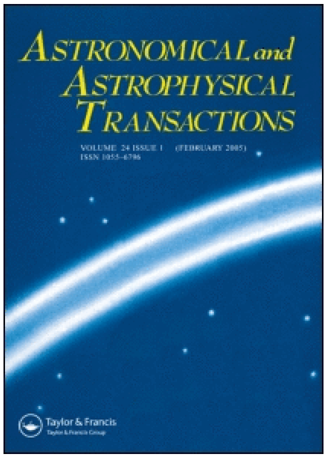


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# The onset of CMEs in the solar corona

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# THE ONSET OF CMEs IN THE SOLAR CORONA

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A pre-eruptive stage of coronal mass ejections is discussed. Source regions of CMEs and CME-associated phenomena are reviewed. It is stressed that the most probable magnetic configuration of a CME source region is a flux rope. This configuration allows a catastrophic process. So the onset of eruption does not need a powerful trigger. We believe that for some classes of CMEs, the problem of the onset of the ejection is similar to the problem of the loss of quiescent filament equilibrium. Since filaments are easily accessible for observation, the regions where CMEs could originate are more or less known. We propose a method to estimate the stability of any observed filament and the probability of its eruption.

KEY WORDS Solar corona, coronal mass ejections, eruptive prominences

## 1 BASIC PROPERTIES OF CMEs

What was very surprising at the beginning of the SOHO operation was that coronal mass ejections (CMEs) are not rare events during the minimum of solar activity. Practically every day or two, a large-scale structure in the corona disrupted and was ejected out of the corona at speeds up to a thousand km $s^{-1}$. The solar corona was found to be more dynamic than the lower layer of the solar atmosphere even in a period of quiet Sun. From the previous study over more than a complete 11-year solar sunspot cycle, it has been found that the frequency of occurrence of CMEs tends to track the solar activity cycle in both amplitude and phase (Webb and Howard, 1994). Really, nowadays LASCO instruments register approximately 5 CMEs a day. Figure 1 shows the average number of CMEs per day during the last years of the SOHO observations as well as the Wolf number.

Each event carries a total mass in the range $10^{15}$–$10^{16}$ g. A CME liberates an energy of the order of $10^{31}$–$10^{32}$ erg, in the form of the work done to lift its mass against gravity and to produce the kinetic energy of the expelled mass (Hovard *et al.*, 1985; Illing and Hundhausen, 1986; Hundhausen, Stanger and Serbicki, 1994).

Coronal mass ejections reveal a wide variety of visible forms depending on the projection of the structure on the sky plane and the particular circumstances of

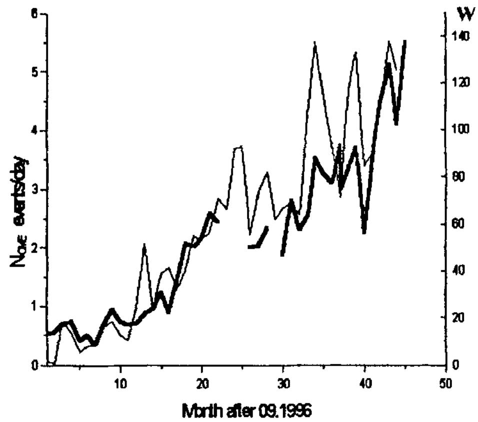


**Figure 1** Average number of CMEs per day during the last years of SOHO observations (bold line) and the monthly Wolf number (thin line). The data on CMEs taken from the Web site http://lasco-www.nrl.navy.mil/cmelist.html are very preliminary. Monthly Wolf numbers are taken from the site of the Brussels World Data Center http://www.astro.oma.be/SIDC/.

the event. Nevertheless, most well-developed CMEs show a typical form of a bright leading shell of material surrounding a dark cavity within which an erupted prominence is found (Illing and Hundhausen, 1986).

