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Coronal Mass Ejections: Observations

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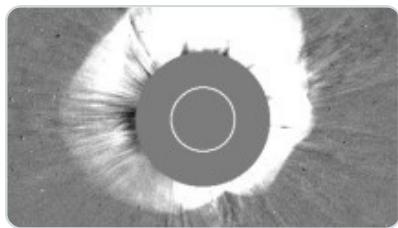
Abstract

Solar eruptive phenomena embrace a variety of eruptions, including flares, solar energetic particles, and radio bursts. Since the vast majority of these are associated with the eruption, development, and evolution of coronal mass ejections (CMEs), we focus on CME observations in this review. CMEs are a key aspect of coronal and interplanetary dynamics. They inject large quantities of mass and magnetic flux into the heliosphere, causing major transient disturbances. CMEs can drive interplanetary shocks, a key source of solar energetic

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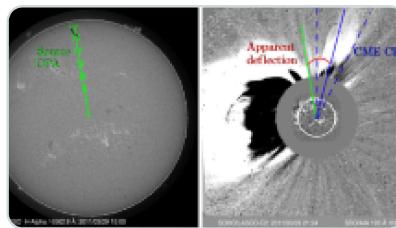
WIND, ACE, STEREO, and SOHO spacecraft, along with ground-based instruments, have improved our knowledge of the origins and development of CMEs at the Sun and how they contribute to space weather at Earth. SOHO, launched in 1995, has provided us with almost continuous coverage of the solar corona over more than a complete solar cycle, and the heliospheric imagers SMEI (2003–2011) and the HIs (operating since early 2007) have provided us with the capability to image and track CMEs continually across the inner heliosphere. We review some key coronal properties of CMEs, their source regions and their propagation through the solar wind. The LASCO coronagraphs routinely observe CMEs launched along the Sun–Earth line as halo-like brightenings. STEREO also permits observing Earth-directed CMEs from three different viewpoints of increasing azimuthal separation, thereby enabling the estimation of their three-dimensional properties. These are important not only for space weather prediction purposes, but also for understanding the development and internal structure of CMEs since we view their source regions on the solar disk and can measure their in-situ characteristics along their axes. Included in our discussion of the recent developments in CME-related phenomena are the latest developments from the STEREO and LASCO coronagraphs and the SMEI and HI heliospheric imagers.

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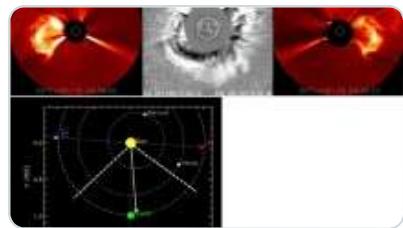
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1 Introduction

Coronal mass ejections (CMEs) consist of large structures containing plasma and magnetic fields that are expelled from the Sun into the heliosphere. They are of interest for both scientific and technological reasons. Scientifically they are of interest because they remove built-up magnetic energy and plasma from the solar corona (Low, 1996), and technologically they are of interest because they are responsible for the most extreme space weather effects at Earth (Baker *et al.*, 2008), as well as at other planets and spacecraft throughout the heliosphere. Most of the ejected material comes from the low corona, although cooler, denser material probably of chromospheric or photospheric origin is also sometimes involved. The CME plasma is entrained on an expanding magnetic field, which commonly has the form of helical field lines with changing pitch angles, i.e., a flux rope. This paper reviews the best-determined coronal properties of CMEs and what we know about their source regions, and some key signatures of CMEs in the solar wind. Observations of Earth-directed CMEs, often observed as halos surrounding the occulting disk of near-Earth coronagraphs, are important for space weather studies.

Until the early years of this century, images of CMEs had been made near the Sun primarily by coronagraphs on board spacecraft. Coronagraphs view the outward flow of density

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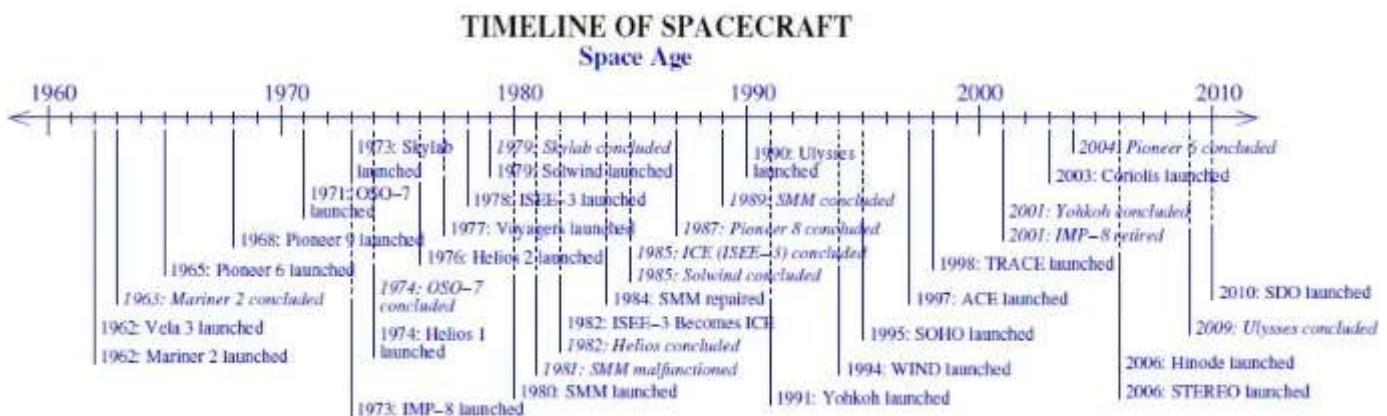
which must be accounted for in the measurements (e.g., Durrig, 1990; Vourlidas and Howard, 2006; Howard and Tappin, 2009). They are faint relative to the background corona, but much more transient, so some form of background subtraction is typically applied to identify them. CME-related phenomena such as flares and prominence eruptions have been known since the late 19th century, and energetic particles (Forbush, 1946), type II and IV radio bursts (Wild *et al.*, 1954), and interplanetary shocks (Sonnett *et al.*, 1964) have been observed since the 1940s, 50s and 60s. The first spacecraft coronagraph observations of CMEs were made by the OSO-7 coronagraph in the early 1970s (Tousey, 1973). These were followed by better quality and longer periods of CME observations using Skylab (1973 – 1974; MacQueen *et al.*, 1980), P78-1 (Solwind) (1979 – 1985; Sheeley Jr *et al.*, 1980), and SMM (1980; 1984 – 1989; Hundhausen, 1999). In late 1995, SOHO was launched and two of its three LASCO coronagraphs still operate today (Brueckner *et al.*, 1995). Finally late in 2006, LASCO was joined by the STEREO CORs (Howard *et al.*, 2008a). These early observations were complemented by white light data from the ground-based Mauna Loa Solar Observatory (MLSO) K-coronameter viewing from $1.2 - 2.9R_{\odot}$ (Fisher *et al.*, 1981; Koomen *et al.*, 1974) and green line observations from the coronagraphs at Sacramento Peak, New Mexico (Demastus *et al.*, 1973) and Norikura, Japan (Hirayama and Nakagomi, 1974).

Throughout the early years also, at larger distances from the Sun, interplanetary transients were observed using interplanetary radio scintillation (1964 – present; Hewish *et al.*, 1964; Houminer and Hewish, 1974; Vlasov, 1981) and from the zodiacal light photometers on the twin Helios spacecraft (1975 – 1983; Richter *et al.*, 1982; Jackson, 1985). The Helios photometers observed regions in the inner heliosphere from $0.3 - 1.0$ AU but with an extremely limited field of view. The new millennium witnessed the arrival of a new class of detector, the heliospheric imager, with the Solar Mass Ejection Imager (SMEI) launched on board the Coriolis spacecraft early in 2003 and the Heliospheric Imagers (HIs) launched on the twin STEREO spacecraft in late 2006. LASCO has detected well over 10^4 CMEs during its lifetime (Yashiro *et al.*, 2004; Gopalswamy *et al.*, 2009b; http://cdaw.gsfc.nasa.gov/CME_list/). SMEI observed nearly 400 transients during its 8.5 year lifetime (Webb, 2004; Webb *et al.*, 2006; Howard and Simnett, 2008); it was switched off in September 2011. The number of “events” reported using the HIs is now over 1340

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These mostly white light observations have been accompanied by those of the solar disk at coronal wavelengths including the SOHO Extreme Ultraviolet Imaging Telescope (EIT), SOHO Coronal Diagnostic Spectrometer (CDS) imagers, STEREO Extreme-UltraViolet Imager (EUVI), and instruments on board the Yohkoh, TRACE, RHESSI, and Hinode spacecraft (see Hudson and Cliver, [2001](#)), as well as near and beyond 1 AU by in-situ experiments on spacecraft including the Voyagers, Ulysses, Helios, Wind, ACE, and STEREO. In February 2010 the Solar Dynamics Observatory (SDO) spacecraft joined the solar disk imaging ensemble, while EIT, Yohkoh, TRACE, SMEI and Ulysses no longer return scientific data. In addition, important new plasma diagnostics of CMEs have been obtained from ultraviolet spectroscopy from SOHO (CDS, SUMER, and UVCS, Hinode (EIS) and SDO (EVE). The UVCS instrument, in particular, which overlaps the same height range as LASCO C2, has provided a wealth of data on the evolution of hundreds of CMEs (see review by Kohl *et al.*, [2006](#)). [Figure 1](#) shows a timeline of the launches of spacecraft relevant to CME study.

Figure 1



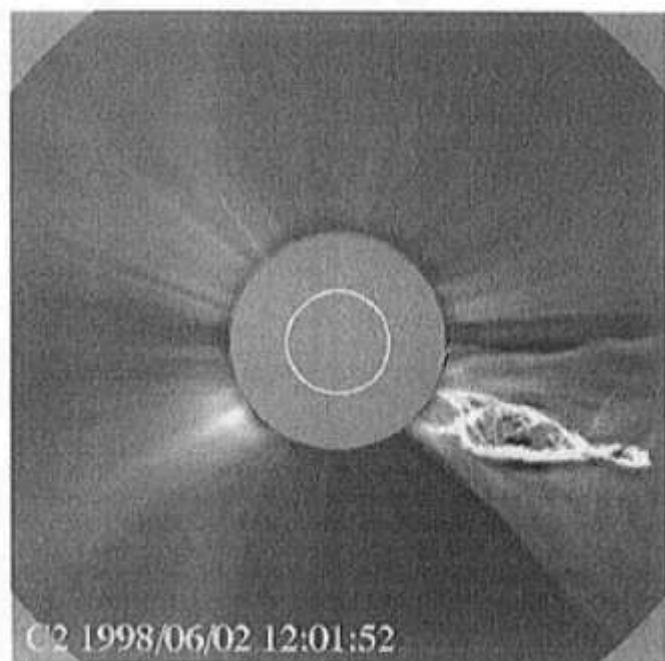
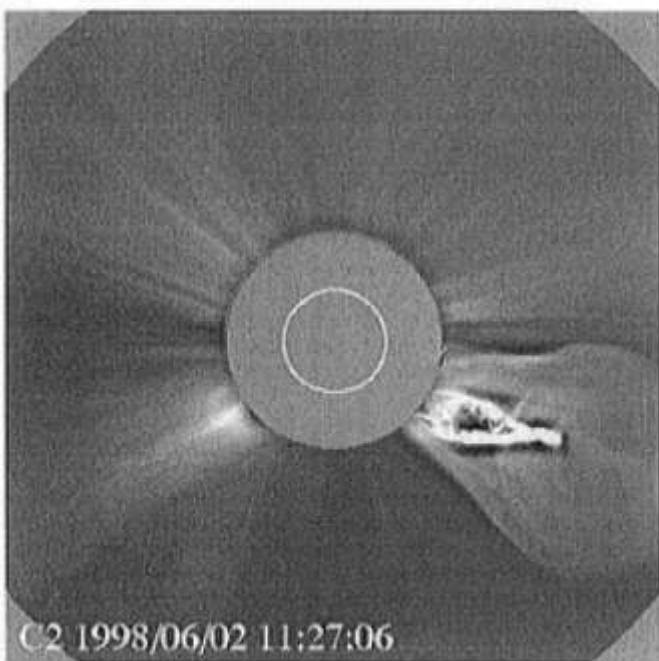
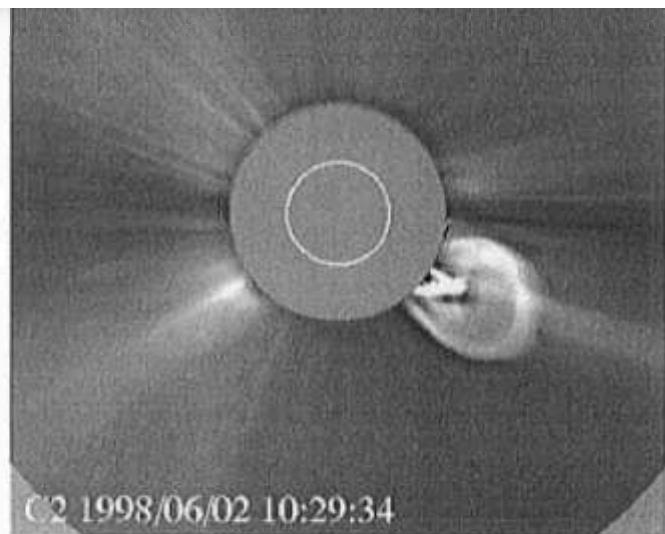
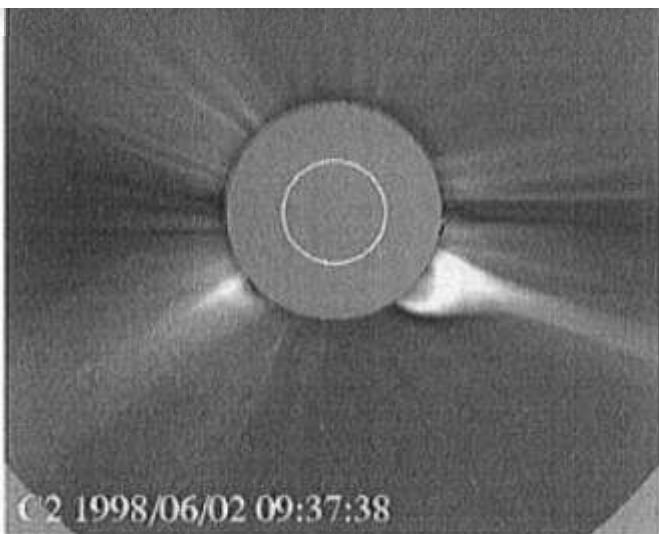
Timeline of the history of spacecraft relevant to CME study. Image adapted from Howard ([2011b](#)).

White light observations of CMEs reveal that, even near the sun, the CME can dwarf the solar disk (see [Figure 2](#)). Coronal images of CMEs have also been obtained at radio frequencies,

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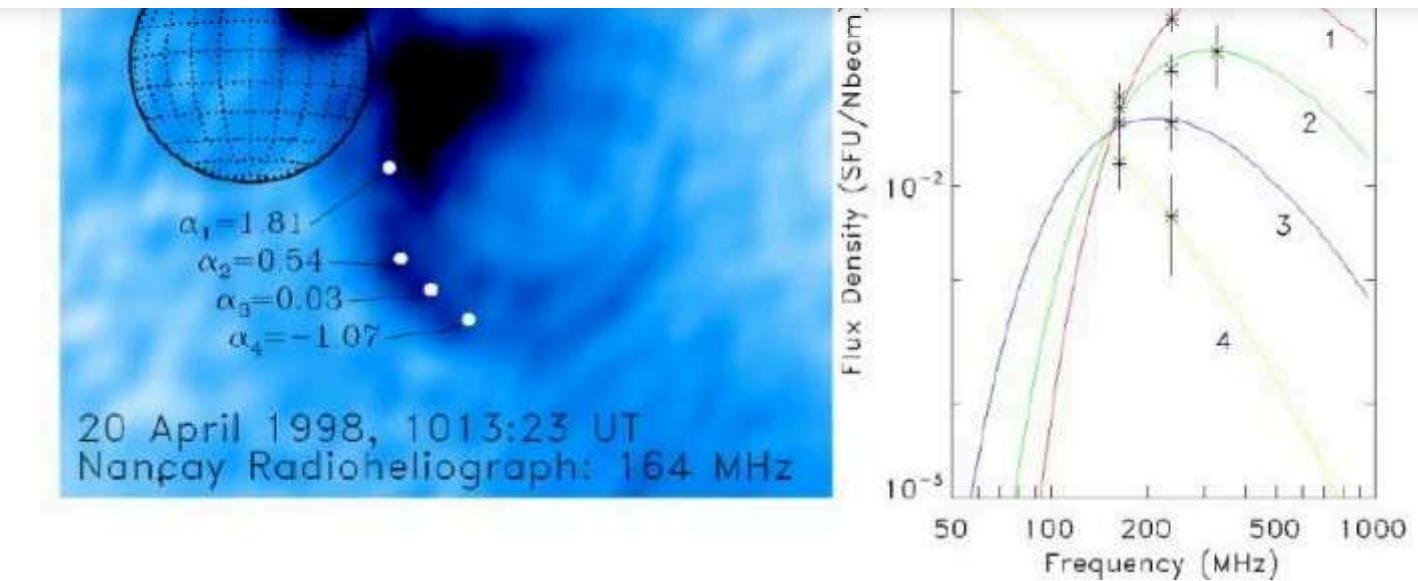
and into the heliosphere, but some minor variability and radio, [1992](#), and non-thermal CME radio emission (such as type IV bursts) have also been imaged. [Figure 3](#) shows a rare image of a radio CME from the Nançay (France) Radioheliograph. The onset of CMEs has been associated with many solar disk phenomena such as flares (e.g., Feynman and Hundhausen, [1994](#)), prominence eruptions (e.g., Hundhausen, [1999](#)), coronal dimming (e.g., Sterling and Hudson, [1997](#); Thompson *et al.*, [1999](#)), arcade formation (e.g., Hanaoka *et al.*, [1994](#); Hudson and Webb, [1997](#)), and X-ray sigmoids (e.g., Canfield *et al.*, [1999](#)). However, the vast majority of the ejected energy assumes the form of mechanical energy carried by the CME and not the associated solar flare, even in the most energetic cases (Emslie *et al.*, [2004](#)). Many CMEs have also been observed to be unassociated with any obvious solar surface activity (Howard and Tappin, [2008](#); Robbrecht *et al.*, [2009a](#)). Most flares occur independently of CME eruptions and it now seems likely that any flare accompanying a CME is part of an underlying magnetic process rather than being a direct cause of the CME launch (Kahler, [1992](#); Gosling, [1993](#)). Recent models describing the onset and early evolution of CMEs (e.g., Moore and Roumeliotis, [1992](#); Antiochos *et al.*, [1999](#); Fan and Gibson, [2003](#); Lynch *et al.*, [2005](#)) provide a variety of mechanisms by which this may be accomplished.

Figure 2

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Evolution of a “classic” CME observed by the LASCO C2 coronagraph on 2 June 1998. Note the circular structures just above the prominence, suggesting a flux rope. Image reproduced with permission from Plunkett *et al.* (2000), copyright by Springer.

Figure 3

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- a) Snapshot map of a radio CME at a frequency of 164 MHz at the time of maximum flux. The background emission from the Sun has been subtracted. Time variable radio emission from a noise storm is present to the northwest (upper right). The brightness of the CME is saturated in the corona because the map has been clipped at a level of $0.04 \text{ SFU beam}^{-1}$, corresponding to a brightness temperature of $2.6 \times 10^5 \text{ K}$. The radio CME is visible as a complex ensemble of loops extended out to the southwest (lower right). Also shown is the spectral index measured at four locations in the radio CME. b) Flux spectra measured at the four points shown in (a). All flux measurements have been normalized to $\text{SFU } N_{\text{beam}}^{-1}$, where N_{beam} is the 164 MHz beam. Model spectra are also shown. Image reproduced with permission from Bastian *et al.* ([2001](#)).

We refer the reader to reviews of these models by, for example, Forbes *et al.* ([2006](#)), rather than discuss them at length here in this review of CME observations. We also draw the reader's attention to other reviews of solar eruptive phenomena and CMEs, including Kahler ([1992](#), [2006](#)), Webb *et al.* ([1996](#)), Hundhausen ([1997](#), [1999](#)), Low ([1997](#)), St Cyr *et al.* ([2000](#)), Webb ([2002](#), [2004](#)), Gopalswamy ([2004](#)), Gopalswamy *et al.* ([2006b](#)), and Aschwanden ([2006](#)). Several recent journal special issue volumes are devoted to CMEs: LASCO-era CMEs ([Kunow *et al.*, 2006](#)), CME and energetic particles ([Gopalswamy *et al.*, 2006a](#)), STEREO results ([Christian *et al.*, 2009](#)), and 3-D measurements ([Mierla *et al.*, 2011](#)). In addition, see also the Living Reviews by Schwenn ([2006](#)) and Chen ([2011](#)), and other Living Reviews in

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Properties of CMEs

The measured properties of CMEs include their occurrence rates, locations relative to the solar disk, angular widths, speeds and accelerations, masses, and energies (e.g., Hundhausen, [1972](#); Kahler, [1992](#); St Cyr *et al.*, [2000](#); Webb, [2002](#); Yashiro *et al.*, [2004](#); Gopalswamy *et al.*, [2005](#), [2006b](#); Gopalswamy, [2010b](#); Kahler, [2006](#); Vourlidas *et al.*, [2010](#)). There is a large range in the basic properties of CMEs, although some of this scatter is likely due to imaging projection effects (e.g., Burkepile *et al.*, [2004](#); Cremades and Bothmer, [2004](#)). Their speeds, accelerations, masses, and energies extend over 2 – 3 orders of magnitude (e.g., Vourlidas *et al.*, [2002a](#); Gopalswamy *et al.*, [2006b](#)), and their angular widths exceed by factors of 3 – 10 the sizes of flaring active regions (e.g., Yashiro *et al.*, [2004](#)). Note that the measured values in the above cited publications make the assumption that all the CME material is in the “plane of the sky”, i.e., in the plane orthogonal to the Sun-Earth line. Thus, for example, unless a CME is exactly at the solar limb, its derived properties will be an underestimate and the width an overestimate. Recent developments using auxiliary data (Howard *et al.*, [2007](#), [2008b](#)) and the multiple viewpoint capability of STEREO (e.g., Mierla *et al.*, [2010](#), and references therein) have attempted to overcome this problem. These are discussed later. [Table 1](#) summarizes the statistical properties from all of the near-Earth space borne coronagraph observations of CMEs (summaries of most CME parameters observed by the STEREO spacecraft are not yet available).

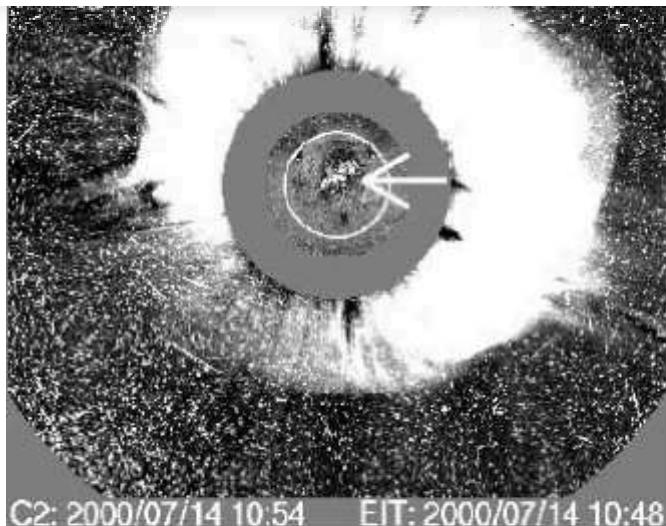
Table 1 Average statistical properties from near-Earth space borne coronagraph observations of CMEs. Updated from Gopalswamy ([2004](#)).^a SMM values from Burkepile *et al.* ([2004](#)).^b Updated by S. Yashiro (2011) priv. comm.^c LASCO masses and energies from Vourlidas *et al.* ([2010](#), [2011b](#)). The Solwind mass and energy values in Vourlidas *et al.* ([2010](#), [2011b](#)) are in error (C.A. de Koning and A. Vourlidas (2012) priv. comm.). Although Solwind operated into 1985, we show only the values for 1979 – 81 from Howard *et al.* ([1985](#)).

CMEs can exhibit a variety of forms, some having the classical “three-part” structure (Illing and Hundhausen, [1985](#)), usually interpreted as compressed plasma ahead of a flux rope

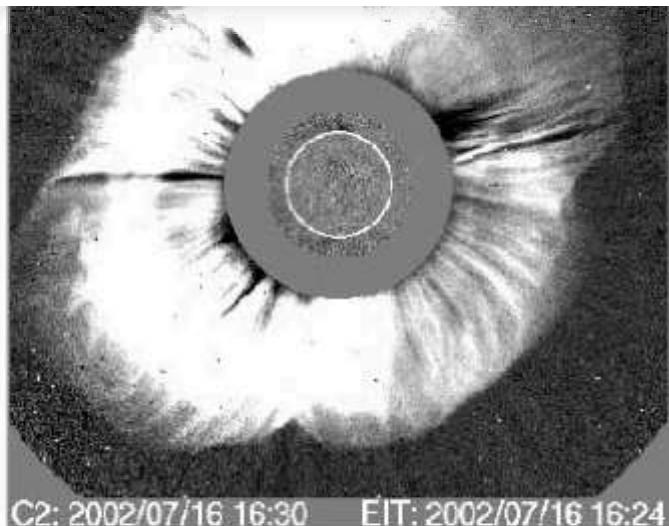
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existing coronal structures (the so-called streamer boundaries), while others appear as wide almost global eruptions. CMEs spanning very large angular ranges are probably not really global, but rather have a large component along the Sun–observer line and so appear large by perspective. These include the so-called halo CMEs (Howard *et al.*, 1982) — see [Section 2.3](#). The CDAW CME catalog (Yashiro *et al.*, 2004) defines a “partial halo” as a CME with an apparent position angle range $> 120^\circ$. Hence, again, the definition of a CME is restricted by its viewing perspective. [Figure 4](#) illustrates several examples of partial and full halo CMEs observed by LASCO.

