# MAGNETIC AND DYNAMIC PRECURSORS OF CMES

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Abstract

Coronal mass ejections (CMEs) play a crucial role in space weather. They are basically magnetic phenomena and since a decade, important advances have been made in understanding the build up and initiation of CMEs because of the launch of new spacecraft (Yohkoh, SoHO, and TRACE). Many CMEs can be associated to flares and are initiated in a relatively small volume compared with the CMEs themselves. About half of all CMEs can be associated with filament eruption, thus the initiation volume is larger than the flare volume but still much smaller than the CME volume. Generally, flare-related CMEs concern a region with a high magnetic field gradient, shear and twist. The region of a filament-related CME could be in a decay phase and the filament erupts just because of loss of equilibrium due to high and increasing level of shear and twist. We present typical examples for both classes of CMEs and highlight the magnetic processes prior to such events.

Key words: solar magnetic field, CME, flare, precursor.

## 1. Introduction

CMEs, which play an important role in space weather, draw their energy from the available free magnetic energy and involve a large-scale re-organization of the solar magnetic fields. CMEs are fundamentally magnetic phenomena. Thus, to improve CME forecasts we have to find out more about the characteristics of the small and large-scale magnetic field in and around their source region prior to the CME occurrence. The study of the magnetic evolution of CME-producing active regions (AR) showed that CMEs are preceded by magnetic evolution during which the helicity of the source region is increasing due to twisted flux emergence, shearing motions between opposite polarity footpoints of subsequently emerging bipoles and, to a smaller extent, by the differential rotation acting on the emerged flux.

Furthermore, we find short-term magnetic precursors of CME events, typically a combination of major flux emergence, cancellation and fast shearing motions in active regions with strong concentrated magnetic fields prior to flare-related CMEs and small-scale cancellation events along the magnetic inversion line in decayed active regions with low magnetic flux density prior to filament eruption-related CMEs. Magnetic helicity plays a crucial role in the CME initiation process, and the lack or presence of near-threshold helicity in the AR during periods when conditions in it match flaring conditions may be a key difference between conditions leading to confined flares or eruptive CMEs. This point is developed in this issue (van Driel-Gesztelyi et al. 2002) and in Démoulin et al (2002 a,b).

In this paper, we define some basic similarities and differences between flares and CMEs and show examples of magnetic evolution of CME-prolific active regions and magnetic precursors of CMEs based on the magnetic and dynamical evolution on a long time scale or in a few hours before the events.

## 2. Magnetic conditions for important flare activity

The appearance of an active region classified as $\delta$ (umbrae of opposite polarities separated by less than 2 heliographic degrees within the same penumbra; Künzel, 1960), or $\gamma - \delta$ (a complex active region in which the positive and negative polarities are irregularly distributed containing one or more delta spots), especially with high magnetic flux content ($\geq$3-4 $10^{22}$ Mx) increases substantially the probabilities for the occurrence of M and even X-class flares (Zirin & Liggett, 1987; Zirin, & Marquette, 1991; Sammis, Tang & Zirin, 2000). Furthermore, observations of magnetic fields associated with solar flares show that flares are likely to occur close to sunspots in regions where the magnetic field is sheared along the polarity inversion line and (1) the maximum shear angle exceeds 85 degrees; and (2) the extent of strong shear (shear angle greater than 80 degrees) exceeds 10,000 km (Moore, Hagyard, & Davis, 1987; Hagyard, Venkatakrishnan, & Smith, 1990; for models see also: Antiochos, 1998; Antiochos, DeVore & Klimchuk 1999).

Confined flares relieve local magnetic stresses, i.e. free accumulated energy from, on the solar scale, a relatively small volume. Such flares re-distribute, but conserve helicity. On the other hand, eruptive flares liberate stored magnetic energy over a larger volume. They lead to the partial opening of the field and helicity does not remain conserved in a volume on the active region scale (Démoulin et al 2002a). For the occurrence of eruptive flares the presence of a sheared arcade or a twisted flux tube (frequently occupied or manifested by a filament), where *the shear or twist are increasing, seem to be necessary conditions*. The scenarios proposed can be roughly divided into two categories, of which we show two recent examples below.

