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Tutorial Review

Initiation of CMEs: A review

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ABSTRACT

Solar coronal mass ejections (CMEs) are a striking manifestation of solar activity seen in the solar corona, which bring out coronal plasma as well as magnetic flux into the interplanetary space and may cause strong interplanetary disturbances and geomagnetic storms. Understanding the initiation of CMEs and forecasting them are an important topic in both solar physics and geophysics. In this paper, we review recent progresses in research on the initiation of CMEs. Several initiation mechanisms and models are discussed. No single model/simulation is able to explain all the observations available to date, even for a single event.

Contents

1. Introduction

The white-light coronagraph on board NASA's seventh Orbiting Solar Observatory (OSO-7) detected the first "modern" coronal mass ejection (CME) on December 14, 1971 (Tousey, 1973). A CME is an observable change in coronal structure that occurs on a time scale of a few minutes to several hours and involves the appearance and outward motion of a new, discrete, bright, white-light features in the coronagraph field of view (Hudson et al., 2006). Large-scale transient releases of solar matter into interplanetary space occur in the form of coronal mass ejections (CMEs) (Hundhausen, 1999). It is now widely recognized that CMEs are the most important manifestation of solar activity that drives the space weather near Earth (Gosling, 1993, 1994). LASCO coronagraph observations from SOHO have been interpreted as evidence that even halo CMEs do not encircle the Sun in 3D but these "halo" CMEs "completely encircle the Sun" in projection on the plane-of-sky only (Howard et al., 1997).

Apart from being the primary cause of major geomagnetic disturbances, CMEs are also a fundamental mechanism by which the large-scale corona sheds helicity (Rust, 2003) and, hence, may play a central role in the solar cycle. Therefore, an understanding of the mechanism for CME initiation has long been a primary goal of solar physicists.

Early models for CMEs proposed that the eruption is driven by explosive flare heating, but it is now known that many CMEs occur with little detectable heating, especially those originating from high-latitude quiet regions. It has also been proposed that CMEs may be due to magnetic buoyancy effects (see, e.g., Low, 1994;

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Wu et al., 1995; Wolfson and Dlamini, 1997), but this would imply that CMEs should be associated with large masses of falling material. During prominence eruptions, material can sometimes be observed to fall back onto the chromosphere, but CMEs often occur with very little evidence for downward moving plasma. Coronagraph observations usually show all the CME plasmas moving outward, in which case buoyancy is unlikely to be the driver. These considerations have led most investigators to conclude that the energy for the eruption must be stored in the magnetic field.

The temporal ordering of CMEs and flares is also demonstrated by using soft X-ray data from Yohkoh and data from the HAO ground-based coronameter. Kahler (1992) concluded that the relationship between flares and CMEs was still unclear, but suggested that flares appear to be a consequence of CMEs. The CME opens up an initially closed coronal magnetic field to eject the mass that was previously trapped in the closed magnetic field. This is followed by reconnection of the open field lines through a dissipative MHD process resulting in a flare, as modeled by Kopp and Pneuman (1976).

The pre-eruptive configuration of a CME is generally characterized by the presence of magnetic shear, the presence of a prominence seating in the configuration along the polarity inversion line, and the occurrence of flux cancellation in the active region (Wang and Sheeley, 2002; Welsch, 2006; Dalda and Martinez Pillet, 2008), and its topology may be either simple or complex. It is to be expected that the magnetic field topologies above active regions would be more complex and depend more on local fields (Li and Luhmann, 2006).

Several mechanisms have been proposed to trigger the CME initiation, e.g., the photospheric converging and shear motions (Forbes et al., 1994; Mikic and Linker, 1994; Antiochos et al., 1994), flux emergence (Feynman and Martin, 1995; Chen and Shibata, 2000), and cancellation (Zhang et al., 2001). Kink instability of coronal flux ropes has attracted more and more attention. Sakurai (1976) was the first to attribute kinked flux ropes to eruptive filaments. Plunkett et al. (2000) found that the writhing took place in a prominence-associated CME. Filament eruptions resulting from the kink instability were reported by several authors (Rust, 2003; Rust and LaBonte, 2005; Williams et al., 2005). In these studies, filaments were taken as magnetic flux ropes, which appeared to be a central component in theoretical modelings. The drainage of plasma from a prominence is also a possible cause for the flux rope to be accelerated (Tandberg-Hanssen, 1974; Gilbert et al., 2000). There have been many analytical and numerical models in which magnetic reconnection are found to play an important role in accelerating the flux rope/prominence after the kink instability or catastrophe occurs (Zhou et al., 2006 and references therein). The magnetic breakout model of Antiochos et al. (1999) suggests that the magnetic reconnection at the top of sheared core fields is fundamental in triggering CME onsets. Recently, a two-current-sheet reconnection scenario has been proposed to account for both the magnetic breakout and the standard flare models (Zhang et al., 2006).

