Session 8

Training Courses for Young (inter)national Astronomers

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https://doi.org/10.1017/S1743921306002493 Published online by Cambridge University Press

Solar Activity and its Magnetic Origin
Proceedings IAU Symposium No. 233, 2006
V. Bothmer & A. A. Hady, eds.

doi:10.1017/S1743921306002493

Observations of Coronal Mass Ejections

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Abstract. Observations of source regions of coronal mass ejections have progressed enormously in the past decade with the observations from SOHO and Yohkoh. Progress has been made on understanding magnetic helicity, coronal dimming, coronal waves and flares in terms of their relationship to CMEs. Observations have been used to verify and disagree with models such as tether-cutting, kink instabilities and the breakout model. We will describe the observations, recent models, and how future observations from the Solar-B and STEREO missions will address many unanswered questions.

Keywords. Solar physics, coronal mass ejections

1. Introduction

Coronal mass ejections (CMEs) are large expulsions of plasma and magnetic flux (up to 10^{13}kg) at high speeds (up to 2000 km/s) from the Sun into the solar wind (where they are known as interplanetary CMEs (ICMEs). They are a critical aspect in understanding the solar terrestrial environment.

CMEs are observed in the outer atmosphere through the use of coronagraphs, such as the LASCO instrument onboard SOHO and the coronagraph on Mauna Loa. They are seen as bright white features in the coronagraph field of view. An example is shown in Figure 1. CMEs have been observed in earnest since the early 70s with the Skylab mission. Since then there have been a series of coronagraphs launched on spacecraft, until the current SOHO-LASCO instrument that has the benefit of 24hr a day data coverage for nearly a full solar cycle. This has allowed us to determine the rate of CMEs which is naturally dependent on the solar cycle. They occur at a rate of 2–5 per day during solar maximum and around 0.5/day during solar minimum (e.g. St. Cyr *et al.*, 2000). The source region of the CMEs also naturally changes during the cycle with higher latitudes being reached during solar maximum. CMEs can be narrow with a width of tens of degrees, up to full ‘halo’ 360 degree events. The wider events are most likely to be Earth directed (or anti-Earthward). In recent years, there have been different diagnostics made of CMEs on the solar disk which has helped our understanding of these phenomena. These include filament eruptions, coronal dimmings and coronal waves.

In this paper we will review the current knowledge of observations and recent models, and discuss how future imminent missions such as Solar-B and STEREO will revolutionise our understanding of these important events.

In the solar wind, ICMEs are observed with an array of in situ instruments on spacecraft. ICMEs can sometimes be observed as a coherent magnetic structure (a magnetic cloud) lasting up to a day at 1AU with a preceding shock. However in many cases things are much more complex. An example is shown in Figure 2.

For a full understanding of the Sun-Earth system it is necessary to link the information from remote sensing data on the Sun and the in-situ data in interplanetary space. In the

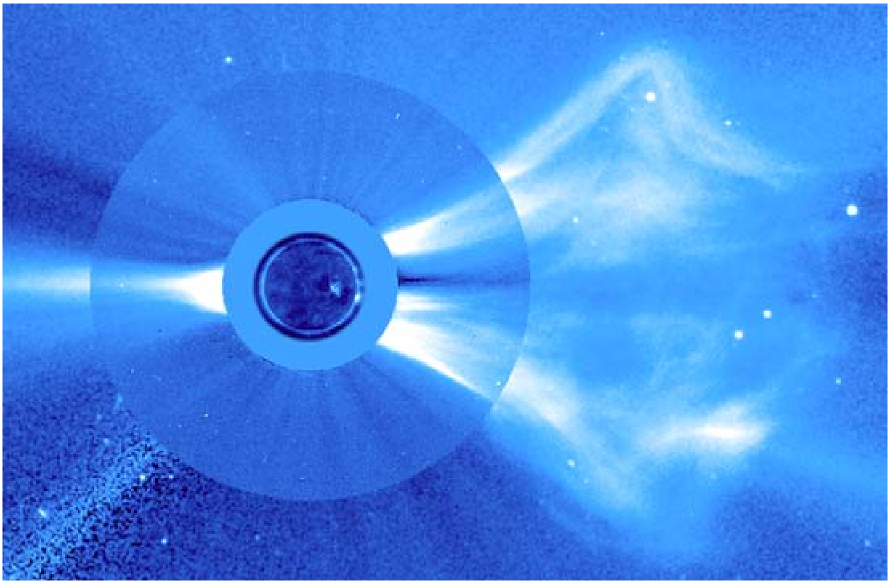

Figure 1. A composite of three images of a large CME. The images are from EIT (the blue Sun in the center) and the LASCO C2/C3 instruments.Credits: Solar & Heliospheric Observatory (SOHO). SOHO is a project of international cooperation between ESA and NASA.

next section we will summarise the solar origins of CMEs, and then in the following section move into interplanetary space to track ICMEs and shocks.

