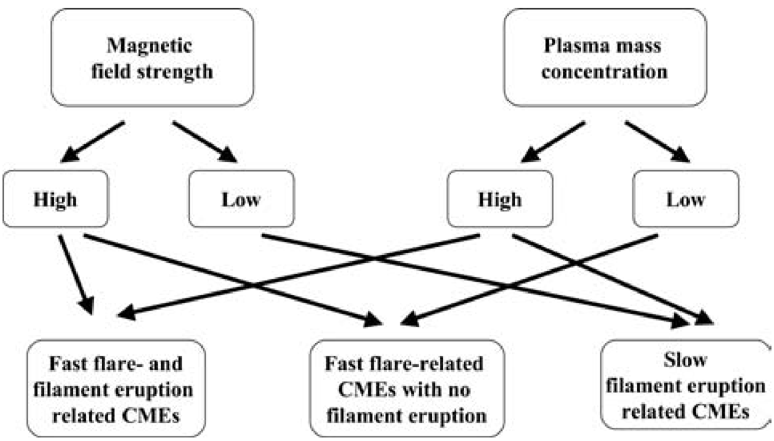
Session 3

Coronal mass ejections source regions



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Coronal and Stellar Mass Ejections
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Source Regions of Coronal Mass Ejections

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Abstract. The majority of flare activity arises in active regions which contain sunspots, while CME activity can also originate from decaying active regions and even so-called quiet solar regions which contain a filament. Two classes of CME, namely flare-related CME events and CMEs associated with filament eruption are well reflected in the evolution of active regions, flare related CMEs mainly occur in young active regions containing sunspots and as the magnetic flux of active region is getting dispersed, the filament-eruption related CMEs will become dominant. This is confirmed by statistical analyses.

All the CMEs are, nevertheless, caused by loss of equilibrium of the magnetic structure. With observational examples we show that the association of CME, flare and filament eruption depends on the characteristics of the source regions: (i) the strength of the magnetic field, the amount of possible free energy storage, (ii) the small- and large-scale magnetic topology of the source region as well as its evolution (new flux emergence, photospheric motions, canceling flux), and (iii) the mass loading of the configuration (effect of gravity). These examples are discussed in the framework of theoretical models.

Keywords. Sun: coronal mass ejections (CMEs), flares, magnetic fields, sunspots

1. Introduction

Coronal mass ejections are episodic expulsions of mass and magnetic field from the corona into the interplanetary medium. They reflect a high level of activity in the solar atmosphere. It would be very important to understand where they come from and what the relationship is between CMEs and other, related, sources of activity (flare activity, filament eruption). In the old days Dodson and Hedeman (1970) postulated that 93% of the flare activity arises in active regions which contain sunspots. However, the span of CME activity is much longer and extends well into the decay phase of active region evolution when the magnetic field is dispersed and the region is classified as quiet solar region containing filament (van Driel-Gesztelyi *et al.* 1999). Subramanian and Dere (2001), based on a sample of 32 CMEs, found that 85% of them were associated with active regions and 15% with so-called quiet regions. They found that 44% of these CMEs were associated with eruption of an active region filament and the 15% coming from "quiet" regions were all associated with filament eruption. These results are in good agreement with other statistical analyses of more numerous events having a narrower multi wavelength coverage (Saint Cyr and Webb, 1991; Webb, 1998; Zhou *et al.* 2003).

The main characteristics of the source regions have been intensively described in the review of Wang (2002). He also emphasized that CMEs are large scale events. An average-size CME is as large as five active regions. Therefore CMEs are frequently related to large scale magnetic structures, such as giant magnetic loops or transequatorial loops (Delannée and Aulanier, 1999), giant filaments or filament channels (Wang *et al.* 2002), or super magnetic configuration consisting of alignments of sunspots (Avignon, Martres and Pick, 1964). Falconer and co-workers found increasing correlation between CME productivity and global non-potentiality measures in the source region (Falconer, Moore and Gary, 2002). CMEs tend to appear in a small-scale core field in a complex magnetic region, where persistent flux cancellation (Deng *et al.* 2001; Zhang *et al.* 2001), new emerging flux or moving magnetic features and consequent activation of filaments are present.