CMEs are frequently associated with the eruption of large-scale, closed magnetic field regions in the corona, known as helmet streamers (Hundhausen, 1993). Prior to eruption, the streamer is often observed to swell and brighten, before lifting off as a loop-like structure that connects back to the Sun. Within this loop, a dark void or cavity is often observed, corresponding to the low density region near the coronal base of the quiescent streamer. A compact bright feature called the core is sometimes observed within the cavity. This core is cool, dense material that may have been the prominence suspended in the streamer cavity prior to eruption. Three-part structure (frontal structure, cavity, and core) of CMEs and the coronal helmet streamers are well observed in eclipse pictures (Saito and Tandberg-Hanssen, 1973). Fig. 1 shows the three-part structure of a CME. The helmet-streamer structure is a large-scale closed field region. The closed field part of the streamer deforms to become the frontal structure of the CME, followed by the coronal cavity and the prominence core (Hundhausen, 1999). The pre-eruption configuration in active regions is probably similar, except for the height of the filament and the strength of the overlying magnetic field. Transequatorial and interconnecting structures may result in CMEs without a prominence core. However, multi-arcade eruptions that span more than one closed region may still contain a prominence core from one of the underlying flux systems (Gopalswamy, 2003). Not all CMEs have this three-part structure (Wu et al., 2001).

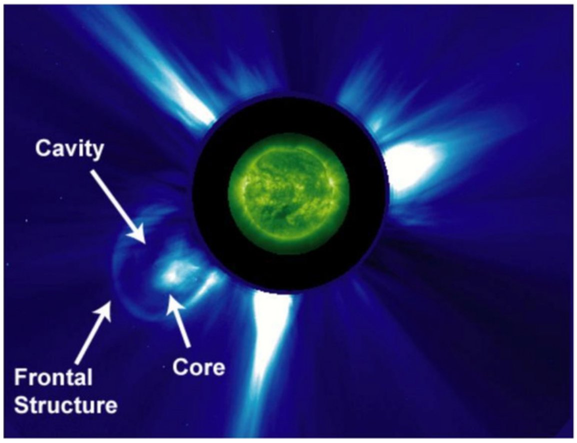

Fig. 1. SOHO/LASCO image (with an EIT 195 image superposed) obtained on 2001 December, 20 showing the three-part structure of a CME above the southwest limb [taken from Gopalswamy et al., 2006].

The internal structure of many CMEs can be observed in some detail in the LASCO images. About one-third of all CMEs observed by LASCO contains circular, concave-outward features near their trailing edges (Dere et al., 1999; Plunkett et al., 2000).

The shock-driving CMEs constitute a small fraction (a few percent) of all CMEs (Gopalswamy et al., 2003), much smaller than the 20% estimated by Hundhausen (1999). The majority of CMEs are likely to be sub-alfvenic and supersonic. These CMEs must be driving slow and intermediate shocks, as suggested by Whang (1987). Flat-top and concave upward morphology observed in some SMM CMEs are thought to indicate the presence of slow and intermediate shocks (Hundhausen, 1999). Most models dealing with CME initiation assume that that CME is a flux rope coming out of an eruption region to be either pre-existing (Low and Zhang, 2002) or formed during eruption (Gosling et al., 1995). The flux of the envelope field is transferred to the flux rope during the eruption, and at 1 AU only the flux rope is observed (Gopalswamy, 2004). The possible evidence for flux ropes before eruption comes from coronal cavities (see e.g. Gibson et al., 2006).

The origin of CMEs is not clearly understood. In the next section, we will discuss some mechanisms and models of CMEs.

2. Initiation of CMEs

CMEs originate from large-scale closed magnetic field regions such as active and filament/prominence regions. Active and filament regions often form complexes. Large-scale closed field lines can also be found interconnecting active regions. During solar minima, the equatorial streamer belt constitutes a dominant closed field structure.

Except some narrow CMEs, which may correspond to a jet (say, reconnection jet) propagating along open field lines, most CMEs are regarded as an erupting flux rope system, with a typical three-component structure in the white-light coronagraph images, although sometimes one or two components are absent possibly due to observational effect or the plasma has not yet condensed to form a filament at the magnetic dips of the flux rope. Flux rope models obviously start as flux ropes, but every model that contains CHSKP flare reconnection adds relatively unsheared overlying field to the erupting structure that creates a significant twist-component and forms a flux rope during the eruption process.

The formation and eruption of prominences is one of the central issues of CME initiation. The occurrence of prominences/filaments over polarity inversion lines is not necessarily related to the CME eruption itself. Prominences/filaments are indicative of highly stressed, non-potential field (sheared or twisted), and therefore of accumulated magnetic free energy, helicity etc. The formation of filaments is a central issue for the build-up or storage of the magnetic energy, which will then be released later as a CME. The flux rope structure naturally provides the necessary "dip" where the filament can reside (e.g. van Ballegooijen and Martens, 1990), and a reduction in the magnetic flux could cause the flux rope to erupt (Linker et al., 2001). Shearing and twisting of magnetic field lines can produce the necessary dips to support the prominence (Antiochos et al., 1994). Martin and McAllister (1997) suggested that the prominence is simply a flowing material and no dip is needed for support.

It is believed that the energy required to propel the CME has to come from the magnetic fields of the solar source region (see, e.g., Forbes, 2000); estimated coronal volume is 10^{30} cm^3 on considering a large active region (photospheric diameter ~ 5 arcmin). An average coronal field of 200 G over this volume implies a magnetic potential energy of $\sim 10^{33}$ erg. Microwave observations of the corona above sunspots have shown magnetic fields exceeding 1800 G (White et al., 1991), so an average of 200 G is not unreasonable (Gopalswamy, 2004). The highest value of potential magnetic energy in active regions surveyed by Venkatakrishnan and Ravindra (2003) is also $\sim 10^{33}$ erg. Since the potential magnetic energy is probably smaller than the total magnetic energy by only a factor < 2 (Forbes, 2000), Gopalswamy (2004) infers that occasionally a substantial fraction of the energy contained in an active region may be released in the form of a CME. Because a CME not only carries a certain amount of coronal plasma to infinity but also opens up the originally closed magnetic field anchored to the Sun. The pre-eruption state must store enough magnetic energy to account for the energy needed to open up the magnetic field in addition to the gravitational potential and kinetic energies of the CME.