2. Solar Origin of CMEs

The first place to start in discussing the origin of CMEs is their relationship to solar flares. This has been a controversial topic in recent years in the well known 'Solar Flare Myth' debate. Currently it is now more generally accepted that CMEs and flares along with phenomena such as filament eruptions are due to a rearrangement of the magnetic fields and energy release. We will discuss the different phenomena that are closely related to CMEs – filament eruptions, eruptive flares, coronal dimming and coronal waves, and sigmoids.

2.1. *Filament eruptions*

Filament eruptions are the most obvious place to look for a source of CMEs since plasma is actually observed to leave the Sun. Filaments (or prominences at the limb) are magnetic structures that suspend cool plasma high in the corona. They tend to be highly twisted, complex structures with many strands and hence can store a lot of magnetic energy which is waiting to be released. These events can be spectacular and can happen on all scales (right up to a large fraction of a solar radius). They can be located both inside and outside active regions. Figure 3 shows an example of a twisted structure erupting as seen by the TRACE spacecraft. Filament eruptions that occur from active regions tend to be faster and more geoeffective than those outside of active regions. Although similar physical processes occur, both the density of the plasma and the magnetic field strength are higher in active regions.

How does a filament eruption become destabilsed so it can erupt? Jing *et al* (2004) showed that in 68% of their large study of eruptions, the destabilisation was closely associated with emerging flux through the photosphere. Small flare-like brightenings have