In this paper we review the principal conditions for CME and then discuss what the different conditions are for flare- and/or filament eruption related to CMEs.

2. Conditions for CMEs

2.1. *General conditions*

There is a consensus that the presence of significant magnetic stresses in the source region is a necessary condition for CME. The magnetic helicity quantifies how the magnetic field is sheared or twisted compared to its lowest energy state (potential field). Observations provide plenty of evidence for the existence of such stresses in the solar magnetic field and their association with flares and CME activity. The first quantitative estimate of the helicity injection into an observed solar active region was made by Wang (1996), who deduced a 10^{43} Mx^2 of helicity increase in an emerging flux region (AR 6233) over a period of just a few hours. He computed change in magnetic helicity density using vector magnetograms and tracing the change of α, the force-free parameter. In young active regions magnetic stresses are increased by (i) twisted magnetic flux emergence and the resulting magnetic footpoint motions (e.g. Chae 2001; Chae *et al.* 2002; Kusano *et al.* 2002; Moon *et al.* 2002; Nindos and Zhang, 2002; Nindos *et al.* 2003; Démoulin and Berger, 2003) as well as (ii) torsional Alfvén waves which bring up helicity from the sub-photospheric part of the flux tube and replenish coronal helicity after CME events (Longcope and Welsch, 2000; Démoulin *et al.* 2002a; Green *et al.* 2002). A possible manifestation of such torsional Alfvén wave is sunspot rotation, which has indeed been observed (e.g. Brown *et al.* 2003). In old, decayed active regions twist can be redistributed through cancellation events transferring helicity from small- towards the large scales, it can be increased by large scale photospheric motions (differential rotation) (DeVore, 2000; Démoulin *et al.* 2002b; Berger and Ruzmaikin, 2000) or brought up by torsional Alfvén waves (Démoulin *et al.* 2002a; Green *et al.* 2002).

Whether the eruption is possible or not, the strength of the magnetic field overlying a sheared arcade or a twisted flux tube may play an important role. Since such overlying field has a stabilizing effect, a strong field can actually prevent the eruption (Török *et al.* 2004; Roussev *et al.* 2003). However, in a magnetically complex configuration such overlying field can be (at least partially) removed by reconnection. The so-called breakout scenario can lead to partial opening of the overlying field which stabilizes the increasingly sheared core field, which can burst open leading to a CME (e.g. Antiochos, 1998; Antiochos, DeVore and Klimchuk, 2000; Aulanier *et al.* 2000; Wang, 2002). Therefore magnetic complexity of the magnetic field in the source region and in its environment is another important factor leading to CME.

2.2. *Conditions for flare-associated CME*

The correlation between a CME and a solar flare depends on the energy that is stored in the relevant magnetic structure, which is available to drive the eruption: the more energy that is stored, the better the correlation is; otherwise, the correlation is poor (Svetska, 1986; Lin, 2004). The correlation between solar flares and CMEs depends on the strength

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of the magnetic field in the source region - strong fields obviously can store more free energy. It is well-known that large, complex magnetic regions with strong and increasing non-potentiality are highly CME productive. Therefore it is important to evaluate the amount of the free energy storage versus time.

2.3. *Conditions for filament eruption associated CME*

The correlation between a CME and eruptive prominence, on the other hand, depends on the plasma mass concentration in the configuration prior to the eruption. If the mass concentration in the source region is significant, CME will be associated with prominence/filament eruption, otherwise a CME develops without an apparent associated eruptive prominence (Lin, 2004).

These results confirm that solar flares, eruptive prominences and CMEs are different signatures of a single physical process that is related to the energy release in a disrupted coronal magnetic field. The impact of gravity on CME propagation is shown to be important in a low background magnetic field (around 20 G). The gravity of a filament or prominence may play an important role in the process of slow CMEs by prohibiting the catastrophe to occur at the very beginning (Isenberg, Forbes and Démoulin, 1993). There are threshold values (mass and magnetic field strength) defining whether CME is possible or not.