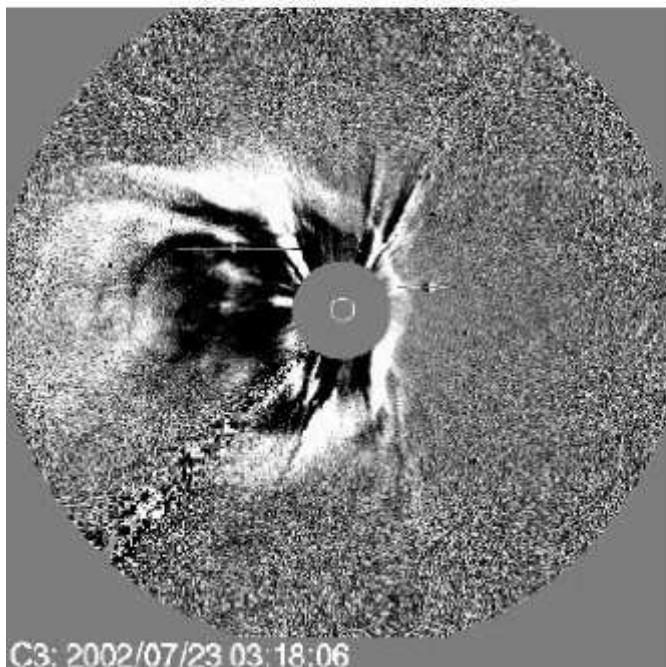
Figure 4

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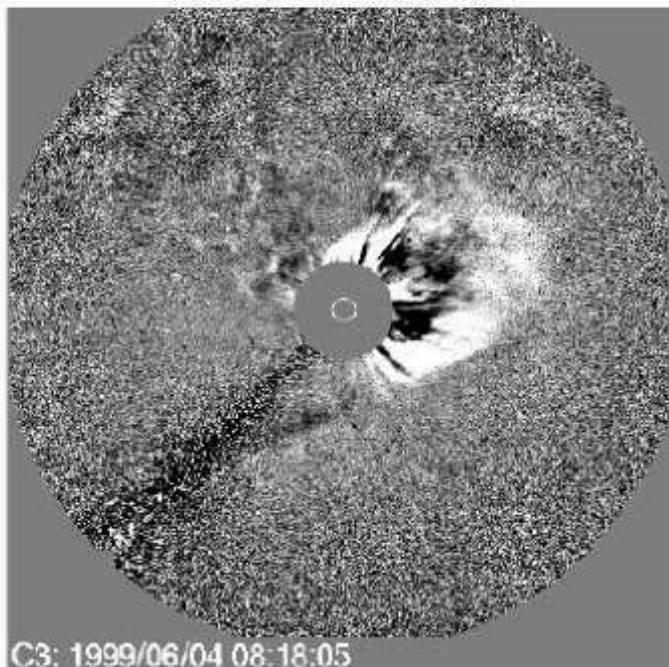
C2: 2000/07/14 10:54 EIT: 2000/07/14 10:48



C2: 2002/07/16 16:30 EIT: 2002/07/16 16:24



C3: 2002/07/23 03:18:06



C3: 1999/06/04 08:18:05

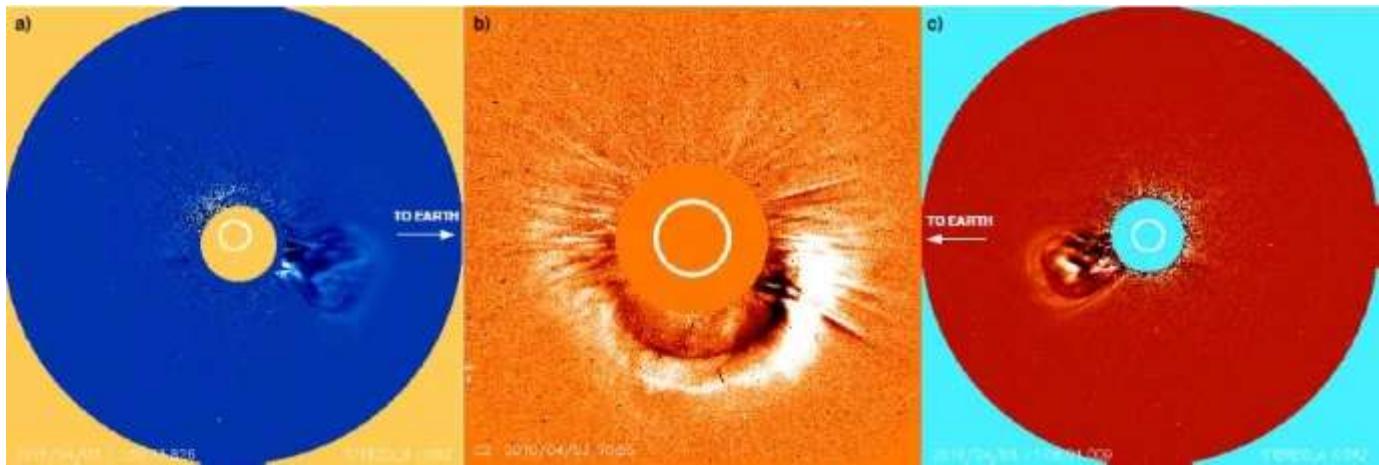
Examples of a variety of halo CME observations, clockwise: a frontside full halo (arrow shows likely source near Sun center); a backside full halo; a partial halo; and an asymmetric full halo. Image reproduced with permission from Gopalswamy *et al.* ([2003a](#)).

Figure 5 shows images of the same event (the Earth-directed CME from early April 2010) observed from three different viewpoints. Figure 5b shows the perspective from LASCO, which is along the Sun-Earth line, where the CME appears as a halo. Figures 5a and c show the same CME as observed by each STEREO spacecraft, which were separated in longitude by

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appearance of this CME, with the only physical change being the viewing location, demonstrates the importance of perspective with respect to measuring CME properties.

Figure 5



Images of the same Earth-directed CME obtained from three different viewing locations within an hour: a) from STEREO/COR2-B on 3 April 2010 at 11:39 UT, b) from LASCO/C2 at 10:55 UT, and c) from STEREO/COR2-A on the same day at 11:08 UT. At this time (April 2010) the STEREO spacecraft were approximately 70° in longitude from the Sun-Earth line and $\sim 140^\circ$ from each other. The different appearances of this same CME observed at around the same time demonstrate the need to consider perspective in measuring CME properties.

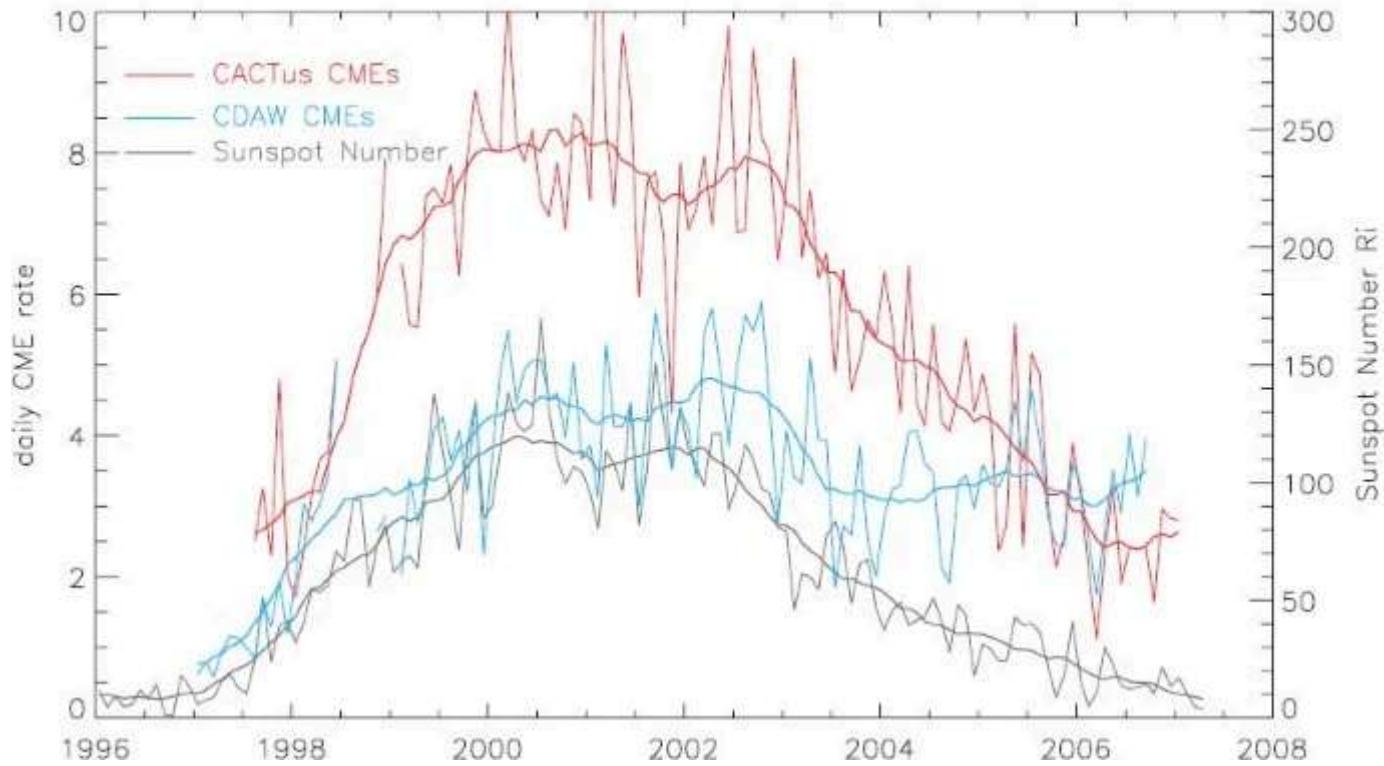
2.1 CME identification and measurement

Traditionally CME observations were obtained by visual inspection of coronagraph images, and many of these “manual” catalogs of CMEs observed by the P78/Solwind (http://lasco-www.nrl.navy.mil/solwind_transient.list), SMM C/P (http://smm.hao.ucar.edu/smm/smmcp_catalog.html), and LASCO C2 and C3 coronagraphs (http://cdaw.gsfc.nasa.gov/CME_list/index.html) are now on-line (Boursier *et al.*, 2009; Gopalswamy *et al.*, 2009b). These catalogs have in recent times been augmented by additional on-line catalogs of CMEs detected by automatic methods. One is the CACTus CME catalog (Robbrecht *et al.*, 2009a), which uses the Hough transform to detect motion of the

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catalogs CMEs detected by the STEREO COR2 coronagraphs, which are in near-1 AU solar orbits.

Comparisons among the LASCO catalogs have shown significant differences. For example, Robbrecht *et al.* (2009a) found that CACTus automatically identified many more events than in the CDAW (manual) catalog but half of them were narrow ($< 20^\circ$ of apparent angular width). In addition, as shown in Figure 6, the shapes of the CME rate curves were quite different with the CACTus and sunspot curves similar, but the CDAW curve flattened out during the cycle decline. This and other comparisons suggest that the CDAW catalog is affected by observer bias since it has been compiled by at least four different observers throughout the lifetime of the SOHO mission. One example of this bias appears in the occurrence rate in later years of the SOHO mission. Occurrence rate increased greatly after 2004, not because more CMEs were physically erupting, but rather because a decision was made to categorize very narrow LASCO features, which were previously disregarded, as CMEs. Another comparison of CME properties of the four LASCO catalogs shows best agreement between the ARTEMIS and SEEDS catalogs (Boursier *et al.*, 2009), which better reflect the early stages of CMEs (i.e., within the LASCO C2 field of view). A recent analysis of LASCO CMEs based on a multiscale method convolving high and low-pass filters with CME images (Byrne *et al.*, 2009) has shown that multiscale values agree much better with the generally smaller SEEDS CME widths than with the larger CACTus and CDAW values. A comparison of the LASCO fast ($v > 1000 \text{ km s}^{-1}$) CMEs between the CDAW and CACTus catalogs shows that the CDAW fast CME widths are considerably wider (Yashiro *et al.*, 2008b). The CACTus CME width distribution is essentially scale invariant in angular span over a range of scales from $20 - 120^\circ$ while previous catalogs present a broad maximum around 30° . Yashiro *et al.* (2008b) found that the CACTus catalog has a larger number of narrow CMEs than CDAW, and that the CDAW catalog missed many narrow CMEs during solar maximum. Another significant discrepancy was that the majority of the fast CDAW CMEs are wide and originate from low latitudes, while the fast CACTus CMEs are narrow and originate from all latitudes. In general, automatic catalogs do not always identify wide CMEs,

[Download PDF](#)**Figure 6**

Daily SOHO LASCO CME rates for Cycle 23 (thin curves: smoothed per month, thick curves: smoothed over 13 months) from 1997 — 2006. These have been extracted using CACTus (red) and the CDAW CME Catalog (blue). As reference, the daily and smoothed monthly sunspot number have been overplotted in gray (produced using the SIDC-Royal Observatory of Belgium). The CME rates have been adjusted to accommodate for duty cycle. Image reproduced with permission from Robbrecht *et al.* (2009a), copyright by IOP.

The above discussion demonstrates that CME identification and measurement remain somewhat subjective and no consensus has yet been achieved regarding the establishment of a standard definition of a CME or of the components within. The original definition of a CME as a new, discrete brightening in the field of view over a time-scale of tens of minutes which is always observed to move outward (e.g., Webb and Hundhausen, 1987) is still generally accepted. However, some workers tend to regard any eruption from the Sun observed in the

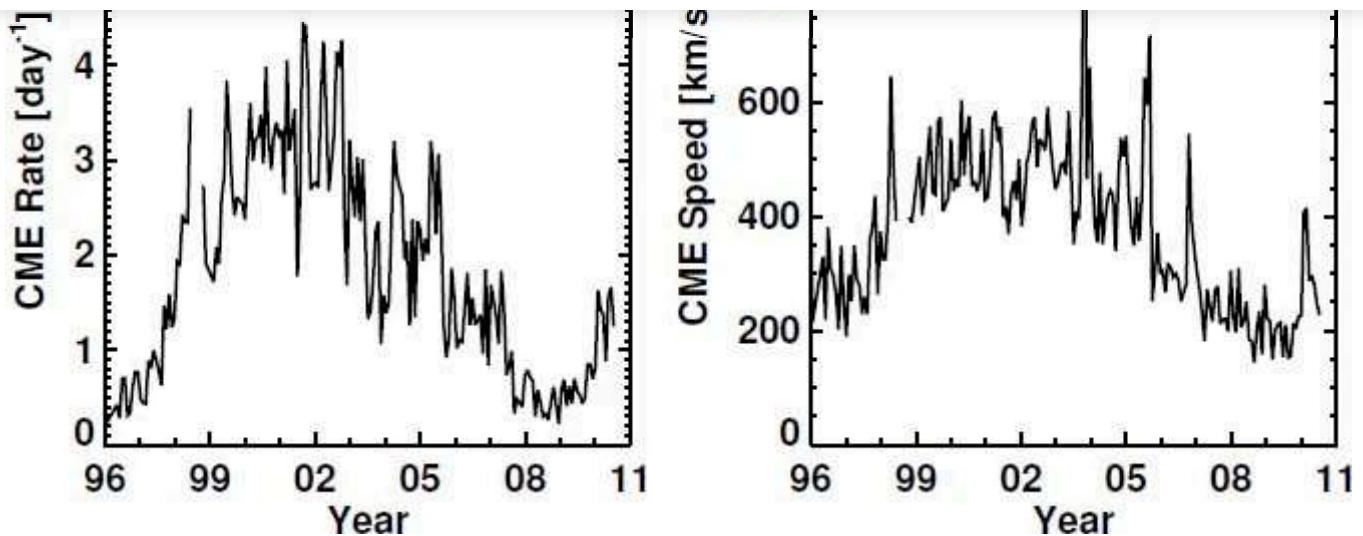
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the eruption of a magnetic flux rope, the structure and magnitude of any coronal magnetic field near the Sun can only be inferred, since we cannot directly measure coronal magnetic fields. Efforts to make the connection between magnetic flux ropes measured in-situ with CME structure observed by coronagraphs have been made, most recently by Howard and DeForest (2012a).

2.2 Frequency of occurrence

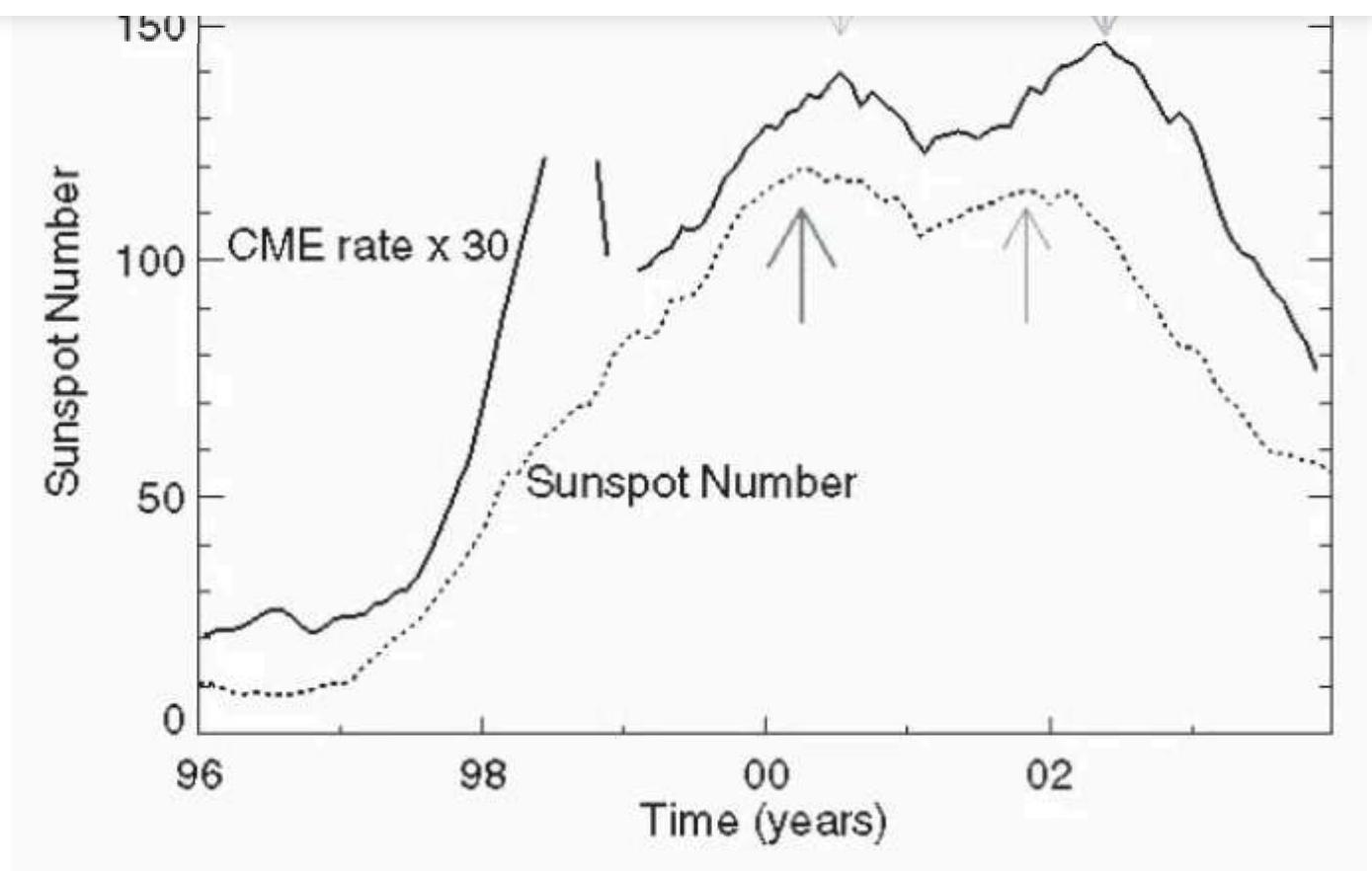
The frequency of occurrence of CMEs observed in white light tends to follow the solar cycle in both phase and amplitude, which varies by an order of magnitude over the cycle (Webb and Howard, 1994). LASCO has now observed the entire Solar Cycle 23 (1996 – 2008) (Figure 7) and continues to observe through this current rising phase of Cycle 24. It has detected CMEs at a rate slightly higher than earlier observations, varying from around one per day around solar minimum to nearly five per day at solar maximum (St Cyr *et al.*, 2000; Gopalswamy *et al.*, 2005, 2006b). This has been attributed to the improved sensitivity of LASCO as opposed to any physical difference between CME activity in Cycle 23 and that in prior cycles. LASCO, for example, observes halo CMEs (Section 2.3) regularly whereas no prior coronagraph observed more than a few (Howard *et al.*, 1985, for example, only identified 20 halos out of 998 CMEs observed with Solwind)]. This demonstrates that a fraction of CMEs were undetectable by coronagraphs prior to LASCO. A 13-month running average of the LASCO CME rate vs. sunspot number shows that both have double peaks, but that the CME peak lagged sunspots by many months (Figure 8). This lag has also been seen in previous cycles and is related to observations that high latitude CMEs arise from polar crown filaments which have a “rush to the poles” near maximum and disappear (erupt) with a frequency that slightly lags sunspot numbers at low latitudes (Cliver and Webb, 1998; Gopalswamy *et al.*, 2003b).

Figure 7

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LASCO CME occurrence rate (left) and mean speed (right) from 1996 to 2011 averaged over Carrington rotations. The large spike in CME speed is due to highly energetic CMEs that erupted in the late 2003 period. Image adapted from Gopalswamy ([2010b](#)), updated by S. Yashiro (2011).

Figure 8

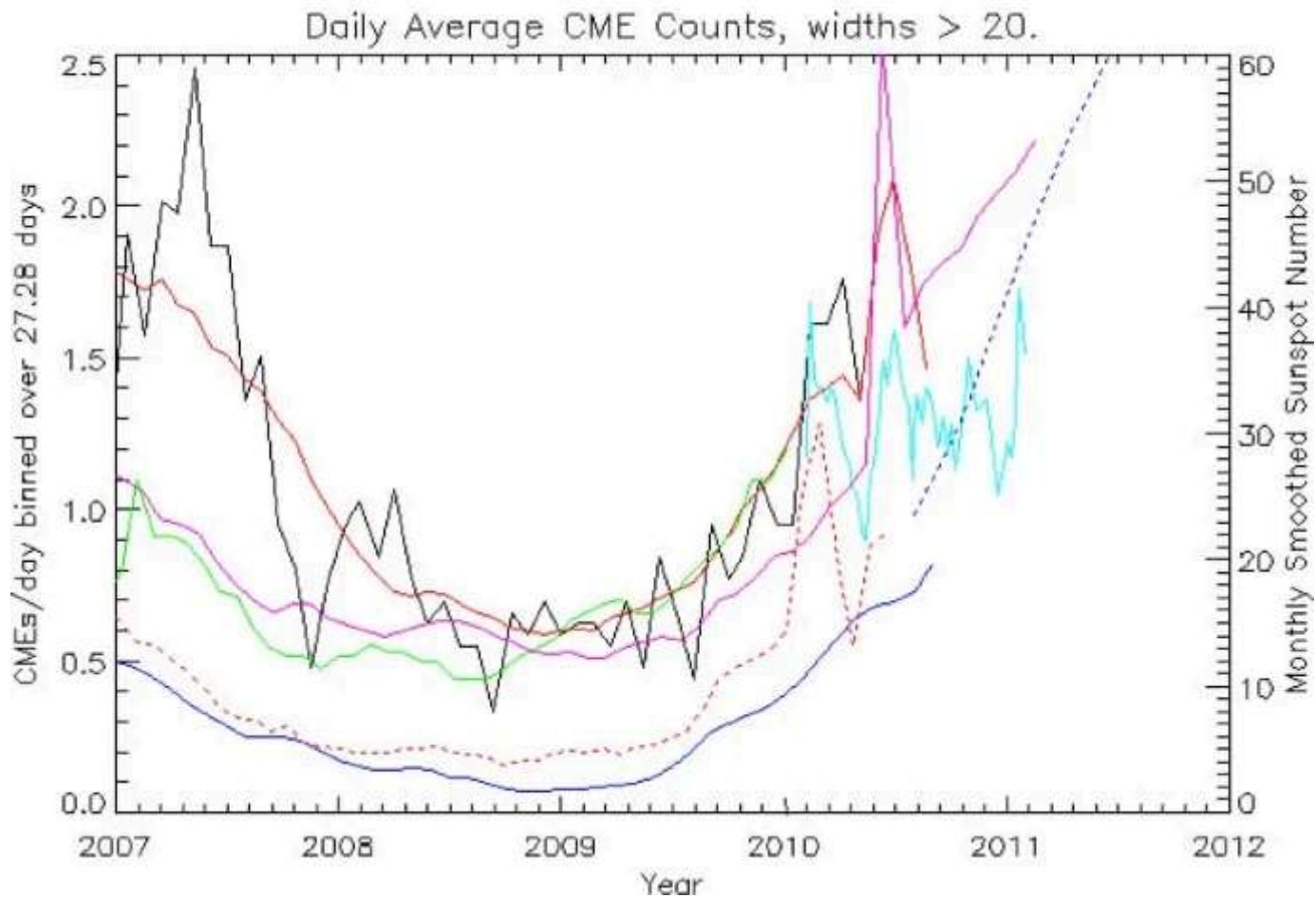
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The LASCO CME rate smoothed over 13 Carrington rotations and compared with the solar sunspot number. Arrows indicate the two maxima in CME rate and sunspot number. Large data gaps occurred during June 1998 to February 1999. Image reproduced with permission from Gopalswamy (2004), copyright by Springer.

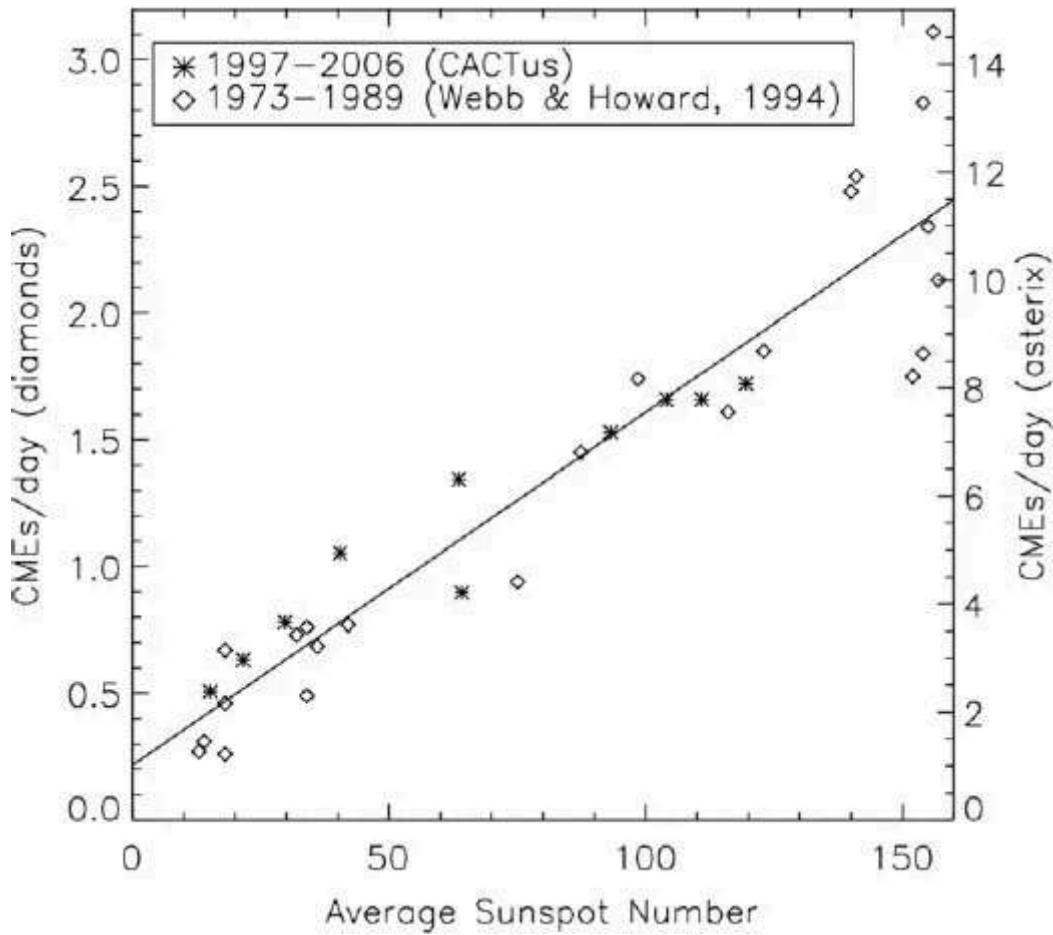
As has been well documented, Solar Cycle 23 had an unusually long decline and flat minimum, extending the cycle to ~ 13 years, with the “true” minimum in late 2008 or early 2009 (Hathaway, 2010). Referring back to the updated LASCO CDAW CME rate in [Figure 6](#), [Figure 9](#) tracks the CME rate from the CDAW, SEEDS and CACTus catalogs from 2007 into 2011 along with the current and predicted SWPC sunspot number. Despite differences in amplitude, it is clear that the CME rate continues to be correlated with the sunspot number through its minimum and initial rise of Cycle 24, with the CME rate minimum in late 2008 or early 2009. The linear relationship between CME rate and sunspot numbers was first shown by Webb and Howard (1994) and recently confirmed for Cycle 23 by Robbrecht *et al.*

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coronagraphs, demonstrating that the CME rate is relatively constant despite the increasing longitudinal angle between the STEREO spacecraft and Earth from 0 – 90° during this period.

Figure 9

Daily CME rate for 2010 – 2011 in the context of the rate through recent solar minimum. CME data sources: LASCO = manual online CDAW catalog (black – NRL, CUA) and our counts since January 2010 (light blue); SEEDS = automatic catalog (dotted red) courtesy J. Zhang and J. Bannick (GMU); CACTus = automatic catalog courtesy E. Robbrecht & B. Bourgoignie (SIDC); STEREO COR1 = manual catalog (green) courtesy C. St. Cyr (NASA) and H. Xie (CUA); Sunspot number (SSN — dark blue is current, dotted blue is predicted) from NOAA SWPC. CDAW and SEEDS rates are for CME widths >

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Daily CME rate vs. SSN both averaged per year. The asterisks refer to rates for Cycle 23 derived from CACTUS (see [Table 1](#)). Its absolute scale is shown on the right y-axis. The daily CME rates derived by Webb and Howard ([1994](#)) are plotted with diamonds. Its absolute scale is shown on the left y-axis. A scaling factor of ~ 4.7 applies between the CACTus and the Webb and Howard rates. Image reproduced with permission from Robbrecht *et al.* ([2009a](#)), copyright by IOP.