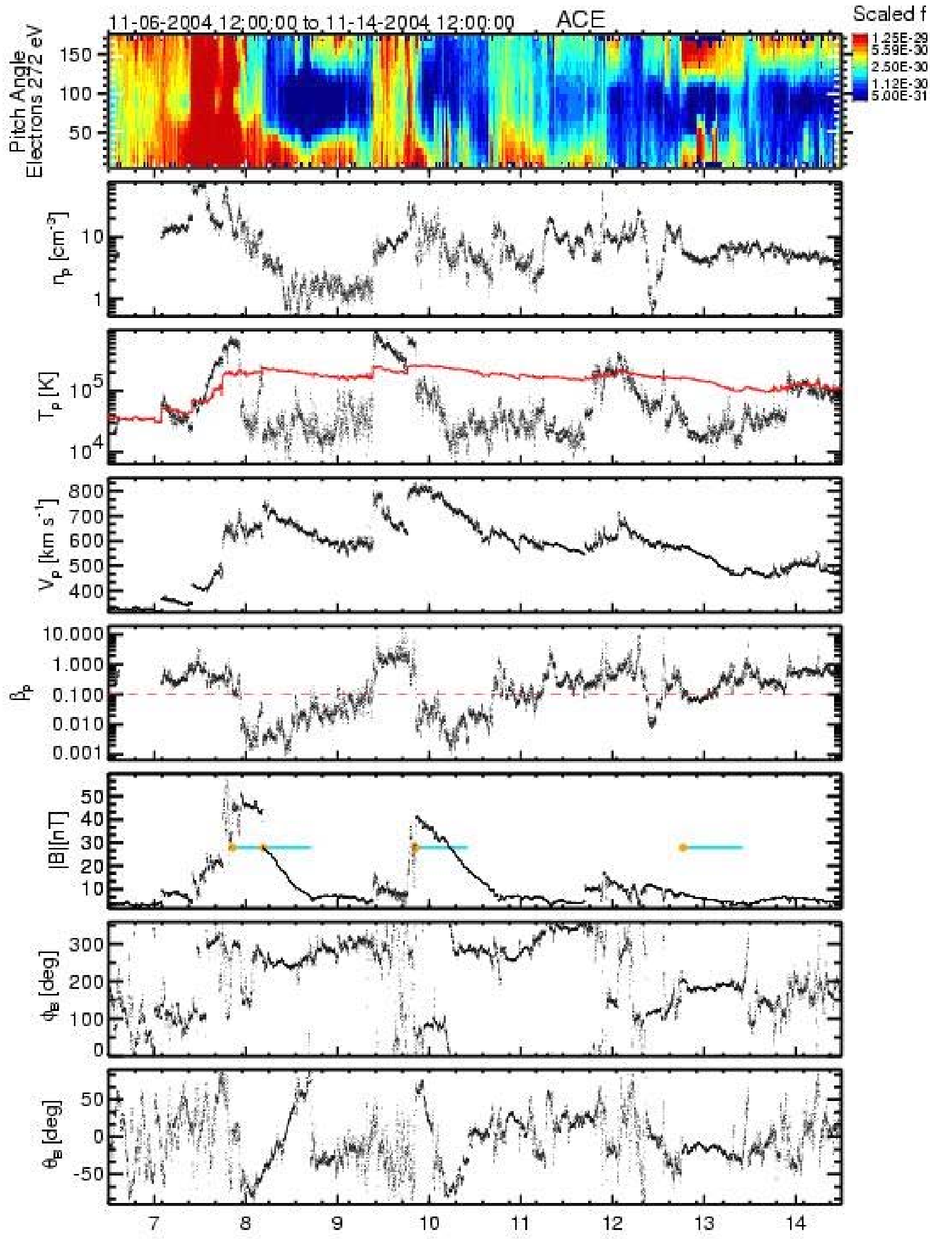

Figure 2. A series of interplanetary shocks and ICMEs observed by the ACE spacecraft during the very active period in November 2004. The horizontal lines show the location of the ICMEs. Figure courtesy of Heather Elliot and Nancy Crooker.

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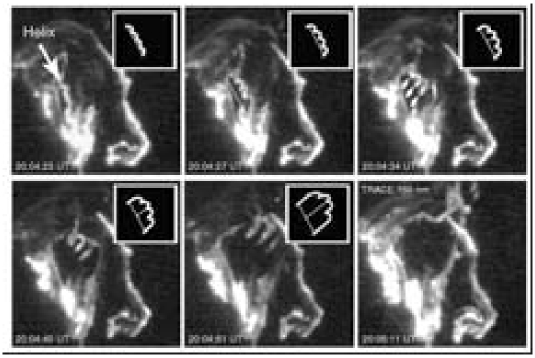

Figure 3. A time sequence from the TRACE spacecraft illustrating the eruption of a twisted structure (from Gary and Moore, 2004).

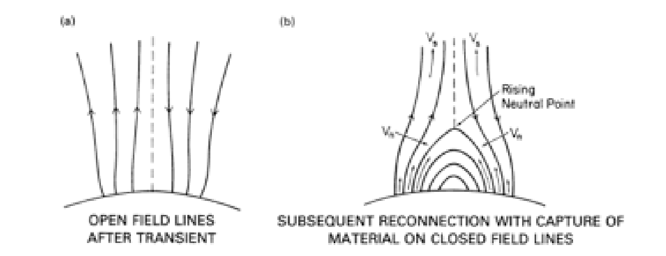

Figure 4. A cartoon illustrating a scenario of an erupting flare and magnetic reconnection (from Kopp and Pneuman).

also been found underneath a rising filament which is suggestive of some reconnection occurring there. There is now much evidence for dynamical changes in the filament occurring for up to several hours before the filament erupts. In any case the overlying magnetic field needs to be removed somehow to allow the filament to leave the Sun.

2.2. *Eruptive flares*

In the 1970s attempts to explain solar eruptions began to focus on magnetic reconnection (e.g. Kopp and Pneuman, 1976). The early models showed a simple bipolar configuration that is opened up through an eruption of the pre-flare corona (this is normally assumed to be due to a filament eruption). The magnetic field lines then return to a closed state through the process of magnetic reconnection. Figure 4 shows a schematic of this process. There is observational evidence that magnetic reconnection is occurring including;

- Mass motions have been observed and the location of these is consistent with the idea that chromosphere is being heated following accelerated electrons hitting this denser region (e.g Harra *et al.*, 2005, Doschek and Warren, 2005).
- Hard X-ray sources have been found above the soft X-ray loops (e.g. Masuda *et al.*, 1995)
- The morphology of the loops occasionally give a cusp-like appearance that you might expect from magnetic reconnection
- Outflowing and downflowing plasma are also expected from the reconnection model. Jets are frequently observed with speeds ranging between 40-400 km/s (e.g. Ohyama and Shibata, 1998) and dark voids have been observed occasionally in the decay phase moving towards the surface with speeds less than 1000 km/s (e.g. McKenzie 2000).