2.4. *Summary*

The field strength, the presence of stress in the magnetic field, the mass of prominence are important ingredients to get CME or not. We have also to consider the pre-eruption magnetic environment of the CMEs. The small as well as the large scale magnetic topology of the source region is an important factors. Furthermore, the strength of the magnetic field overlying a sheared arcade, appears to be very important. The overlying field has a stabilizing effect, and may prevent eruption. The highly stressed (sigmoid) regions appear in large and also in small scale configurations, which poses the question whether the size of the source region influences or not its eruptive nature. We shall review these different aspects of the CME process through different examples of CME observations and modeling studies.

3. Review of examples

3.1. *Large strength of magnetic field and high stress*

Commonly, active regions with strong magnetic field and high stresses are sites of large energetic flares producing fast CMEs (e.g. 15 June 2000, the Bastille day flare and the twelve X-ray class flares during the period of October–November 2003 in three complex active regions NOAA 10484, 10486 and 10488). All three source regions are delta-spot regions formed through numerous episodes of flux emergence. As an example, the active region NOAA 10486 had an overall quadrupolar magnetic configuration on October 28 2003. The magnetic field strength was still high although the active region had entered into its decaying phase, when an X17 GOES class flare and associated CME occurred (Figure 1). The magnetograms of Huairou indicate strong shear along the two parallel inversion lines which squeezed a bridge of negative polarities between two positive polarities (Zhang *et al.* 2003).

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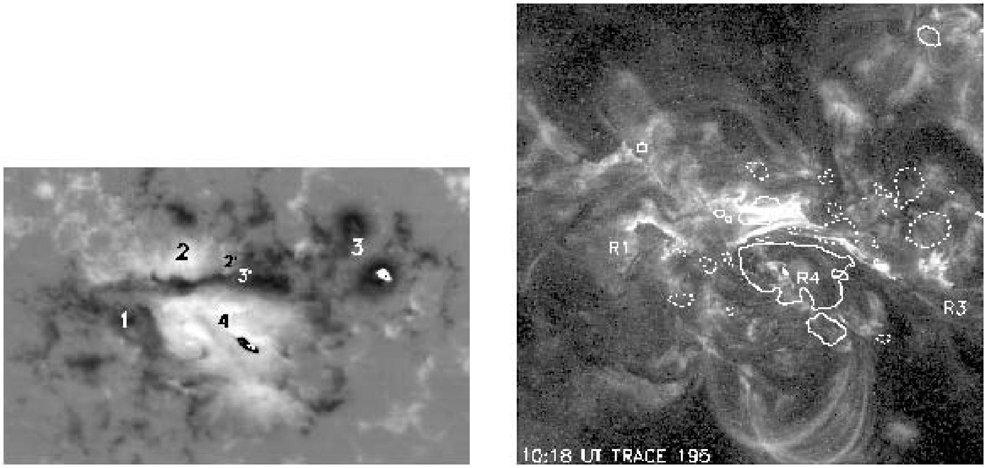

Figure 1. X-ray 17 Flare of October 28, 2003, right panel: TRACE observations of the four ribbons signature of a quadrupolar reconnection before the flare , left panel: Complexity of the magnetic topology of the active region 10486, where the main X17 flare occurs (Schmieder *et al.* 2005)

3.2. *Evolution of magnetic flux density, stresses and activity through the life of two active regions*

Comprehensive analyses of the long term evolution of two active regions confirm that evolving magnetic flux density plays an important role in flare and CME activity and its evolution must influence all the activity signatures (van Driel-Gesztelyi *et al.* 1999, 2003; Green *et al.* 2002). The complex analysis concerns an isolated active region (NOAA 7978 July-December 1996). The magnetic field of the AR was clearly distinguishable for at least seven solar rotations. It was found that flares mainly occur when the magnetic field of the AR has the highest complexity and magnetic flux density during the two main flux emergence phases (1st two rotations in July and August 1996) and while the number of CME is sustained and may be more closely related to the magnetic stresses in the region, since the value of the linear force-free α parameter was found to be roughly proportional with the CME rate (Table 1). During the first observed flux emergence phase 10^{22} Mx flux surfaced. During the decay phase magnetic flux gradually spreads over an ever increasing area, flare activity shows a sharp decrease and practically ceases with the disappearance of sunspots, while CME activity remains on a relatively high level (3-4 CMEs per rotation). During the decaying phase of the active region cancelling flux along the major inversion line were identified and could participate to the redistribution of the twist. The filament which was lying along the inversion line erupted after a sustained period of cancellations. Similar evolutionary pattern was found in NOAA AR 8100 by Green *et al.* (2002).