An eruptive flare scenario, developed for the 14 July 1999 flare, was described by Aulanier et al (2000). These authors showed that shearing motions in a delta-spot led to a field line expansion which caused first a slow, then a fast reconnection in the vicinity of the 3-D null-point present above the AR, and led to partial field line opening. Besides the increasing shear, the complex magnetic topology and the presence of the null-point were necessary conditions in the eruptive flare process, as predicted in the "break-out model" by Antiochos et al. (1999).

in another scenario, which concerns a twisted flux tube, according to Titov and Démoulin (1999) and Fang et al (2000), the flux rope (or filament) loses its equilibrium and moves upward. A current sheet is formed below the filament leading to reconnected lines (cusp), a well-known signature of eruptive solar flares.

## 3. Are the conditions for flare and CME activity different?

About 93 % of the flare activity (only part of them are eruptive!) arises in active regions which contain sunspots (Dodson & Hedeman, 1970), while the span of CME activity is much longer and well extends into the phase of active region evolution when the magnetic field is dispersed and the region is frequently classified as a 'quiet solar region', which contains a filament (van Driel-Gesztelyi et al, 1999). The two classes of CMEs, namely the flare-related CME events and the CMEs associated with a filament (or, on the limb, prominence) eruption are well reflected in the evolution described above: in a young active region with major sunspots mainly flare-related CMEs appear, and as the magnetic flux of the active region is getting dispersed, the non-flare, filament-eruption related CMEs will become dominant. However, since filaments are present even in active regions which still contain strong magnetic field concentrations (spots), and flare events in such regions are associated with the eruption of the filament, mixed cases are not rare.

A high level of magnetic non-potentiality, which is normally associated with flaring young active regions, may persist or can even grow after the strong magnetic concentrations (sunspots) disappear (van Driel-Gesztelyi et al, 1999; Démoulin et al, 2002b). Thus, it is important to follow solar active regions throughout their evolution well into their decay phase and monitor their level of magnetic non-potentiality and CME activity, in order to understand the underlying physics and to enable us to forecast CMEs like the strongly geoeffective 6 January 1997 halo CME, which came from a dispersed magnetic region and had only very weak lower coronal signatures.

In the 'eruptive flare + filament eruption $\rightarrow$ CME' scenario described above (Titov and Démoulin, 1999; Fang et al, 2000) the first step is that a flux rope loses equilibrium and starts rising. However, questions remain *why* the flux rope is present and *why* such loss of equilibrium occurs leading to a CME.

A twisted flux tube can be formed in the corona either by magnetic reconnection in a sheared arcade or by emergence from the convective zone (for a discussion see van Driel-Gesztelyi et al, 2000). Both processes can progressively bring the magnetic configuration to an unstable state. Such eruption of a twisted flux-tube has been proposed by several authors (e.g. Martens and Kuin 1989; Moore and Roumeliotis 1992; Forbes 1992; Lin et al. 1998; Titov and Démoulin 1999). The main characteristics predicted in such models are (i) a sheared arcade and a twisted flux tube embedded in it, (ii) reconnection forms a long sigmoidal loop and short loops in the middle of the arcade, (iii) the sigmoid expands, due to a re-distribution of the twist during the reconnection and a subsequent instability, building a current sheet below it, which creates a cusp above the short reconnected loops. Note that an unstable state is probably reached by increasing shear and/or twist (see Fig.10 in van Driel-Gesztelyi et al. 2000).

## 4. Flare-related CME events in strong magnetic field active regions

The south hemispheric AR 8100 produced at least nine flare/CME events during its disc passage in November 1997 (Delannée et al, 2000). The magnetic topology of NOAA 8100 became complex due to repeated flux emergence at its NW edge (see Fig. 2 in van Driel-Gesztelyi et al. 2001). One of these new bipoles was the primary centre of eight of the nine eruptive events (CMEs), which originated from this region. The magnetic stresses were not high in the AR as a whole (Yan & Sakurai, 2000), but local stresses were created between the fast-moving trailing parts of the new bipoles and the leading spots of the main bipole, since they moved in opposite directions.