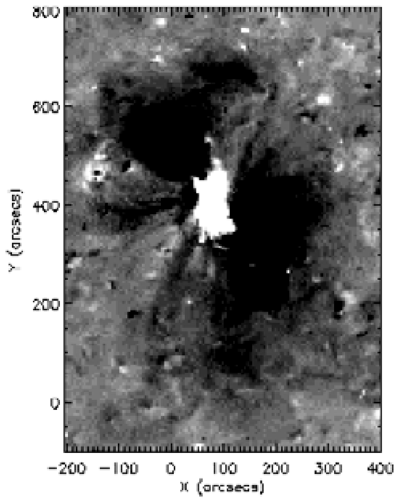

Figure 5. A base difference of an EIT image illustrating dimming following an eruptive event. The southern dimming was the main source of the CME (from Attrill *et al.*, 2006).

Most flares that occur are significantly more complex than that depicted in Figure 4, and the observational evidence that is consistent with reconnection often does not fit quantitatively with the models (e.g. the magnitude of speeds measured if often lower than that predicted from models). The flare duration is the one quantity that is found to be indicative of whether the flare is associated with a CME – if the flare lasts more than 2 hrs then it is highly likely that a CME will be associated with it. This correlation is, of course, not telling all the story, as many small (less than GOES C-level) flares with a short duration have also been found to be associated with CMEs.

2.3. *Sigmoids*

In order to produce flares and CMEs it is necessary for a significant source of energy to be obtained. If the magnetic field is twisted then it is clear that these must be unstable and hence susceptible to eruption. The search for S-shaped (or reverse S-shaped), twisted structures began with work by Rust and Kumar (1996) who found that many flares associated with CMEs were S-shaped. Since then further work has found that sigmoidal structures are more likely to erupt than non-sigmoidal ones. However if an S-shaped structure is observed this does not automatically mean that you will then observe a CME. Predicting when such a structure will erupt has proved difficult from observations - and not all S-shaped structures do indeed erupt.

2.4. *Coronal dimming*

When a CME occurs it is clear that there should be reduction in the density of the remaining plasma – this is observed as ‘coronal dimming’. A good example of dimming was described by Sterling and Hudson (1997). The dimming in this case was related to the eruption of a sigmoid and a halo CME. They estimated the mass from the dimming regions to make up at least part of the CME mass. A similar ’clean’ example of dimming occurred on the 12th May 1997 (the dimming is shown in Figure 5). A careful examination

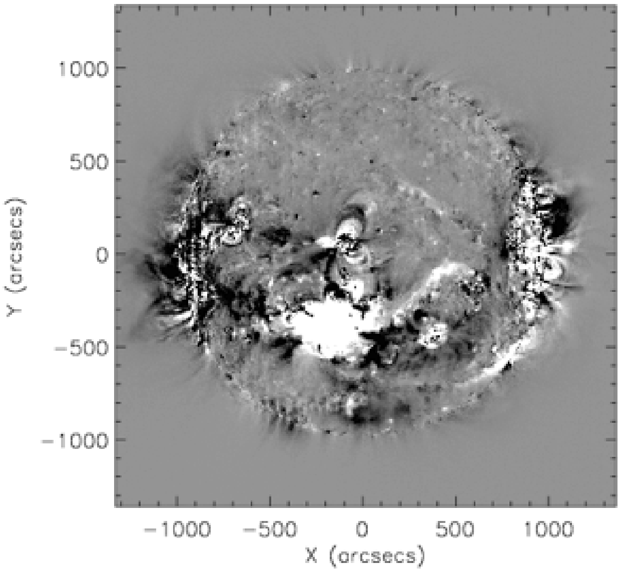

Figure 6. A base difference image of the 28 October 2003 event showing the complexity of dimming regions.

of the temporal evolution of the light curves shows different behaviour in each dimming region. Attrill *et al.* (2006) demonstrated that only the southern most region made up part of the CME. This differs from preliminary analyses of this event or intuition which would lead you to assume that the dimming regions are the footpoints of a flux rope. Most dimming measurements are made with imagers, and some caution needs to be used, since a decrease in intensity in a filter band may be due to a change in temperature or movement of plasma that does not necessarily leave the Sun.

2.5. *The global impact*

CMEs are such large structures that it is hard to imagine that they originate from a small region of the Sun. There are many observations that illustrate the global impact of CMEs. These include multiple dimming regions across the disk. Figure 6 illustrates the complexity of this for the event on the 28th October 2003. Many events have such a large impact – another example being the well known Bastille day event studied by Chertok and Grechnev (2005). They explain the multiple dimming regions as due to many large loops connecting to the active region and being involved in the eruption.