2.1. The standard flare–CME relationship

In the classical reconnection model, oppositely directed magnetic field lines get stretched out to form a current sheet defined by a diffusion region where the magnetic field reconnects, releasing energy (e.g. Kopp and Pneuman, 1976). The catastrophic loss of equilibrium occurring in a coronal magnetic configuration somehow re-activates the Kopp–Pneuman-type models of solar eruptions (Kopp and Pneuman, 1976). The closed magnetic field in the corona is so stretched in the catastrophic process that it is usually thought to 'open' to infinity and a local Kopp–Pneuman structure is formed including a thin current sheet (Fig. 2). In most reconnection models the formation, or at least presence, of a current sheet is crucial for reconnection to occur.

Magnetic reconnection invoked by plasma instabilities inside the current sheet eventually not only creates the separating flare ribbons on the solar disk and growing post-flare loop systems in the corona (Forbes, 2003), but also helps the extended part of the magnetic structure escape into the outermost corona and interplanetary space (see Lin and Forbes, 2000; Forbes and Lin, 2000; and Lin, 2002), resulting in CMEs and the consequent disturbance in space.

The loss of equilibrium is a sudden transition from one quasi-equilibrium state to another, where the final state typically has a greater flux rope height than the initial state. In the 2D model, Forbes and Lin (2000) slowly move the point sources for the overlying restraining field, so the system evolves quasi-statistically until the bifurcation point and a jump in flux rope height become energetically favorable. They conjecture that this loss of equilibrium jump is what triggers the large-scale current sheet formation, and that magnetic reconnection is required at the current sheet to allow the flux rope to escape to infinity (otherwise the flux rope is perfectly happy to sit there at its new height in a slightly lower energy state). In some sense, the kink instability or other ideal MHD instabilities may be considered to lead to the loss of equilibrium in 3D.

Lin (2004) shows that the magnetic configuration that determines the catastrophic loss of equilibrium starts before any magnetic reconnection site appears, and the onset of a CME taking place in such kind of configuration always precedes the associated flare.

Fig. 2 schematically indicates how a CME process in the high corona and space is intrinsically related to a traditional two-ribbon flare process.

Initial models based on the assumption of flare produced CMEs (Dryer, 1982) have largely been abandoned because CME onset often precedes flare onset (e.g., Wagner et al., 1981). After this, the emphasis shifted to loss of equilibrium (Low, 1996).

The model of catastrophic loss of equilibrium consists of two main phases:

1. The opening of a closed magnetic configuration, originally supposed to be closely related to the eruption of a filament/prominence, which creates an inverted Y-shaped magnetic configuration with a current sheet extending to greater heights above a closed magnetic configuration.
2. Long-lasting magnetic reconnection in this current sheet leading to the energy release in the main flare phase.

The later includes the partial reclosing of the configuration by reconnected field lines in the downward reconnection outflow. The released energy is dumped at the magnetic foot points in the chromosphere by energetic particle precipitation and heat conduction. These results in the formation of flare ribbons and of hot and dense flare loops through chromospheric evaporation; these loops turn later into cooling post-flare loops.

The study of Forbes and Isenberg (1991) of the energetics of the flux rope implied that there is enough magnetic energy stored in the flux rope to fuel a CME. Another aspect in understanding the initiation of a CME is to study the stability of a magnetostatic corona.

Models (Lin and Forbes, 2000; Linker et al., 2001) predict that an extended, long-lived current sheet must be formed for any physically plausible reconnection rate. Formation of the current sheet in such a configuration drives conversion of the free energy in the magnetic field to thermal and kinetic energy, and can cause significant observational consequences, such as growing