3.3. *Sigmoids of small and large scale*

Sigmoids, in many cases, indicate the presence of high magnetic stresses and have been linked to CMEs (Gibson *et al.* 2002; Manoharan *et al.* 1996). Though the sigmoid-CME connection is still statistically ambiguous (Canfield et al., 1999; Glower *et al.* 2000) it has been suggested that the magnetic helicity content in S-shaped magnetic configuration may reach a threshold leading to instability and eruption (van Driel-Gesztelyi *et al.* 2000; Török and Kliem, 2003). In the same way as CMEs can range from large-scale

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Table 1. Evolution of flare- and CME activity and of the magnetic stresses in AR 7978
Note, that above the horizontal line sunspots are present in the active region, while under it it becomes a spotless 'plage' region.

No. of rotation	Date of CMP	Flares (GOES class) X	M	C	B	CMEs	α $10^{-2} Mm^{-1}$
1^{st}	07/07/96	1	2	14	11	11	1
2^{nd}	02/08/96	-	-	-	16	5	0.3-0.75
3^{rd}	30/08/96	-	-	1	8	3	0.9-1
4^{th}	25/09/96	-	-	-	-	5	1-1.4
5^{th}	23/10/96	-	-	-	-	4	0.9-1.4
6^{th}	18/11/96	-	-	-	-	3	0.9
Total		1	2	15	35	31	

to very narrow events, the scale of erupting structures can range from interconnecting transequatorial loop size to the size well below of a typical AR.

The well known geoeffective CME event of January 6, 1997, produced a large magnetic cloud that damaged a satellite. For two-three days prior to the CME MDI observations of the active region show persistent cancellation of magnetic flux along the magnetic inversion line in the center of the AR (van Driel-Gesztelyi *et al.* 2002), that, through magnetic reconnection, is thought to lead to a reorganization of the magnetic configuration, increasing the twist in the large-scale magnetic structure of the overlying filament. In soft X-rays the region had a sigmoidal shape. Van Driel-Gesztelyi *et al.* (2000) proposed a model involving reconnection in a sheared arcade, which lead to the formation of short, highly sheared loops in the center and long sigmoidal loops connecting the outer edges of the bipole. The long sigmoidal loops may become unstable leading to a CME. As the sigmoid expands, a current sheet is formed under it and a cusp structure appears.

A similar event was observed in the center of the disk but related to a very small dipole, which had a two orders of magnitude less magnetic flux than a usual active region. Mandrini *et al.* (2004), carrying out a multi-wavelength analysis of a sigmoidal coronal bright point, found a high level of non-potentiality in the magnetic field and provided several independent evidence for its eruptive behavior (flaring followed by dimming and appearance of cusped loops, change of shape of the sigmoid from elongated prior to and compact after the eruption) (Figure 5 and Figure 8 in Mandrini *et al.* 2004). Using a linear force-free model of the pre- and post-eruption coronal loops they computed the change in coronal helicity due to the eruption (CME). Analyzing in-situ data obtained by the WIND spacecraft, they found a small magnetic cloud, which could be linked to the small solar eruption by timing, spatial magnetic orientation and field direction. Modeling the magnetic cloud and having constraints on the length of its flux tube from the short lifetime of the solar source region, they calculated its helicity. The helicity change in the corona and the helicity content of the MC were very similar, -2.7±0.4 x 10^{39} Mx^2 in the corona and 2.3 ±0.8 x 10^{39} Mx^2 in the cloud, which, given the unusually small size of the source region, can be regarded as a lower bound for the helicity loss due to CME.

4. Role of magnetic topology

Do CME source regions have bipolar or quadrupolar magnetic structure?

Forbes and Isenberg (1991) and Isenberg, Forbes and Démoulin (1993) developed a model where the eruption is preceded by converging motions towards the magnetic inversion line of a bipole. A loss of equilibrium leads to the rise of a flux rope situated along the inversion line. Reconnection occurring in the current sheet formed under the

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flux rope allows the flux rope to escape. Converging motion of opposite polarities and consequent cancellation along the magnetic inversion line before CMEs have indeed been observed (e.g. van Driel-Gesztelyi *et al.* 2002, Schmieder *et al.* 2005).