Large scale structures such as trans-equatorial loops and filaments are increasingly being recognised as an important component of CMEs. Large trans-equatorial loops have been directly observed to erupt and form part of a CME by Khan and Hudson (2000). A trans-equatorial filament has been found to closely associated to the CME initiation in Bastille Day of 2000 (Wang *et al.* 2006). Zhou *et al.* (2006) carried out a statistical study to understand what caused halo CMEs. They found that 40% were associated with trans-equatorial loops and 13% with trans-equatorial filaments.

EIT 'coronal' waves were discovered in the past few years and show a propagating bright front with a dimming region behind it. They can traverse the whole solar disk in 1 hour. Interestingly they have been found to always be associated with CMEs (Biesecker *et al.*, 2002). There are two main competing explanations for these coronal waves. The

https://doi.org/10.1017/S1743921306002493 Published online by Cambridge University Press

first is that they are the coronal counterpart of the Moreton wave which is explained by a flare shock wave. The second is that the wave is actually the CME lifting off the Sun in response to a phenomena such as a filament eruption. Different waves have shown correspondence with both of these explanations with the main difficulty being the low time cadence of the EIT instrument. Future missions will aid the understanding of these important events.

3. How theory and models explain the origin of CMEs

The 'standard' reconnection has already been described earlier. They has been much work to explain observations of CMEs with two main concepts emerging – tether-cutting and breakout. Both of these require magnetic reconnection to occur, but it will happen in different locations. In tether-cutting reconnection occurs between elements within the core region field causing eruption (e.g. Rust and LaBonte, 2005). In the case of the breakout model, reconnection occurs in the overlying field which weakens the field over the core field allowing it to erupt (e.g. Antiochos, DeVore and Klimchuk, 1999). Zhang *et al.* (2006) proposed a double-current-sheet reconnection model for interdependent tether-cutting and break-out. An alternative mechanism to produce an eruption is the kink instability. In this scenario twist in the magnetic fields is abruptly converted into writhe.

4. Sun-Earth connection

Connecting what happens to the Sun to what happens at the Earth is not a trivial task. It is often difficult to locate the source of the CME because of multiple events happening on the Sun. Even when you locate the CME, it is not always obvious what the magnetic orientation is as it leaves the Sun and if this will change en route due to untwisting or interaction with overlying magnetic field.

Bother and Rust (1997) did find a correlation between the handedness of magnetic clouds and whether the associated quiet Sun filament erupted from the northern or southern hemispheres. This suggest a possibility to track quiet Sun filaments from the Sun to the Earth. Other studies such as Leamon *et al.* (2002) found no relationship between twisted sigmoidal structures in the corona and magnetic clouds, suggesting that significant changes occur during the eruption.

5. Future missions

There are two space missions due to be launched in the next few years which will make leaps forward in understanding coronal mass ejections. These are briefly described below.

5.1. *Solar-B*

Solar-B is a Japan/UK/US missions and uses a combination of optical, EUV and X-ray instrumentation to study the relationship between the Sun's magnetic field and its atmosphere. There are 3 instruments onboard – the Solar Optical Telescope (SOT), the X-ray Telescope (XRT) and the EUV Imaging Spectrometer (EIS). These will provide measurements of magnetic fields, electric currents and velocity fields, which coupled with imaging and spectroscopy of the corona will reveal the trigger for flares and CMEs.

5.2. *STEREO*

STEREO (Solar TErrestrial RElations Observatory) is a NASA mission consisting of two nearly identical observatories to provide 3-D measurements of the Sun. There is a mixture of in situ and remote sensing instrumentation. STEREO will also be launched in 2006 and will provide the 3-D global view.

5.3. *Solar Dynamics Observatory (SDO)*

SDO is a NASA mission that will provide continuous observations of the Sun's interior and outer atmosphere.

6. Summary

Huge progress has been made in the past few years in understanding CMEs. The future instrumentation will push forward the following unanswered questions;

- What is the origin of the Sun's magnetic field and where how does it become twisted?
- What triggers ejection of plasma and magnetic field?
- What happens to an ejection as it leaves the Sun?
- Can we predict the orientation of a CME from when it leaves the Sun to when it reaches the Earth?

The future will hold answers to these questions.

Acknowledgements

LKH would like to acknowledge the Leverhulme trust for the award of a Philip Leverhulme Prize that has allowed the collaboration to take place with NAOC. JW is supported by the key project of NSFC (10233050).

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