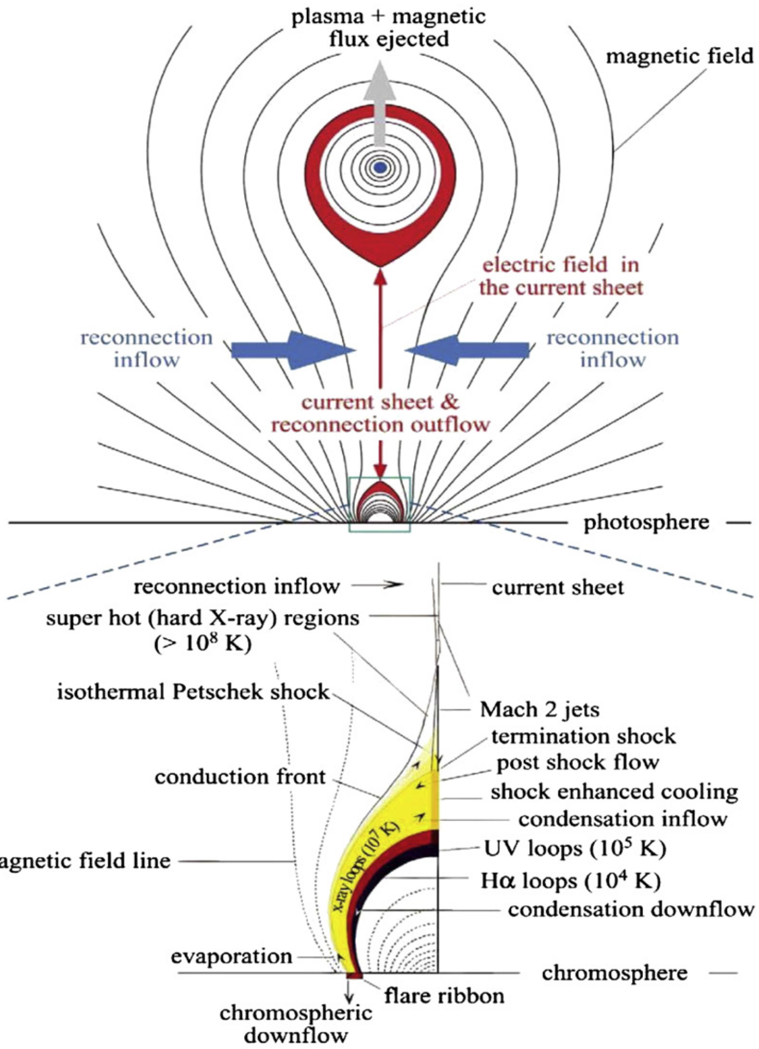

Fig. 2. Schematic diagram of a disrupted magnetic field that forms in an eruptive process. Catastrophic loss of equilibrium, occurring in a magnetic configuration including a flux rope, stretches the closed magnetic field and creates a Kopp–Pneuman-type structure [taken from Lin, 2004]. Upper part: sketch of the flux rope/CME model of Lin and Forbes (2000), showing the eruption of the flux rope, the current sheet formed behind it, and the post-flare/CME loops below, as well as the inflows and outflows associated with reconnection. Lower part: enlarged view of the post-flare/CME loops (from Forbes and Action, 1996).

post-flare/CME loop system in the corona, and fast ejections of the plasma and the magnetic flux. In order to confirm the role of reconnection in CME initiation, it is therefore necessary (although not sufficient) to determine whether current sheets can be identified behind an erupting CME. Such a current sheet would be extremely thin due to the high electrical conductivity of the solar corona (Ko et al., 2003), making observation of this phenomenon difficult.

Recently, a number of investigations have confirmed the presence of large-scale narrow structures behind an erupting CME suggestive of the classic current sheet topology. Sui and Holman (2003) have reported the formation of a large-scale current sheet associated with an M1.2 flare observed by RHESSI on 15 April 2002. This conclusion is based on a number of different observations. The temperature structure of this flare suggests that a current sheet formed between a source high in the solar corona and the top of the flaring loops (Schwenn et al., 2006).

CME eruptions observed in white light and UV coronagraph data have also pointed to the existence of current sheets in the corona. Webb et al. (2003) show that bright rays observed in conjunction with CMEs and SMM are consistent with the existence of current sheets lasting for several hours and extending more than 5 solar radii into the outer corona. The evidence for current sheets was further strengthened by UVCS observations, which exhibited a very narrow and a very hot feature in the Fe XVIII line between the arcade and the CME, consistent with the eruption driven current sheet predicted by initiation models (Ciaravella et al., 2002). Ko et al. (2003) found the properties and behavior of the observed plasma outflow and the highly ionized states of the plasma inside these streamer-like structures expected from magnetic reconnection in a current sheet (Schwenn et al., 2006).

2.2. *Emerging flux mechanism*

Early in the 1970s, it was found that weak X-ray activities often precede solar flares (Datlowe et al., 1974), which were described as the soft X-ray precursor of CMEs by Harrison et al. (1985). Flux emergence has been considered as a possible trigger of CMEs, which initiates small-scale reconnection near the filaments. Feynman and Martin (1995) examined the magnetic flux in the source regions of CMEs associated with filament eruptions and found that many CMEs are strongly associated with emerging flux that possesses polarity orientation favorable for magnetic reconnection between the emerging flux and the pre-existing coronal field either inside or outside the filament channel. Feynman and Martin (1995) also reported that the distance of the emerging flux from the filament channel was also important. If the new flux appeared within the channel, then either polarity (favorable or unfavorable) would trigger an eruption, and it was only when the emergence occurred outside the channel, the polarity was important (Lin et al., 2001). In the model of Lin et al. (2001), there is no single relation between the distance of the emerging flux and the importance of the emerging bipole's polarity, but there is some tendency or such a behavior to occur. Wang and Sheeley (1999) studied a set of filament eruptions and confirmed the strong correlation between CMEs and reconnection-favorable emerging flux and concluded that flux emergence serves as a catalyst, rather than a trigger of the filament eruption. The study of Lin et al. (2001) suggests that the eruptions observed by Feynman and Martin (1995) and Wang and Sheeley (1999) were most likely to be triggered by new flux produced by sources moving upwards.

Lara et al. (2000) found significant changes in the flux at the time of CMEs in small sub-regions within the overall regions of eruption. The flux change was also observed during flares without CMEs, but the largest changes were found at the times of CMEs. When the flux from the entire region of eruption was tracked, the changes were not significant. The flux changes were also found to be substantial only close to the photospheric neutral line. Subramanian and Dere (2001) found flux emergence in many cases of CMEs events studied by them, but there were eruptions with no substantial flux emergence.

Coronal dimming represents depletion of material in the corona (Hudson et al., 1998). Therefore, pre-eruption dimming may correspond to small-scale opening of magnetic field lines in the eruption region.

Using numerical simulation, Chen and Shibata (2000) demonstrated the eruption of arcades overlying the filaments as CMEs due to reconnection between emerging and existing magnetic field lines. In Chen and Shibata's (2000) model, the emerging flux can trigger magnetic reconnection and cause a pre-existing flux rope to have a CME-like expulsion.