However, the highly CME-active source regions are magnetically complex! What is the main role of a multipolar magnetic structure in the CME process?

The analysis of the magnetic field evolution, topology and multi-wavelength data before and during the X 17 flare on October 28, 2003, shows how a large twisted flux tube supporting the long filament lying along the main inversion line was first formed then erupted. The slow build-up of magnetic stress through converging motions along the magnetic inversion line begins well before the eruption. If we try to classify the X 17 flare within the scenario of "storage and release" models (Klimchuk, 2001) i.e. tether cutting or tether straining, it appears that two mechanisms could be present: firstly, twist in the flux rope is built up as small-scale cancellation events (reconnection) occurs in a sheared arcade aligned along the main neutral line. The flux tube starts to rise slowly, as more and more tethers are being cut. During that time the twist in the tube increases. Before the X 17 flare, two episodes of large-scale quadrupolar reconnection occur in the active region. The second episode, being more intense, implies more important field-rearrangements. These quadrupolar reconnection events remove stabilizing field lines from above the flux rope (filament) which succeeds to break out. Reconnection under the erupting flux rope starts after the lift-off, forming a post-flare loop arcade. This evolution is similar to the breakout model in quadrupolar configurations proposed by Antiochos, DeVore and Klimchuk (1999). These models require reconnection above the erupting arcade prior to the CME eruption. Multiwavelength observations combined with modeling provided one of the first convincing observational evidence that breakout model is indeed a viable model for CME (Aulanier *et al.* 2000).

In the breakout models the quadrupolar magnetic configuration is a necessary condition. However, it is still a question whether topological complexity is indispensable for CMEs or not. Is the loss of equilibrium of a flux rope, in which twist exceeded threshold level (see Török, Kliem, and Titov (2004) and references within), provides sufficient condition for CME? The latter seem to work even in a simple bipolar magnetic configuration. Since the Sun is complex, we must leave open the possibility that more than one CME model might be correct!

It has been a long-standing question which comes first: flare or CME? Both observations and models suggest that an inflation of the magnetic structure due to increasing magnetic stresses is the first step - this makes observers say that CME starts before flare. The main flare energy release occurs during the reconnection of field lines extended by the eruption, which, again, points towards that CME should come first. However, both in the tether cutting (flux rope) and the tether straining (break-out) models pre-eruption reconnection is required under or above, respectively, of the erupting twisted/sheared magnetic structure (filament). In the break-out model this pre-eruption reconnection is expected to occur high in the corona in a region of weak field, releasing too little energy to be observed. However, if the reconnection occurs in a strong field region, like in a complex active region, where tethers are not external weak fields overlying the sheared core field but they are part of the active region having a quadrupolar configuration, the released magnetic energy can be high enough to qualify as flare, therefore we may find that (an impulsive, quadrupolar) flare precedes the CME, while the latter includes a filament eruption and a related two-ribbon flare representing the post-eruption arcade. Similar scenario was proposed for the 15 July 2002 CME by Gary and Moore (2004), and for the 28 October 2003 CME by Schmieder *et al.* (2005).