## 2 SOURCE REGIONS OF CMEs

Many CMEs originate from the disruption of coronal helmet streamers (Hundhausen, 1993), while there are clear examples of CMEs that are not caused by the disruption of helmet streamers. The streamer usually reforms a day or so later. Most CMEs are observed not far from the large-scale polarity inversion line (Shilova, 2000). This fact points to the magnetic nature of CMEs and makes clear the association of CMEs with other phenomena related to the neutral line such as streamers, prominences and flares. So far as the global magnetic structure in the solar atmosphere varies with the phase of the cycle, the latitude distribution of CMEs changes from very broad near the cycle maximum to clustering about the equator at minimum (Webb, 1998).

## 3 CME-ASSOCIATED PHENOMENA

Statistical association studies typically indicate that CMEs are most frequently associated with near-surface activity in the form of erupting filaments and X-ray long duration events (Webb and Hundhausen, 1987; St.Cyr and Webb, 1991; Sheeley *et al.*., 1983) but not H$\alpha$ flares. However, the fastest, most energetic CMEs are

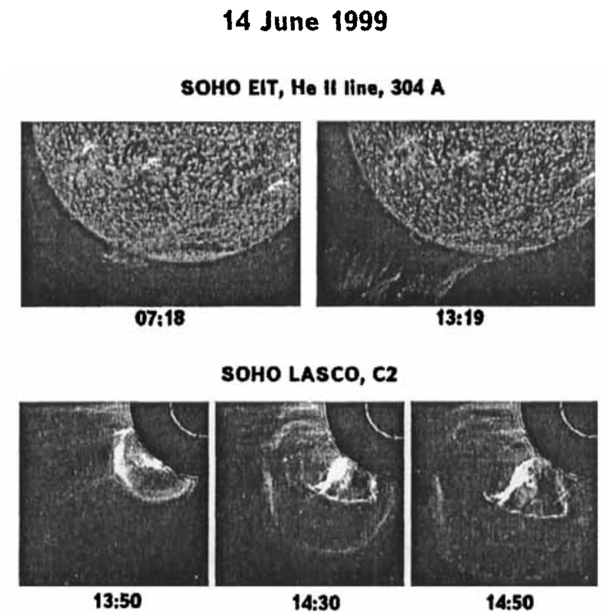


**Figure 2** Polar crown filament eruption visible in SOHO EIT He II line (top row) and the following CME observed with LASCO C2 (bottom row). (Courtesy of SOHO/EIT and SOHO/LASCO consortiums. SOHO is a project of international cooperation between ESA and NASA.)

usually flare-associated (Munro *et al.*., 1979; Webb, 1992). Figure 2 shows the polar crown filament eruption on 14 June 1999 visible in the SOHO EIT He II line and the following CME. The projection of the erupting filament was favorable to recognize the twisted structure of the filament loop in the core of the CME up to distances of 3 solar radii.

There are a number of low coronal phenomena seen in UV and X-rays which were not regularly observed until the last few years. These include the 'EIT waves' (often interpreted as a coronal Moreton waves), fast moving waves radiating out from a central disturbance (Moses *et al.*, 1997; Thompson *et al.*, 1998). Another phenomenon is 'coronal dimming', darkenings in the immediate region of the disturbance which can last for minutes or hours (Gopalswamy and Hanaoka, 1998; Zarro *et al.*, 1999; Delannee *et al.*, 2000). The coronal dimming when seen off the limb appears as dark open regions with bright edges corresponding to the CME cavity and legs. One interpretation of the dimming signature is that the initially closed field lines are opening during the onset of a CME, in analogy to transient coronal holes observed against the disk.

Some CMEs are preceded by the disappearance of transequatorial interconnecting loops seen in soft X-ray images (Khan, 2000; Akiyama *et al.*, 2000). These disappearances, which are interpreted as eruption of the loops, appear to be initiated by coronal shock waves propagating from the flare site at one end of the interconnecting loop structure.

S-shaped or inverse-S shaped sigmoid structures in the soft X-ray solar corona are also treated as the source regions of at least of some CMEs (Canfield *et al.*, 1999; Sterling, 2000). The sigmoids mark the presence of non-potential magnetic 'core field' structures which erupt to form a portion of the CME. After eruption, these source regions take the form of more nearly potential field arcades, often with a cusp structure.