Chen (2008) proposed an emerging flux trigger mechanism for CMEs. As shown in Fig. 3 by Chen (2008), when the reconnection-favorable emerging flux appears inside the filament channel, it will cancel the small magnetic loops near the polarity inversion line. Then, the magnetic pressure decreases locally. When the reconnection-favorable emerging flux appears outside the filament channel, it reconnects with the large-scale magnetic arcades that cover the flux rope. The magnetic tension force along the curved field line pulls the arcades to move upward, with the flux rope following immediately. The rising flux rope pulls the overlying field lines up, and a current sheet is formed near the null point below the flux rope. Similarly, the magnetic reconnection at the current sheet leads to a two-ribbon flare and the fast eruption of a CME.

This model shows that the onset of the CME is triggered by the localized reconnection between emerging flux and the pre-existing coronal field. It is however, not clear whether the small-scale energy release is a consequence of the lifting off of the cavity or overlying arcade.

2.3. Flux cancellation mechanism

Flux cancellation is another mechanism that can trigger CMEs (Mikic and Lee, 2006; Forbes et al., 2006). The process of flux cancellation has been defined observationally as the mutual disappearance of magnetic fields of opposite polarity at the neutral line separating them (Martin et al., 1985). Flux cancellation has also been identified as a key element in the formation of prominences and filaments (Gaizauskas et al., 1997; Martin, 1998; Litvinenko and Martin, 1999; van Ballegooijen et al., 2000; Martens and Zwaan, 2001).

Because of the close relationship between flux cancellation and solar eruptions, the role of flux cancellation in prominence formation, eruption, and CME initiation has been studied extensively using numerical models (Gopalswamy et al., 2006 and references therein). Amari et al. (2000) considered bipolar case and suggest that flux cancellation leads to the formation of a twisted flux rope in equilibrium, which may be able to support a prominence in its magnetic dips, and eventually to a non-equilibrium phase during which the configuration experience a global disruption. Amari et al. (2000) also show that flux cancellation is not only a trigger driving the eruption of a configuration, which has already stored most of its free energy, but it also plays a role in the storage process itself by causing the free energy to increase considerably. Welsch (2006) showed flux cancellation can increase the relative free magnetic energy. Linker et al. (2003) and Roussev et al. (2004) have run simulations of flux cancellation CME initiation in the large-scale corona. Amari et al. (2007) show that the existence of a non-zero shear in the initial configuration has been obtained by applying twisting motions to a current-free configuration, but it is not to say that this is the only physical process, which may lead to a sheared coronal field. Shear can be also produced by the emerging of current carrying flux-tubes, or it may be left as a remnant of previous disruption in which the field has not fully relaxed to a current-free state , but only to a linear or nonlinear force-free one.

These models show that a magnetic configuration subject to flux cancellation can initially exhibit stable behavior with a magnetic field topology that can support prominence material. The configuration erupts when flux cancellation is continued beyond a critical value presumably because the outward magnetic

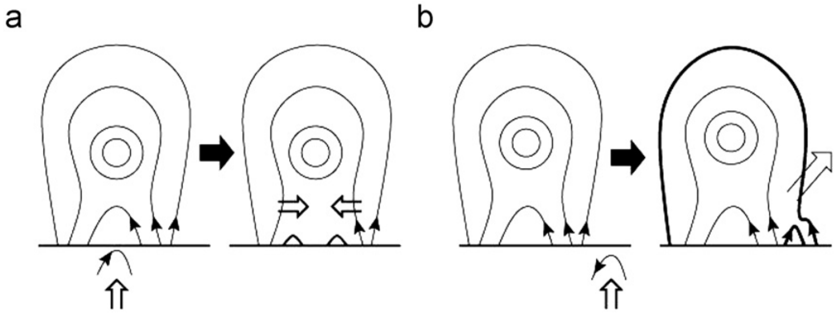

Fig. 3. Schematic diagram of the emerging flux trigger mechanism for CMEs [taken from Chen, 2008].

pressure from the flux rope/arcade becomes greater than the downward magnetic tension of the overlying field. When the configuration is close to the critical state, even a small amount of flux cancellation can trigger a violent eruption. Hence, the triggering event may appear to be unremarkable in photospheric magnetograms.

2.4. Breakout model

Antiochos (1998); Antiochos et al. (1999), DeVore and Antiochos (2008); Lynch et al. (2004) develop a model, which describes the eruption of multipolar topology configuration wherein the reconnection between sheared arcade and neighboring flux system triggers the eruption and allows the CME to escape into interplanetary space, called "Breakout model". Breakout model is based on a 2.5D numerical simulation carried out using an ideal MHD code in spherical geometry and it requires a multipolar magnetic field. Antiochos et al. (1999) in their 2.5D numerical simulations placed a sheared arcade in an overlying weak opposite polarity field. This configuration created a multipolar topology in which reconnection between the sheared arcade and neighboring flux systems could trigger an eruption. In this "magnetic breakout" model, reconnection "removes" the unsheared field above the low-lying, sheared core flux near the neutral line, thereby allowing this core flux to burst open (Fig. 4). The opening is only partial. The eruption is driven by the magnetic free energy stored in the closed arcade. The shear could be produced by emergence of flux or motions in the photosphere.

van Driel-Gesztelyi et al. (2000) suggest that a large-scale complex magnetic topology is a necessary condition for "magnetic breakout" model and also suggest that twisted magnetic configurations are good candidates for being the source regions of CMEs because the twisted field indicates stored magnetic energy for sigmoid expansion related CME events.

