ, two antiparallel magnetic fields are brought together. Reconnection takes place, and thus the magnetic energy is transferred into kinetic energy in form of the outflow jets and heat. Despite their work in explaining energy release phenomenon in solar flares, the Sweet-Parker model could only predict slow reconnection, which was too slow compared to the time scale of solar flares occurrence. To solve this problem, Petschek developed another model. The magnetic energy is dissipated in slow mode shocks separated by Inflow and outflow. A faster reconnection rate is achieved in this model.

  DOI: 10.25236/iccem.2021.060

4. Sweet-Parker, Petschek

The Sweet-Parker model is the earliest attempt to study the reconnection process quantitatively. It provides a detailed description of resistive magnetic reconnection. They consider the reconnection region in a two-dimensional plane in a current sheet with half-length L and half-width δ with uniform density ρ and resistivity η. The model assumes a steady state. There is a uniform out-of-plane electric field, with equal substance entering the sheet and substance leaving it. Also, the current sheet is elongated. So the kinetic energy and the magnetic energy of Inflow can be neglected. It also ignores the resistivity outside the current sheet. Magnetic field lines in opposite directions merge and then form reconnected field lines, finally move out from the reconnection region. According to the conservation of mass: the mass flux in equals the mass flux out.

$$LV_{in} \sim \delta V_{out} \ldots \qquad \ldots(2)$$

Also, the conservation of energy: the magnetic energy flux in equals the kinetic energy flux out.

$$LV_{in}\left(\frac{B_{in}^2}{8\pi}\right) \sim \delta V_{out}\left(\frac{\rho V_{out}^2}{2}\right)\ldots \qquad \ldots(3)$$

By combining these two equations, the outflow speed can be calculated. It scales with the upstream Alfvén speed.

$$V_{out} \sim V_A \equiv \frac{B_{in}}{\sqrt{4\pi\rho}}\ldots \qquad (4)$$

The ideal electric field outside the current sheet balances the resistive electric field inside the sheet.

$$\frac{V_{in}B_{in}}{c} \sim \eta J \ldots \qquad \ldots(5)$$

According to Ampere's Law,

$$J \sim \frac{c}{4\pi}\frac{B_{in}}{\delta}\ldots \qquad \ldots(6)$$

Inflow occurs when balanced by resistive diffusion

$$V_{in} \sim \frac{D_\eta}{\delta}\ldots \qquad \ldots(7)$$

$$D_\eta \equiv \frac{\eta c^2}{4\pi}\ldots \qquad \ldots(8)$$

The reconnection rate scales as

$$\frac{V_{in}}{V_A} \sim \frac{1}{S^{1/2}}\ldots \qquad \ldots(9)$$

S is the Lundquist number, the ratio of the resistive diffusion time scale to the Alfvén wave crossing time scale

$$S \equiv \frac{LV_A}{D_\eta} = \frac{\tau_{res}}{\tau_{Alf}}\ldots \qquad \ldots(10)$$

S is between 10^9 and 10^{20} when considered in astrophysics. Because of this limitation, the Sweet-Parker model predicts slow reconnection, which has time scales of months. It is much slower than the reconnection observed in solar flares and plasmas.

The cause of the problem is that many of the model's approximations are not suitable. The stability of the elongated current sheets cannot be guaranteed above a critical Lundquist number of $S_{c \sim 10}{}^4$(the astrophysical Lundquist number is much larger).

To predict fast reconnection in large Lundquist number plasmas, Petschek built a model under new mechanics. Petschek proposed an X-point geometry, meaning there is no bottleneck from the conservation of mass. The Inflow and outflow are separated by slow mode shocks where most of the magnetic energy is dissipated. In this model, the reconnection rate $\frac{V_{in}}{V_A} \sim \frac{1}{\ln S}$. This is fast reconnection. However, there are still some problems with the Petschek model. First of all, there is not much observed evidence for the Petschek model in laboratory and space plasmas. Only very few slow shocks are occasionally observed in space plasmas. Secondly, localized dissipation, such as anomalous resistivity, is needed to get a Petschek reconnection in resistive MHD simulations. Anomalous resistivity needs collisionless effects. On the other hand, these effects occur only on short-length scales where the break-down of MHD leads to collisionless reconnection. Thus, the original Petschek model is not a feasible mechanism for fast reconnection.