There was a significant flux imbalance in the AR due to flux emergence in its trailing part. Flux imbalance forces the AR to develop external magnetic connections. Indeed, large-scale loop connections between the North hemispheric AR 8102 and AR 8100 were seen. The eruption of these large-scale loops made the CMEs truly large-scale (Kahn & Hudson, 2000; Maia et al, 1999).

Delannée, & Aulanier (2000) analysed the flare which occurred on 3 November 1997 at 10:31 UT in the vicinity of the new flux emergence in the NW part of the AR, the positive polarity part of which they refer to as parasitic

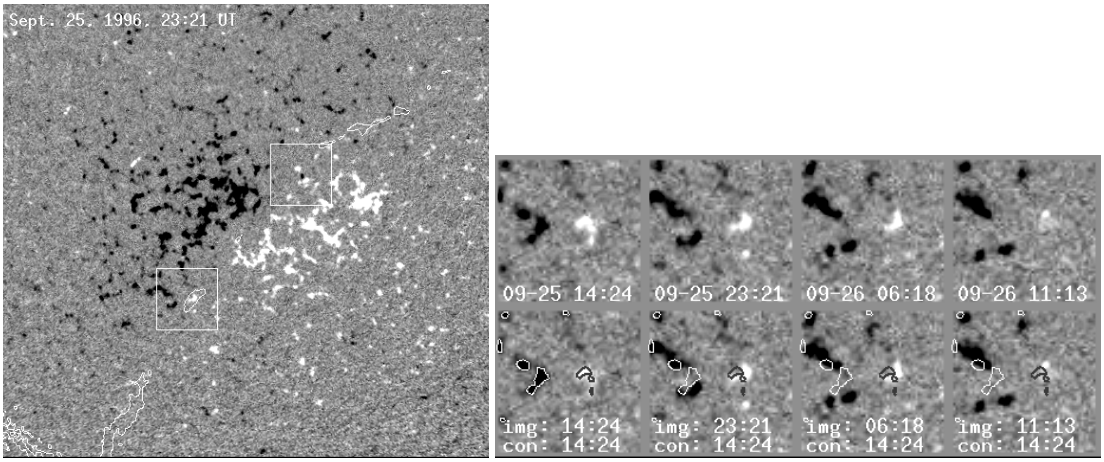


*Figure 1. SOHO/MDI magnetogram of Sept 25, 1996 at 23:21 UT with the 2 boxes where we follow the evolution of the small polarities (e.g. left panel: new emergence and cancellation of magnetic field in the lower box). The contours indicate the position of the Hα filament*

polarity. Using SOHO/EIT 195 Å observations, they identified the brightening of thin transequatorial loops connecting AR 8100 and AR 8102, and dimmings located between the two active regions. EIT difference images showed a loop-like structure rooted near the flare location. The coronal magnetic field derived from potential extrapolations from a SOHO/MDI magnetogram showed that the topology was complex near the parasitic polarity and a so-called 'bald patch' was present (where the magnetic field is tangent to the photosphere), which is a flare-active magnetic topology (Titov et al, 1993; Aulanier et al 1998). Delannée, & Aulanier (2000) proposed that the large-scale transequatorial field lines were pushed up by the opening of low-lying sheared field lines forming the bald patch. In this scenario the large-scale magnetic topology combined with magnetic evolution in the principal CME source region both are crucial conditions in the CME initiation. A similar scenario can be applied to the 6 Nov. 1997 event (Maia et al, 1999 and the 2 May 1998 event (Pohjolainen et al, 2001), which both involved the eruption of transequatorial loops.