Antiochos et al. (1999) arrived at two important conclusions:

(i) very low-lying magnetic field lines at the photosphere can open toward infinity during a eruption; and (ii) the eruption is driven solely by magnetic force and the energy is stored in a closed, sheared arcade.

The coronal magnetic topology is due to a multipolar flux distribution at the photosphere and it contains at least one null point where reconnection can occur as an essential signature of a CME. The multipolar field topology has an important theoretical implication for energy storage and it demonstrates an interesting way to bypass the constraints of the aly-conjecture (Aly, 1991, Sturrock, 1991) which states that, as the field opens up in space, the magnetic energy of the system must increase. Only the central bipolar lobe of the multipolar field has to open up but not the whole coronal field (Zhang and Low, 2005). Breakout cannot operate in a truly bipolar field. Breakout requires the occurrence of external reconnection that transfers a substantial amount of flux from the overlying erupting filament channel.

Breakout model requires strongly sheared fields near the neutral line as observed in filament channel. In breakout model,

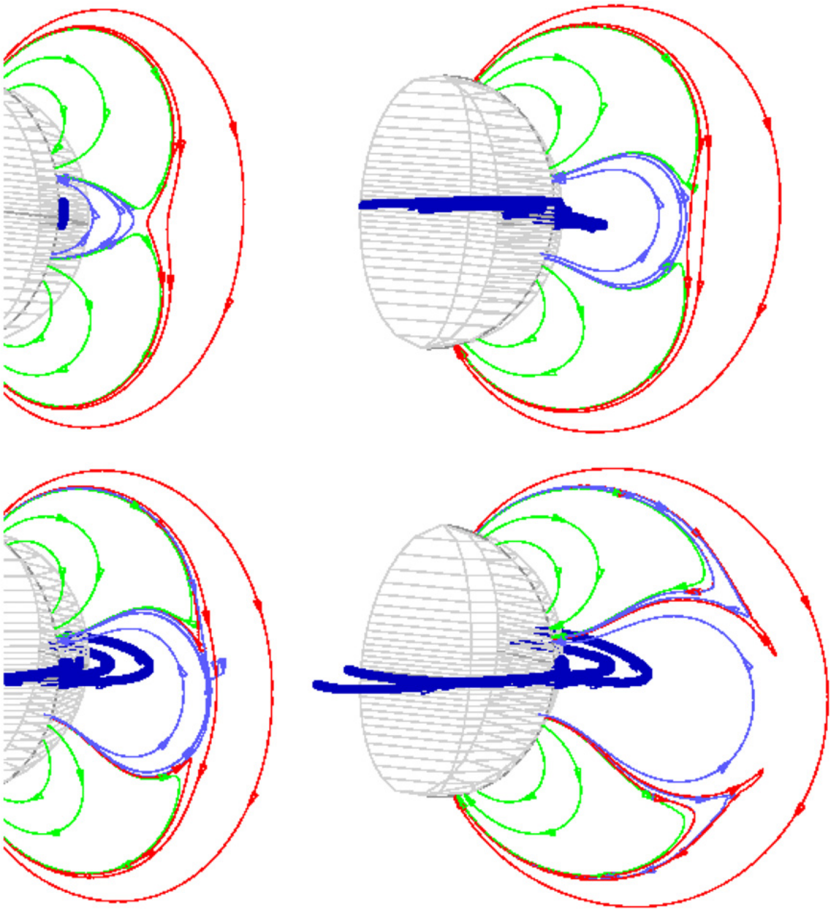

Fig. 4. Schematic of breakout model (taken from Antiochos et al., 1999). The first sketch shows magnetic field configuration at an early stage and the second at a later stage of eruption. A force-free current is created by shearing the arcade (thick lines) at the equator but a current layer horizontal to the solar surface is also created as the sheared region bulges outward. The process of reconnection of magnetic field lines in this layer allows opening of the sheared field line outward to infinity.

the reconnection of the high field lines in the arcade with the overlying field lines in the surrounding flux system releases the magnetic tension that holds down the central arcade (Mikic and Lee, 2006).

The breakout model is expected to be insensitive to the details of the filament channel formation process. Breakout model works for either flux emergence or cancellation, and either a sheared arcade or a twisted flux rope whereas most of the other models require a particular form for the photospheric evaluation and the filament field in order to obtain eruption (Forbes et al., 2006).

MacNeice et al. (2004) resolved the numerical cavitation issue in Antiochos et al. (1999) and showed full flux rope formation and followed the CME propagation to ~20 Rs. Lynch et al. (2004) analyzed the 2.5D simulation for general observational properties. DeVore and Antiochos (2008) showed the breakout mechanism works in 3D for a four-flux system with a null line in the corona and Lynch et al. (2008) showed the breakout mechanism works for a more general two-flux system in 3D with a true coronal null point.

2.5. Other mechanisms

Magnetically dominated configurations generally involve a balance between the upward force of magnetic pressure and the downward force of magnetic tension. The field lines that provide the tension are sometimes called tethers. Moore and LaBonte (1980) show that the reconnection occurs between elements within the core field causing the eruption is tether-cutting magnetic reconnection. Sturrock et al. (1984) proposed a tether-cutting model based on reconnection, which occurs in initially sheared bipolar arcades, leading to the formation of a magnetic island or plasmoid, which is then ejected. When a rope is cut, two free ends are created. This can never happen to a magnetic field line, since it would imply the existence of magnetic monopoles. Instead, a pair of magnetic field lines (or two sections of a single field line that doubles back on itself) reconnects at a point of contact to produce two new field lines with different connectivity (i.e., different topologies) from the original pair. On observing quiet Sun prominence eruption, Sterling and Moore (2003) show that there are flare-like brightness occurring beneath the rising prominence, which is consistent with the magnetic field lines (tethers) that hold the prominence in place for magnetic reconnection.