2.3 Halo CMEs

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~~Circular brightenings that completely surround the coronagraphic occulting disk (Figure 4).~~

Observations of associated activity on the solar disk are necessary to help distinguish whether a halo CME was launched from the front or backside of the Sun relative to the observer. This has had limited success, as frontsided CMEs that do not have a solar surface association can be mistaken for backsided events. Halo CMEs are important for three reasons:

1. The source regions of frontside halo CMEs are likely to be located within a few tens of degrees of Sun center from the perspective of the observer (Cane *et al.*, [2000](#); Webb, [2002](#); Gopalswamy, [2004](#); Gopalswamy *et al.*, [2010b](#)). Thus, these regions can be studied in greater detail than for most CMEs which are observed near the limb, but at the cost of reduced information about the CME itself because of projection. In recent years several CMEs have been observed by the “three eyes” of STEREO-B, LASCO and STEREO-A by a variety of viewing points, thus reducing this latter problem (e.g., Howard and Tappin, [2008](#); Wood and Howard, [2009](#); Robbrecht *et al.*, [2009b](#); Möstl *et al.*, [2009](#), [2010](#); Patsourakos and Vourlidas, [2009](#)).
2. Lacking significant deflections in the interplanetary medium, frontside halo CMEs should travel with part of their structure approximately along the Sun–observer line, so their internal material can be sampled in-situ by the observer.
3. When they are Earth-directed (i.e., observed as halos by spacecraft on the Sun–Earth line like SOHO), they are the key link between solar eruptions and major space weather phenomena such as geomagnetic storms and solar energetic particle events. This “geoeffectiveness” of halo CMEs depends on the source location on the disk. CMEs that are aligned near the relative disk center tend to be more geoeffective while those nearer the relative solar limb are less so. This center-to-limb variation of the geoeffectiveness has been documented (e.g., Gopalswamy *et al.*, [2007](#)). The vast majority of the most intense geomagnetic storms of Cycle 23, for example, were caused by halo CMEs (Gopalswamy, [2010a](#)). Three spacecraft, SOHO, Wind and ACE, provide solar wind measurements upstream of Earth, and the twin STEREO spacecraft provide similar measurements from their perspectives drifting away from the Sun–Earth line.

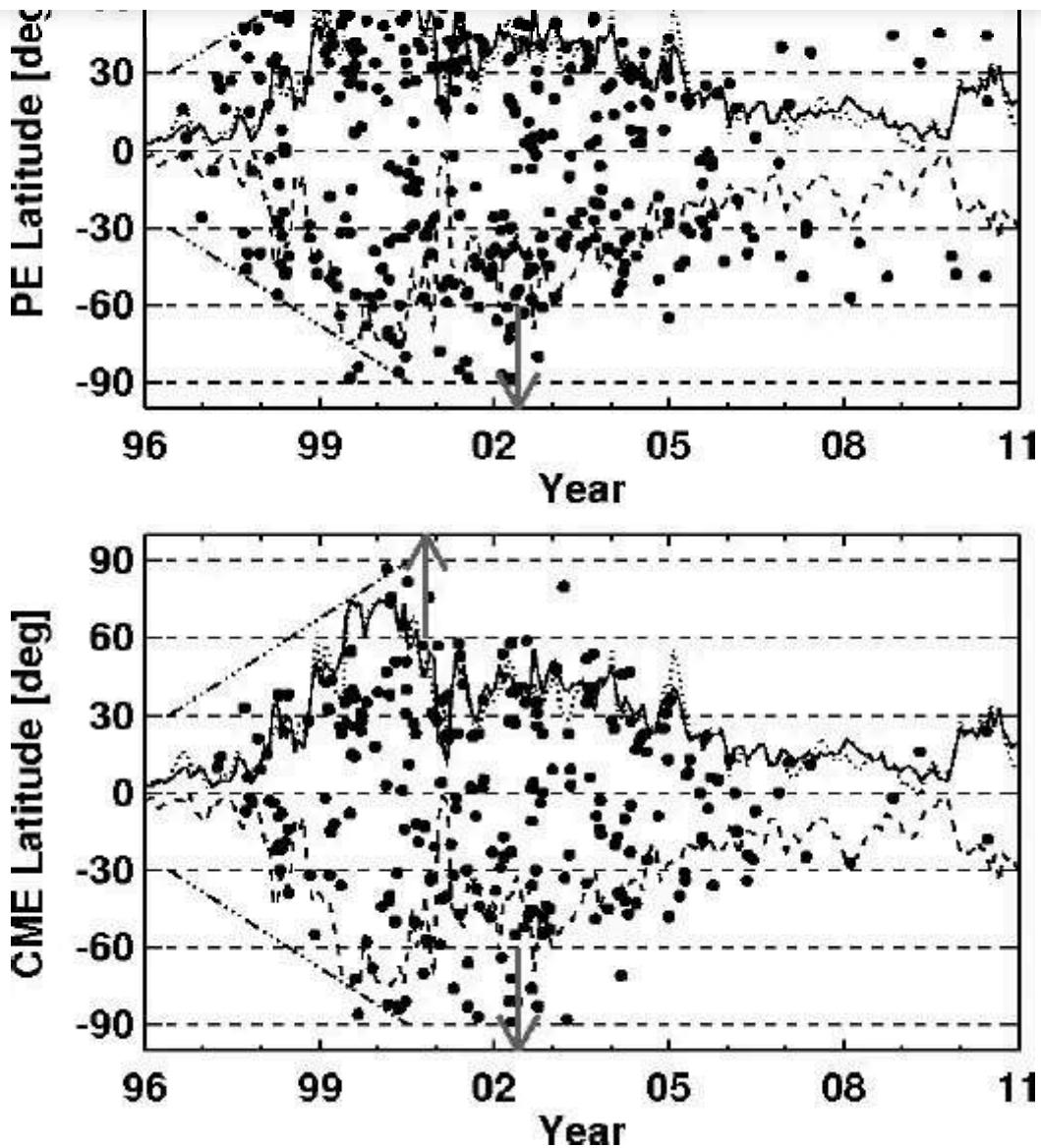
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et al., 2010), that halo CMEs appear to be faster and more energetic than non-halo CMEs. This, of course, does not imply that halo CMEs are somehow physically different, but rather it shows that even with LASCO some CMEs are not detected. LASCO does not observe faint (weak) CMEs near Sun center. Studies investigating this include those involving post-eruptive arcades (Tripathi *et al.*, 2004), interplanetary transients and shocks (Cane and Richardson, 2003; Howard and Tappin, 2005), and heliospheric imagers (Howard and Simnett, 2008). All found that between 3–7% of the studied CME-associated events were not associated with LASCO CMEs. Howard and Simnett (2008) further deduced that around 15% of interplanetary transients observed far from the Sun by SMEI were associated with either very weak CMEs or with those that had measurement problems, e.g., related to the large height and time separations between the LASCO and SMEI fields of view. However, this study did not exclusively involve halo CMEs.

2.4 Locations, widths, geometry

The latitude distribution of the central position angles of CMEs tends to cluster about the equator around solar minimum but broadens over all latitudes near solar maximum. Hundhausen (1993) first noted that this CME latitude variation more closely parallels that of streamers and prominences than of active regions or sunspots. This pattern also is closely linked to the variation of the global solar magnetic field, as exemplified by the tilt angle of the heliospheric current sheet (HCS) when the Sun makes its transition from solar minimum to maximum. This pattern including the match between CMEs, prominence eruptions and the HCS has been confirmed with the LASCO data (Figure 11 — Gopalswamy, 2004; Gopalswamy *et al.*, 2010a). On this figure also note the sharp decrease in the rate of CMEs and prominence eruptions in ~ 2006 when the HCS became flatter below 30° solar latitude.

Figure 11

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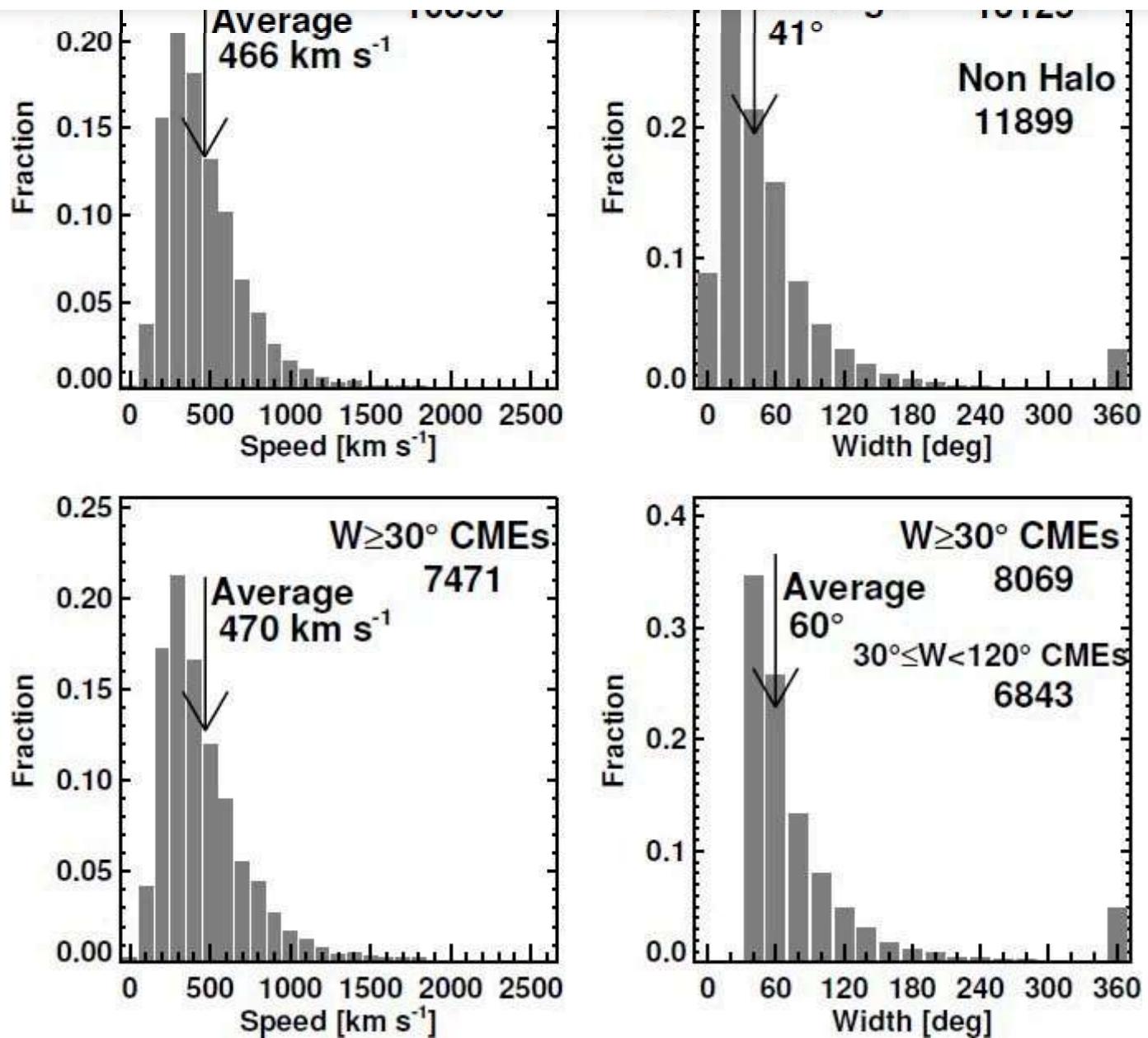
Latitudes of LASCO CMEs (filled circles) with known solar surface associations (identified from microwave prominence eruptions) plotted vs time, by Carrington Rotation number. The dotted and dashed curves represent the tilt angle of the heliospheric current sheet in the northern and southern hemispheres, respectively; the solid curve is the average of the two. The up and down arrows denote the times when the polarity in the north and south solar poles, resp., reversed. Note that the high latitude CMEs and PEs are confined to the solar maximum phase and their occurrence is asymmetric in the northern and southern hemispheres. PEs at latitudes below 40° may arise from active regions or quiescent filament regions, but those at higher latitudes are always from the latter. Image adapted from Gopalswamy (2004); Gopalswamy *et al.* (2010a), updated by S. Yashiro (2011).

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the CORs is affected by their increased detection of very wide CMEs, especially halos.

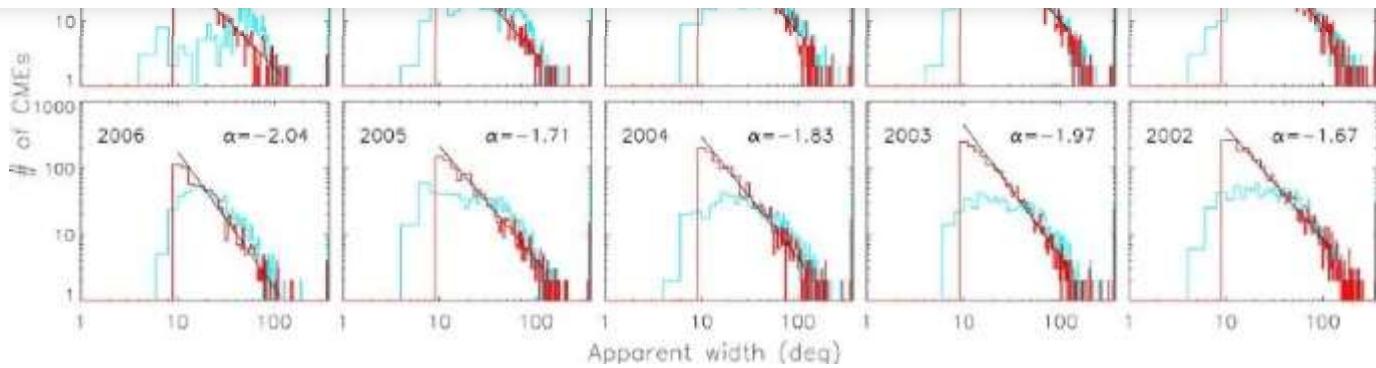
Including halo CMEs from January 1996 – June 1998, St Cyr *et al.* (2000) found the average (median) width of LASCO CMEs was 72° (50°). Including all measured LASCO CMEs of $20 - 120^\circ$ in width through 2002, Yashiro *et al.* (2004) found the average widths to vary, from 47° at minimum to 61° at maximum (1999), then declining again. Figure 12 from Gopalswamy *et al.* (2010a) gives the updated distributions of LASCO CME speeds and widths. The average width of 41° corresponds to nonhalo (width $\leq 120^\circ$) CMEs, whereas inclusion of all CMEs yields an average width of 60° . On the bottom are the speed and width distributions of all LASCO CMEs with widths $> 30^\circ$. That the CACTus automatic catalog contains many more narrow CMEs is illustrated in Figure 13 from Robbrecht *et al.* (2009b). Shown on a log-log scale are the CACTus and CDAW width distributions for each year from 1997 – 2006; CACTus does not measure structures with widths below 10° .

Figure 12

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Speed and width distributions of all CMEs (top) and wider CMEs ($W \geq 30^\circ$; bottom). The average width of wider CMEs is calculated using only those CMEs with $W \geq 30^\circ$. Image reproduced with permission from Gopalswamy *et al.* (2010a), copyright by Springer.

Figure 13

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Apparent CME width distributions, displayed per year in log-log scale. The CACTus distribution corresponds to the red curve; the CDAW distribution is represented by the light blue curve. The distributions are not corrected for observing time. Image reproduced with permission from Robbrecht *et al.* (2009a), copyright by IOP.

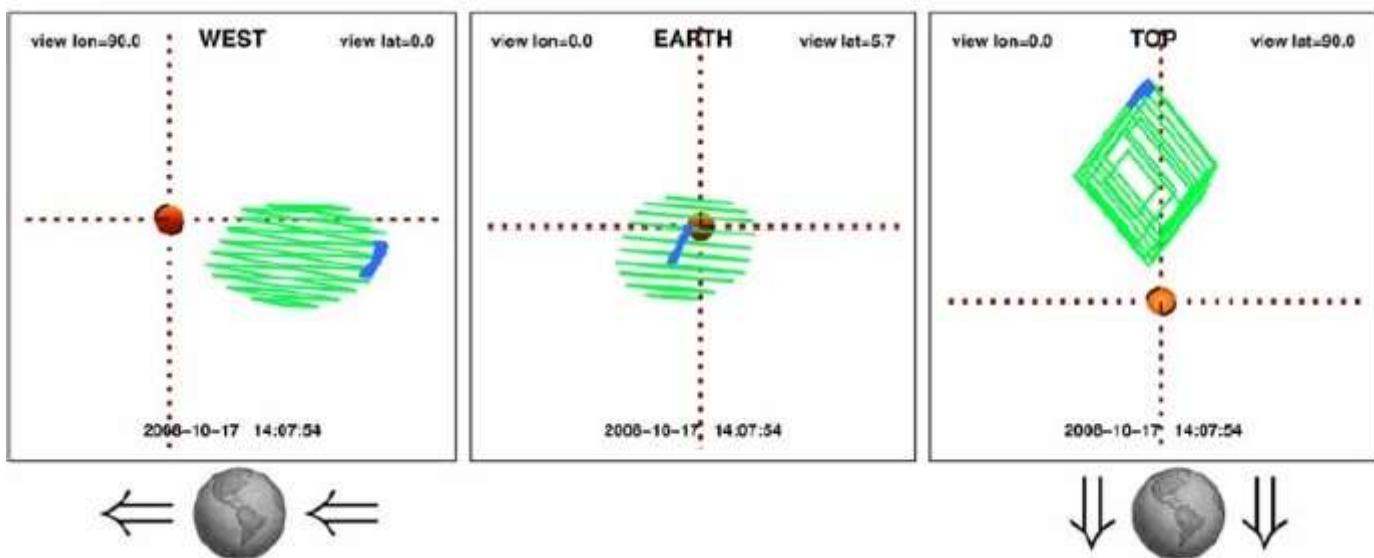
Along with their white light imaging capabilities, the benefits of polarized images have also been demonstrated with some instruments. A polarizing strip across a fixed radial was part of the C/P instrument on board SMM and polarizing capabilities were part of the Skylab and Solwind coronagraphs as well (Sheeley Jr *et al.*, 1980; Crifo *et al.*, 1983). Polaroid filters can help determine distances of CME material along the line of sight and, therefore, give an idea of its three-dimensional structure. This is because the Thomson scattered light that enables us to observe CMEs has a polarization degree that is dependent on the direction of observation (Billings, 1966; Howard and Tappin, 2009). In what has become two of only a few studies making use of the SOHO/LASCO polarizing capabilities, Moran and Davila (2004) and Dere *et al.* (2005) presented analyses of LASCO C2 polarized CME observations and showed loop arcades and filamentary structure in six CMEs. The STEREO coronagraphs provide a constant stream of polarized images enabling for the first time their regular utility for 3-D property extraction. Publications making use of this ability include Mierla *et al.* (2009), Moran *et al.* (2010), and de Koning and Pizzo (2011).

The STEREO instruments allow us to attempt to remove the projection effects using geometry, that is to use geometric triangulation on features commonly observed between observers. An early attempt to do this using LASCO and COR2 data was performed by Howard

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Earth limb (and vice versa from each other). [Figure 14](#) shows the results from a geometric localization technique, also using LASCO and COR2 data, devised by de Koning *et al.* ([2009](#)). Rather than attempt to perform 3-D triangulation on a series of points comprising the CME, they confine the CME to within a polygon bound by the limits of the CME's extent. While this does not provide as much information as one may assume can be obtained with 3-D triangulation, it is actually a powerful technique, as the optical thinness of CMEs makes it nearly impossible to identify the same point in 3-D space when observing from different perspectives.

Figure 14



The 3-D spatial location of the CME on 17 October 2008 at 14:08 UT as calculated using geometric localization. The CME appeared as a west-limb event in STEREO-A, as an east-limb event in STEREO-B, and as a halo CME by LASCO. The absence of space weather disturbances at Earth associated with the CME suggests that it was a backside halo event. The green quadrilaterals indicate the bounding volume of the CME as a whole; the blue quadrilaterals indicate the bounding volume of the leading-edge shell. The hash marks on the plots indicate the scale used; the distance between each mark is $1R_{\odot}$. The viewing latitudes and longitudes on the plots refer to the observer's position in HEEQ coordinates. The left plot is for an observer hovering over the west limb of the Sun; Earth is on the left-hand side of the plot. The center plot is for an observer at Earth. The right plot is

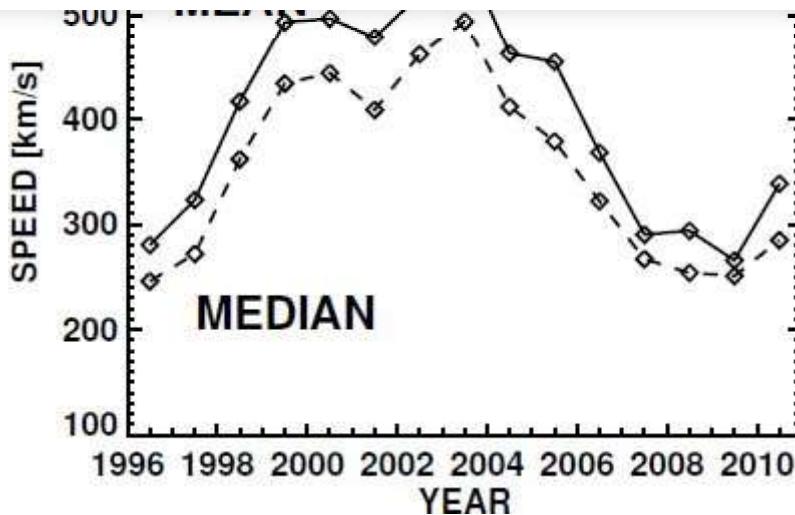
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Many workers have now devised geometrical techniques for determining 3-D information on CMEs, including forward modeling (e.g., Thernisien *et al.*, 2006; Wood *et al.*, 2009), tie-pointing (e.g., Mierla *et al.*, 2009), and inverse reconstruction (Antunes *et al.*, 2009). Other triangulation efforts have also been made by (for example) de Koning *et al.* (2009), Liewer *et al.* (2009), and Temmer *et al.* (2009). The review by Mierla *et al.* (2010) discusses many of these new and emerging techniques. Attempts to identify the 3-D structure using triangulation has proven to be difficult, and techniques that place the CME within a volume bound by a polygon (e.g., de Koning *et al.*, 2009; Byrne *et al.*, 2010; Feng *et al.*, 2012) may have greater success.

2.5 Kinematics

Estimates of the apparent speeds of the leading edges of CMEs range from about 20 to $> 2500 \text{ km s}^{-1}$, or from well below the sound speed in the corona to well above the Alfvén speed ([Figures 8](#) and [12](#)). The annual average speeds of Solwind and SMM CMEs varied over the solar cycle from about $150 - 475 \text{ km s}^{-1}$, but their relationship to sunspot number was unclear (Howard *et al.*, 1986; Hundhausen *et al.*, 1994). However, LASCO CME speeds did generally track sunspot number in Solar Cycle 23 (Yashiro *et al.*, 2004; Gopalswamy, 2010b), from 280 to $\sim 550 \text{ km s}^{-1}$ at the maximum and following it in 2003 ([Figure 15](#)). Above a height of about $2R_\odot$ the speeds of typical CMEs are relatively constant in the field of view of coronagraphs, although the slowest CMEs tend to show acceleration while the fastest tend to decelerate (St Cyr *et al.*, 2000; Yashiro *et al.*, 2004; Gopalswamy *et al.*, 2006b). This may be expected, given that CMEs must push through the surrounding solar wind, believed to have a speed of around 400 km s^{-1} in the outer corona.

Figure 15

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Annual mean and median speeds of LASCO CMEs from 1996 – 2010. There are two peaks, the first near solar activity maximum and the second in 2003. Thus, high speeds were still prevalent during the early declining phase. Image adapted from Gopalswamy (2004), updated by S. Yashiro (2011).

The early acceleration for most CMEs must occur low in the corona ($< 2R_{\odot}$). Despite its increased field of view, only 17% of all LASCO CMEs exhibit acceleration out to $30R_{\odot}$ (St Cyr *et al.*, 2000). St Cyr *et al.* (1999) compared ground-based Mauna Loa, HI MK3 and SMM observations of CMEs above $1.15R_{\odot}$. These had either constant speed or constant acceleration profiles. The average acceleration of the events was found to be $+264 \text{ m s}^{-2}$, clearly much faster than the near-zero values of acceleration for LASCO CMEs (Yashiro *et al.*, 2004, and our Table 1). Those features associated with active regions were found to be more likely to have constant speeds and those associated with prominence eruptions to have constant accelerations. Using observations of flare-associated CMEs close to the limb in the LASCO C1 field of view ($1.1 - 3.0R_{\odot}$), Zhang *et al.* (2001, 2004) found a three-phase kinematic profile: a slow rise ($< 80 \text{ km s}^{-1}$) over tens of minutes; a second phase with a rapid acceleration of $100 - 500 \text{ m s}^{-2}$ in the height range $1.4 - 4.5R_{\odot}$ during the flare rise phase; and a final phase with propagation at a constant or declining speed. Gallagher *et al.* (2003) and others have narrowed the strong ($> 200 \text{ km s}^{-1}$) acceleration region of impulsive CMEs to $\sim 1.5 - 3.0R_{\odot}$. Using LASCO data, Sheeley Jr *et al.* (1999) and Srivastava *et al.* (1999) found that gradually accelerating CMEs were balloon-like in coronagraph images, whereas fast CMEs moved at

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While fast CMEs have ragged structure and accelerate (Sheeley Jr et al., 1999), Tsurmilo et al.

(2004) found that slow CMEs tend to accelerate and fast CMEs decelerated through the LASCO field of view, with those around the solar wind speed having constant speeds. Thus, CMEs attain fast acceleration low in the corona until gravity and other drag forces slow them further out. This process continues into the interplanetary medium. More recently, the high temporal and spatial resolution STEREO COR and EUVI and SDO AIA imagery has been used to investigate the initial formation and kinematics of CMEs erupting from active regions (see, e.g., papers by Zhang et al., 2012; Liu et al., 2011; Patsourakos et al., 2010a,b; Temmer et al., 2010).

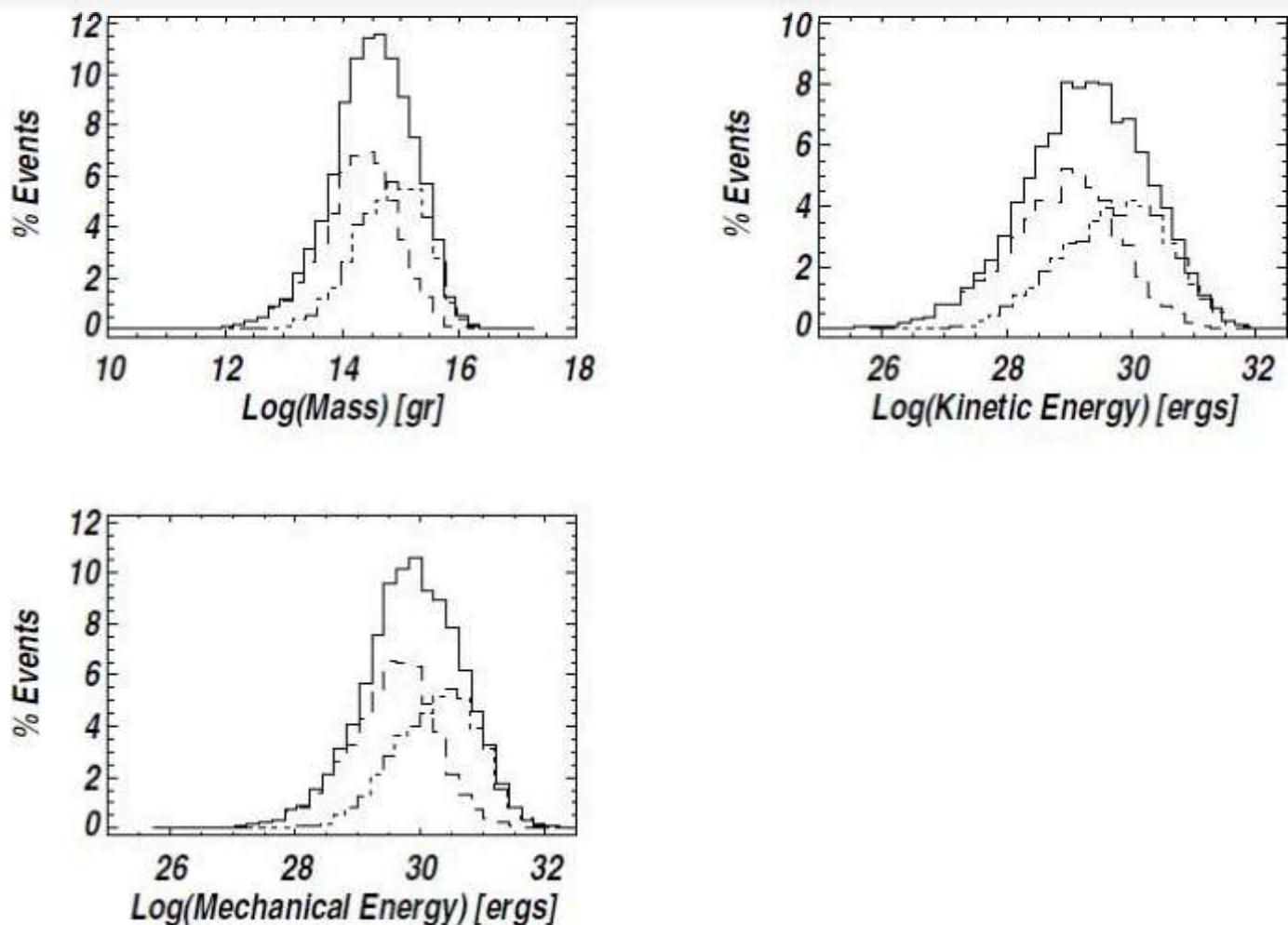
Sheeley Jr et al. (1999) used LASCO data to suggest that there were two dynamical classes of CMEs: gradual CMEs, which are slower, accelerate in the coronagraph fields of view, and are preferentially associated with prominence eruptions; and impulsive CMEs, which are faster, decelerate in the coronagraph fields of view, and are preferentially associated with solar flares. This appeared to confirm the flare-prominence eruption distinction found by MacQueen and Fisher (1983) using Mauna Loa, Skylab and SMM data. The tendency for fast CMEs to be associated with solar flares has been known since the earliest observations of coronagraph CMEs (for example, Gosling et al. (1976), using Skylab observations of CMEs, found a tendency for faster CMEs to be associated with solar flares and slower ones to be associated with prominences). However, prominence eruptions are often associated with two-ribbon flares and flares can be also accompanied by prominence eruptions, especially in active regions. The basic question then is whether there are two physically different processes that launch CMEs or whether all CMEs belong to a dynamical continuum with a single physical initiation process. This issue was revisited at several SHINE workshops (e.g., Crooker, 2002), with no definitive answer. In addition, Low and Zhang (2002) proposed a model of two kinds of erupting prominence-CMEs depending on whether they had normal or inverse magnetic geometries. They found that CMEs arising in normal polarity eruptions have more energy and higher speeds. To the contrary, in a comparison of flare-associated and non-flare CMEs, Vršnak et al. (2005) found considerable overlap of accelerations and speeds between the two CME groups. While flare-associated CMEs are generally faster than those without flares, there is also a correlation between CME speeds and flare X-ray peak

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et al. (2005), found that the speeds of both accelerating and decelerating transients are distributed lognormally, implying that the speeds of both groups result from many simultaneous processes or from a sequential series of processes. Recently, Howard and Harrison (2012), using historical observations, argue in favor of a single launch mechanism and a continuum of energies.

