Observing CMEs without coronagraphs

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Abstract. A coronal mass ejection (CME), strictly speaking, is a phenomenon observed via a white-light coronal imager. In addition to coronagraphs, a wide variety of other instruments provide independent observations of CMEs, in regimes ranging from the chromosphere to interplanetary space. In this paper we list the most important of these non-coronagraphic signatures, many of which had been known even before CMEs were first identified in coronagraph observations about 30 years ago. We summarize the new aspects of CMEs discovered in the past several years, primarily with instruments on the *Yohkoh* and SOHO satellites. We emphasize the need for detailed statistically-based comparisons between SOHO CMEs and their non-coronagraphic manifestations. We discuss how the various aspects of CMEs fit into the current standard model (sigmoids – flux rope – double dimming – arcade). While a class of CMEs follows this pattern, it does not appear to work for all events. In particular some CMEs involve extended dimming regions and erupting trans-equatorial X-ray loops, indicating a more complex geometry than a simple bipolar magnetic configuration.

1. Introduction

Coronal mass ejections (CMEs) are eruptions of magnetized plasma from the Sun, as observed by a coronagraph capable of blocking the direct photospheric light. They can be fast, huge and spectacular; see *Hundhausen* [1997, 1999] for reviews based on early (pre-SOHO) space observations. The numbers of CMEs vary with other indicators of solar activity, with several per day occurring during solar maximum [*Webb and Howard*, 1994]. While there had been many observations of solar ejecta prior to the identification of CMEs about 30 years ago by early spaceborne coronagraphs, the frequency and great spatial scale of CMEs were not anticipated. Their discovery has had a profound effect on solar and solar-terrestrial physics (see the papers in *Crooker et al.* [1997]).

CMEs are best viewed with coronagraphs in space above the scattered light from the Earth's atmosphere. Coronagraphs occult the intense light of the solar disk and inner corona and observe CMEs via sunlight Thompson-scattered from free electrons; the observed signal is roughly proportional to the integrated mass along the line of sight. Nevertheless in spite of this (and the name CME) the essential physics of the phenomenon probably resides in the magnetic field or its associated current systems, which (except in interplanetary space) we cannot observe so directly as we can observe the mass itself.

In addition to direct observations of CMEs with coronagraphs, a wide variety of other instruments provide direct and indirect evidence of solar eruptions. These associated observations round out our picture of CMEs and are critical to a complete understanding of the phenomenon. In this paper we review the various non-coronagraphic manifestations of CMEs, as observed from the chromosphere through interplanetary space.

A CME launch typically also involves a perturbation of the low corona, usually in the form of a flare or a flare-like disturbance, and the flare effects (radiative and dynamical) may be closely related to the early evolution of the CME. Coronagraphs and X-ray/EUV imagers generally cannot observe the same material at the same time, however, because the coronagraph observations only show that part of the disturbance lying above the occulter edge. In addition many CMEs arise from behind the limb, and for these we currently have no means of observing the low corona. Nevertheless the new X-ray and EUV observations have greatly eased the tasks of identifying CME counterparts near the solar surface, and of following the early development of the eruptions.

Interplanetary observations show clearly identifiable effects of CMEs, but by *in situ* techniques quite remote (both in space and in style) from the direct CME observations with coronagraphs. Thus we have three major observational domains associated with CMEs – the chromosphere and low corona as shown by on-disk observations and by coronal emission-line observations above the limb; the middle corona above the limb as shown by coronagraphs; and interplanetary observations. To these we can add observations of solar and interplanetary radio emissions, which mainly show energetic particles associated with the eruptions; the Helios coronal photometry, which provided remote-sensing observations in deep space [*Jackson and Leinert*, 1985]; and interplanetary scintillations of background radio sources.

Section 2 summarizes the enormous range of these non-coronagraphic observations of CMEs or of phenomena closely related to CMEs. Section 3 briefly reviews the working picture of CMEs and eruptive flares that was in place prior to *Yohkoh* and SOHO – the well-known "CSHKP" model. An extensive review of CME knowledge prior to these missions appears in the proceedings of the 1997 Chapman Conference on CMEs [*Crooker et al.*, 1997] that covers the basic coronagraphic material from OSO-7, Helios, *Skylab*, the Solar Maximum Mission, P78-1, and ground-based observations. In Section 4 we summarize the key new observations relating to CMEs, mainly from *Yohkoh* and SOHO, and in Section 5 we outline the current standard model: sigmoid – flux rope –

double-dimming – arcade. This is essentially the "CSHKP" model with account taken of new observations and of theoretical developments relating to flux ropes. In Section 6 we discuss how well the standard model can account for the various non-coronagraphic signatures of CMEs, and comment on various specific issues. The conclusion (Section 7) contains a list of practical questions that should be answerable with the data in hand.