## 5. Filament-eruption related events in regions with dispersed magnetic field

The set of CMEs of 25/26 September 1996 was related to the bipolar remnant NAAA 7978 which was the unique large AR existing during the solar minimum. The AR started to emerge in July 1996, rapidly reached its maximum development and was decaying during the next 6 months with a progressive diffusion of its magnetic field. Many large flares and CMEs occur during the first 3 months after its birth, later on only CMEs were observed (Démoulin et al 2002 b). On 25 September 1996 the magnetic field of the region was well dispersed and the inversion line was bent about 45 $^{0}$ due to the differential rotation (Fig 1). There was a filament along the inversion line stretching southward from the center of the AR which joined to the E-W polar crown filament channel forming a "switchback" inversion line with a sharp change of direction. Turbulent activity of about two hours preceded the eruption of the south section of the filament (at 23:46 UT) which was followed by a long and complex CME well observed with LASCO (van Driel-Gesztelyi et al. 1998). A detailed magnetic analysis indicates emerging and cancelling flux in the filament channel prior to the CME (Fig 1). The position and the time of this flux cancellation suggest that it could be responsible for the destabilization of the filament which was close to loss of equilibrium. The CME was related to a large-scale reorganization of the corona.

Another similar case: opposite polarity magnetic field concentrations moved towards the magnetic inversion line and cancelled under a filament augmenting the shear before the geoeffective 6 January 1997 halo CME event (van Driel-Gesztelyi et al., 2001).

## 6. Dynamics of filaments prior to eruption and CME

Forty percent of the CMEs are preceded by filament eruptions (Delannée 2000). Such eruptions could concern filaments in decaying active regions or quiescent filaments.

Eruptions of filaments have different phases of evolution. A few hours before the eruption, different phenomena are observed: heating of the matter visible by TRACE or Yohkoh, stretching of the fine structures during the ascend of the filament (well visible in EIT 304 Å), slow rise, turbulence and twisted motions of the filament, and finally acceleration and lift up. Schmieder et al (2000) show the stretching of the field lines andthe partial heating of the filament using EIT (304 and 195 Å) a few hours before a CME. With spectroscopic diagnostics (SUMER and CDS) high velocities were identified two hours before the eruption (Figs. 3 and 4). Some dynamical precursors of eruption have been known since decades (Schmieder et al. 1985, Sterling et al. 2001). These observations are well described by the scenario proposed by Raadu et al (1988). The upward motion of the filament leads to the expansion of the flux tube since the surrounding magnetic pressure is decreasing. Conservation of the

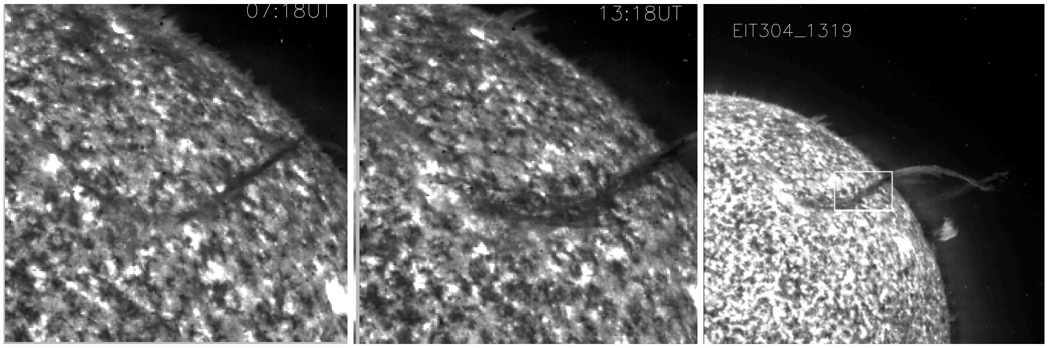


*Figure 3. Eruption of a filament and stretching of filament footpoints before eruption observed with EIT (304 Å) on May 31 1997 (Schmieder et al. 2000)*