5. Solar/Stellar Flares and Coronal Mass Ejections

5.1 Background Information Regarding Coronal Mass Ejections

Typically, scientists have agreed that reconnection is the basic element in solar flares and coronal mass ejections(CMEs). When reconnection takes place in the coronal, magnetic topology changes, the arcade of flare loop structures grows, the 'current sheet' structure forms above the flare loops, plasma moves into and out of the reconnection region. Above the loop top, hard X-ray emission takes place.

Existing Solar flare models

In the passage, three flare models have been discussed: the emerging-flux model, the sheared-arcade model, and the High-temperature turbulent current sheet model.

Emerging-flux model

The emerging-flux model is a famous current sheet model. This analytical model was built in correspondence with the observations in the 1970s. Scientists noticed a correlativity between solar flares and new magnetic flux emerging in the convection zone and directing into the chromosphere. Scientists wanted to find an explanation for this relationship between solar flares and magnetic flux. They conclude that new magnetic flux may help to store magnetic energy in the corona. A current sheet is formed when a new magnetic loop points in an opposite direction of the pre-existing loop. When new magnetic loops keep emerging, the current sheet will be extended, reaching a higher altitude, becoming much more unstable to magnetic tearing. Under this condition, a solar flare will be formed.

Though it is theoretically correct that when reaching a critical length, the current sheet will suddenly become unstable, there is no accurate emerging flux model that can help explain how the process works. The popularity of the emerging-flux model keeps reducing, because it cannot explain the form of CME. The reconnection of current sheets can merely affect the structure of magnetic field slightly. The observed phenomenon of a large plasmoid ejection is highly unlikely in the model. Some scientists even suggest that emerging flux is not the direct trigger of the solar flare. It is only a prerequisite. A more critical and more direct trigger of solar flares is the sheared magnetic field structure. Therefore, more attention was paid to building new models that shear the footpoints of magnetic loops arcade.

Sheared Arcade model

By shearing an arcade of magnetic loops, scientists began building new models for solar flares. In sheared arcade models, footpoints on different sides of the arcade are moved in antiparallel directions. This leads to a force-free current that stores magnetic energy by flowing from one side of the arcade to the other side. When the shearing grows, the arcade extends upwards, and more energy is stored.

According to the sheared-arcade model, the helical flux rope is generated by reconnection, and the total flux is tethered to the solar surface. The toroidal flux of the magnetic rope is identical to the constituent of the reconnection flux, which is solely joined at both ends of the helical construction. This portion of the reconnection flux is often tiny compared to the overall reconnection flux. Magnetic reconnection cause twists along the magnetic rope axis by transferring mutual helicity from sheared arcades to magnetic rope's self-helicity. The total figure of twists is proportional to the total figure of reconnections. Along the axis under magnetic flux, reconnection flux is similar to twisted flux, or poloidal flux. Suppose the helix of the flux rope is produced primarily in situ. In this case, the reconnection flux is predicted to be larger than the toroidal flow and conversely near to and probably corresponding to the poloidal flux.

However, to form a coronal mass ejection, the arcade must be disrupted to create an open field configuration to release the energy stored. In a sheared arcade model, no way is found to disturb the arcade. It is suggested that an arcade can never be disrupted. The rearrangement of the footpoints of the arcade can only lead to an extension of the arcade and an increase in energy.

High-temperature turbulent current sheet model

The fast plasma outflows, also known as jets, are the most critical energy source in solar flares. They are also one of the signatures of current sheets reconnection. The velocities of fast plasma outflows approach the Alfvén speed and mostly depend on the temperatures of electrons and ions. The high-temperature turbulent current sheet(HTTCS) model discusses the outflows that originated in the HTTCS reconnection process for both preflare and hot phase conditions. The jets lead to symmetric, nonthermal broadening in the soft X-ray lines observed in solar flares.

Turbulence velocity and nonthermal line broadening in flare onset, according to the model, might be linked to one or more current sheets in which magnetic reconnection is taking place. It supposed the existence of one or a few large reconnecting current sheets or many small sheets as an alternative. Considering the configuration of magnetic fields, we can use Figure 1 is to describe the high-temperature plasma velocity distribution.