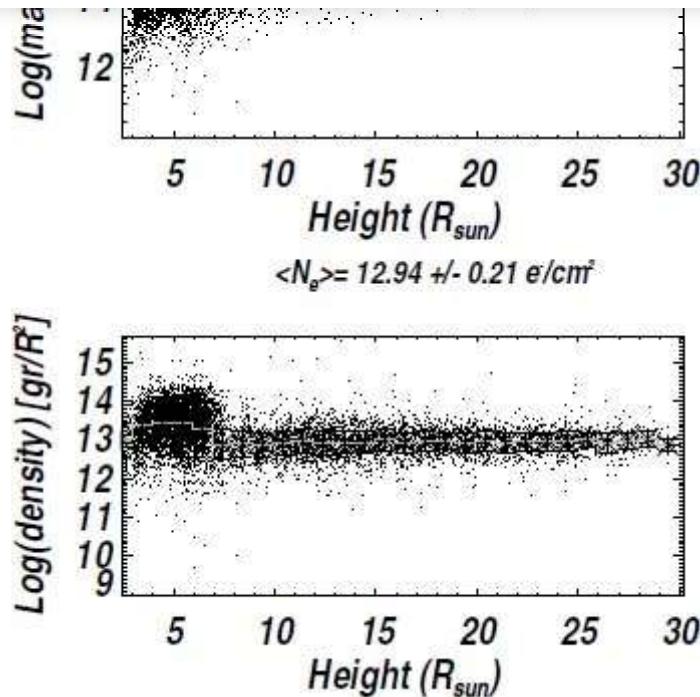
2.6 Masses and energies

CME mass calculations require a conversion from the coronagraph-observed intensity to electron (and therefore plasma) density using the physics of Thomson scattering. Most workers today follow the theory outlined in Billings (1966) (the necessary equations conveniently appear on a single page of this text) but more recent reviews of this theory, along with its adaption for heliospheric imaging appear in Howard and Tappin (2009), Howard (2011b) and Howard and DeForest (2012b). Masses and energy calculations of CMEs therefore require difficult instrument calibrations and have large uncertainties. The average mass of CMEs derived from the older coronagraph data (Skylab, SMM and Solwind) was a few times 10^{12} kg (see Table 1). LASCO calculations indicate a slightly lower average CME mass, 1.6×10^{12} kg (Figure 16), likely because LASCO can measure smaller masses down to the order of 10^{10} kg (Vourlidas et al., 2002a, 2010, 2011b; Kahler, 2006). Studies using Helios (Webb et al., 1996) and LASCO (Vourlidas et al., 2000, 2010, 2011b) data suggest that the older CME masses may have been underestimated because mass outflow may continue well after the CME's leading edge leaves the instrument field of view. For example, Vourlidas et al. (2010) estimated that CME masses may be underestimated by a factor of two and CME kinetic energies by a factor of 8. LASCO results of the mass density of CMEs as a function of height suggest that this density rises until $\sim 7R_\odot$, then levels off — Figure 17. The implication is that CMEs with larger masses reach greater heights, and are more likely to escape the Sun. Indeed, there is a population with a mass peak $< 7R_\odot$; these CMEs are less massive and slower and may not reach IP space. This begs the question whether the outward motion of coronal mass that is not clearly “ejected” should be called a “CME” or something else. Downward motions of prominence material during eruptions are common, but similar downward motions of mass in white light CMEs are rare, though it has been reported (e.g., Tripathi et al., 2007).

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Histograms of LASCO CME mass distribution (upper left), kinetic energy (upper right), and total mechanical energy (bottom left) for 7668 events. Also shown are the histograms for events reaching maximum mass $< 7R_{\odot}$ (dashed lines) and events reaching maximum mass $7R_{\odot}$ (dash-double dot). Not all detected CMEs have been included because mass measurements require: (i) a good background image, (ii) three consecutive frames with CMEs, and (iii) CMEs well separated from preceding CMEs. Image adapted from Vourlidas *et al.* (2010, 2011b), courtesy A. Vourlidas (2011).

Figure 17

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Top: scatter plot of the logarithm of maximum CME mass vs. the height where it was measured. Two populations are present: CMEs reaching maximum mass $< 7R_{\odot}$ and CME with maximum mass $> 7R_{\odot}$. *Bottom:* scatter plot of the logarithm of CME surface density (e cm^{-2}) vs. height. The CME density is constant above $\sim 10R_{\odot}$. A histogram with $1R_{\odot}$ bins is calculated and the average density (asterisks) and in each bin is overplotted. Note the small spread of the CME density values above $\sim 10R_{\odot}$. Its average value is shown on the plot. The height spread is mostly due to the noise and flatness of the mass measurements at those heights which tend to shift around the height of the maximum mass. Image adapted from Vourlidas *et al.* (2010, 2011b), courtesy A. Vourlidas (2011).

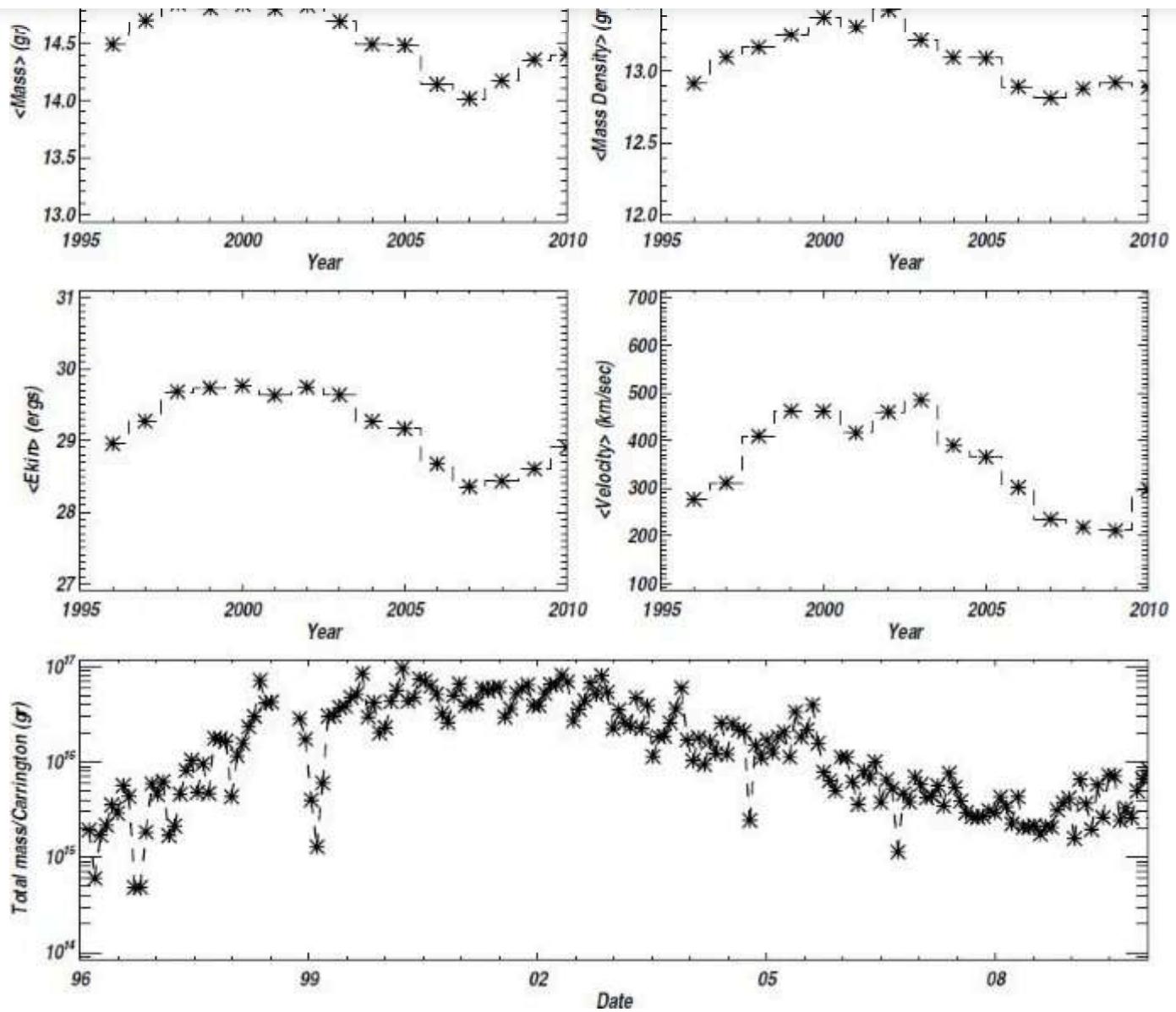
Mass estimates of a few CMEs have also been made with radio (Gopalswamy and Kundu, 1993; Ramesh *et al.*, 2003) and X-ray observations (e.g., Rust and Hildner, 1976; Hudson and Webb, 1997) and, more recently, in the EUV (e.g., Harrison *et al.*, 2003; Aschwanden *et al.*, 2009). Many X-ray and EUV measurements involve “coronal dimming” (Section 3.4) regions associated with a CME, and these estimates are usually lower than that of the equivalent white light masses. This is probably because the material leaving the coronal dimming region is only part of that comprised in the CME. The radio, X-ray, and EUV techniques provide an independent check on CME masses because their dependency is on

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previous measurements, 2.0×10^{12} erg (Vourlidas et al., [2010](#) — [Figure 10](#)). The CME kinetic energy distribution appears to have a power law index of -1 (Vourlidas et al., [2002a](#)), different than that for flares (-2; Hudson, [1991](#); Yashiro et al., [2006](#)).

[Figure 18](#) shows plots of the solar-cycle dependence of the LASCO CME mass and kinetic energy (Vourlidas et al., [2010](#), [2011b](#)). The bottom panel shows the total CME mass per Carrington rotation. The mass, mass density, and kinetic energy all have minima in 2007 that are 2 – 4 times below the 1996 minimum and reflect the unusual extended activity in Solar Cycle 23. The total mass reaches a minimum in 2009 and is roughly equivalent to the 1996 minimum. MacQueen et al. ([2001](#)) found that the mass density variation between Solar Cycle 22 minimum and maximum varied by a factor 4 even in the background corona.

Figure 18

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Solar cycle dependence of the CME mass and kinetic energy. *Top left*: log CME mass. *Top right*: log CME mass density in g R^{-2} . *Middle left*: log CME kinetic energy. *Middle right*: CME speed. All four plots show annual averages. Bottom panel: total CME mass per Carrington rotation. The data gaps in 1998 and the drop in 1999 are due to spacecraft emergencies. The plot is an update of [Figures 14](#) and [1](#) in Vourlidas *et al.* ([2010](#), [2011b](#)) to include events to July 31, 2010, courtesy A. Vourlidas ([2011](#)).

Measuring CME masses and energies using white light images farther from the Sun has proven to be a difficult task (see [Section 5.3](#)), due to the lack of calibration information and the uncertainties imposed by the faintness of the CMEs compared to the background noise.

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estimates generally agree with the mass of the same CMEs as derived from LASCO data.

Some attempts are currently being made using some highly developed processing techniques with the STEREO SECCHI images. DeForest *et al.* (2012) performed some mass measurements on a small disconnection event (i.e., not a CME) using photometric measurements and the theory of Thomson scattering. The technique is currently being applied to CME measurements.

The reader must note that as with the kinematical properties, mass calculations are based on coronagraph images and, therefore, subject to the same problems of projection and perspective. For example, the CME mass calculations in the CDAW catalog make the assumption that all of the CME mass is in the sky plane, as has always been the standard assumption. The Thomson scattering theory from which the density is derived includes a direction term χ , and so the direction of propagation is an integral component of the density calculations. Traditionally, auxiliary data such as solar flare or filament location have been used provide an estimate of CME direction but more recent work making use of the stereoscopic capabilities of STEREO have provided more accurate measurements (Colaninno and Vourlidas, 2009). Finally, the Thomson scattering theory provided by Billings differs somewhat from the initial treatment by Schuster (1879) and Minneart (1930). An alternative treatment of this theory and its applications to both coronagraphs and heliospheric imagers can be found in Howard and Tappin (2009), Howard (2011a) and Howard and DeForest (2012b). This latest theory implies that the sky plane assumption may be more appropriate than has been previously assumed (see also van Houten, 1950).

A poorly understood topic is that of the energy budget available to the eruption of CMEs and associated solar activity. The next section discusses many of the phenomena that are known to be associated with CMEs and all of them require substantial quantities of energy. If we assume that the total energy arises from magnetic energy stored in the pre-launch corona then we may allocate an energy budget for the CME and its associated phenomena. Few studies have been conducted to address this topic, largely because of the difficulty in acquiring accurate measurements of both the available budget and the energies available from each associated phenomenon. These publications have revealed that the mechanical

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Liu et al. (2004) found the CME mechanical energy to be an order of magnitude greater than that of the associated flare and to consume the majority of energy available from the magnetic field. Ravindra and Howard (2010) found the mechanical energy of the CME was over an order of magnitude greater than that of the associated flare, and that half-to-all of the energy removed from the magnetic field during the eruption was consumed by the flare–CME–associated eruption combination. The uncertainties associated with the calculations in all of these studies, unfortunately, are too large to draw any firm conclusions.

3 Signatures of CME Origins

As stated in the previous section, the early acceleration phase of typical CMEs has mostly ceased by the time it has reached around $2R_{\odot}$. This indicates that over this distance the CME, which has a mass of the order of 10^{13} kg must be accelerated to speeds of several hundred km s^{-1} (and sometimes exceeding 2000 km s^{-1}). Hence, the erupting magnetic structure that becomes the CME must have access to a mechanism providing vast amounts of energy over a relatively short time scale. Some theoretical models suggest that this involves an interaction between the erupting and the surrounding field, perhaps via runaway magnetic reconnection. The CME onset itself must involve some instability disrupting the equilibrium between the closed magnetic field in the corona and the tendency of the corona towards its natural state of expansion. We have thus far been unable to directly observe this mechanism or the instability responsible for its onset, although we can find clues via near-solar-surface phenomena that are known to be associated with the initiation of CMEs. These are mostly observed with instruments other than coronagraphs, typically imagers observing various regions of the electromagnetic spectrum: this makes the direct association between a CME and the associated phenomena difficult. In this section we review these phenomena. We also draw the reader's attention to other recent reviews, including Webb (2002), Cliver and Hudson (2002), Gopalswamy (2004, 2010b), Kahler (2006), and Howard (2011b).

The release of the stored free magnetic energy that probably drives a CME can take many forms including (predominantly) mechanical in the form of an expanding CME and erupting filament, electromagnetic emission in the form of a flare, and also in the acceleration of energetic particles, magnetic field reconfiguration and bulk plasma motion. We mentioned

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most recently, Ravindra and Howard (2010).

As noted in the introduction ([Section 1](#)), the formation and early development of CMEs can now be observed and followed near the surface, especially in EUV images (see, e.g., Hudson and Cliver, [2001](#)). The first well-defined observation of the initial development of a CME “bubble” was with SOHO EIT images by (Dere *et al.*, [1997](#)). More recently, the high temporal and spatial resolution STEREO COR and EUVI and SDO AIA imagery has been used to study the initial formation of CMEs (see, e.g., Patsourakos *et al.*, [2010a,b](#); Vourlidas *et al.*, [2012](#)). These demonstrate the rapid expansion of CMEs and their associated cavities and flux ropes.

EUV spectral observations from the UVCS, CDS, and SUMER instruments on SOHO and the SOT and EIS instruments on Hinode have helped us to measure the densities, temperatures, ionization states, and Doppler velocities of CMEs (e.g., Raymond, [2002](#); Kohl *et al.*, [2006](#); Landi *et al.*, [2010](#)). [Table 2](#) is a summary of the spectral lines that have been observed in CMEs by the UVCS instrument (Kohl *et al.*, [2006](#)). The UVCS instrument is unique in that it can sample the CME material at relatively high heights, e.g., out to $\sim 10R_{\odot}$, in the corona compared to the other spectrometers. Most CME material observed in UVCS is cool ($< 10^5$ K) and concentrated in small regions (Akmal *et al.*, [2001](#)), although this is not the case for fast CMEs associated with X-class flares (Raymond *et al.*, [2003](#)). Heating rates inferred from models using UVCS observations show that heating of the material continues out to $3.5R_{\odot}$ and is comparable to the kinetic and gravitational potential energies gained by the CMEs (Akmal *et al.*, [2001](#); Landi *et al.*, [2009](#)). The Doppler information from UVCS combined with the EIT and LASCO images has shown in one case the unwinding of a helical structure (Ciaravella *et al.*, [2000](#)). Doppler shifts are usually high, ~ 1000 km $^{-1}$, within halo CMEs, where compressed or deflected coronal material along the flanks of a CME is measured. H I Ly α emission also suggests that dense material is present (Kohl *et al.*, [2006](#)).

Table 2 Spectral lines observed by UVCS in CMEs (Kohl *et al.*, [2006](#)).

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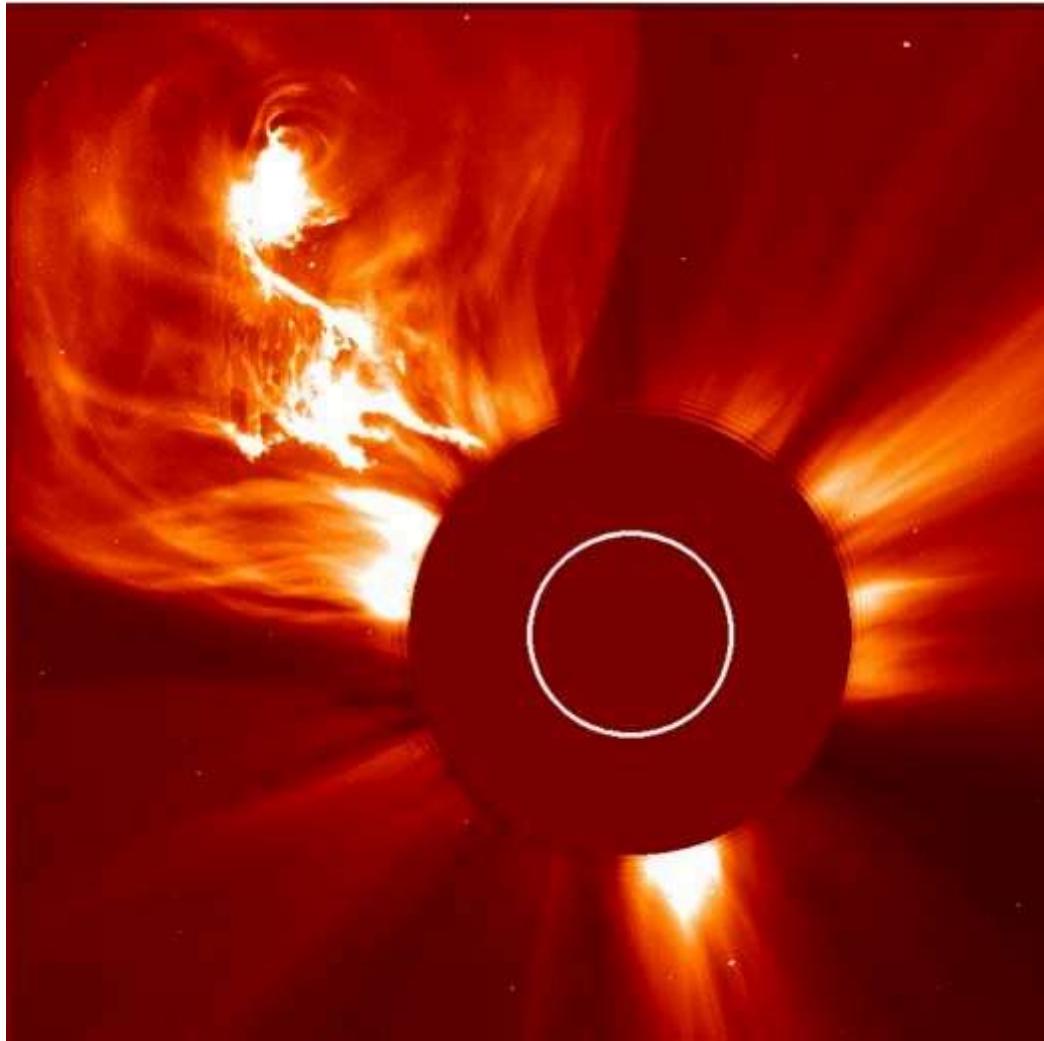
the opening of which is a consequence of the eruption. Many CMEs viewed at the solar limb also appear to arise from large-scale, pre-existing coronal streamers which often overlie active regions (e.g., Hundhausen, [1993](#)). Many energetic CMEs actually involve the disruption (“blowout”) of such a structure, which can increase in brightness and size for days before erupting as a CME (Howard *et al.*, [1985](#); Illing and Hundhausen, [1986](#); Hundhausen, [1993](#)). Possible causes of such disruptions include the emergence through the surface of new magnetic flux, the dynamical evolution of arcades, or the shearing of magnetic field lines. Other variants of streamer changes associated with different types of filament activity have been noted by Gopalswamy *et al.* ([2004a](#)).

A streamer is a bright (dense) structure containing closed and open fields, which help guide denser, outward-flowing solar wind material. They are observed by coronagraphs (and during solar eclipses) above the solar limb and are often found above active regions. Blowout CMEs viewed when the surface eruption is at the solar limb mostly display the classic three-part structure (Burkepile *et al.*, [2004](#)). In these cases prominence material can actually be followed from at or near the solar surface (as viewed in the H α line) into the coronagraph field of view ([Figures 2, 19, and 20](#)), where it forms the bright core of the CME. CMEs exhibit radial velocity dispersion, with the leading edge being fastest, followed by the speed decreasing through the prominence material (Webb and Jackson, [1981](#); Simnett, [2000](#)). The kinematic profiles of erupting prominences and their associated CMEs are usually similar in that both will exhibit acceleration, deceleration or constant speed with height. The SMM coronagraph had an H α filter, which was used for studies of a few CMEs containing large prominences. Illing and Athay ([1986](#)) compared the H α and white light images from eight prominence/CMEs finding that some CME prominence masses exceed 10^{12} kg: a large fraction of the total CME mass. They also concluded that the prominence material usually becomes nearly fully ionized as it moves outward through the low corona. UVCS results are limited in this regard, because its best diagnostics are for plasma typically in the 10^5 K range. The brightest UVCS emission seen during CMEs is likely in the core or prominence material. Proton temperatures and ionization states suggest plasma of $10^{4.5} - 5.5$ K, so the material has probably been heated from the original prominence temperatures and it must be heated continually as it moves out to counteract cooling and radiative losses (Kohl *et al.*, [2006](#); J.

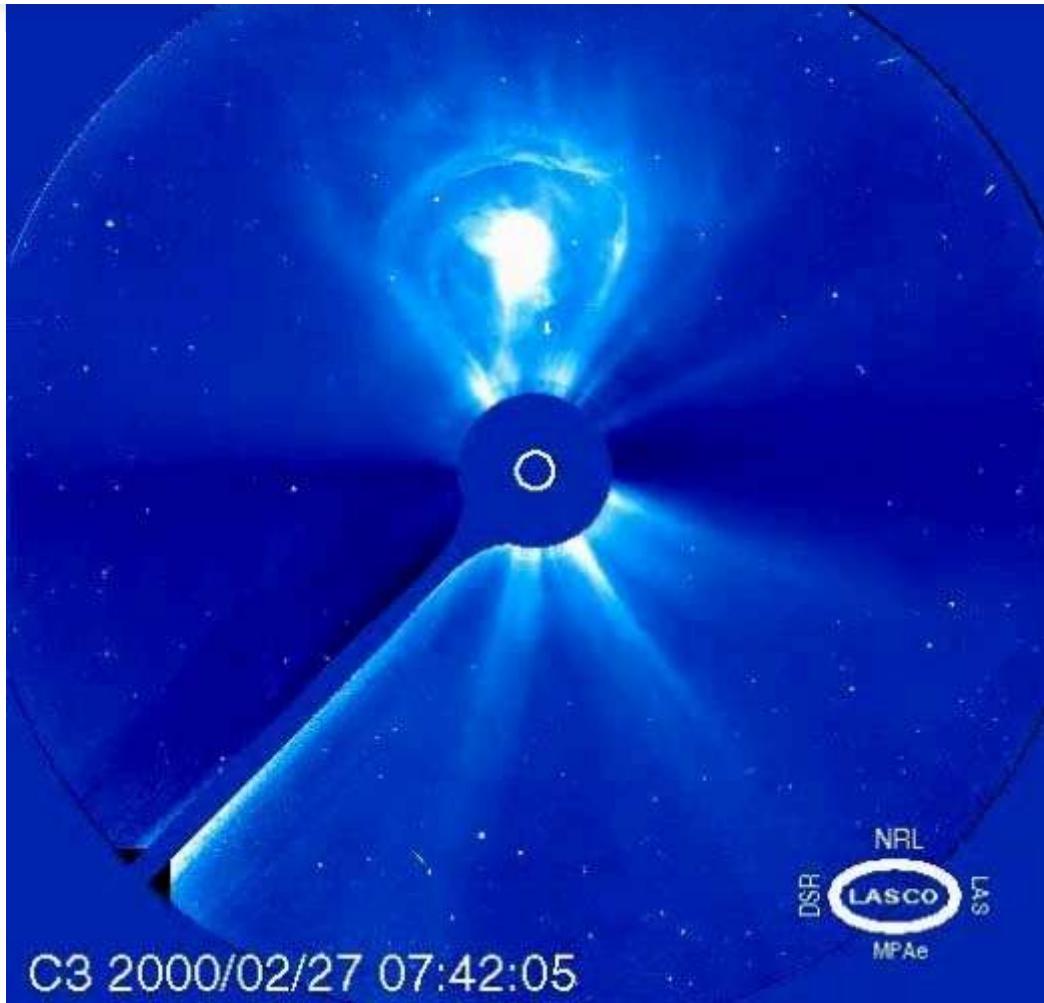
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plasma is the EOS result for the 9 April 2000 event by Lario et al. ([2010](#)). Also, many EIT and TRACE observations of erupting prominences near the surface show them changing from absorption to emission, indicative of heating.