Low (1981) investigated the quasi-steady evolution of solar magnetic fields in response to gradual photospheric changes and established a threshold for sudden eruptions in the solar atmosphere. This sudden eruption causes the originally closed magnetic field configuration to become open, such that the plasma can be ejected from the surface. Magnetic energy is believed to be the major source of the energy to propel CMEs. A 1D model to demonstrate that the CME is magnetically driven was constructed by Anzer (1978). Yeh (1989) presented a theoretical, magneto-hydrodynamic model for coronal loop transients {combining occasionally phenomena with coronal loops, sometimes shear and twist in the coronal loops (when increased to a critical limit of the twist) may trigger the flare and eruption}. He showed that the sideways motion of a transient loop, as exhibited by the translational displacement of the axis of the loop, is driven by the magnetic force exerted by the ambient medium.

Low (1984) presented a set of exact, analytical, self-similar solutions of magneto-hydrodynamic flow to illustrate white-light coronal transients (sudden change in the coronal structures i.e. flare, CMEs). This assumes that the coronal transient is a result of a hydromagnetic system becoming gravitationally unstable in the lower corona.

Observations have shown various kinds of evolving magnetic structures. van Ballegooijen and Martens (1989) proposed that the converging motion of magnetic arcades, by which a filament may be formed, can also lead to the destabilization of the filament. Mikic et al. (1988) found that after large enough shear, the closed magnetic arcades would asymptotically approach the open field, while a resistive instability can result in the eruption. Kusano et al. (2004), however, found that reversed magnetic shear could also trigger the eruption. Chen et al. (1997) and Krall et al. (2001) proposed that the injection of poloidal magnetic flux into the flux rope would cause the flux rope to erupt.

The "injection of poloidal flux" model relies on increasing the net line current associated with the flux rope structure and it is the imbalance of the jxB hoop force associated with the increased line current that drives the eruption. Physically, this scenario is much closer to the torus instability (Kliem and Torok, 2006). However, it is by no means obvious that large-scale net current structures can be formed and maintained in the solar corona especially because of the recent discovery of the lack of photospheric net currents in Hinode vector magnetograms of sunspots (Venkatakrishnan and Tiwari, 2009). Many eruption cases have been used to determine event-specific functional forms of the current (poloidal flux) injection profile used in the Chen et al. (1997) and Krall et al. (2001) model flux rope. The kink instability is an ideal MHD instability that, after a critical twist threshold is reached, attempts to minimize the twist energy of the system by making the flux rope axis longer via a sudden increase in the axial writhe (Torok and Kliem, 2004). Recently, Fan (2009) has shown that it is relatively easy to obtain what is effectively a net current structure by emerging magnetic flux into the corona from below the photosphere. As a current carrying flux emerges into the corona, a shielding current forms around it, so that technically its net current is zero. However, the extensive expansion of the field as the flux emerges into the corona moves the shielding current out to very large distances. What remains in the lower corona is a flux rope that, at least locally, has a net current (Fan, 2009).

Zhou et al. (2006) show that mass drainage seems to play an important role in triggering the eruptions. During the activation phase, some materials in the prominence are seen to drain to the solar surface. Assuming that the materials experience a free fall from the apex of the prominence to the solar surface along a quarter-circle, it will take about 42 min, which is close to the duration of the prominence reactivation phase. So Zhou et al. (2006) suggest that gravity may play an important role, through kink instability and the mass drainage in prominences, in triggering the onset of CMEs, as proposed by Low (2001).

Kuznetsov and Hood (2000) consider a model of quasi-static equilibrium of the twisted magnetic tubes emerging into the solar corona and explain CME as a result of heating and break of equilibrium of the emerging tubes in the transition zone. They show that loops losing a larger amount of mass (slow rise of fast mass outflow) are not subjected to eruptive instability, whereas the loops losing less mass (fast rise of slow mass outflow) experience eruptive instability in mass ejection. The warming of the tube in the transition zone is suggested as a mechanism of the pressure increase in the tube leading to the loss of equilibrium.

Klimchuk (1990) suggest that shearing of coronal loop arcade always leads to an inflation of the entire magnetic field and thus a satisfactory fast driver is expected to produce a CME-like expulsion. Such a driver mechanism is called flux injection (Chen, 1989, 1997, 2000; Krall et al., 2000), which corresponds to one of the three scenarios: (1) pre-existing coronal field lines become twisted; (2) new ring-shaped field lines rise upwards in the corona while becoming detached from the photosphere; and (3) new arc-shaped field lines emerge into the corona while staying anchored at their photospheric foot points.

In first scenarios, the problem is that the required foot point motion has to be at least two-orders of magnitude faster than the observed one (Krall et al., 2000). The amount of entrained mass has never been observed and no obvious forces exist to lift the mass; so second scenario become unlikely. The third scenario with emerging flux is more likely but there are issues whether the required increase in vertical flux through the photosphere is consistent with observations (Aschwanden, 2004). The launch of CMEs balances the conservation of magnetic helicity during the solar cycle by simultaneously liberating small-scale twist and large-scale writhe of opposite sign (Blackman and Brandenburg, 2003).