There have been some attempts to find changes in the photospheric magnetic field during CMEs. Variations in the magnetic flux do exist inside the active regions and are often in the form emerging parasitic polarities (Subramanian and Dere, 2000). However, the changes are not very significant (Lara *et al.*, 2000).

There are also observations of radio sources in the low corona which may be associated with CMEs (Gopalswamy *et al.*, 1999; Chertok *et al.*, 1998).

## 4 CME MECHANISMS

It is now widely accepted that CMEs are driven magnetically. The class of models which require a thermal or pressure pulse as the driver no longer seem viable (Dryer, 1994; Webb *et al.*, 1994). For instance, such models are not consistent with CMEs which exhibit significant accelerations over large distances. One more difficulty for hydrodynamic models is in the observable sometimes non-radial motion of a CME in the corona. Obviously in these cases the large-scale coronal magnetic field guides the material motion.

Most models of CMEs assume that they are created by the release of magnetic energy stored in coronal currents. Several mechanisms have been proposed for creating coronal currents. They include shearing of the coronal field by photospheric flows (Mikic *et al.*, 1988; Wolfson and Low, 1992), the convergence and reconnection of the photospheric field (van Ballegooijen and Martens, 1989; Ridgway and Priest, 1993), and transport from the convective zone (McClymont and Fisher, 1989).

The configuration which includes the coronal current in the form of a flux rope allows a catastrophic process (Forbes and Isenberg, 1991). As the boundary conditions vary slowly, the system evolves quasi-statically, except at certain critical points where only a dynamic transition is possible. At a critical point the system jumps suddenly from one equilibrium state to another at a lower energy. In terms of potential energy this means that the potential well becomes more and more shallow and then disappears at altogether.

At equilibrium, a flux rope is stretched along the polarity inversion line. It is covered by a coronal arcade which may pass into a helmet streamer. The long helical field lines of the flux rope may be anchored to the photosphere at two ends but, nevertheless, they are significantly isolated from the source of plasma at the coronal base. In combination with the magnetostatic equilibrium condition this can explain the existence of a cavity with reduced density inside a streamer (Low, 1996). At the bottoms of the helixes where the upward-concave shape of field lines gives an upward directed magnetic tension force, the accumulation of dense prominence

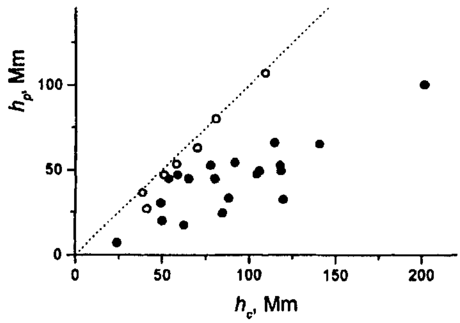


**Figure 3** Limiting height of stable filament equilibrium $h_c$ versus observed prominence height above the limb $h_p$. The dotted line, corresponding to equality of these quantities, is the stability boundary (Filippov and Den, 2001).

material is possible. An ascending flux rope current as a source of magnetic field should make an appreciable rearrangement of coronal density in a large volume surrounding an eruptive filament. Plasma compression near the surface $\beta = 1$ leads to formation of a dense envelope which can be identified with the outer loop of a CME (Filippov, 1996).

A flux rope model is consistent with the measurements of inverse polarity in the majority of prominences (Demouline, 1998).

Additional evidence of validity of the flux rope model arises from measuring magnetic fields in plasma clouds, which propagate through space after solar explosions. Many interplanetary magnetic clouds have the structure of a flux rope with the same orientation and polarity as associated erupting solar filaments (Lepping *et al.*, 1990; Martin, 1998). The sign of the helicity, or the twist of the erupting fields is conserved during propagation over 1 a.u.

## 5 FORECAST

It is not so easy to observe a flux rope on the Sun because most of its volume is filled with rear plasma and has only weak emissions. Only prominence material reveals the flux rope not only on the limb but also on the disk as a twisted filament.