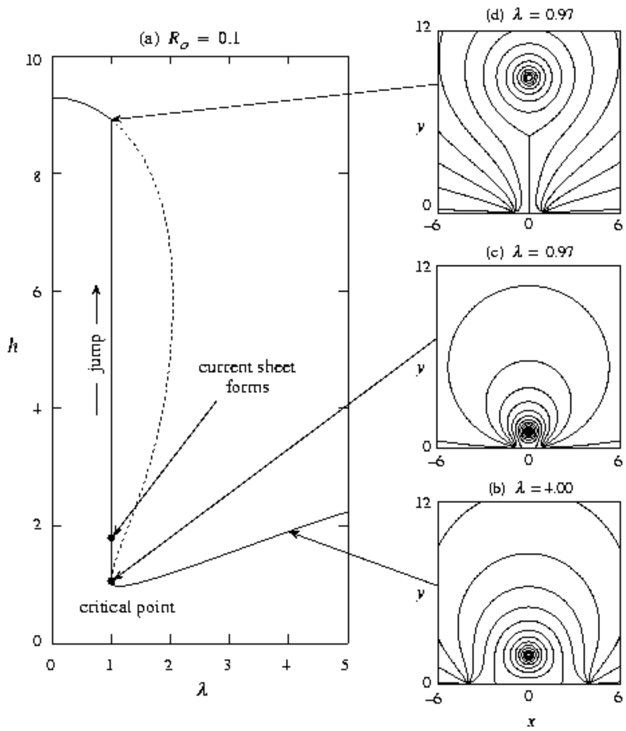


*Figure 2. Model of loss of equilibrium of a filament: (a) Flux rope height h as a function of the separation λ between two photospheric sources, (b-d) Contours of the flux in the x-y plane at the three locations indicated in (a). (Forbes and Priest, 1995)*

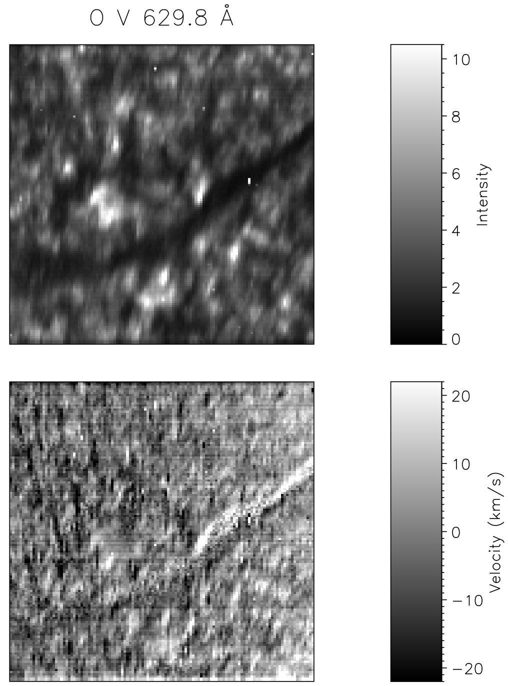


*Figure 4. Observation of the dynamics of a filament before eruption with CDS (O V) on May 31 1997 (Schmieder et al. 2000)*

current and the magnetic flux along the filament requires motions as the flux rope adjusts to a new equilibrium as it rises into the corona. The cause of the destabilization could be due to reconnection process as new emerging flux emerges.

Recently a new series of works suggests that a catastrophic loss of equilibrium rather than reconnection might be the primary mechanism for driving eruptions (Forbes and Priest 1995). The ideal MHD models are based on two-dimensional configuration of a flux rope nested within an arcade anchored in approaching magnetic sources (Fig. 2). During the first stage the energy is stored slowly while in the second stage it is released within an Alfvén time scale. If there is no reconnection or the reconnection is not fast, the filament will finally stop rising, while when fast reconnection occurs, the filament erupts. This could be the case of the September 26, 1996 event (section 5). Recently, the curvature of the solar surface has been taken into account introducing a rather significant force in driving the CMEs (Lin et al. 1998).

## 7. Discussion on the role of magnetic evolution of the source region in the initiation of CMEs

Aulanier et al (2000), analysing the 14 July 1999 (Bastille-day) flare, which occurred in a delta-spot group, showed that shearing motions in the delta-spot led to a field line expansion which caused first a slow, then a fast reconnection in the vicinity of the 3-D null-point present above the AR. The resulting eruptive flare and CME, therefore, were preceded by important sunspot motions. More precisely, it was the magnetic evolution, indicated by the sunspot motions, which was one of the causes of the eruption. However, the complex magnetic topology and the presence of the null-point were other necessary conditions in the flare/CME process. In other active regions, like NOAA 8100 in November 1997 and NOAA 8210 in May 1998 which produced several CMEs during their disc passage (at least nine [Delannée et al, 2000] and five, respectively), both ARs showed important magnetic evolution involving flux emergence and cancellation, and again, shearing motions between opposite polarity spots belonging to pre-existing and emerging bipoles. The commencement of CME activity in these regions coincided with the appearance of new flux and ensuing shearing motions. Though the magnetic field topology can be quite different, a scenario similar to the 1999 “Bastille-day flare” could be applicable to AR 8100 and other complex active regions.