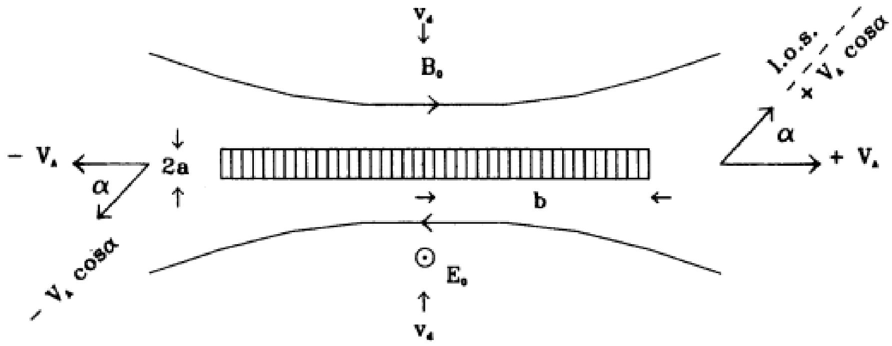

Fig.1 Reconnecting Current Sheet: Magnetic Field Lines and High-Temperature Plasma Velocities[3]

The HTTCS model can be applied when the Alfvén speed is much greater than the drift velocity, and the temperature of the inside plasma is much higher than that of the surroundings. Both conditions are proved true by earlier studies and observations. The Alfvén speed can express the average outflow velocity along the line of sight(LOS):

$$V = V_A \cos\alpha \ldots \qquad \ldots(11)$$

α is the angle between the direction of plasma outflows and the LOS.

The model makes another assumption that there is a balance of magnetic and air pressure across the HTTCS. Thus the Alfvén speed can be written in:

$$V_A(T_s) = \sqrt{\frac{2k}{M}}\left(1+\theta^{-1}\right)^{1/2}\sqrt{T_s} \ldots \qquad \ldots(12)$$

T_s is the electron temperature of the plasma inside the current sheet, θ is the electron-to-ion temperature ratio. The value of θ depends on the state of plasma turbulence in HTTCS.

$$T_{i,s} = \theta^{-1} T_s \ldots \qquad \ldots(13)$$

Thus,

$$V(T_s) = \sqrt{\frac{2k}{M}} f(\theta)\sqrt{T_s}\cos\alpha \ldots \qquad \ldots(14)$$

$$f(\theta) = \left(1+\theta^{-1}\right)^{1/2}. \qquad \ldots(15)$$

As shown in Figure 1, the current sheet has a symmetric shape. The average outflow velocities are directed on opposite sides along the line of sight, leading to broadening the XUV lines ejected by the plasma.

At the flare onset, plasma outflows down the line of sight with equal and opposing velocity components, yielding in a symmetric nonthermal broadening of soft X-ray spectral lines. Flare plasmas exhibit enhanced nonthermal mobility when the energy is initially released in outflows from a reconnecting current sheet. The detected soft X-ray source currently consists primarily of plasma heated in the current sheet and discharged from it at the Alfvén velocity. It has direct information about the reconnecting region. The projected nonthermal velocities are a function of the temperature inside the current sheet, according to the HTTCS model.

CME model

Coronal mass ejections, where solar material is blasted out into interplanetary space from closed magnetic field regions in the solar atmosphere that have not formerly participated in solar wind expansion, are the most common type of disturbance in the corona. The magnetic topology of flux ropes, defined by a sequence of helical field lines wrapped around a central axis, appears to be present in roughly 1/3 of all CMEs in the solar wind. The term “magnetic clouds” is used to describe such CMEs.

Two Dimensional Reconnection in CMEs

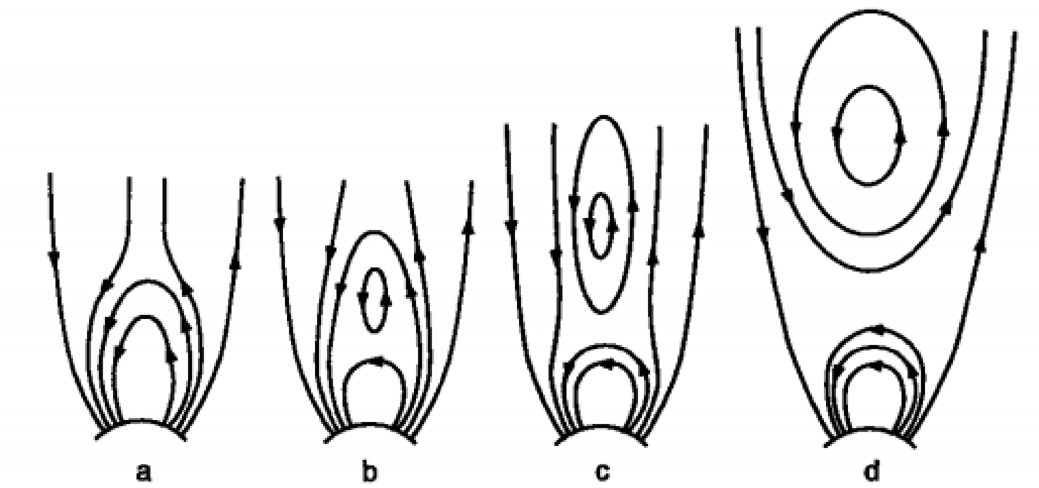

Fig.2 Magnetic Reconnection Amid Rising Coronal Loops in Two Dimensions.[11]

