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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.

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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).

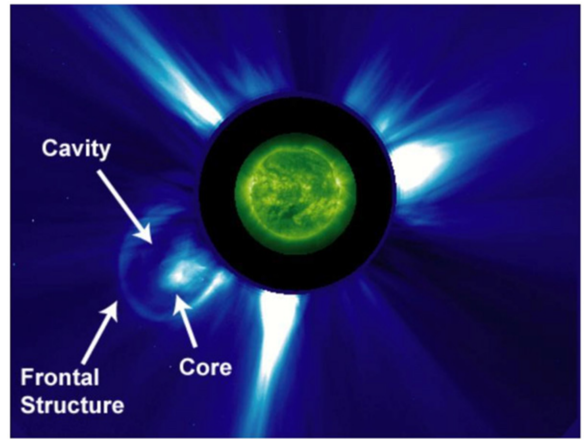

Fig. 1. SOHO/LASCO image (with an EIT 195 image superposed) obtained on 2001 December, 20 showing the three-part structure of a CME above the southwest limb [taken from Gopalswamy et al., 2006].

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