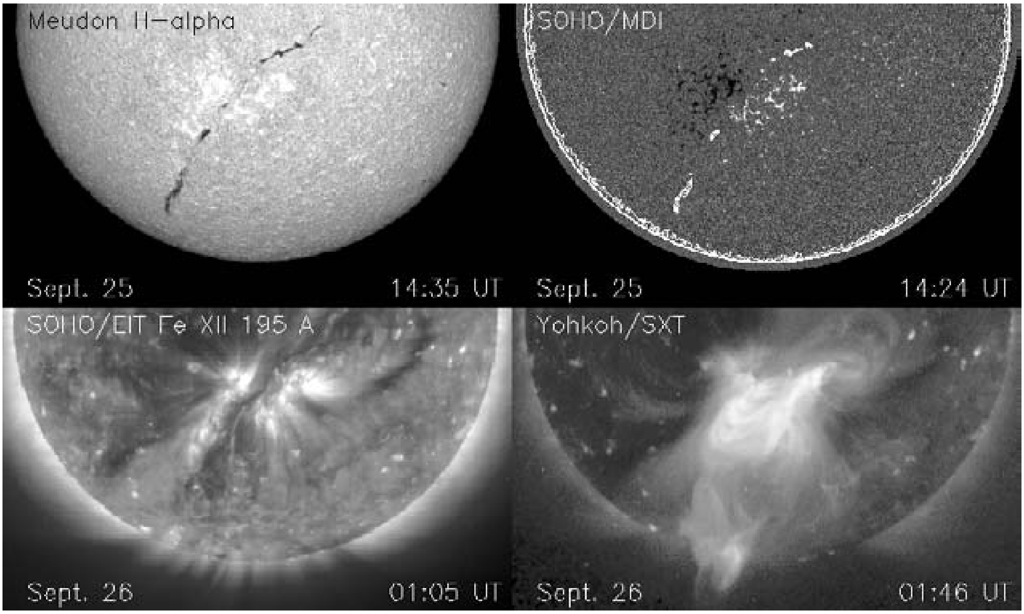

Figure 2. CME of September 26, 1996 due to the eruption of a filament in a non active region

In any case, in the models most relevant to observations (storage and release models) the build-up of magnetic stresses, i.e. strong shear and twist are necessary conditions for CME to occur. In observations twisted CME structures are frequently seen (Fig. 4) and there is amounting evidence that considerable amount of twist is being carried away from the Sun by CMEs. These emphasize the importance of magnetic helicity in the CME process.

5. Mass loading in prominences

The free energy stored in a stressed magnetic structure prior to the eruption depends on the strength of the background field. The stronger the background field is, the more free energy can be stored, and thus the more energetic the eruptive process is (Lin 2004). This eruptive process refers to any disruption of the coronal magnetic field that causes either a flare, or a filament eruption or CME or all of them. In the case of CMEs related to quiet sun region, there is a critical strength of the background magnetic field (<27 G) where the effect of gravity becomes significant enough to prevent the CME from progressing (Isenberg, Forbes and Démoulin 1993). If the field is larger than this value, the system evolves smoothly in response to the slow change in the boundary conditions and can end up with a slow CME (Schmieder *et al.* 2000). The gravity of the filament or prominence may play an important role in the process of slow CMEs by prohibiting the catastrophe to occur at the very beginning. A prominence rises slowly before erupting and can reach altitude as high as 200 Mm (Figures 2 and 3). The mass of CMEs inferred from SOLWIND observations from 1979 to 1981 (Howard *et al.* 1985) ranged from 2×10^{14} to 4×10^{16} g. The amount of mass and the mass concentration should be important for the CME-eruptive prominence association.

Two aspects derived from the observations have to be taken into consideration after this statement. On one hand a filament appears darker in chromospheric images before eruption. This indicates a higher density of plasma or new condensation of material.

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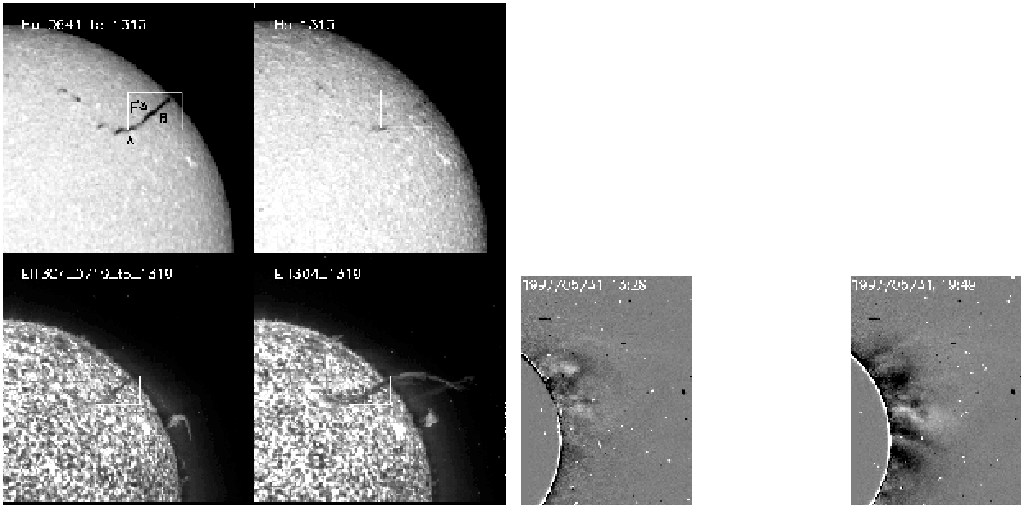