The inner loop is the start of the reconnection process. It forms a closed, separated loop together with a new coronal loop that is connected to the Sun on both ends, as demonstrated in Figure 2-b. Rising loops with footpoints that are becoming more distant away from the loop system's core rejoin later to produce new pairs of coils that are attached and detached, shown in Figure 2-c. In the end, in Figure 2-d, opposite open field lines recombine to produce new coronal loops and U-shaped field lines with both ends linked to the outer heliosphere. Reconnection does not necessarily go through all of these steps and can be stopped at any time. It is tough to imagine how two dimensions of reconnection may create open field lines within CMEs in solar wind. Yet, figure 2 helps to demonstrate the process of magnetic reconnection from a rising loop system’s center moves outward.

This process is challenging to depict directly in 3-dimensional reconnecting drawings, but it follows a pattern identical to the one shown in Figure 2. The image, in addition, shows how, as reconnection continues, connected loops form in progressively greater altitudes in the solar atmosphere. To exemplify this phenomenon, Hiei et al. [1993] presented a beautiful case in the solar atmosphere following a CME emission in their study.

Three Dimensional Reconnection in CMEs

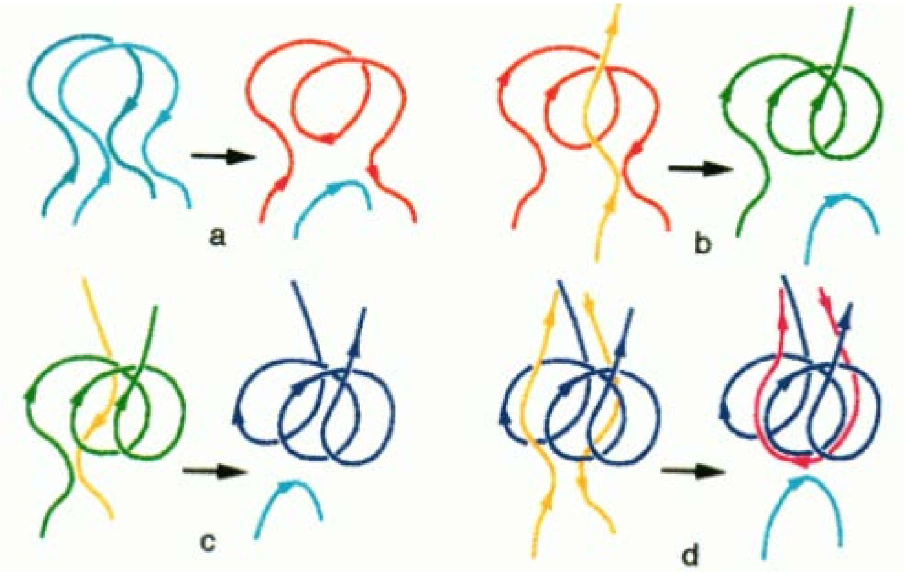

Fig.3 Topologies of Field Resulting from 3-Dimensional Reconnection.[11]

In figure 3, every part depicts a different step of the reconnection procedure. Figure 3-a shows, in the initial CME (light blue), two sheared loops reunite and thus produce a helical field line (red) with both ends linked to the Sun and a lower closed flux loop in the corona (light blue). It is considered as the fundamental mechanism where interplanetary flux ropes are created. The reconnection might be limited to two neighboring loops, as illustrated, or it can involve three or more loops that have been linked together. Counterstreaming fluxes of suprathermal electrons coming from different field lines differentiate field lines connected to the Sun with the two ends in interplanetary space.

The reconnection in a closed plasmoid field line (red) and an open solar wind field line (yellow) occurs in Figure 3-b, producing a new coronal loop (light blue) and an open plasmoid field line (green). A stream of suprathermal electrons would then expose the open plasmoid field line in interplanetary space. A plasmoid field line (dark blue) which is connected to the outer heliosphere at both ends and another new coronal loop (light blue) is formed by the combination of an open plasmoid field line (green) and an open steady solar wind field line (yellow). Because high-temperature electrons along the field line quickly escape to the outer heliosphere, this disconnected plasmoid field line would be observed as a dropout in the flow of suprathermal electrons in the solar wind. Surprisingly, the dropout could be observed both in the plasmoid and in the region immediately around it. Finally, another new coronal loop (light blue), together with the formation of a U-shaped field line (magenta) which is separated from the Sun and which circles the plasmoid, is caused by the reconnection of two open fields lines of the standard solar wind (orange) in Figure 3-d. The U-shaped field line likewise causes a dropout flow in the suprathermal electron.