Of course, the presence of a significant amount of prominence material in the flux rope is not a necessary condition for its existence in the corona, but in those cases when prominences or filaments are observed they can supply us with important information on some flux rope characteristics. First of all, it is interesting to know what is the relative value of the total electric current. Is it enough to expect an eruption of the configuration in the near future?

In flux rope models, the equilibrium height of a filament is related to the value of the electric current (Van Tend and Kuperus, 1974; Molodensky and Filippov, 1987; Martens and Kuin, 1989). The stronger the electric current, the higher the filament.

So, we can use the filament height for an estimation of the coronal current. However, the equilibrium and stability of a filament depend not only on its current but on the characteristics of the external magnetic field as well. So, we should compare the observed prominence height with some value characterizing the photospheric magnetic field. For this purpose we may use a limiting height which can be found from the distribution of the vertical gradient of the magnetic field above the polarity inversion line (Filippov and Den, 2000). The result of such calculations is shown in Figure 3, where one axis is the prominence height and the other one is the limiting height. The filaments, which are safely past the west limb, are marked with the solid circles while the filaments, which disappeared on the disc, are marked with open circles. It is seen that the solid circles more or less evenly fill the angle between the bisector and the horizontal axis while the open circles tend to cluster about the bisector. This shows that the eruptive prominences were near the limit of stability a few days before an eruption. We believe that a comparison of the real heights of prominences with the limiting heights could be a basis for the prediction of filament eruptions and ensuing CMEs.

### *Acknowledgments*

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### *References*

Akiyama, S., Hori, K., Nakagima, H., and Hara, H. (2000) *International Conference on Solar Eruptive Events*, Abstract book, p. 12, Center for Solar Physics and Space Weather, The Catholic University Of America, Washington, DC.

Canfield, R. C., Hudson, H. S., and McKenzie, D. E. (1999) *Geophys. Res. Lett.* **26**, No. 6, 627.

Chertok, I. M., Gnezdilov, A. A., and Zaborova, E. P. (1998) In: B. Rompolt, J. Jakimiec, and P. Heinzel (eds.) *Proc. of XIVth Consultation on Solar Physics*, p.173, Astronomical Institute of the Academy of Sciences of the Czech Republic, Ondrejov, Czech Republic.

Delannee, C., Delaboudiniere, J.-P., and Lamy, P. (2000) *Astron. Astrophys.* **355**, 725.

Demouline, P. (1998) In: D. Webb, D. Rust, and B.Schmieder (eds.) *New Perspectives on Solar Prominences*, IAU Colloquium 167, *ASP Conference Series*, **150**, , p. 78, Astron. Soc. of the Pacific, Calif.

Dryer, M. (1994) *Space Sci. Rev.* **67**, 363.

Filippov, B. P. (1996) *Astron. Astrophys.* **313**, 277.

Filippov, B. P. and Den, O. G. (2000) *Astron. Lett.* **26**, 322.

Filippov, B. P. and Den, O. G. (2001) *J. Geophys. Res.*, in press.

Forbes, T. G. and Isenberg, P .A. (1991) *Astrophys. J.* **373**, 294.

Gopalswamy, N. and Hanaoka, Y. (1998) *Astrophys. J.* **498**, L179.

Gopalswamy, N., Nitta, N., Manoharan, P. K., Raoult, A., and Pick, M. (1999) *Astron. Astrophys.* **347**, 684.

Hovard, R. A., Sheely, N. R. Jr., Kooment, M. J., and Michels, D. J. (1985) *J. Geophys. Res.* **90**, 8173.

Hundhausen, A. J. (1993) *J. Geophys. Res.* **98**, 13177.

Hundhausen, A. J., Stanger, A. L., and Serbicki, S. A. (1994) *Proc 3rd SOHO Workshop*, ESA, Paris, p. 409.

Illing, R. M. and Hundhausen, A. J. (1986) *J. Geophys. Res.* **91**, 10951.

Khan, J. I. (2000) *International Conference on Solar Eruptive Events*, Abstract book, p. 31, Center for Solar Physics and Space Weather, The Catholic University Of America, Washington, DC.