Figure 3. Quiet region source of a CME due to a filament eruption on May 31, 1997 (Spectroheliograms of Meudon, EIT images, LASCO C1 images (Schmieder *et al.* 2000)

A strength of the stresses in the magnetic field supporting the prominence can result of this increasing mass. The models of magnetic support of prominences show a higher complexity of the field lines as the stress increases (Aulanier, DeVore, and Antiochos, 2002). Another possibility to explain this increasing density is the following. Before the eruption the plasma in prominences is commonly heated, the optical thickness of Hα increases and it is in favor to see darker filaments before the eruption (Schmieder, Tziotziou, and Heinzel, 2003). This latter mechanism does not imply increasing magnetic stresses due to mass loading.

On the other hand it has been recently found that solar filaments observed in EUV lines are much more extended than their Hα counterparts (Heinzel *et al.* 2001, Schmieder, Tziotziou, and Heinzel, 2003a). This was explained by a large difference between the hydrogen Lyman-continuum and Hα opacities. Two different MHD models were suggested to explain the EUV filament extensions: the model based on parasitic polarities (Aulanier and Schmieder, 2002) and the model with twisted flux tubes (Anzer and Heinzel, 2003). The latter model tentatively describes the possibility of the EUV extension to be located relatively high in the atmosphere (Schmieder *et al.* 2004). These heights can be computed using a new spectroscopic model of EUV filaments (Heinzel *et al.* 2003a). The mass which is loaded into the EUV filament extensions is then estimated on the basis of non-LTE transfer calculations. The total filament mass is larger than that derived for the Hα filament itself by a factor 1.5 or 2 and this may have consequences for the structure and the mass loading of CMEs (Heinzel *et al.* 2003b).

6. Conclusion

The driver behind solar flares, prominence eruptions and CMEs is the instability of stressed coronal magnetic fields which have been driven towards a highly stressed state by photospheric motions and twisted flux emergence. From a theoretical point of view (Lin, 2004) and observations of CME source regions it appears that some parameters are important to determine which type of CMEs the region is able to expel. The strength of magnetic field and the complexity of the magnetic configuration prior to the eruption determines the correlation between flares and CMEs, and the impact of the gravity on

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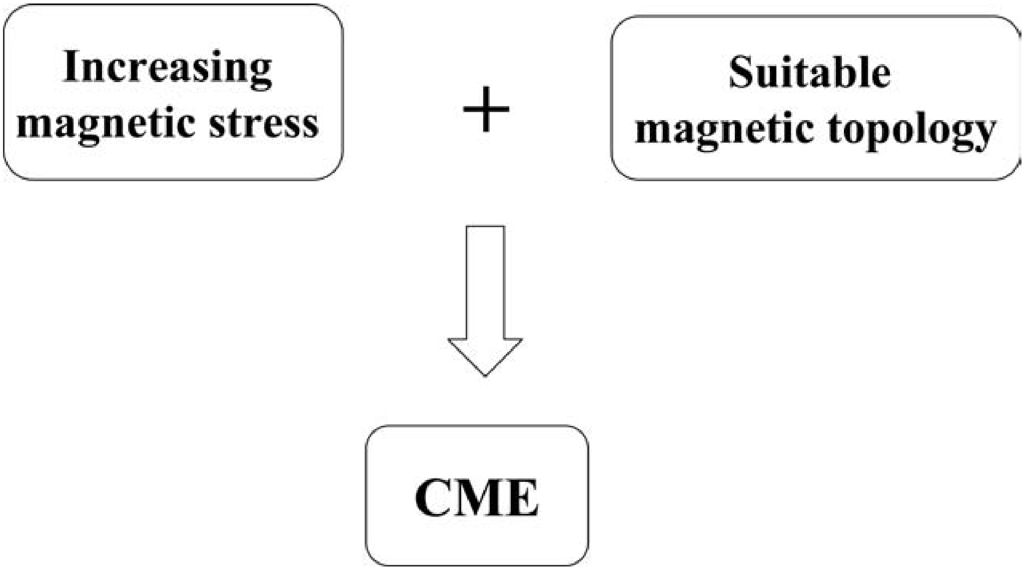