CMEs, according to popular belief, generate more magnetic flux into interplanetary space. The reconnection process in CME otherwise decreases the amount of flux. It is worth noticing that when reconnection reaches the point depicted in Figure 3-b, the CME provides no open magnetic flux to interplanetary space. When the CME reaches the location shown in Figure 3-c, it causes a net reduction in available magnetic flux in the interstellar medium while raising the number of flux blocked off near the Sun.

Field lines stringing the core of the plasmoid are exposed to conventional open field lines of reverse polarity at the bottom of the plasmoid at the terminals of the overall loop system due to the shear of the initial CME loops. These are the plasmoid field lines that open up first in models for the geomagnetic tail situation. Consequently, a plasmoid can include a wide range of field topologies at the same time. A non-reconnected growing magnetic loop in the plasmoid's interior may interact with a plasmoid field line jointed the Sun and an open plasmoid field line. It is important to notice that reconnection along the flanks of the sheared loop system might result in open or unconnected field lines in the plasmoid's center.

The simple truth that many CMEs have a flux rope topology and that additional coronal loops frequently emerge in solar atmosphere shortly after CME leaves the Sun, however, implies that, in general, the first state in the 3-dimensional reconnection process depicted in Figure 3-a happens frequently. Other investigations of brief intervals of open field lines contained in CMEs also indicate that the second stage depicted in Figure 3-b occurs on occasion. Moreover, we believe that such reconnection is the most plausible interpretation for the emergence of open field lines in CMEs. It also explains the comparatively uncommon CMEs that lack the counterstreaming electron signal near and beyond 1 AU. Furthermore, we are aware of rare occurrences in which the suprathermal electron flow is lost for short periods (usually 1/2 hr at 1 AU) within CME-like regions or in the adjacent plasma. These imply that CMEs sometimes are partially or even totally disconnected from the Sun.

Suprathermal electrons detected in interplanetary space originate primarily from the solar corona. These electrons travel nearly without collision along with the IMF and act like sensitive probes to track the magnetic topology of solar wind disturbances in the lack of magnetic connections to powerful interplanetary shocks or planetary bow shocks, which may either lead to high-temperature electrons in interplanetary space. Many field lines in CMEs are yet connected at both ends to the Sun as simple loops or reconnected field lines, according to studies of suprathermal electron fluxes between 1 and 5.4 AU.

6. Conclusion

Most people accept solar flares to be caused by the Sun's magnetic field. However, if magnetic reconnection is required to explain solar flares is still up for debate. The main argument for assuming that reconnection happens during flares is that it is the only process that can give a reasonable answer to the transmission of flare loops through the chromosphere and corona presented thus far.

In theory, magnetic energy can be stored and released efficiently if magnetic reconnection occurs quickly. But only one model, the magnetic-flux-rope model, gives a realistic mechanism for a current filament ejection into an interstellar medium when simultaneously lowering the system's total magnetic energy. A current filament is suspended in the corona by a combination of magnetic compression and tension in the flux-rope model. Through compressing the field lines caught between the photosphere and the filament, the filament is pushed higher. In contrast, the filament is caused downwards by the tension of field lines linked to the photosphere and crossing the filament.

The magnetic topology of CMEs coming from 3-dimensional reconnection in the solar wind is investigated. The geomagnetic tail is an analogy since thorough simulations of 3-dimensional reconnection in a roughly identical shape are accessible. Disconnected field lines that wrap back on themselves are uncommon in three dimensions; instead, disconnected field lines are generally connected to the outermost heliosphere on both ends. 3-dimensional reconnection not only includes a plausible reason for the development of the flux rope field topology found in many CMEs, but also gives a better description for the existence of open field lines deeply ingrained within certain CMEs on rare occasions. Field lines connected to the outer heliosphere at both ends may sometimes be found within CMEs and in the neighboring solar wind plasma. The reconnection occurrences detected in solar wind have comparable analogs in those reported in numerical simulations of MHD turbulence, according to data analysis. Solar wind measurements can yield an ideal testing ground for evaluating the theory of turbulent reconnection prediction quantitatively with in situ reconnection data.

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