Figure 19



LASCO C2 image from 4 January 2002 image of a Coronal Mass Ejection (CME) showing detail in the ejected material. The solar limb Sun is represented by the white circle. Available from SOHO online image gallery: <http://sohowww.nascom.nasa.gov/gallery/bestofsoho.html>.

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mpg-Movie (455.255859375 KB) Still from a movie showing LASCO C3 images of lightbulb shaped CME on 27 February 2000. Classic three-part structure with outer shell, void and inner bright structure, in this case an erupting prominence. From SOHO online movie gallery:

<http://sohowww.nascom.nasa.gov/gallery/Movies/flares.html>. (For video see appendix)

3.2 Flares

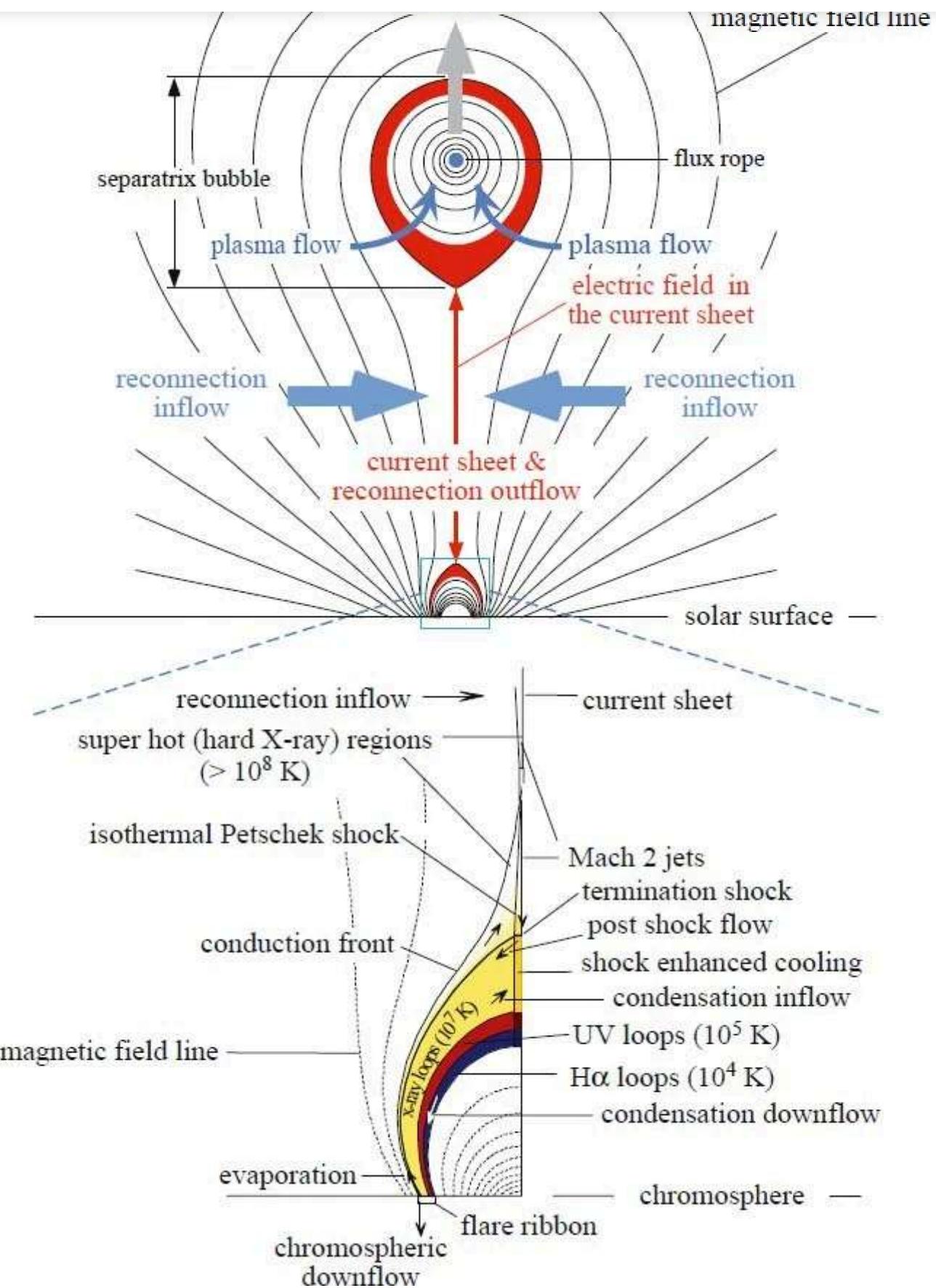
Throughout most of the history of detailed solar observation (i.e., since ~ 1850) it was generally accepted that the solar flare was the cause of interplanetary disturbances and major space weather effects on Earth. So when interplanetary shocks were discovered by Mariner 2 at the dawn of the space age (Sonnett *et al.*, [1964](#)), most believed them to be blast waves from solar flares. Likewise, when CMEs were discovered in 1973, many thought they

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and geomagnetic storms. This was initially established in the controversial paper by [Crosby \(1993\)](#) which, however, was disputed in several other papers, best summarized in [Hudson et al. \(1995\)](#). Workers now typically regard CMEs and flares as sometimes related phenomena and not as one being the cause for the other.

There is no one-to-one relationship between CMEs and flares. Many CMEs are associated with solar flares but many are not, just as most flares are not associated with mass ejection. When CMEs and flares occur together, the CME onsets seem to precede the flares in many cases, and the CMEs contain far more total energy than that radiated by the flare itself ([Section 2.6](#)). It is now generally accepted that CMEs and flares are part of a single magnetically-driven “event” and, therefore, it is more appropriate to consider a unified model that accounts for both. A schematic of one such unified model is shown in [Figure 21](#) ([Lin, 2004](#)). This “standard” flare model has been developed and refined over the last few decades and has become known as Flux Cancellation or the Catastrophe model (e.g., [Švestka and Cliver, 1992](#); [Shibata et al., 1995](#); [Lin and Forbes, 2000](#); [Lin, 2004](#)). In this model a stressed magnetic arcade that may contain a magnetic flux rope at its core begins to rise. A current sheet develops beneath it as external pressure causes oppositely directed magnetic field lines to converge and reconnect. Some of the liberated energy heats the CME plasma and adds mass and magnetic flux to it. Other energy is directed downward in the form of shock waves, energetic particles, and/or rapidly moving plasma. This energy can heat the low-lying or reconnecting magnetic loops and travel down the loops to the chromosphere, producing the flare. In some cases, especially if a prominence lifts off slowly, there may be too little energy deposited in underlying structures to produce a detectable surface brightening, or flare. Typical flares are “confined” or “compact” and do not have sufficient energy or magnetic topology to open up the ambient field and produce an eruption or ejection. However, [Shibata and colleagues have argued that impulsive, compact flares might also have narrow, plasma ejections yielding small CMEs.](#)

Figure 21

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created by incorporating the traditional two-ribbon flare model (bottom), from Forbes and Acton (1996) with the CME model (top) of Lin and Forbes (2000). Colors denote the different hierarchies of plasma in the configuration. Image reproduced with permission from Lin (2004), copyright by Springer.

Other models have been developed to describe the relationship between flares and CMEs. The so-called Breakout model of Antiochos *et al.* (1999), for example, involves the launch of the CME via magnetic reconnection between a core and the surrounding strapping magnetic field, which produces underlying magnetic reconnection (that may give rise to a flare) later in the process. It also allows for the passage of the core field past the strapping field, which is an essential process for ensuring that the net energy throughout the CME eruption is reduced.

Comparisons of low coronal soft X-ray, EUV and radio data with the white light observations provide many insights into the source regions of CMEs. Previous statistical association studies indicated that erupting prominences (EPs) and X-ray events, especially of long duration, were the most common near-surface activity associated with CMEs. Gopalswamy *et al.* (2003b) showed that 73% of microwave EPs, and nearly all those attaining high heights, were associated with CMEs, confirming results first found during Skylab (e.g., Munro *et al.*, 1979). There is a strong correspondence between X-ray ejecta and CMEs. Nitta and Akiyama (1999) found that flares with X-ray ejecta were always associated with CMEs and the X-ray ejecta corresponded with CME cores, likely dense, heated prominence material (also see Rust and Webb, 1977).

Although most flares occur independently of CMEs, the fastest, most energetic CMEs do tend to be associated with bright flares, and reported flares are associated with most frontside, full halo CMEs (e.g., Webb, 2002; Gopalswamy *et al.*, 2007). This rate may be high because the surface sources associated with halo CMEs can be clearly viewed near sun center and halo CMEs appear to be faster and more energetic than average CMEs. Thus, either or both

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Sheeley Jr *et al.* (1983) first showed that the probability of associating a CME with a soft X-ray flare increased linearly with the flare duration, reaching 100% for flare events of duration > 6 hours. Confirming previous results with lower statistical validity, Yashiro *et al.* (2005) found that the LASCO CME association rate with X-ray flares also increased linearly with the peak X-ray intensity. Thus, the more energetic the flare, the more likely it was to be associated with mass ejection. When longitudinal visibility effects were accounted for, Yashiro *et al.* found that nearly all flares above the M5 level were associated with CMEs. The SMM CME observations indicated that the estimated departure time of flare-associated CMEs typically preceded the flare onsets. Harrison (1986) found that such CMEs were initiated along with weaker soft X-ray bursts that preceded any subsequent main flare by tens of minutes, and that the main flares were often spatially offset to one side of the CME. Also, the location of flares is more closely associated with the footpoint, rather than the center, of the CME (Simnett and Harrison, 1984, 1985). We note however, that more recent results using the LASCO data reported by Yashiro *et al.* (2008a) showed more variation between flare location and CME span, with X-flares usually centered under the CME. More details about solar flares appear in the Living Review by Benz (2008).

3.3 Erupting prominences

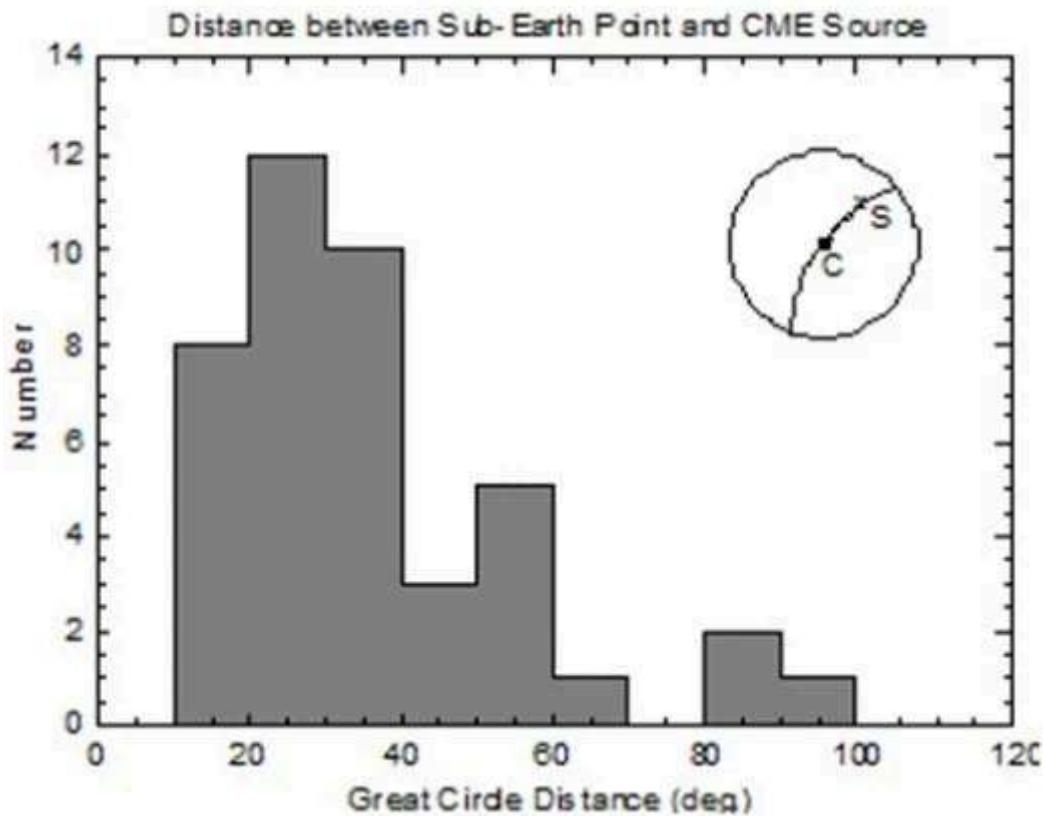
Prominences are observed in coronagraphs often as the bright, central core of the CME structure (the filament component of the classic three-part CME). They are also observed by instruments that observe the solar disk, so through erupting prominences a direct comparison between coronagraphs and solar data can be made. Prominences are believed to be caused by the formation of a flux rope low in the magnetic structure that eventually erupts to form the CME. Many CME onset models (e.g., flux cancellation, mass loading) require the presence or formation of a prominence in order for the CME to erupt.

The latitude distribution of LASCO CMEs peaks at the equator (Section 2.4), but the distribution of EIT EUV activity including prominence eruptions associated with these CMEs is bimodal with peaks 30° north and south of the equator (Plunkett *et al.*, 2002). This offset is confirmed for the distribution of disk source regions associated with halo CMEs (Figure

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can erupt under the same CME canopy (Webb *et al.*, 1997; Simnett, 2000). A particularly good example of the former is shown in Figures 7 – 11 of Hundhausen (1988) which combine Mauna Loa and SMM H α and white light data of a CME (see also Webb, 1992).

Figure 22



Histograms of “source” longitudes of halo CMEs. Image reproduced with permission from Webb (2002).

Using SOHO LASCO, EIT, and MDI and ground-based H α data, Cremades and Bothmer (2004) concluded that a simple scheme can be used to relate CME white light topology to the heliographic position and orientation of the underlying magnetic neutral line. When the neutral line is approximately parallel to the solar limb, the CME appears as a linear feature parallel to the limb having a broad, diffuse inner core. When the neutral line is

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line and CME orientations are reversed for the solar backside, so backside CMEs are viewed predominately orthogonally to frontside CMEs at each limb. These CME orientations are generally valid only for CMEs with source regions in the active region belts, $< 50^\circ$ heliolatitude. The CME orientations will be different for polar crown filaments (McAllister *et al.*, 2002; Gopalswamy *et al.*, 2003a) or for CME source regions outside the active regions, where the neutral lines do not obey Joy's law. However, in an older, related study using SMM data, Webb (1988) found no clear pattern between the orientation of filaments, i.e., neutral lines, and the morphology or widths of associated CMEs.

There have been several recent studies of the kinematics and rotations of prominences using STEREO EUVI data. Joshi and Srivastava (2011) used a stereoscopic reconstruction technique to study the motions of two polar crown prominences. They found evidence of two different motions, a helical twist in the prominence spine and overall non-radial equatorward motion of the entire prominence structure, and two phases of acceleration during the eruptions. Bemporad *et al.* (2011) used the tie-pointing technique with COR1 and EUVI data to reconstruct the 3-D shape and trajectory of an erupting prominence. They found evidence for a progressive clockwise rotation of the prominence by $\sim 90^\circ$, and helical motion providing evidence for the conversion of twist into writhe. Finally, (Vourlidas *et al.*, 2011a) used SECCHI and LASCO data with a forward-fitting model to determine the 3-D orientation of a 3-part CME with embedded prominence. The found that the CME had a fast rotation rate, and suggested it was possibly due to disconnection of one of the CME footpoints.

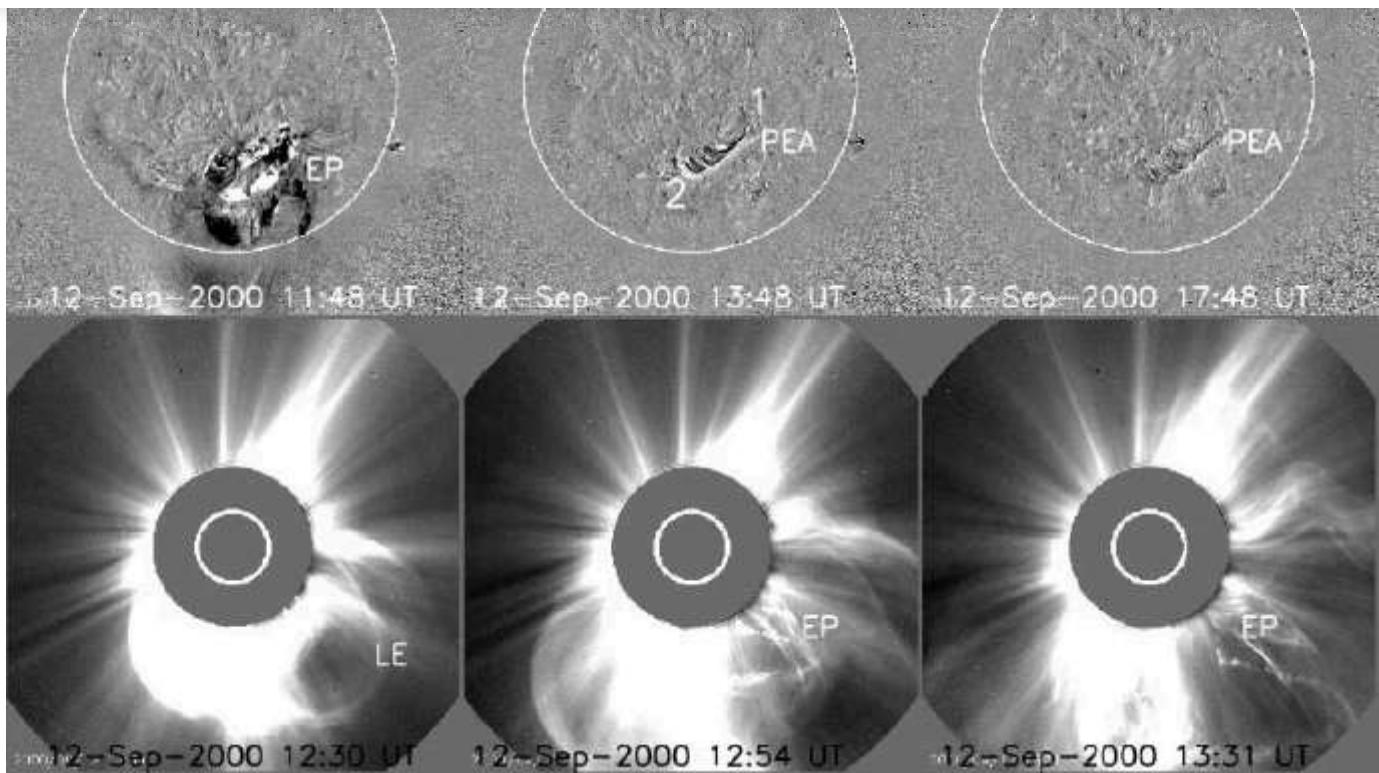
The physical (as opposed to observational, defined earlier) definition of a CME involves material in a magnetic field that is expelled from the corona (Hundhausen, 1999), so we assume that all the material observed moving away from the Sun in coronagraphs escapes the corona. However, in a few CMEs with relatively slow speeds material in bright cores has been observed to collapse back to the Sun with speeds of ~ 50 to 200 km s^{-1} (Wang and Sheeley Jr, 2002). These collapses have been interpreted in terms of gravitational and magnetic tension forces as well as the drag forces of the ambient solar wind. It is not clear

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3.4 Coronal dimming to arcade formation

The most obvious coronal signatures of CMEs in the low corona are the arcades of bright loops that develop after the CME material has erupted (Kahler, [1977](#) — Skylab; McAllister *et al.*, [1996](#); Hudson and Webb, [1997](#) — Yohkoh; Hanaoka *et al.*, [1994](#) — radio; Tripathi *et al.*, [2004](#) — EIT). Prior to the eruption, an S-shaped structure called a sigmoid can develop, typically observed in X-rays, sometimes in association with a filament activation. A sigmoid is indicative of a highly sheared, non-potential coronal magnetic field, and might be an important precursor to certain types of CMEs (e.g., Canfield *et al.*, [1999](#)). However, McKenzie and Canfield ([2008](#)) point out that X-ray sigmoids actually consist of separate J-shaped loops that support a bald-patch separatrix surface model for sigmoids. Eventually an eruptive flare can occur within or in the proximity of the sigmoid, resulting in the bright, long-duration arcade of loops. Sterling *et al.* ([2000](#)) call this process “sigmoid-to-arcade” evolution. These arcades suggest the eruption and subsequent reconnection of strong magnetic field lines associated with the CME system. Tripathi *et al.* ([2004](#)) found that nearly all (92%) EIT post-eruptive arcades (PEAs) from 1997 – 2002 were associated with LASCO CMEs ([Figure 23](#)). Recent analyses of Hinode XRT and SDO AIA data reveal new information of the space and temperature evolution of arcades (e.g., Reeves *et al.*, [2010](#); Reeves and Moats, [2010](#); Reeves and Golub, [2011](#)), which help to further constrain the “standard” eruptive flare model (e.g., [Section 3.2](#) and [Figure 20](#)).

Figure 23

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Erupting prominence, dimming regions and arcade associated with a fast CME on 12 September 2000. Top: SOHO EIT 195 Å running-difference images; bottom: CME leading edge and erupting prominence (EP) seen in SOHO LASCO C2 images. Image reproduced with permission from Tripathi *et al.* (2004), copyright by ESO.

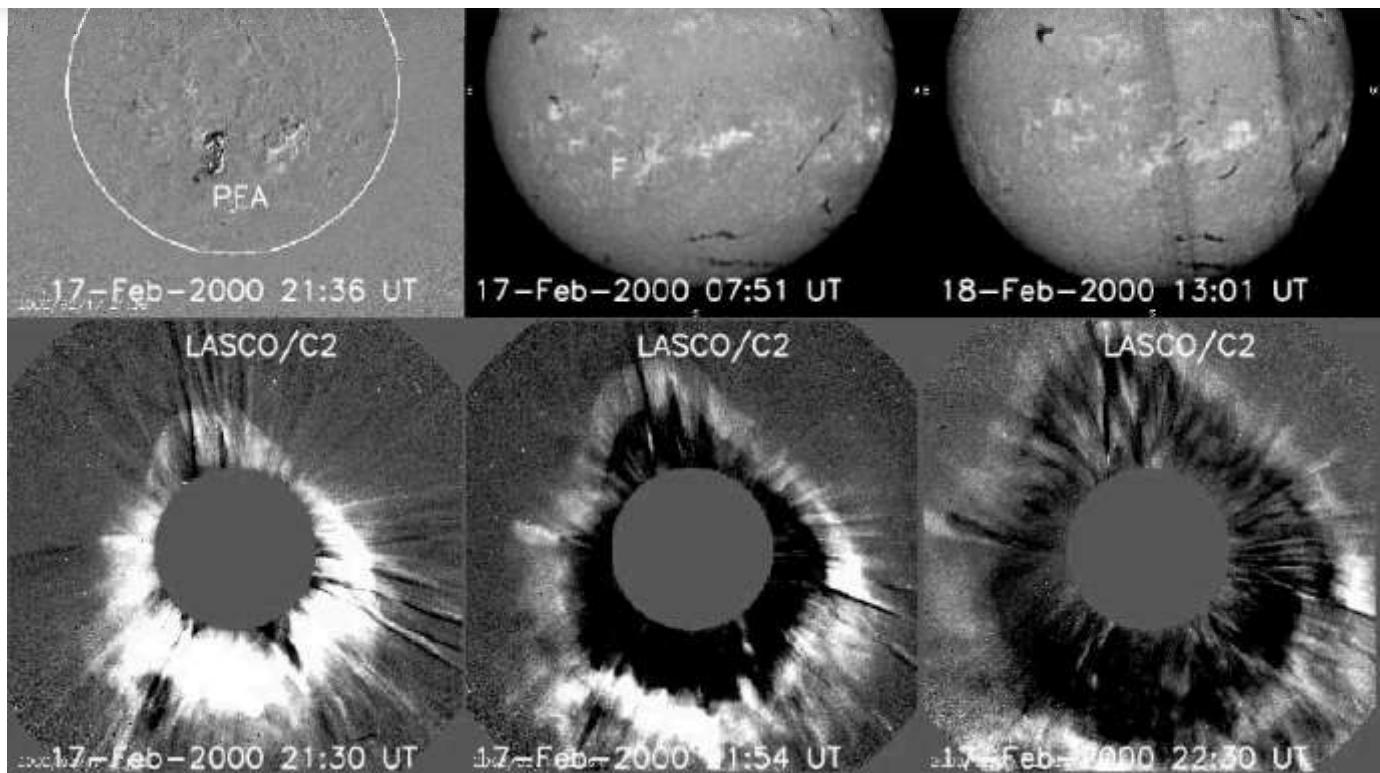
Coronal dimming is the reduction in intensity on the solar disk across a large area, observed in X-ray, EUV and more recently in H α , and coincident in timing with the launch of a CME above. Measurements imply that the reduction in intensity is due to the evacuation of mass from the low corona (Hudson and Webb, 1997) and not a temperature change (e.g., Harrison and Lyons, 2000; Harrison *et al.*, 2003). The dimming regions can be much more extensive than any associated flaring activity and can map out the apparent base of the associated CME (Thompson *et al.*, 2000; Harrison *et al.*, 2003). They have also been shown to extend deep into the corona and possibly the chromosphere and photosphere (McIntosh *et al.*, 2007), thereby indicating that the initial terminology of “transient coronal hole” is probably more physically appropriate. Coronal dimmings are good indicators of the area on the Sun corresponding to the CME and of the behavior of the local magnetic fields following the CME

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CMEs by COR2, Aschwanden *et al.* (2009) found a nearly 1:1 correspondence between the EUV and white light masses. The self-similar evolution of the mass from the low to outer corona was also successfully modeled. For their sample of EIT dimming events, Reinard and Biesecker (2008) found mean lifetimes of 8 hours, with most disappearing within a day. Other results suggest that there may be two types of dimming, “core” dimmings directly associated with the source active region and flare, and “secondary” dimmings farther away that may be associated with loop motions or evacuation (e.g., Attrill *et al.*, 2010).

Surveys of solar activity associated with frontside halo CMEs have been made primarily with low coronal images from the SOHO EIT and Yohkoh Soft X-ray telescope (SXT) instruments, although surveys with STEREO and Hinode are emerging. The activity associated with halo CMEs includes the formation of dimming regions, long-lived loop arcades, flaring active regions, large-scale coronal waves and filament eruptions (Figure 24). Webb (2002) found that 2/3 of halo CMEs were associated with either or both filament eruptions and dimmings, and Reinard and Biesecker (2008) found that about half of all frontside halo CMEs have dimmings. Coronal dimming has not been observed as frequently as other associated eruptive phenomena but the most recent, very sensitive results (e.g., Schrijver and Title, 2011) from SDO imply that dimming is more common than measurements from previous instruments have implied.

Figure 24

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A filament eruption and post-eruption arcade near Sun center on 17 February 2000 (top). It was associated with a symmetrical LASCO halo CME (bottom). Image reproduced with permission from Tripathi *et al.* (2004), copyright by ESO.

3.5 Coronal waves

The frequent detection of coronal waves observed in EUV was an exciting discovery from the SOHO EIT observations (e.g., Thompson *et al.*, 1998). They were originally termed EIT waves, but are now often referred to as EUV waves or, more generally, as coronal waves. These waves were originally considered to be a candidate for a CME-associated Moreton wave. According to the theory by Uchida (1968), a flare may trigger an impulse that will propagate along the solar surface as a fast traveling front with an increase in emission. In the photosphere and chromosphere it can best be observed in H α as a Moreton wave. However, the EUV (EIT) waves propagate across the solar disk at typical speeds of 200 – 400 km s $^{-1}$ (Thompson and Myers, 2009), slower than the 1000 km s $^{-1}$ typical of Moreton waves. Observational evidence, such as the association of Type II radio bursts with coronal waves, suggests that at least some of

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waves. For example, [Vrsnak \(2002\)](#), found that only about half of frontsideside radio events have EIT waves, and Cliver *et al.* ([2005](#)) found that there are ~ 5 times as many frontside CMEs as EIT waves. Thus, their nature is still under intense debate. Competing models include fast-mode MHD waves, slow-mode waves or solitons, and “pseudo waves” related to a current shell or successive restructuring of field lines at the CME front. Details of observations and models can be found in recent reviews ([Warmuth, 2007](#); [Vršnak and Cliver, 2008](#); [Wills-Davey and Attrill, 2009](#); [Gallagher and Long, 2011](#)).