Lara, A., Gopalswamy, N., and DeForest C. (2000) *International Conference on Solar Eruptive Events*, Abstract book, p. 34, Center for Solar Physics and Space Weather, The Catholic University Of America, Washington, DC.

Lepping, R. P., Burlaga, L. F., Jones, J. A. (1990) *J Geophys. Res.* **95**, 11957.

Low, B. C. (1996) *Solar Phys.* **167**, 217.

Martens, P. C. H. and Kuin, N. P. M. (1989) *Solar Phys.* **122**, 263.

Martin S. F. (1998) In: D. Webb, D. Rust, and B.Schmieder (eds.) *New Perspectives on Solar Prominences*, IAU Colloquium 167, *ASP Conference Series*, **150**, , p. 419, Astron. Soc. of the Pacific, Calif.

McClymont, A. N. and Fisher, G. H. (1989) In: J.H. Waite, Jr., J.L. Burch, and R.L. Moore (eds.) *Solar System Plasma Physics*, p. 219, American Geophysical Union, Washington, DC.

Mikic, Z., Barnes, D. C. and Schnack D. D. (1988) *Astrophys. J.* **328**, 830.

Molodensky, M. M. and Filippov, B. P. (1987) *Soviet Astron.* **31**, 564.

Moses D., Clette, F., Delaboudiniere, J.-P., Artzner, G. E *et al.*. (1997) *Solar Phys.* **175**, 571.

Munro, R. H., Gosling, J. T., Holdner, E., MacQueen, R. M., Poland, A. I., and Ross, C. L. (1979) *Solar Phys.* **61**, 201.

Ridgway, C. and Priest, E. R. (1993) *Solar Phys.* **146**, 277.

Shilova, N. S. (2000) *Astron. Astrophys. Suppl. Ser.* **144**, 371.

Sheeley, N. R. Jr., Howard, R. A., Koomen, M. J., and Michels, D. J. (1983) *Astrophys. J.* **272**, 349.

St.Cyr, O. C. and Webb, D. F. (1991) *Solar Phys.* **136**, 379.

Sterling, A. C., Hudson, H. S., Thompson, B. J., and Zarro, D. M. (2000) *Astrophys. J.* **532**, 628.

Subramanian, P. and Dere, K. P. (2000) *International Conference on Solar Eruptive Events*, Abstract book, p. 49, Center for Solar Physics and Space Weather, The Catholic University Of America, Washington, DC.

Thompson, B. J., Plunkett, S. P., Gurman, J. B., Newmark, J. S., St. Cyr, O. S., and Michels, D. J. (1998) *Geophys. Res. Lett.* **25**, No.14, 2465.

Van Tend, W. and Kuperus, M. (1978) *Solar Phys.* **59**, 115.

van Ballegooijen, A. A. and Martens, P. C. H. (1989) *Astrophys. J.* **343**, 971.

Webb, D. F. (1992) In: Z.Sdestka, B.Jackson and M.Machado (eds.) *Eruptive Solar Flares*, p. 234, Springer-Verlag, New York.

Webb, D. F. (1998) In: D. Webb, D. Rust and B. Schmieder (eds.) *New Perspectives on Solar Prominences*, IAU Colloquium 167, *ASP Conference Series*, **150**, , p. 463, Astron. Soc. of the Pacific, Calif.

Webb, D. F., Forbes, T. G., Aurass, H., Chen, J., Martens, P., Rompolt, B., Rusin, V., Martin , S. F., and Gaizauskas, V. (1994) *Solar Phys.* **153**, 73.

Webb, D. F. and Hundhausen, A. J. (1987) *Solar Phys.* **108**, 383.

Webb, D. F. and Howard, R. A. (1994) *J. Geophys. Res.* **99**, 4201.

Wolfson, R. and Low, B. C. (1992) *Astrophys. J.* **391**, 353.

Zarro, D. M., Sterling, A. C., Thompson, B. J., Hudson, H. S., and Nitta, N. (1999) *Astrophys. J.* **520**, L139.