Figure 4. What are the magnetic conditions for getting CMEs?

the above correlation can be important (mass and concentration of mass in prominence) if the background magnetic field is weak. The size of the region is not an important parameter, even very small magnetic regions are able to produce CME. An increase of stress in the source region is a crucial factor, and the strength of the field determines how much free energy can be stored in it. However, the strength of the overlying field, which has an important stabilizing effect, appears to play an important role in whether eruption occurs or not. The correlation between CME and eruptive prominence depends on the amount and the concentration of the plasma mass in the related magnetic configuration. The CME may commence with an apparent prominence eruption if the mass inside the structure is larger than 4.5x 10^{15} g. Our conclusions are summarized in two charts (Figs. 4, 5).

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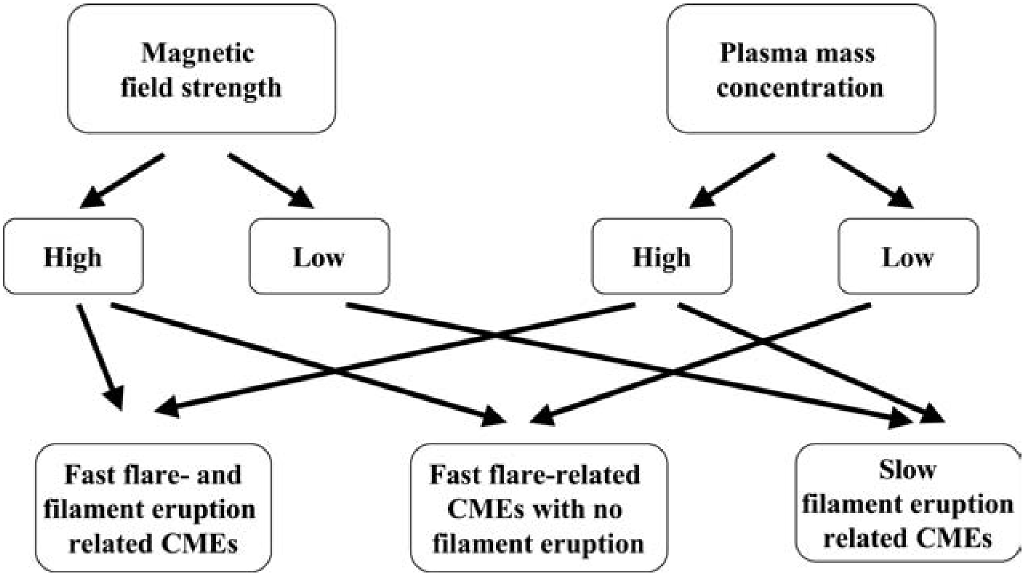

Figure 5. Summary of the different characteristics of the source regions producing flares, filament eruptions, CMEs

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Discussion

Sterling: Do you think the apparent darkening of filaments before eruption could be due to a slow rise of the filament rather than due to an increase of filament mass?

Schmieder: Yes, it could be motion combined with increased turbulence. I think that turbulence is more likely than mass increase.

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Schwenn: Assume you had been able to follow the evolution on Oct. 28 in real-time and analyze it fast enough: at which time would you have predicted the big flare to occur? In other words: will your analysis lead to better flare/CME predictions?

Schmieder: I was the PI of the campaign (Oct 20-30, 2003) and I chose this active region on Oct 26 because of its complex topology due to continuous emerging flux. This is a necessary condition to get flares and CMEs. Of course it is not sufficient to know at what time these events will occur.

Koutchmy: From white light observations we know that an important component of CMEs is the cavity part, including the magnetic field associated with the cavity. Considering quiescent filaments, you described observations bringing even more material around filaments, so what about the cavities?

Schmieder: The cavities observed around filaments in coronal lines ($\lambda < 912$ Å) could contain cool material not observed in Hα but optically thick enough to get absorption of the coronal emission by Lyman continuum.

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