The relatively poor cadence (~ 12 minutes) of the EIT observations of propagating EUV disturbances were partially alleviated by STEREO EUVI imagery. These have shown that the EUV wave kinematics are more consistent with coronal MHD waves (e.g., [Long *et al.*, 2008](#); [Patsourakos and Vourlidas, 2009](#)). Using the Atmospheric Imaging Assembly (AIA) on SDO, [Liu *et al.* \(2010\)](#) show that there can be multiple wave components with rippling effects. In one of the best observed wave events using the AIA EUV images, it was found that the shock and metric type II burst appeared simultaneously ([Gopalswamy *et al.*, 2012](#)). Also the wave propagation can be inhibited and possibly reflected from coronal holes (e.g., [Gopalswamy *et al.*, 2009c](#)). [Veronig *et al.* \(2010\)](#) presented evidence from STEREO/EUVI observations that the wave initially appears as a dome-shaped spherical structure surrounding the CME. [Chen and Wu \(2011\)](#) interpret an EUV event using SDO/AIA data as consisting of a fast mode wave followed by a slower disturbance.

3.6 Shock waves and SEPs

If the speed of a CME exceeds the local Alfvén speed in the corona and interplanetary medium it can drive a forward shock. Type II radio bursts, caused by Langmuir waves forming as a result of plasma motion ahead of a shock, are associated with CMEs. Type IV bursts, especially “moving” bursts associated with CMEs, imply magnetic plasma ejections, possibly associated with EPs, and nonthermal particles from field-line reconnection. Studies performed using SOHO data seem to confirm that metric type II bursts arise from shock waves driven by CMEs ([Cliver *et al.*, 1999](#)) although the association between metric type II bursts and solar activity has been established since their discovery in the 1950s. Type II bursts in various wavelength domains appear to be organized by the kinetic energy of the

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and extending to kilometric (km) wavelengths (covering the entire Sun-Earth distance) are associated with CMEs of the largest energy. This hierarchical relationship implies that all type II bursts are associated with CMEs, i.e., mass ejecta (e.g., Gopalswamy *et al.*, [2005](#)). More details about solar radio events will appear in an upcoming Living Review; also see Schwenn ([2006](#)).

Historically, identifying shocks in white light coronagraph images has been very difficult. Kinks in streamers deflected by CMEs and changes in type II dynamic spectra have been used to infer the existence of shocks on the flanks of CMEs. Sharp, bright rims ahead of fast CMEs occasionally observed by LASCO are now considered by some to be evidence of shocks (e.g., Vourlidas *et al.*, [2003](#); Ontiveros and Vourlidas, [2009](#); Vourlidas and Ontiveros, [2009](#)). The kinematics of a spherical shock ahead of a bubble CME has been determined in EUV data from SDO-AIA (Ma *et al.*, [2011](#)).

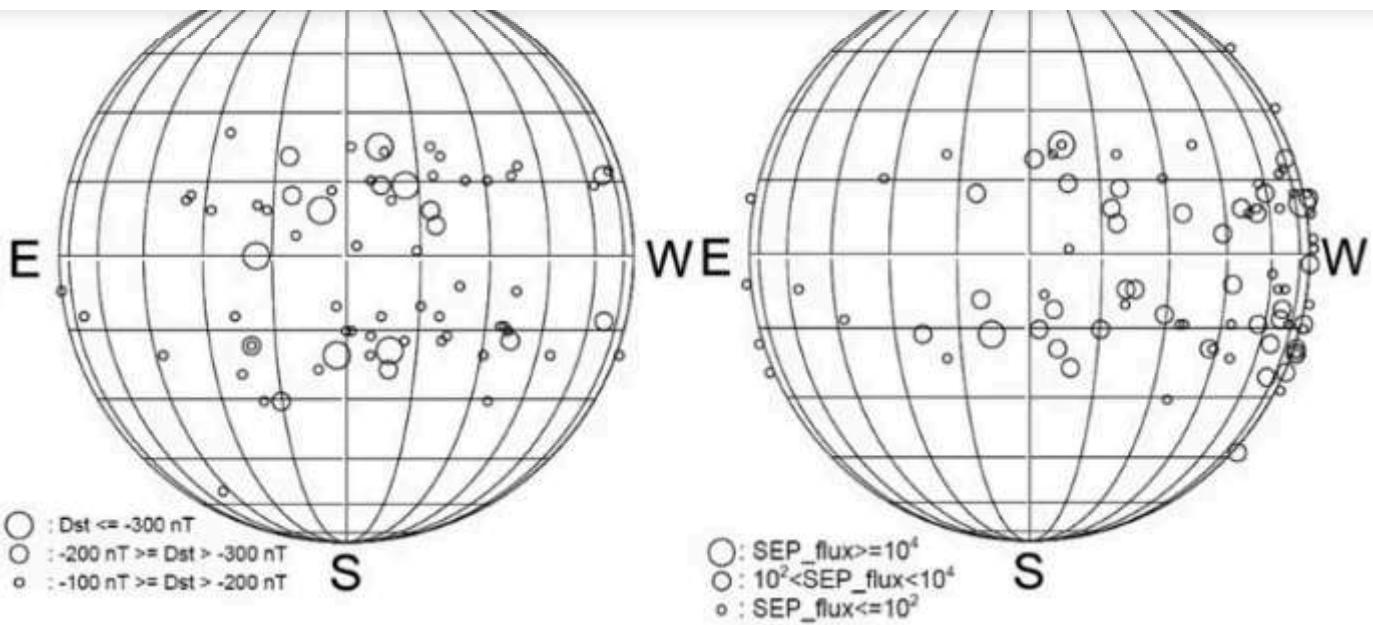
Ultraviolet spectroscopy provides an unambiguous means to observe coronal shocks and determine their properties (Kohl *et al.*, [2006](#)). Shock compression causes an immediate increase in the emissivity of dominant ions, and the bulk motion of the shocked plasma causes Doppler dimming of H I Ly α and O VI lines. Electron heating causes a more gradual change in the ionization state, and heating of the ions can be measured through line width increases. However, since the shocked gas passes quickly through the UVCS slit, the signatures of only a few shocks have been reported. In all these cases broad O VI profiles were detected and the O temperatures were $> 10^8$ K.

Using SOHO and radio observations of a fast CME, Bemporad and Mancuso ([2010](#)) were able to provide a complete characterization of pre- and post-shock plasma physical parameters in the corona. The UVCS slit was centered at $4.1R_\odot$ in the flank of the expanding CME, the highest UV detection of a shock obtained so far with UVCS. The white-light and EUV data were combined to estimate the shock compression ratio, plasma temperature, and the strength of the magnetic fields. For the compression ratio of 2.06, the coronal plasma was heated across the shock from an initial temperature of 2.3×10^5 K up to 1.9×10^6 K, while the

[Download PDF](#)~~two times larger than the thermal energy density increase.~~

CME-driven shocks can accelerate electrons and ions producing solar energetic particle (SEP) events. The close association between SEP events and fast CMEs implies that SEPs are accelerated by CME-driven shocks (Reames, 1999). Early work with solar energetic particles in the 1960s suggested that a two-stage acceleration process must take place to achieve the energies observed in these particles (Wild *et al.*, 1963), a process later confirmed using in-situ data in the 1980s and 1990s (e.g., Gloeckler *et al.*, 1994). The first stage, up to around 100 keV for electrons, is provided by the flare, and the rest provided by a fast magnetohydrodynamic (MHD) shock, now believed to be produced by the CME. A few hundred large SEP events have been recorded during the SOHO period, most of them occurring around the solar maximum (e.g., Gopalswamy *et al.*, 2008). The associated CMEs were fast (average speed $\sim 1500 \text{ km s}^{-1}$), apparently wide (mostly full halos) and decelerating (possibly due to coronal drag). Large SEP events with the most energetic particles, ground level enhancements (GLEs — e.g., Forbush, 1946), are associated with the fastest CMEs ($> 2000 \text{ km s}^{-1}$; Gopalswamy *et al.*, 2008). The fastest particles can arrive at Earth only minutes after the impulsive flare and associated shock. A comparison of the LASCO fast ($v > 1000 \text{ km s}^{-1}$) CMEs between the CDAW (manual) and CACTus (automatic) catalogs shows that the CDAW CME widths are considerably wider (Yashiro *et al.*, 2008b), but nearly all of the CMEs associated with GLEs are halos ($W > 180^\circ$) in both catalogs. The source regions of the SEP-associated CMEs are generally located in the Sun's western hemisphere, because the particles travel along the Parker spiral interplanetary field lines. The SEP-CME distribution is different from that of the CMEs producing geomagnetic storms (Figure 25). Thus, all frontsided fast and wide CMEs are potentially important for Earth's space weather. An important SOHO result is that the high-intensity SEPs are associated with active regions that are associated with repeated CMEs, suggesting that CME interactions may be important in accelerating the particles in large SEPs (e.g., Gopalswamy *et al.*, 2004b).

Figure 25

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Locations of associated solar surface activity related to CMEs that produce major ($Dst \leq -100 \text{ nT}$) geomagnetic storms (left) and large SEP events (right). The circle sizes represent the significance of the resultant event (Gopalswamy, [2010b](#)).

Emslie *et al.* ([2004](#)) have shown that the CME kinetic energy is by far the largest component in the energy budget of an eruption. As much as 10% of the CME kinetic energy might go into SEPs, suggesting that CME-driven shocks are very efficient particle accelerators (Mewaldt, [2006](#)). More details about Solar Energetic Particles will appear in an upcoming Living Review; also see Schwenn ([2006](#)).

3.7 Evidence of reconnection and current sheets

In [Section 3.2](#), we discussed the Flux Cancellation flare–CME model involving field line reconnection. A consequence of this process is the formation of a current sheet that connects the outgoing CME/flux rope with the reforming coronal loop arcade near the surface ([Figure 21](#)). Evidence for this seems to have been observed by a number of instruments. Yohkoh/SXT and Hinode/XRT observations have provided substantial X-ray evidence of current sheet formation, such as cusp-shaped loops (Shibata, [1999](#)) and supra-arcade downflows (SADs — McKenzie and Hudson, [1999](#), [2001](#); Sheeley Jr *et al.*, [2004](#); Savage *et al.*, [2010](#)), of post-CME

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above post-CME hair arcades. SADs have trajectories which show as they reach the top of the arcade, consistent with post-reconnection magnetic flux tubes retracting from a reconnection site high in the corona until they reach a lower-energy magnetic configuration. Savage *et al.* (2010) showed for a single XRT event following a limb CME that SADs can also appear as shrinking loops rather than downflowing voids. In that event, for the first time both the current sheet and the outgoing CME were imaged in soft X-rays and followed into the LASCO C2 field of view.

Sui and Holman (2003) first discussed a hard X-ray event observed by RHESSI that showed a compact X-ray source above the top of a roughly vertical current sheet in which they claimed magnetic reconnection was occurring. Subsequently, Sui *et al.* (2005), Saint-Hilaire *et al.* (2009), and others have analyzed similar events in which the coronal sources appear to move both downwards and outwards with time. The hard X-ray emission indicates a very hot source, $\sim 10^{7-8}$ K, with the outgoing packet associated with the magnetic X-point where oppositely-directed field lines reconnect. The downward source is likely hot plasma from the most-recently reconnected arcade loops that are shrinking, as well observed in the soft X-ray observations.

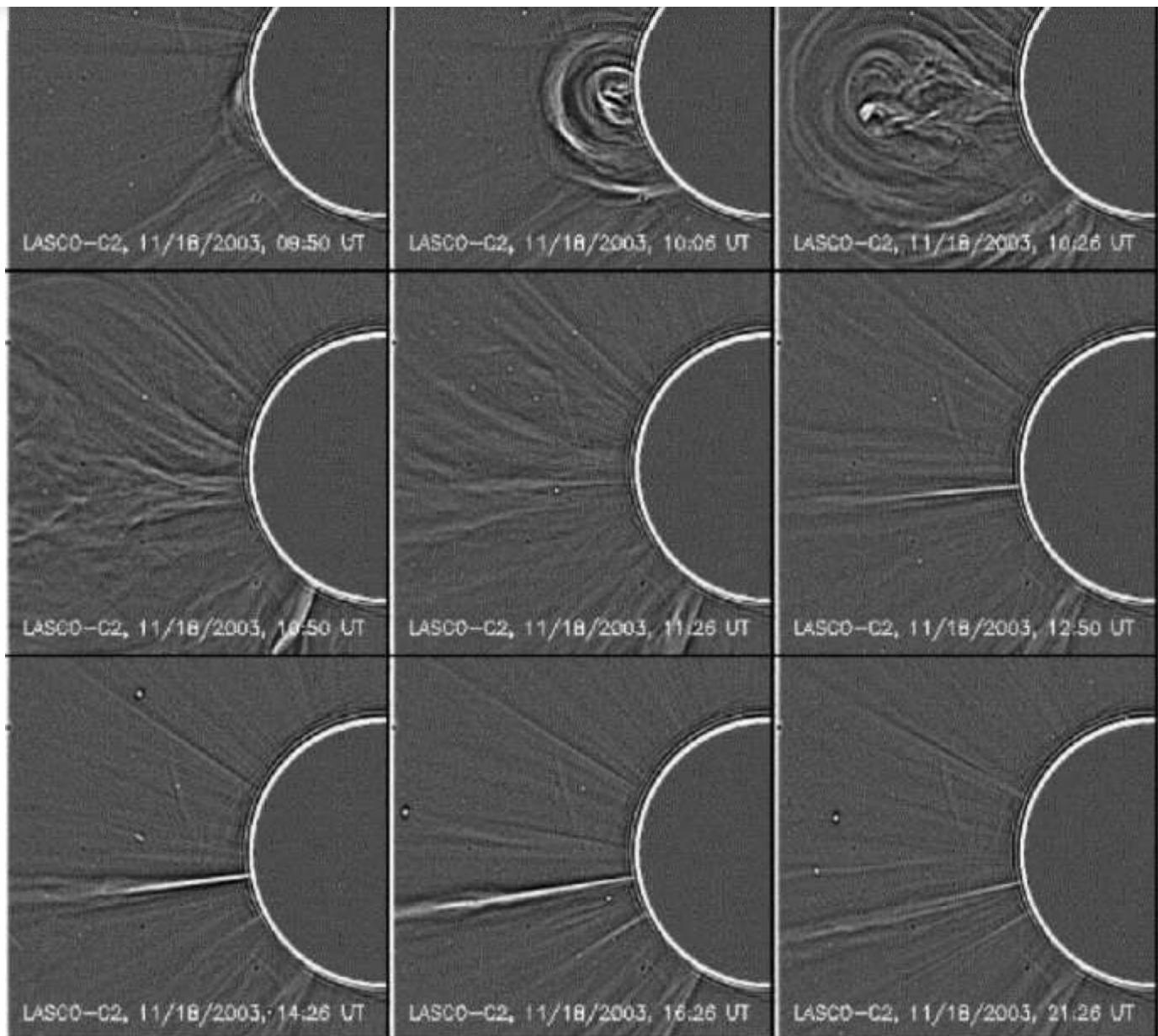
The current within the current sheet is confined to a surface. In MHD theory, an electric current passing through part of the volume of a fluid tends to be expelled by magnetic forces from the fluid, compressing the current into very thin layers within the volume. We now have growing evidence for the existence of such current sheets in the corona trailing CMEs when the observing conditions are appropriate. Following earlier studies of concave-outward structures and reforming helmet streamers after CMEs, Webb (1995; 2004) analyzed SMM CMEs with concave-outward bright regions, finding that about half were followed by coaxial, bright rays suggestive of newly formed current sheets lasting for several hours and extending more than five solar radii into the outer corona.

With the advent of LASCO data, cases of CMEs with rays and Y-shapes were reported by Simnett *et al.* (1997), and St Cyr *et al.* (2000) found such features in one third to one half of all LASCO CMEs. Bright narrow features with enhanced temperatures ($3 - 6 \times 10^6$ K),

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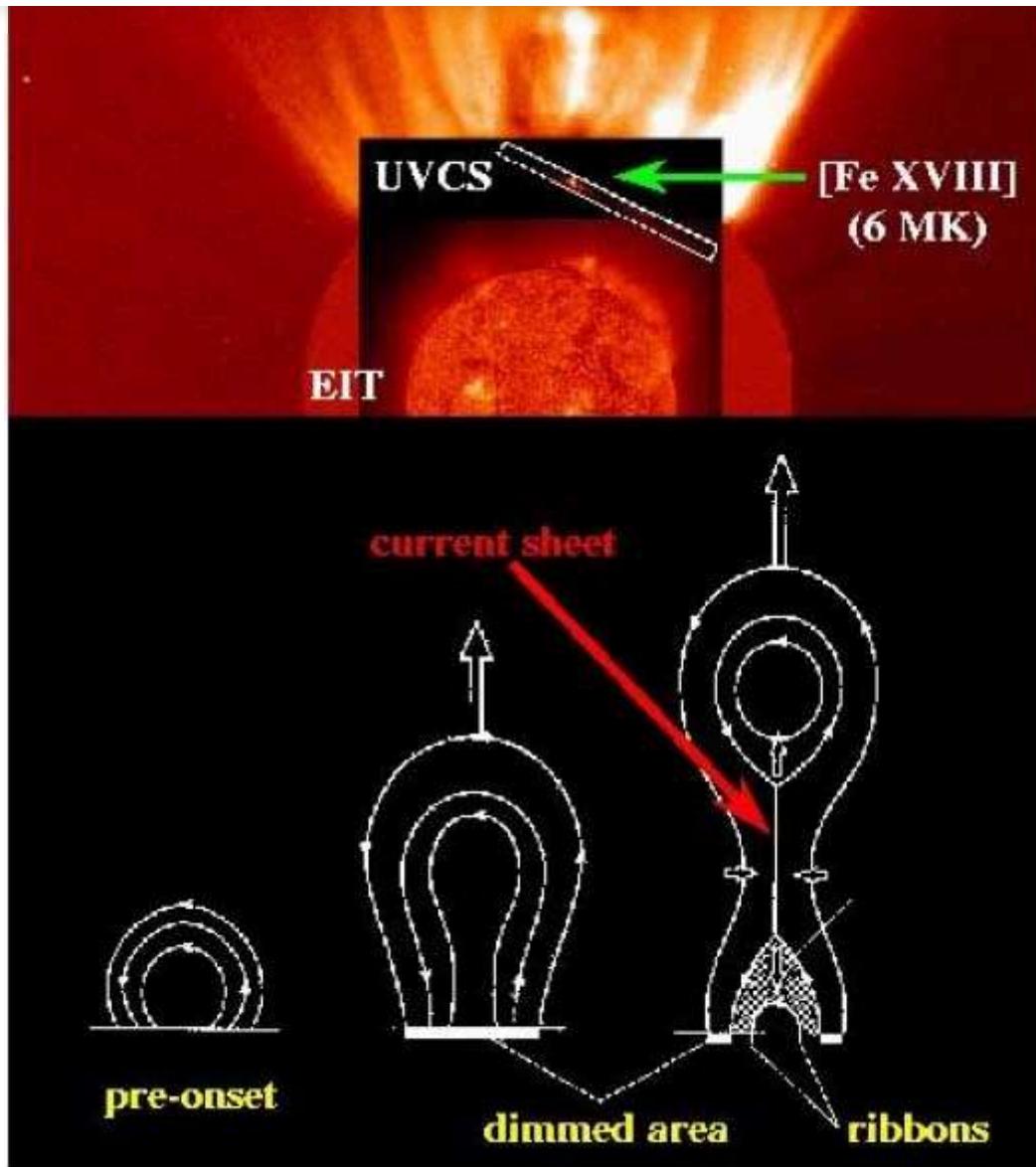
[2003b](#)) and very fast (1800 km s^{-1} ; Ko *et al.*, [2003](#); Lin *et al.*, [2005](#)) CMEs. [Figure 26](#) shows enhanced images of the 18 November 2003 event; the CME had a concave-outward, flux-rope like appearance followed by a rapidly brightening ray (Lin *et al.*, [2005](#)). Blobs moved along the ray at $\sim 1000 \text{ km s}^{-1}$ suggesting bursty reconnection in the current sheet, as MHD modeled for example by Riley *et al.* ([2007](#)). [Figure 27](#) shows an example of SOHO observations of a classic three-part CME with narrow enhanced Fe XVIII emission centered under the CME where the current sheet should lie (as in the standard-flare-model cartoon sketched at the bottom of the figure). Yokoyama *et al.* ([2001](#)), Simnett ([2004](#)), Sheeley Jr and Wang ([2007](#)), Vršnak *et al.* ([2009](#)), and Savage *et al.* ([2010](#)) also identified bi-directional flows in SOHO and Hinode images moving away from a common point in the low to mid-corona that were interpreted in terms of reconnecting current sheets.

Figure 26

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A very fast CME with flux-rope structure followed by a narrow ray on 18 – 20 November 2003. The ray also shows evidence of bursty reconnection in the current sheet (bottom panels). Image reproduced with permission from Lin *et al.* ([2005](#)).

Figure 27

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A LASCO “Light-bulb CME” on 23 March 1998 (see Ciaravella *et al.*, 2003a). The UVCS slit at $1.5R_{\odot}$ reveals hot Fe XVIII emission trailing the CME, an expected spectroscopic signature of a current sheet. Image courtesy A. Ciaravella.

Ciaravella and Raymond (2008) were the first to combine UVCS and white light data to derive both the density and thickness in a current sheet, rather than assuming one to estimate the other. Bemporad and Mancuso (2010) derived turbulent speeds and their evolution in time, which is the main constraint for turbulent current sheet models. In these and other results (e.g., Lin *et al.*, 2009), the thickness of the current sheet was calculated to

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hyperdiffusion. The reconnection mechanism (Furthick, 1984), and turbulent reconnection is consistent with these results.

3.8 “Problem” and “stealth” CMEs

So-called “problem” geomagnetic storms lack historically obvious signatures of related solar activity, such as flares and large disappearing filaments (e.g., Dodson and Hedeman, 1964; McAllister *et al.*, 1996, and references therein). An event on 6 – 10 January 1997 was the first such problem storm for which the antecedent CME was actually observed (Webb *et al.*, 2000b). The associated solar surface activity was so weak and unimpressive that, had the faint LASCO halo CME not been observed, the storm would not have been forecast. During the LASCO period, partial or full halo CMEs that had no obvious surface association were usually attributed to “backside” events directed away from the Sun-Earth line (e.g., Demastus *et al.*, 1973; Munro *et al.*, 1979; Webb and Hundhausen, 1987). Non-halo CMEs occurring near the limb were mostly attributed to unseen sources behind the limb.

The absence of solar surface activity with observed CME activity is not a new observation (Howard and Harrison, 2012). The launch of STEREO in 2006, however, afforded us the opportunity to study the origins of CMEs simultaneously from multiple lines of sight. Robbrecht *et al.* (2009a) presented a study of a streamer blowout CME without a clear source region. The STEREO spacecraft were sufficiently widely separated (53°) that the CME and its source region could be viewed edge-on in STEREO A and face-on in STEREO B. STEREO B saw the CME as a faint halo and it was detected in-situ as a magnetic cloud 5 days later. Robbrecht *et al.* suggested that the CME originated high enough up in the corona such that no surface signatures were evident. Subsequently, Ma *et al.* (2010) performed a statistical study of all CMEs observed during the first 8 months of 2009 when the STEREO lines of sight were nearly perpendicular to each other. They found that about a third of the CMEs were “stealth”, having no distinct surface association, and tending to be slow, i.e., $< 300 \text{ km s}^{-1}$. Faint coronal changes could be detected in about half of the stealth CMEs, again suggesting a higher launch site. It is noted that this period was during the recent unusual extended solar minimum, so the fraction of such CMEs may be different at other times. Howard and Harrison (2012) in a recent review paper discuss the use of the term “stealth CME”.

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CME begins well before the appearance of any associated surface activity such as flares or erupting prominences. Some of the energy released during a CME could drive precursor activity, and there is some evidence of precursor activity tens of minutes to hours before the onset of surface activity and even before CME onset (see Webb, [1992](#) and Gopalswamy *et al.*, [2006b](#) for a recent review called “The Pre-CME Sun”).

Jackson and colleagues described evidence for two kinds of coronal precursors occurring before the onset of Skylab CMEs. The first were called “forerunners”, large, faint regions of enhanced brightness that were found to rim the CMEs themselves (Jackson and Hildner, [1978](#)). The outer boundaries of the forerunners maintained a constant offset of $1 - 2R_{\odot}$ from the CME. The reality of such features would be significant for two reasons:

1. The volume of the affected corona would be much larger than the subsequent CME;
2. The onset of the material ejection would begin higher in the corona and earlier than previously thought.

Jackson ([1981](#)) noted that in some events forerunner material was actually in motion prior to the associated surface activity. However, using Solwind data, Karpen and Howard ([1987](#)) concluded that forerunners were either an artifact of the contouring process used or were structures not separate from the CME itself. Although this controversy was never fully resolved, with the larger dynamic range of LASCO rims of material detected ahead of fast LASCO CMEs are now considered evidence of shock waves, and emission can be detected ahead of slower speed CMEs as low-level brightness enhancements due to the expanding streamer (see [Section 3.6](#)).

A second type of CME precursor reported by Jackson *et al.* ([1978](#)) was the statistically significant temporal clustering of Culgoora type III radio bursts an average of 6 hours before Skylab CME onsets. Culgoora radioheliograph positional data revealed that these same type IIIs clustered spatially at the limb within 20° of the centroid of the CME. Recently, Jackson *et al.* ([2010c](#)) reported that imaging measurements from the French Nançay radio array

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Data nearer the time of CME onset indicate the existence of precursor activity before some, but not all CMEs. During the SMM era it was found that the departure times of flare-associated CMEs often preceded flare onsets. Harrison (1991) concluded that CME onsets preceded any subsequent associated H α or X-ray flares by an average of 17 minutes. CME onsets were associated with precursor X-ray arches having large scale sizes of $\sim 10^5$ km and interconnecting two active regions. In addition, most X-ray flares observed by the SMM HXIS instrument were preceded by weak soft X-ray bursts, but more recent results using soft X-ray and EUV data do not show such a clear pattern (Harrison, 1991; Harrison *et al.*, 1990; Yashiro *et al.*, 2008a).

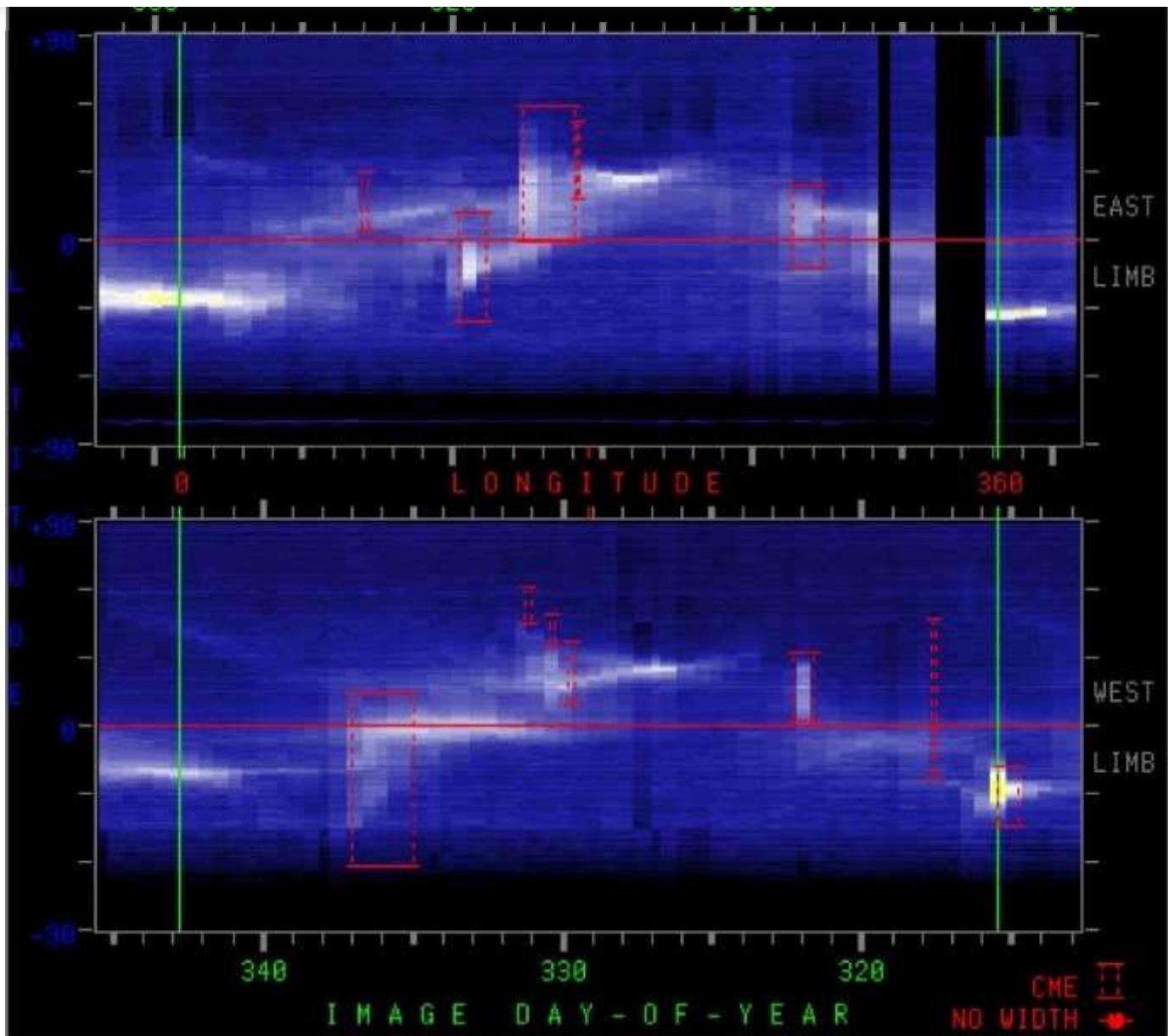
As discussed in [Section 3.4](#), an S or reverse S-shaped structure called a sigmoid sometimes develops, and can be associated with a filament's activation. Like the filaments themselves, sigmoids are indicative of sheared coronal magnetic fields. Since many CME onset models require a magnetic shear to be established for the field to erupt, these sigmoids may be a precursor of a CME. It is well known that various kinds of filament/prominence activity precede the eruption of the filament itself by tens of minutes. Since erupting prominences are the most common type of surface activity associated with CMEs and appear as bright cores within many CMEs (Webb and Hundhausen, 1987), pre-eruptive filament activity is a form of CME precursor. Tens of minutes before their eruption, some large filaments darken and get broader (e.g., Martin, 1980). The cancellation of magnetic flux near filament channels can also build energy prior to an eruption, a process already referred to as Flux Cancellation (Martin and Livi, 1992). Kahler *et al.* (1988) found that the eruption of H α filaments began before the onset of associated flare impulsive phases, suggesting that these erupting filaments, and by analogy the CMEs associated with them, were driven before and independently of the flare and its impulsive phase.