Theoretical studies compare the total magnetic energy in pre- and post-eruptions equilibrium configurations in order to demonstrate the plausible transition from a higher to a lower energy state (Aschwanden, 2004 and references therein). There are two forms of mass loading: (1) by prominences, which are extremely dense, contained in a compact volume, and of chromospheric temperature. The fundamental role played by prominences in the launch of CMEs (Low, 1996, 1999) is supported by the observations with coincident starts of prominences and CMEs; and (2) by a relatively higher electron density distributed over a large volume, which is unstable to the Rayleigh–Taylor or Kruskal–Schwarzschild instabilities, if it overlays a volume of lower density (Aschwanden, 2004). Unstable mass loading over a larger volume is supported by observations of CMEs from helmet streamers that contain lower density cavities (Hundhausen, 1999), but there are also numerous counter examples without any signs of internal low density regions.

3. Discussion and conclusions

In the seventies, it was suggested that CMEs were caused by flare-energy release (Dryer, 1982). This is not supported by the observed time-line that shows that the flare generally appears from minutes to an hour after the CME (Harrison, 1986; Hundhausen, 1999).

A variety of models for flare/CME initiation have been proposed, and they can be classified in several different ways based on their physical attributes (e.g., Forbes, 2000; Klimchuk, 2001).

Appearance of a large-scale closed magnetic field structure on the Sun can be considered as the lowest form of pre-CME evolution necessary for a CME. Thus, the ability of the Sun to impel closed field structure from below the photosphere into the atmosphere is a basic requirement for a CME. Active regions and filament channels are the basic units of closed field structures, which often occur together and in clusters. During solar maximum, a large number of these structures are present on the Sun with a correspondingly higher CME rate. Also the latitudinal distributions of the magnetic regions, governing the locations of eruptions on the Sun, are different between solar maximum and minimum.

Presumably a CME occurs when the balance of forces that maintains an equilibrium is upset. Something causes the upward forces to become dominant over the downward ones. What are these forces? Gravity and gas pressure play important roles in some models. However, the magnetic field dominates the plasma throughout much of the corona ($\beta = 8\pi P/B^2 \ll 1$), especially within active regions and at lower altitudes, and many models ignore the plasma altogether. In this case, the only forces are magnetic (Klimchuk, 2001).

Flux emergence and cancellation, and shear and converging flows are some of the photospheric signatures that indicate energy build-up. During the build-up phase, minor energetic events occur, which are denoted as precursors or pre-eruption energy release. Both thermal (soft X-rays, EUV, Hα) and non-thermal (radio, hard X-rays) precursors have been observed. Sometimes it is difficult to decide whether a pre-eruption energy release is a true precursor or a separate eruption. Even a prior smaller eruption may lead to a bigger subsequent eruption by destabilizing the larger structures in the eruption region. While this simplified picture provides insight, the reality is more complex and we are far from predicting whether an active region is likely to erupt by looking at its evolution prior to eruption.

Antiochos et al. (1999) proposed a magnetic breakout model, i.e.; only the sheared part of the closed field lines near the polarity inversion line is opened during the CME. The essence of this model is that the overlying background magnetic field reconnects with the sheared arcade at the magnetic null point above the latter, by which the constraint over the sheared arcade is removed gradually like an onion-peeling process.

The analytical investigation by Isenberg et al. (1993) illustrates that the gradual decay of the background magnetic field would also cause the flux rope to lose equilibrium catastrophically. The evolving magnetic structure either increases the magnetic pressure below the flux rope or decreases the magnetic tension force above the flux rope; thereby the flux rope cannot sustain its equilibrium (Chen, 2008).

According to the characterization of the photospheric field changes, CME can be triggered through emergence of a newly magnetic flux with a polarity favorable to trigger reconnection processes in an area with pre-existing opposite polarity flux or through the process of continuous cancellation of magnetic flux, or through flux changes in a near-by active region neighboring the filament site that destabilize the magnetic arcade overlying the disappearing filament (Bothmer and Tripathi, 2007).

The process of creating a CME begins long before a coronal structure capable of producing a CME has formed. Magnetic flux systems generated by the dynamo in the solar interior continually emerge through the photosphere into the corona, carrying with them the significant magnetic helicity. The shearing of the field and the introduction of a pre-existing flux rope are different forms of introducing the accumulated helicity in the model. Magnetic reconnection can readily release the excess magnetic energy in each closed magnetic structure of the corona but cannot remove this accumulated helicity. As further flux emergence brings additional helicity into the structure, the field will finally get into a state when the self-confinement of the closed structure fails and a CME-like expulsion occurs as a result. The CME will not only take the mass that had served its role in confinement, but also the trapped magnetic helicity, out into the interplanetary space (Zhang and Low, 2005).

Suzuki et al. (2007) determined the direction of mass ejection by the magnetic field configuration around the source region and the location of the initial energy release in the magnetic field structure.

Amari et al. (2007) show that the topological complexity of a pre-erupting configuration cannot be taken as a criterion for eliminating the flux cancellation model in favor of the well-known breakout model.

Any physical model of solar eruptions has to meet the following requirements for it to agree with the observations. In the first place, any physical model developed to explain solar eruptions has to account for the fundamental trigger of the eruption. Secondly, these models must account for the wide variety of features that form and develop in the eruptive process, such as bright Hα ribbons on the solar disk, rising soft X-ray and Hα loop systems in the corona, and EIT dimmings, among the other phenomena that accompany a solar eruption.

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