However, the presence of sunspots and sunspot motions is not a necessary condition for flare and especially not for CME occurrence. As active regions decay, their flux is getting more and more dispersed and the spots disappear. Along the lenghtening inversion line, which is more and more bent by the differential rotation, long filaments form and their eruption is also related to CME events. In magnetic movies using MDI magnetograms with a 96-min cadence we *found small-scale magnetic changes preceding the initiation of the CME*. In most of the cases *the magnetic cancellation started a few hours or days before the CME* in the centre of the AR, along the magnetic inversion line under the filament, e.g. in the remnants of AR 8003 (CME of 6 January 1997) and of AR 7978 (26 September 1996 CME). However, we would like to stress that *such small-scale magnetic changes represent just the “last drop in the glass”* in destabilising a magnetic system which is already close to its stability threshold.

## 8. On the large-scale nature of CMEs

The CMEs are usually large scale phenomena compared with the AR size. It is relatively common that active regions have trans-equatorial loop connections, and *an eruptive flare in the AR may make the large-scale loops erupt as well*. Most of the CMEs which involved eruptive flares in NOAA 8100 (in Nov. 1997) and also in NOAA 8210 (in May 1998) became large-scale events due to the eruption of their trans-equatorial loop connections (Delannée and Aulanier, 1999; Pohjolainen et al, 2001; Khan and Hudson, 2000). Canfield, Pevtsov, McClymont (1997) and Pevtsov (2000) found that there is a tendency for ARs which have the same handedness (helicity sign) to form trans-equatorial loops. This implies that one of the ARs should disobey the hemispheric helicity rule (Seehafer 1990). NOAA 8100 was a south hemispheric region, which had negative helicity (Green et al, 2002a,b) opposite to the majority of ARs on that hemisphere. It was connected to the vicinity of the northern hemispheric NOAA 8102, where a “backward-S” shaped sigmoid (negative helicity) was seen in YOHKOH/SXT images for several days. Thus, these two active regions had the same helicity indeed.

## 9. Conclusions

The following conditions are necessary for CMEs to occur:

- eruptive flare occurrence: complex magnetic topology, presence of a magnetic null low in the corona, presence of large-scale magnetic stresses, high level of helicity, magnetic evolution increasing shear or twist;
- filament eruption: high level of helicity, magnetic evolution in the form of

  (a) small-scale flux emergence or flux cancellation along the magnetic inversion line, i.e. under the filament;
  (b) flux emergence or, in general, magnetic field evolution in the vicinity of the filament.

Conditions for large-scale trans-equatorial CME events:

- having the same sign of helicity increases the probability of inter-AR connectivities, which can be destabilised by eruptive events at either footpoint; in case of trans-equatorial connectivities this implies that one of the ARs disobeys the hemispheric helicity rule; such peculiar regions may be highly CME productive.

The main *similarities* between confined flares and CMEs:

- they both are preceded by instabilities of the magnetic configuration;
- their process involve magnetic reconnection;
- they liberate free magnetic energy.

The main *differences* between confined flares and CMES:

- **confined flares** release localised magnetic energy and do not create open field line configurations, do not change the helicity (though may redistribute it), and they are initiated when local magnetic stresses reach threshold.
- **CMEs** are large-scale instabilities, release free magnetic energy from an extended volume and carry away magnetic helicity, relieving the Sun from the continously amounting helicity; CMEs may be initiated by helicity reaching threshold.

This work provides one of the starting points of an large project on the study of CME initiation, propagation and interaction in which we combine multiwavelength observations with modelization and MHD simulations of such events following them from the Sun to the Earth (see also Poedts et al.2001, 2002 and van Driel-Gesztelyi et al.2001).

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