Some of the most massive and energetic CMEs are the so-called streamer blowout events, which were first described in detail by Sheeley Jr *et al.* (1982) and Illing and Hundhausen (1986). The preliminary statistics of streamer-blowout CMEs observed by LASCO were presented by Vourlidas *et al.* (2002b). In such events, a pre-existing streamer typically

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later a recurring feature (Hundhausen and Hundhausen, 1992). These events appear on white light synoptic charts as “bugles”: portions of the streamer belt that brighten and widen with time until they disappear during a CME (Figure 28 — Hundhausen, 1993). Most streamer blowouts involve a pre-existing prominence sitting within a coronal void or cavity; this then erupts to form the classic “three-part” CME structure. Thus, the early filament/prominence activations discussed above are probably related to streamer swellings and blowouts.

Figure 28

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Coronal synoptic maps from the SMM C/P coronagraph showing the white light emission at a height of $3.4R_{\odot}$ over the east (top) and west (bottom) limb. The coronal streamer belt is evident on these maps. Narrow vertical streaks on the maps indicate CMEs. These were first called “bugles” by Hundhausen (1993), since streamer-blowout CMEs appear on synoptic maps as vertical streaks usually preceded by brightening and widening streamers. Such bugle shapes are left-facing on synoptic maps because time runs from right to left. The locations and widths of all CMEs on this rotation are marked by dashed boxes. Image adapted from Hundhausen (1993), courtesy J. Burkepile, NCAR/HAO.

4 CME Models

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(refer to Kahler, [1992](#) and Gosling, [1993](#) for reviews debunking the “Solar Flare Myth”), some remnants still remain in some circles, particularly those outside the solar physics community. Early mathematical models (and some still in use today) regard solar mass ejections as eruptive solar flares in opposition to the majority of flares which are “confined”. Because the corona is a highly conducting medium, the plasma is essentially “frozen in” to the magnetic field such that for an eruption to occur, the field lines must open up to allow the plasma to escape. But flares and CMEs can have very different properties, not least their spatial scales, and CMEs can occur without flares, so most researchers now consider flares and CMEs to be different aspects of magnetic field reconfiguration on the Sun. For details of CME models in general, see the Living Review by Chen ([2011](#)). Here we describe only those models that pertain to material eruption (see, e.g., Aschwanden, [2006](#) and Forbes *et al.*, [2006](#) for reviews).

Contemporary models describing the launch and early evolution of CMEs must overcome two major physical obstacles:

1. How to provide vast quantities of energy over a short time period (mentioned previously);
2. How to physically justify the CME as an opening of a magnetic field when the completely open field state is higher in energy than the pre-erupted closed state (the so-called Aly-Sturrock limit).

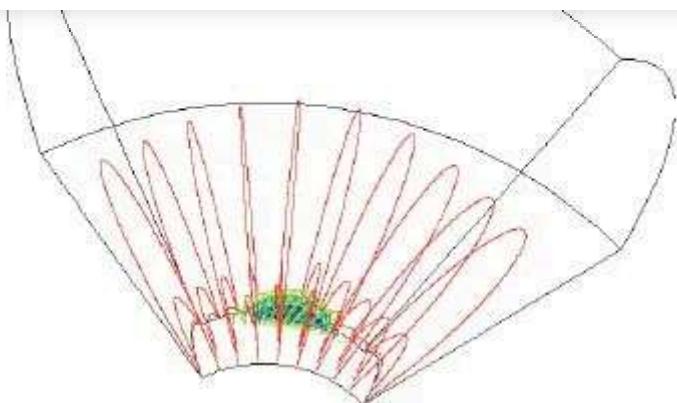
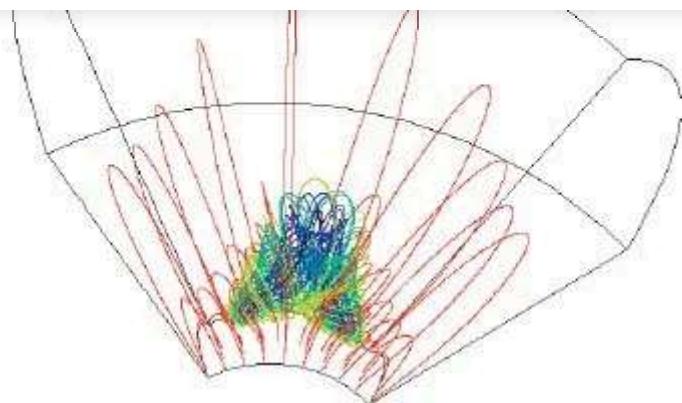
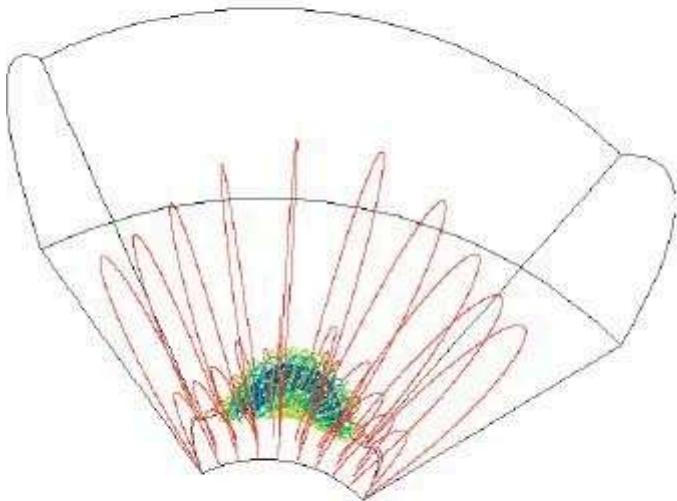
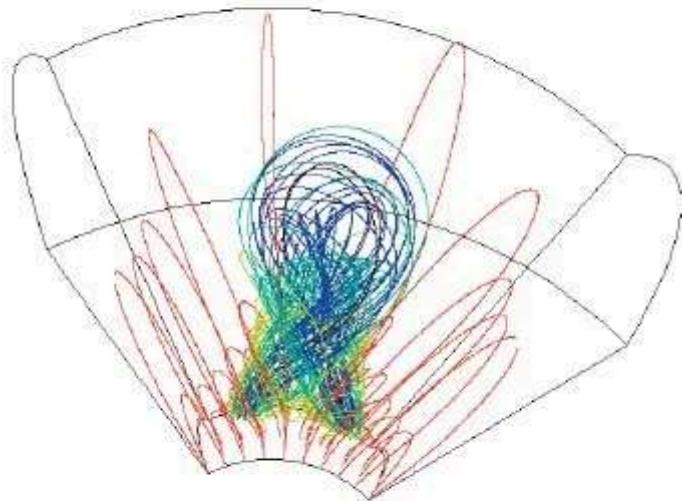
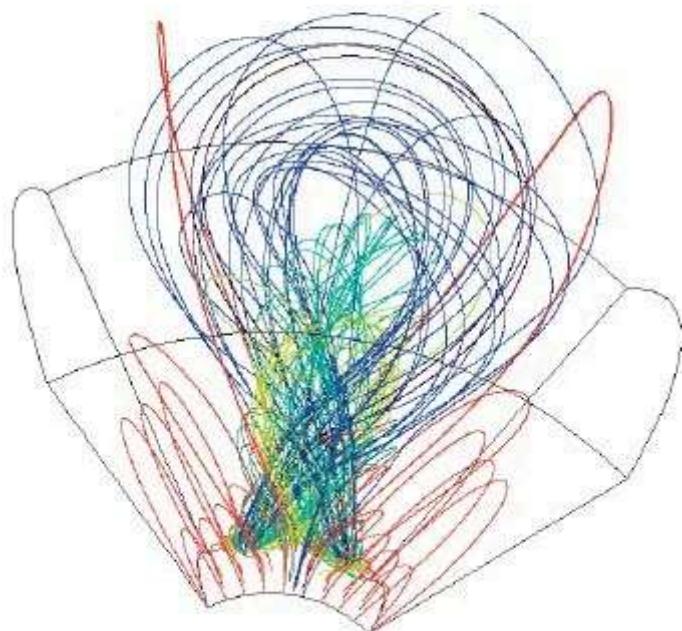
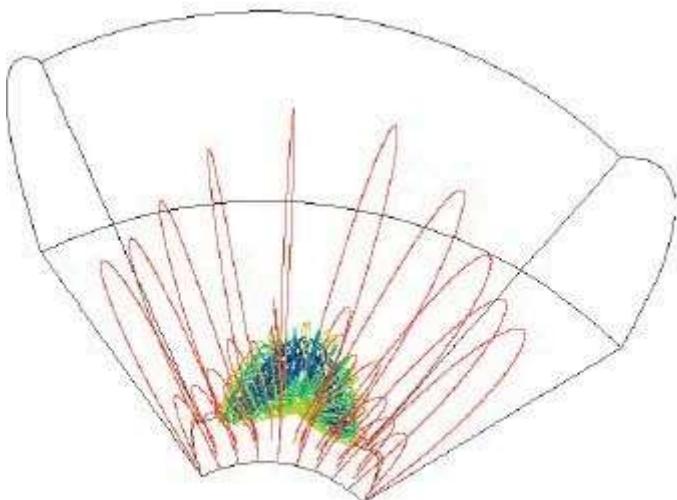
While the physical mechanism to launch the CME may vary between models, the overall picture is essentially the same: A magnetic field configuration held in equilibrium is disrupted somehow, causing the system to erupt. The initial configuration typically involves an underlying sheared field often called the core (e.g., Moore and Roumeliotis, [1992](#)) held down by an overlying strapping field. The onset mechanism itself that causes the eruption is actually less important — eventually one will occur. It may take the form of magnetic reconnection or even a simple field reconfiguration could accomplish an equilibrium disruption. The core then erupts beyond the strapping field.

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accepts that the strapping field must be stretched by the erupting core, which must presumably stretch it out to infinity. This, however, violates the Aly-Sturrock limit meaning it has been difficult to explain physically why a CME would spontaneously move to a more energetic state. This problem has been overcome with the use of 3-D models. In three dimensions, the core can erupt without stretching the strapping field along with it — instead it can simply push the strapping field aside as it erupts. Hence, in 3-D the Aly-Sturrock limit does not pose a problem.

To overcome the first obstacle, that of energy provision, a number of models have emerged. Some, such as the breakout model (e.g., Antiochos *et al.*, 1999; Lynch *et al.*, 2008), involve runaway magnetic reconnection between the erupting core and the strapping field, while others, such as the kink instability (e.g., Török and Kleim, 2003; Török and Kliem, 2005; Fan and Gibson, 2004) involve the twisting of the core field. [Figure 29](#) shows a 3-D diagram of the kink instability, also showing how the strapping field is pushed aside to make way for the erupting core.

Figure 29

[Download PDF](#) $t = 45$. $t = 90$. $t = 70$. $t = 97$.

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the overlying strapping magnetic field (rea). This field is pushed aside during this process. Image reproduced by permission from Fan ([2005](#)), copyright by AAS.

After the CME has erupted the magnetic field left behind eventually closes, probably via some form of large-scale magnetic reconnection. The recent models of this process describe the late phase of CMEs reasonably well (cf. Švestka and Cliver, [1992](#)). Kahler and Hundhausen ([1992](#)) found that the bright structures following many SMM CMEs are streamers probably newly-formed by reconnection. Observations from Yohkoh and from MLSO of the reformation of a giant helmet streamer also provide strong evidence of reconnection following CMEs (Hiei *et al.*, [1993](#)). As discussed earlier, the white light and spectroscopic evidence for current sheets trailing CMEs also provide support for the reconnection of the surface fields. Reeves and Moats ([2010](#)) have examined the relationships among the CME kinematics, thermal energy release and soft X-ray emissions using the Lin and Forbes ([2000](#)) loss-of-equilibrium model, finding good correlations among the parameters.

An extensive survey of post-eruptive arcades in SOHO/EIT 195 Å images has shown that every arcade is associated with a LASCO CME (Tripathi *et al.*, [2004](#)). These observations have been interpreted in terms of a basic model of reconnecting magnetic fields behind a magnetic flux rope and over a magnetic arcade (e.g., Lin, [2004](#)), which results in a disconnection of CME fields from the Sun, as shown in [Figure 21](#). This model has been called the CSHKP model to reflect its provenance. The acronym stands for Carmichael, Sturrock, Hirayama, Kopp, and Pneuman, each of whom developed configurations which have now evolved into a “standard” model that continues to be supported by observations and simulations (see Švestka and Cliver, [1992](#), for the original CSHKP description). Correlations found between inferred magnetic reconnection rates in arcades and the speeds of associated CMEs provide further confirmation of the model (Jing *et al.*, [2005](#)). Radio imaging of the moving and quasi-stationary type IV bursts can provide upper limits to the current sheet length by bracketing the reconnection region (Pick *et al.*, [2005](#)).

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equations which cannot realistically describe the complex evolution of the pressure, magnetic and gravitational forces acting on a magnetically closed coronal structure (e.g., Hundhausen *et al.*, 1994). The class of models which require a thermal or pressure pulse (i.e., flare) as driver no longer seem viable (cf. Dryer, 1994). For instance, such models are not consistent with CMEs that exhibit significant accelerations over large distances. Causes of the evolution of these coronal structures, especially streamer configurations, include the emergence of magnetic flux, the dynamical evolution of arcades (Mikić and Linker, 1994), and the shear of field lines across inversion lines (Wolfson and Low, 1992; Mikić and Linker, 1994). However, no strong consensus has yet emerged.

Models attempting to describe CME evolution at large distances from the Sun can be categorized in order of their increasing complexity. It is important to note that the most complex model does not necessarily indicate the more accurate; sometimes the simpler description can be the most appropriate. We divide models for CME evolution into three categories: 1) A disturbance in the ambient solar wind, 2) an embedded lump of plasma, and 3) an embedded magnetic flux rope. All of these essentially begin with the same foundation, that of a background solar wind into which some form of anomaly is introduced.

The first category, that of a disturbance in the solar wind, is really a derivative of the original idea that CMEs were blast waves from flares. This has since been proven to be a physically incorrect description of CMEs, but nonetheless some of these models have been able to sometimes reproduce well the appearance and propagation characteristics of CMEs. This is probably because at large distances from the Sun the most prominent observable feature is the built-up solar wind material in the sheath, which is governed by the theory of interplanetary shock propagation. The most popular of these models include the Shock Time Of Arrival (STOA) model (Dryer and Smart, 1984), its later version ISPM (Smith and Dryer, 1990), and HAFv2 (Hakamada and Akasofu, 1982; Fry *et al.*, 2001).

The second category, which consists of a lump of material embedded into the solar wind, takes simple and more complex forms, but essentially is based on the assumption that the embedded material responds hydromagnetically to the surrounding solar wind. The simplest

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This includes [Cargill \(2004\)](#), and [Tappin \(2006\)](#). A more complex version of this is the L1111 model ([Odstrčil, 2003](#)) which takes into consideration plasma density, CME structure and extrinsic magnetic field as well as the kinematic properties of the CME and solar wind.

The third category treats the CME as a magnetic flux rope which is embedded into the solar wind. These models attempt to include the magnetic interaction between the CME and the interplanetary magnetic field (e.g., [Chen, 1996](#); [Manchester IV et al., 2005](#)).

It is important to note that the models discussed above describe the evolution of the CME once it is some distance away from the Sun, i.e., they do not describe the physics of the onset and early evolution. The assumption is that the physics become simplified once the CME has escaped the gravitational and magnetic pressure forces at or near the Sun.

5 CMEs in the Heliosphere

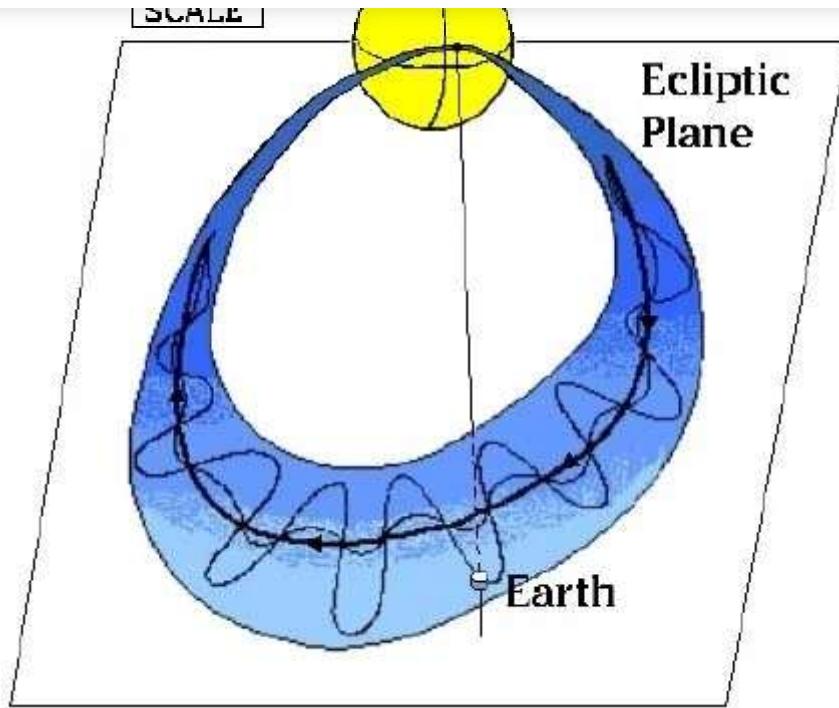
CMEs carry into the heliosphere large amounts of coronal magnetic fields and plasma, which can be detected by remote sensing and in-situ spacecraft observations. Here they are known as interplanetary CMEs or ICMEs ([Zhao and Webb, 2003](#); [Dryer, 1994](#)). The term ICME or “interplanetary CME” was originally devised as a means to separate the phenomena observed far from the Sun (e.g., by in-situ spacecraft) and those near the Sun (e.g., by coronagraphs). However, in the SMEI and STEREO era, where CMEs can now be tracked continuously from the Sun to 1 AU and beyond, the term has become largely redundant. Consequently, in a recent workshop on remote sensing of the heliosphere in Wales (June 2011) it was decided to no longer use the term ICME, and in this review we drop the term.

The passage of CME material past a single spacecraft is marked by distinctive signatures, but with a great degree of variation from event to event (e.g., [Gosling, 1993](#)). These signatures include transient interplanetary shocks, depressed proton temperatures, cosmic ray depressions, flows with enhanced helium abundances, unusual compositions of ions and elements, and magnetic field structures consistent with looplike topologies. Many of these signatures were first identified in the plasma which followed an IP shock by several hours and was considered to be the piston (CME) driving the shock. Some signatures can also be

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Often observed in in-situ data are highly structured magnetic field configurations corresponding to the arrival of a CME. The field assumes the structure of a spiral (or helix), and is accompanied by other signatures including strong magnetic field with low field variance, low plasma beta, and low temperature. Such structures were called magnetic clouds by Burlaga *et al.* (1981) citing early theoretical work dating back to the 1950s (Morrison, 1954). [Figure 30](#) shows a schematic of such a cloud impinging on the Earth in May 1997. Such a structure is often modeled as a flux rope, which is a series of helical field lines like the coils of a spring with pitch angles increasing toward the outer edge. Since, as we have seen, many if not all CMEs are now considered to contain flux ropes, it is logical to expect magnetic clouds to form the core of CMEs. In a recent report, one magnetic cloud observed in-situ was tracked continuously back to its coronagraph origins and it was found to be the cavity component of the three-part CME structure (Howard and DeForest, 2012a). This reinforced the largely-accepted view that the cavity component was the CME flux rope (e.g., Forsyth *et al.*, 2006). Theoretical work involving the development of cavities includes Fuller *et al.* (2008).

Figure 30

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Schematic drawing of modeled flux rope on 15 May 1997, including estimate of its dimensions and orientation with respect to the ecliptic plane; the axis of the cloud lay nearly in the ecliptic plane and pointed toward the east. Also drawn is the Sun-Earth line at time of cloud passage by Wind near the L1 point. Image reproduced with permission from Webb *et al.* (2000b), copyright by AGU.

Models have been developed for the force free (e.g., Lepping *et al.*, 1990; Lynch *et al.*, 2005) and non-force free (Hu and Sonnerup, 2001) states of magnetic clouds observed in-situ, the latter also known as the Grad-Shafranov technique. Around 30% (Gosling *et al.*, 1991) to 50% (Cane *et al.*, 1997) of CMEs observed in-situ show a clear signature of a magnetic cloud. It remains unknown whether the remainder does not show the signature because the imbedded flux rope is less structured, is absent, or whether the spacecraft did not pass through the flux rope component (i.e., skirted its flank).

Some magnetic clouds have been associated with solar filament disappearances. Since filament plasma is embedded in helical, horizontal magnetic fields, the close association of CMEs with filament eruptions and shearing fields near the surface also supports the view that flux ropes form the core of CMEs. One idea is that the interior fields of a rising, sheared

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associated erupting filaments at the Sun. Furthermore, larger magnetic arrays have twisted in the same sense in a given hemisphere, even though the hemispherical polarity reverses every solar cycle. Filament eruptions and CMEs may be important ways that the Sun sheds magnetic helicity, as well as flux built up over the solar magnetic cycle.

Since the in-situ signatures of CMEs are well described in several recent reviews (Schwenn, 2006; Zurbuchen and Richardson, 2006; Richardson and Cane, 2010), we will not discuss them further here. We will, however, discuss the remote sensing of CMEs, especially as achieved recently by the new class of white light imagers: heliospheric imagers.

5.1 Remote sensing of CMEs at large distances from the Sun

Several techniques have been developed to remotely detect and track disturbances related to CMEs in the interplanetary medium (e.g. Jackson, 1992). These have utilized radio and white light wavelengths to detect and image these structures. The techniques are kilometric radio observations from space and metric radio interplanetary scintillation (IPS) observations from the ground. The kilometric observations can track the emission typically from strong shocks traveling ahead of fast CMEs. Such instruments have been flown on the ISEE-3 and Ulysses spacecraft and are currently on board Wind and STEREO.

5.2 Interplanetary scintillation (IPS) observations

The IPS technique relies on measurements of the fluctuating intensity level of a large number of point-like distant meter-wavelength radio sources. They are observed with one or more ground arrays operating in the MHz-GHz range. IPS arrays detect changes to density in the (local) interplanetary medium moving across the line of sight to the source. Disturbances are detected by either an enhancement of the scintillation level and/or an increase in velocity. When built up over a large number of radio sources a map of the density enhancement across the sky can be produced. The technique suffers from relatively poor temporal (24-hour) resolution and has a spatial resolution limited to the field of view of the radio telescope. For example, high-latitude arrays such as the long-deactivated 3.5 ha array near Cambridge in the UK could not observe sources in the mid-high latitude southern hemisphere. Scattering efficiency also poses a limitation on IPS measurements as increasing

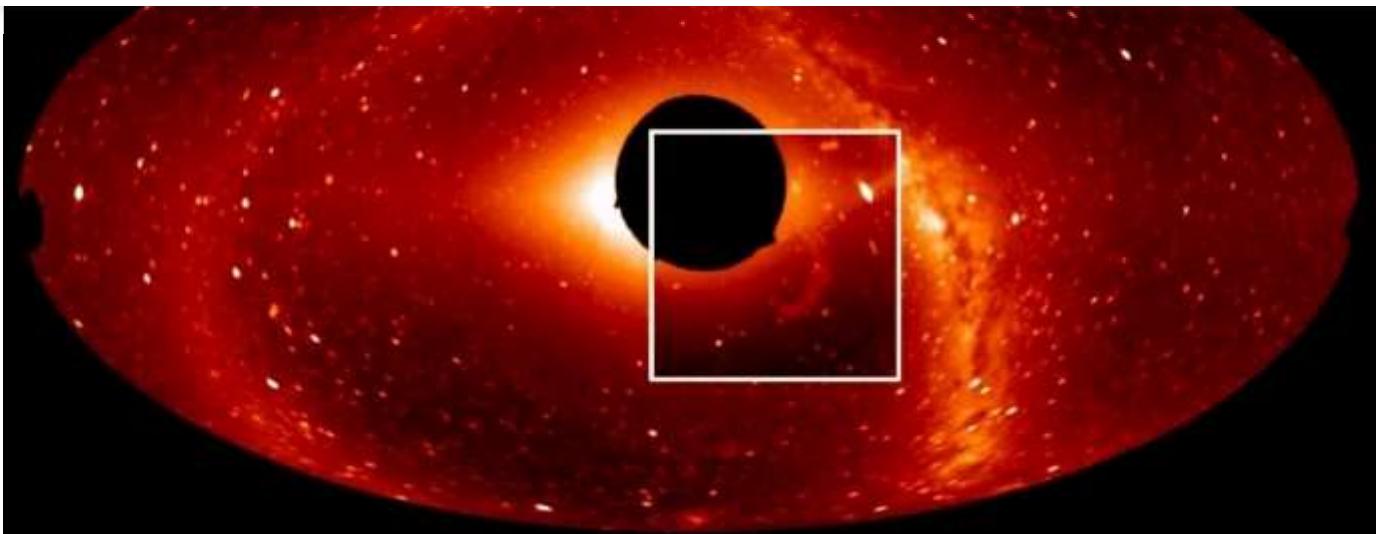
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is effectively decreased. Finally, ionospheric noise limits viewing near the Sun and near the horizon, and a model-dependence for interpreting the signal as density or mass. Workers have, however, been working with these difficulties for 50 years and a number of techniques have evolved to extract reliable CME measurements using IPS. Recent papers involving such measurements include Jones *et al.* (2007), Bisi *et al.* (2008), Jackson *et al.* (2010b), Tappin and Howard (2010), and Manoharan (2010).

5.3 Heliospheric imagers

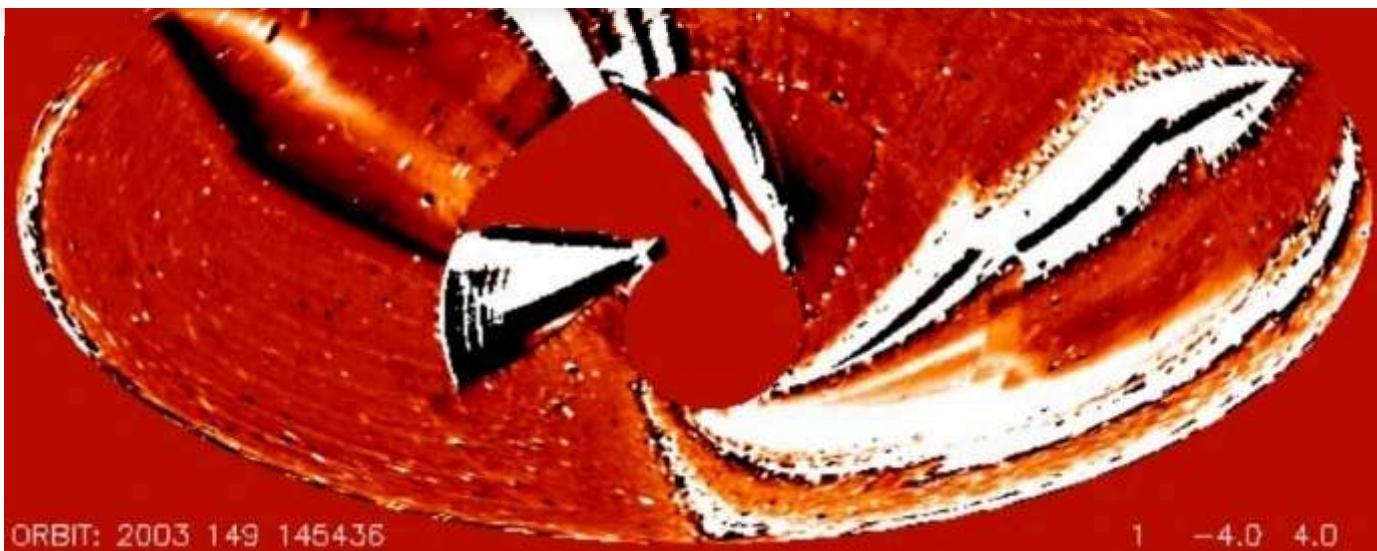
Today's heliospheric imagers are the successors to the zodiacal-light photometers (Leinert *et al.*, 1975) on the twin Helios spacecraft flown in solar orbits in the 1970s and early 1980s. SMEI, in particular, was designed to exploit the heliospheric remote sensing capability demonstrated by that instrument (Jackson, 1985; Webb and Jackson, 1990). Unlike Helios, which could only observe a few narrow strips across the sky, this new generation of imager could observe large areas simultaneously. SMEI was the first such imager, developed as a proof-of-concept U.S. Air Force experiment for operational forecasting. Launched in January 2003 on the Coriolis spacecraft, SMEI imaged nearly the entire sky in white light once per 102-minute spacecraft orbit, using three baffled camera systems. Individual frames are mapped into ecliptic coordinates to produce a nearly complete sky map (Figure 31). SMEI was deactivated in September 2011 and over its 8.5 year lifetime it observed nearly 400 CMEs (e.g., Webb *et al.*, 2006; Howard and Simnett, 2008) many of which were Earth-directed (e.g., Tappin *et al.*, 2004; Howard *et al.*, 2006; Webb *et al.*, 2009) allowing the comparison with in-situ spacecraft and prediction of arrival times and speeds. Unlike with in-situ spacecraft, however, SMEI enabled the comparison with coronagraph events in any direction, enabling large-scale tracking and 3-D reconstruction. Figure 32 is a movie of a halo-type CME that was tracked by SMEI until it produced a major geomagnetic storm at Earth.

Figure 31

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A composite all-sky image from SMEI taken in February 2003. An equal-area Hammer-Aitoff projection centered on the Sun with North and South ecliptic poles at top and bottom. The dark circle is a zone of exclusion 20° in radius usually centered on the Sun. The inset box shows a large, loop CME in May 2003 superimposed on the all-sky image. CMEs can only be detected in the SMEI data by careful subtraction of backgrounds that include particle contamination because of its Earth orbit (for details see, e.g., Webb *et al.*, [2006](#)).

Figure 32

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mpg-Movie (10681.5 KB) Still from a movie showing Orbit difference images of an Earthward halo from SMEI. Halo was visible as an arc over $\geq 150^\circ$ of sky (arrows). Blacked-out areas are due to shuttering of bright sunlight and CCD noise from particles in Coriolis' 840 km circular Earth orbit. (For video see appendix)

SMEI was used for CME tracking (Tappin *et al.*, 2004; Webb *et al.*, 2006; Howard *et al.*, 2006, 2007), space weather forecasting (Howard *et al.*, 2006; Webb *et al.*, 2009; Howard and Tappin, 2010), and 3-D reconstruction (Tappin and Howard, 2009; Jackson *et al.*, 2010b). SMEI observations have been compared with coronagraph and in-situ spacecraft measurements (Tappin *et al.*, 2004; Tappin, 2006; Howard *et al.*, 2006, 2007; Howard and Simnett, 2008; Webb *et al.*, 2009) and compared with IPS observations (Jackson *et al.*, 2008b; Bisi *et al.*, 2008). While SMEI observed the entire sky beyond 20° elongation, its field of view was often obscured by energetic particle saturation during its passage through the magnetospheric polar caps and the South Atlantic Anomaly, and by hot pixel degradation.

In October 2006, the twin STEREO spacecraft were launched carrying the Heliospheric Imagers (HIs) (Howard *et al.*, 2008a; Eyles *et al.*, 2009). The HIs are part of the SECCHI suite of imaging telescopes on each spacecraft and view the inner heliosphere starting at an elongation of 4° from the Sun. HI-1 has a FoV of 20° , from $4 - 24^\circ$ elongation ($\sim 12 - 85R_\odot$), and HI-2 of 70° , from $\sim 19 - 89^\circ$ elongation ($\sim 68 - 216R_\odot$). There is a 5.3° overlap between

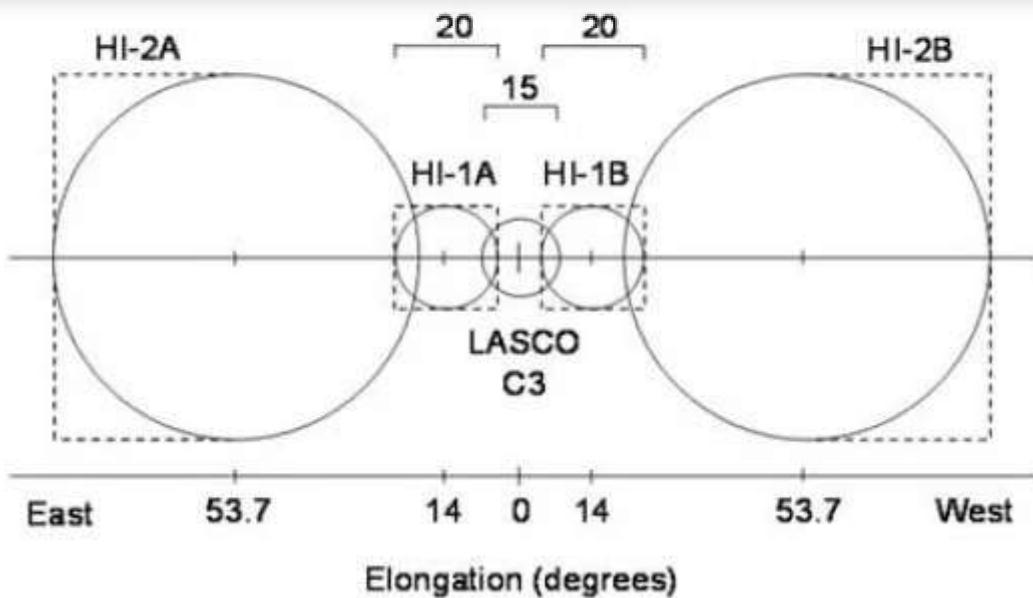
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viewing either east (HI-A) or west (HI-B) of the Sun. They do not suffer the same problems

with particle saturation as SMEI did, but are constrained by their fields of view about the ecliptic plane. Combined with the coronagraphs, the HIs do provide for the first time a continuous view from the Sun to around 1 AU and the stereoscopic viewpoints enable the possibility for 3-D reconstruction using the coronagraphs and HI-1.

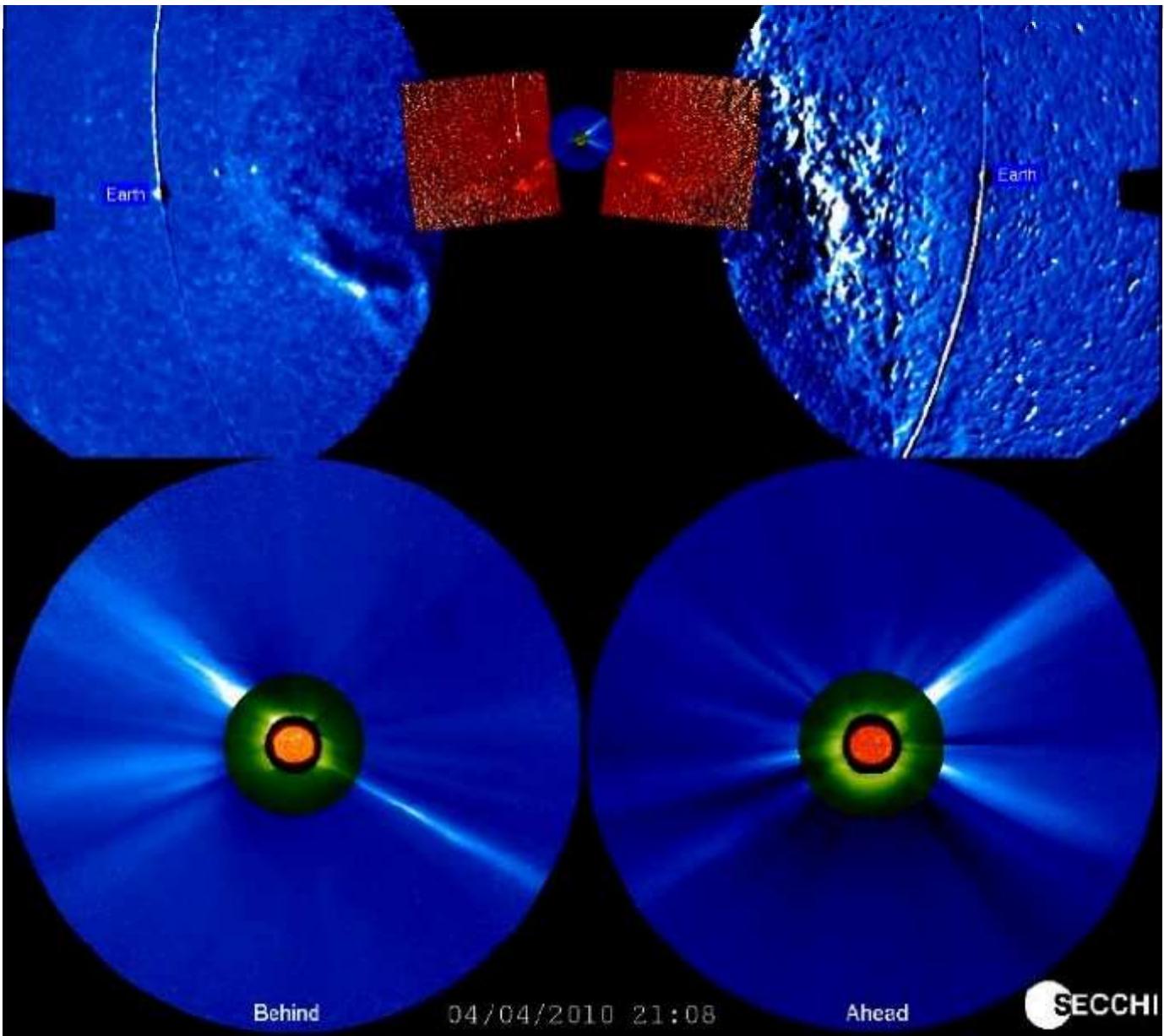
The STEREO spacecraft share similar ~ 1 AU orbits about the Sun as the Earth but separate from the Sun-Earth line by 22.5° per year. STEREO-A (Ahead) leads the Earth in its orbit, while STEREO-B (Behind) lags. [Figure 33](#) is a schematic showing the fields of view of the SECCHI telescopes. [Figure 34](#) is a movie that illustrates these views from all the telescopes during a series of CMEs in early April 2010 that produced several geomagnetic storms at Earth ([Davis et al., 2011](#)). The bottom shows the B and A views of the EUVI disk, COR1 and COR2 coronagraph imagers out to $15R_\odot$, and the upper set shows the HI-1 and -2 fields viewing east (left, HI-A) and west (right, HI-B) of the Sun beyond the EUVI, COR1, COR2 set shown to scale. Most of the early work involving the STEREO-HIs and CMEs have focused on their detection and tracking, and comparison with in-situ spacecraft. Publications include [Harrison et al. \(2008\)](#); [Davies et al. \(2009\)](#); and [DeForest et al. \(2011\)](#).

Figure 33

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The fields of view of the STEREO SECCHI HI telescopes flanking that of the SOHO/LASCO C3 instrument. The SECCHI EUVI, COR1, and COR2 telescopes are Sun-pointed like LASCO but the COR2 field extends to only half that of C3. Image adapted from Harrison *et al.* (2008).

Figure 34

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mpg-Movie (28363.8935547 KB) Still from a movie showing Combined views from all of the STEREO SECCHI telescopes during a series of CMEs in early April 2010. The bottom panels show the ST-B and ST-A views of the EUVI disk, COR1 and COR2 imagers out to $15R_{\odot}$, and the upper set shows the HI-1 and -2 fields viewing east (left, HI-A) and west (right, HI-B) of the Sun beyond the EUVI, COR1, COR2 set shown to scale. From the online data at: <http://secchi.nrl.navy.mil/index.php?p=movies>. (For video see appendix)

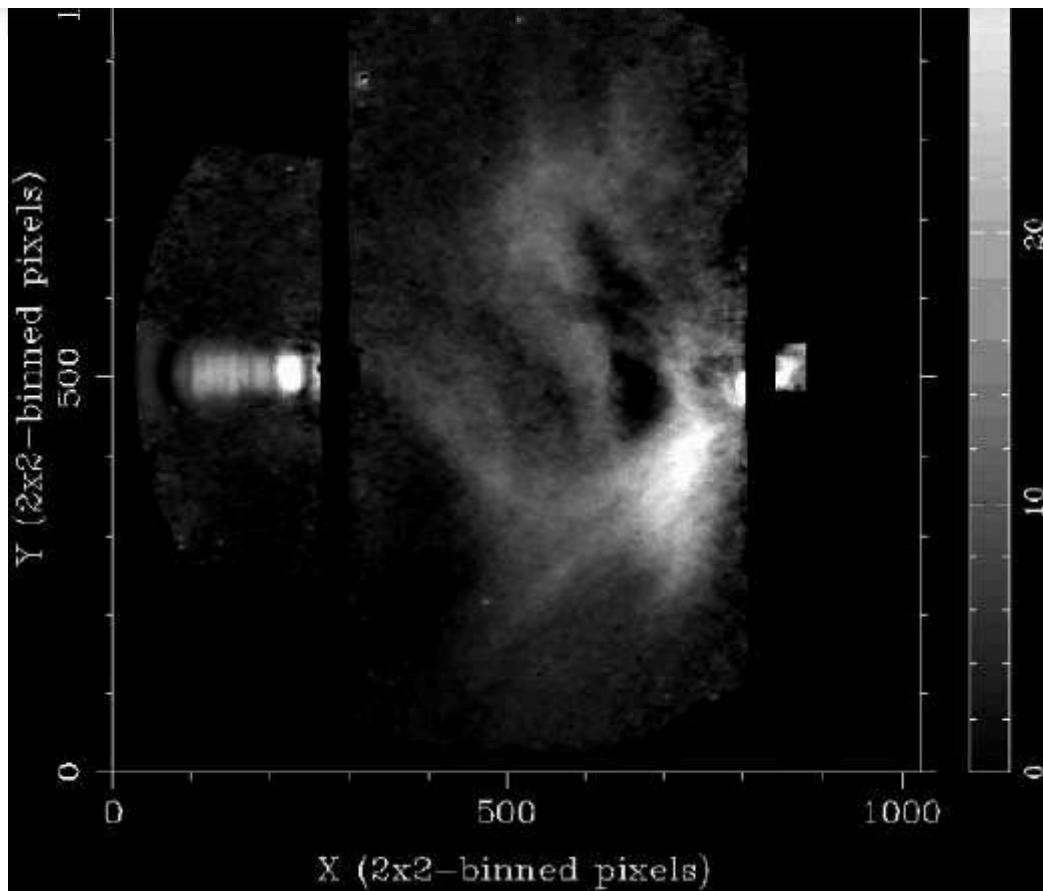
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~~THE COVERAGE OF SMEI, THEIR LOCATION OUTSIDE THE EARTH'S MAGNETOSPHERE REMOVES MOST~~

sources that decreased the quality of SMEI images, such as energetic particle saturation from the cusp and South-Atlantic anomaly, glare from the moon, and the aurora. A number of large-scale solar wind transients have been tracked through the SECCHI field of view, including CMEs (e.g., Harrison *et al.*, 2008; Davis *et al.*, 2009; Möstl *et al.*, 2010), corotating interaction regions (e.g., Sheeley Jr *et al.*, 2008; Rouillard *et al.*, 2008; Tappin and Howard, 2009), and solar wind “puffs” (e.g., Rouillard *et al.*, 2010) and “blobs” (e.g., Sheeley Jr *et al.*, 2009; Sheeley Jr and Rouillard, 2010).

The most recent scientific developments using SECCHI data involve a processing pipeline that reduces many sources of noise (starfield, F corona) from the dataset. This has permitted the tracking and measurement of features that were previously inaccessible. Analyses of these pipeline data are still in the preliminary stages, but early results include observations and measurements of CME flux ropes (Howard and DeForest, 2012a) and disconnection events (DeForest *et al.*, 2012). [Figure 35](#) shows an image from a HI-2 movie from DeForest *et al.* (2011), the movie is also included in this paper.

Figure 35

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mpg-Movie (70268.6445312 KB) Still from a movie showing STEREO/HI2-A images following the latest data processing pipeline for SECCHI (DeForest *et al.*, 2011). (For video see appendix)

The important difference between heliospheric imagers and coronagraphs is that 3-D information is available in heliospheric imagers that is not available in coronagraphs. This is because the assumptions imposed on coronagraphs (Thomson scattering assumptions, low angles) are not adequate at large elongations and across large distances. This increases the difficulty of the analysis, but makes available additional information on the structure and kinematics of the CME. This thereby removes the need for auxiliary data to provide this information. The theory describing this ability is developed by Howard and Tappin (2009). More recently, papers are beginning to emerge that consider the 3-D structure of the CME, including Wood and Howard (2009), Lugaz *et al.* (2009, 2010), and Howard and Tappin (2009, 2010). Techniques involving the extraction of 3-D properties from heliospheric image data are reviewed by Howard (2011a).

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0.1 Summary

We have discussed the origins and characteristics of coronal mass ejections and their associated phenomena. These have been discussed as occurring near the Sun in terms of their basic coronal properties and what we know about their source regions, and their manifestation in the heliosphere and near Earth. Kinematically there appears to be a continuum of accelerations and speeds of CMEs ranging from gradually accelerating CMEs that have smooth and balloon-shaped profiles, to rapidly accelerating CMEs that are less homogeneous and move through the outer corona at relatively constant speed. The rate of occurrence of CMEs correlates with solar activity, but the size scales of CMEs are much larger and their latitude distributions different than those of near-surface activity like flares or active regions. CMEs arise in large-scale closed coronal structures, the most evident being helmet streamers, which blow out and reform. Statistically, CMEs are most frequently associated with erupting filaments and X-ray long duration events, and not optical flares. However, new X-ray and EUV data are helping reshape our ideas on these associations. Large-scale coronal arcades are frequently observed, and may result from reconnection of closed field systems opened by CMEs, and indeed long current sheets are now observed connecting the arcade and the rising CME. The size scales and field strengths of these associated systems are a function of latitude. Thus, CMEs involve the destabilization of large-scale coronal structures which result in reconfiguration of the larger-scale, weaker fields at higher latitudes and of the smaller-scale, stronger fields at low latitudes. The magnetic structures involved with the source regions of CMEs can be complex and multipolar. The earliest X-ray signatures of the onset of a CME in the low corona appear to include outward-moving loops and the dimming or depletion of coronal material before and above the bright arcade. Against the disk the arcades are preceded by S-shaped structures associated with and aligned along the axis of filaments, which erupt forming cusp-shaped arcades. EUV waves are now frequently observed in association with CMEs.

CMEs carry into the heliosphere large quantities of coronal magnetic fields and plasma which are detected by remote sensing and in-situ spacecraft observations. Measured at a single spacecraft, this material has distinctive plasma and magnetic field signatures with a large amount of variation. One of the most important signature classes is of magnetic clouds

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carry strong, directional fields that can be very geoeffective. As carriers of such magnetic structures, CMEs may provide an important way for the Sun to shed the magnetic flux and helicity that is built up over the solar magnetic cycle.

In terms of space weather, CMEs are now identified as a crucial link between activity at the Sun and its propagation through the heliosphere to the Earth and other locations. The interplanetary manifestations of CMEs can result in extensive transient disturbances that, when directed Earthward, can cause major geomagnetic storms at Earth. In addition, significant particle and radiation hazards at Earth can arise from CMEs launched from western solar longitudes and, thus, are not necessarily Earth-directed (see [Figure 24](#)). The association of erupting filaments and magnetic clouds with CMEs has led to the view that flux ropes form the cavity of a CME and help drive it outward. Halo CMEs are important in terms of forecasting space weather and enhancing our understanding of CMEs and flux ropes. It appears that shocks and magnetic clouds are also likely to be detected at Earth following such solar events. Moderate storms not associated with CMEs are usually caused by Earth passage through the heliospheric current sheet (HCS) and related corotating interaction regions (CIRs). More details about space weather appear in two respective Living Reviews ([Schwenn, 2006](#); [Pulkkinen, 2007](#)).

6.2 Unsolved problems

Several enigmatic or outstanding problems remain regarding the origin, propagation, and heliospheric consequences of CMEs. We conclude this review by discussing several of these that we feel are the most important needing to be resolved.

The CME initiation follows storage of energy in closed magnetic field regions on the Sun over a certain period of time but we do not know what triggers the release of that energy. The stored energy that is released during eruption is the free energy available to be released in the form of CMEs, flares, and other eruptive phenomena. The magnetic source of the CME has to build up the free energy. Identification of the signatures of this energy build-up is a crucial step in deciding whether and when a CME will occur. During the build-up phase, minor energetic events occur, but it is difficult to know whether a pre-eruption energy

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know, however, that flares occur without observed CMEs, just as many CMEs are not always accompanied by flares. Flares accompanying CMEs are generally of lower temperature compared to flares not accompanied by CMEs. This may indicate that the many smaller flares without CMEs may contribute to coronal heating (Yashiro *et al.*, 2006), while CMEs carry away the mass and magnetic field into the heliosphere. Based on the highest mass (10^{14} kg) and speed (~ 3500 km s $^{-1}$) observed one can estimate a maximum kinetic energy of $\sim 6 \times 10^{34}$ erg. Assuming that only a fraction of the stored energy is released in a single episode and that the CME derives all of its energy from a single active region, we can set a limit of $\sim 10^{36}$ erg for the maximum free energy available in a solar active region. This is consistent with the size and magnetic field strengths in solar active regions (Kahler, 2006).

CMEs are subject to propelling and retarding forces in the corona and interplanetary medium (see, e.g., Vršnak *et al.*, 2004). The propelling force is not properly identified yet. Solar gravity and the drag force due to momentum exchange between CMEs and the ambient medium constitute the main retarding forces. The net result is that most CMEs tend to acquire the speed of the ambient solar wind at large distances from the Sun. This can be quantified as an effective interplanetary acceleration (Gopalswamy *et al.*, 2000, 2001). However, CMEs come in all sizes and shapes and the ambient solar wind also is highly variable. The propagation of CMEs is also affected by the presence of preceding CMEs (Lyons and Simnett, 2001), especially during solar maximum years when CMEs occur in quick succession (Gopalswamy, 2004). CMEs may also be deflected by other CMEs and by nearby coronal holes (Gopalswamy *et al.*, 2009a) and the CME itself may contain some intrinsic driving property (Howard *et al.*, 2007). We need a proper quantification of these effects to accurately predict the arrival of a CME at a desired location in the heliosphere, once its launch has been observed and the initial speed measured. Another issue is the true speed with which CMEs propagate toward a location in the heliosphere. Coronagraphs measure speeds in the sky plane, but the travel time prediction needs space speed. For example if we consider CMEs heading towards Earth, we need to de-project the sky-plane speed and re-project it along the Sun-Earth line. There have been several attempts to convert the sky plane speed into Earth-directed speed using cone models with reasonable success, but more work is needed (Xie *et al.*, 2006; Michalek *et al.*, 2006; Howard *et al.*, 2008b).

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that particle acceleration is a complex issue with multiple sources (shocks and flares), and multiple factors deciding the acceleration efficiency (Kahler, [2001](#); Gopalswamy, [2004](#); Kahler and Vourlidas, [2005](#)). We do not know what the flare and shock contributions are for a given SEP event. We also do not know how the ambient medium consisting of previously ejected CMEs, shocks, and SEPs determines the properties of a subsequent event.

We need to more fully understand how the remotely-sensed CMEs evolve into CMEs observed in-situ in the solar wind. Magnetic clouds observed within CMEs in the solar wind have specific magnetic properties, notably their flux rope structure. But flux rope structures near the Sun can only be inferred, although the three-point views from the STEREOs and LASCO and the continuous field of view of SECCHI from the corona into the inner heliosphere have improved our understanding. Prominences are themselves thought to be flux ropes near the Sun, but observations in the interplanetary medium are not compatible with that. Magnetic clouds are observed with high charge states implying high temperature (several million K) at the source, whereas prominences are cooler structures with a temperature of only ~ 8000 K. Such cool prominence material is rarely observed in-situ, another unsolved problem. Coronal cavities observed in eclipse pictures and inner coronal images in X-rays and EUV are thought to contain flux ropes, but an alternative explanation is that these are highly sheared magnetic structures. Recent quantitative comparison between reconnected flux at the eruption site and the azimuthal flux in flux ropes in the solar wind suggest that the two fluxes are approximately the same (Qiu *et al.*, [2007](#)), implying that the flux ropes are formed during the eruption process rather than present in the pre-eruption state. White-light CME observations mainly provide information on the mass content of the CME, but very little on the magnetic structure. Many related observations (magnetic and other) need to be pooled to try to obtain the magnetic structure of CMEs. Another related issue is whether all CMEs contain flux ropes, and the related question of whether all interplanetary CMEs are magnetic clouds? If they are, that implies a definite magnetic structure, from which one can infer the onset time of geomagnetic storms for space weather purposes. The magnetic cloud structure indicates a definite leading and trailing field orientation, which decides the day-side reconnection with Earth's magnetic field that ultimately results in the magnetic storm. While flux ropes in the interplanetary medium have a well defined

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Properties of solar active regions at the photospheric or chromospheric levels, but the eruption itself starts in the corona.

High temporal and spatial resolution images are needed to identify and study pre-eruption signatures, which is crucial to predicting the onsets of CMEs. We still lack a quantitative understanding of how the magnetic complexity in a source region relates to CME productivity. Since vector magnetograms provide key information on the free energy available in active regions, they need to be developed and the results assimilated into various models, including MHD. Finally, the developing science of helioseismic subsurface imaging of sunspots and active regions suggests important clues to the build-up of energy in active regions that can lead to large flares and CMEs (e.g., Webb *et al.*, [2011](#)).

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inner ring structure, in this case an erupting prominence. From SOHO online movie gallery: <http://sohowww.nascom.nasa.gov/gallery/Movies/flares.html>.

41116_2016_3_MOESM2_ESM.avi

mpg-Movie (10681.5 KB) Still from a movie showing Orbit difference images of an Earthward halo from SMEI. Halo was visible as an arc over $\geq 150^\circ$ of sky (arrows). Blacked-out areas are due to shuddering of bright sunlight and CCD noise from particles in Coriolis' 840 km circular Earth orbit.

41116_2016_3_MOESM3_ESM.mpeg

mpg-Movie (28363.8935547 KB) Still from a movie showing Combined views from all of the STEREO SECCHI telescopes during a series of CMEs in early April 2010. The bottom panels show the ST-B and ST-A views of the EUVI disk, COR1 and COR2 imagers out to $15R_\odot$, and the upper set shows the HI-1 and -2 fields viewing east (left, HI-A) and west (right, HI-B) of the Sun beyond the EUVI, COR1, COR2 set shown to scale. From the online data at: <http://secchi.nrl.navy.mil/index.php?p=movies>.

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mpg-Movie (70268.6445312 KB) Still from a movie showing STEREO/HI2-A images following the latest data processing pipeline for SECCHI (DeForest *et al.*, [2011](#)).

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