2. Non-coronagraphic observations

The range of observing modes now available for CME studies is quite remarkable. We have taken what we think to be the most important non-coronagraphic signatures of CMEs and listed them in Table 1. Detailed comparisons of direct CME observations with the various listed phenomena represent "calibrations" of the latter. By this we mean surveys with quantitative comparisons between any of the non-coronagraphic data sets and the new LASCO coronagraph observations. Many of the non-coronagraphic observations have already been thoroughly investigated with older data sets and are in this sense already "calibrated." For example, *Munro et al.* [1979] and *Webb and Hundhausen* [1987] studied in detail the chromospheric and low-coronal counterparts of CMEs observed by *Skylab* and SMM. Even for these better-studied phenomena, however, a revisitation using the new CME observations and the knowledge gained in the intervening years can be illuminating (*e.g. Delannée et al.* [2000]). Please note that the calibrations should work in both directions; for example, we would like to know what fraction of CMEs involved two-ribbon flares, but we would also like to know what fraction of two-ribbon flares led to CMEs (in order to investigate the difference between those that did and those that didn't).

Table 1 Table 1

Table 1 could be extended, but we believe that we have listed the main phenomena that tell us about CME physics. The Table includes references to early work in each area plus more recent literature giving calibrations of the non-coronagraphic data against LASCO CME observations. The Table also lists the numbers of CME events in these chosen surveys. Most of the calibration entries are "None," meaning that a proper survey (one that covers a LASCO CME sample larger than one event) has yet to appear in the literature. The work of *Nitta and Akiyama* [1999] provides a good example of what we feel is needed – straightforward overviews of reasonable samples of events observable in common by coronagraphs and by non-coronagraphic instruments. We urge workers to carry out basic LASCO calibrations along these lines. Cross-signature calibrations (statistical comparisons between non-coronagraphic phenomena in Table 1) are equally important: Examples of these include *Weiss et al.* [1996], comparing interplanetary events with soft X-ray images, and *Klassen et al.* [2000], comparing EIT waves and metric Type II bursts. Table 1 includes only two of the many possible manifestations of CMEs in the interplanetary medium; *Zwickl et al.* [1983] noted that a CME might have almost any subset of these or other signatures. The "magnetic cloud" and "bidirectional streaming" phenomena that appear in the Table are particularly important because of their relevance to the magnetic-field structure and connectivity (to the Sun).

There are other items that could arguably be included in Table 1. For example *Leblanc et al.* [1983, 1985] linked series of "outwardly propagating" metric U-bursts to CMEs. The flare nimbus [*Ellison*, 1960] represents a more shadowy kind of evidence for a CME and more work will be needed to establish its reality [see *Neidig et al.* 1997]. The "giant arches" discovered by *Švestka et al.* [1982] with SMM observations, and more recently by *Švestka et al.* [1995] in *Yohkoh* data, provide possible evidence, not yet well-understood nor properly calibrated against coronagraph observations, of large-scale coronal restructurings associated with CMEs. From a space-weather point of view, one could consider Forbush decreases (decreases of galactic cosmic-ray intensity), sudden-commencement geomagnetic storms, and large solar energetic-particle events as diagnostics of CMEs (*e.g.* *Kahler* [1992]).

It is important to note that not every CME is accompaniend by all of the non-coronagraphic signatures in Table 1 – far from it. In general, the listed phenomena correspond to the most energetic CMEs, and some CMEs (e.g. the one discussed by *Webb et al.* [1998]) exhibit scarcely any of the tabulated items.

3. The pre-*Yohkoh*, pre-SOHO situation

The favored early paradigm for a two-ribbon solar flare – the eruption of a bipolar field, followed by large-scale reconnection in the resulting coronal current sheet – incorporated many of the non-coronagraphic manifestations of CMEs. The key study of *Bruzek* [1964] introduced the pre-modern synthesis, which linked Hα observations of such flares on the disk with post-flare loop systems best seen at the solar limb. The successful CME observations by a spaceborne coronagraph on OSO-7 [*Brueckner*, 1974] and the extensive observations by *Skylab* and P78-1 from the 1970s and 1980s led to the recognition that long-duration flare emissions in microwaves and soft X-rays were reliable proxies for CME occurrence [*Sheeley et al.*, 1975; *Kahler et al.*, 1977; *Sheeley et al.*, 1983], and that such flares form a physically distinct class of events [*Pallavicini et al.*, 1977]. The long-duration X-ray and microwave thermal emissions have an easy interpretation in terms of the prolonged reconnection envisioned by the "Kopp and Pneuman model" [*Carmichael*, 1963; *Sturrock*, 1966; *Hirayama*, 1974; *Kopp and Pneuman*, 1976; see also *Heyvaerts et al.* 1977]. This prolonged reconnection corresponds to extended energy release [*MacCombie and Rust*, 1979; *Moore et al.*, 1980]. The gradual coronal emission components result from the ablation ("evaporation") of chromospheric material, and the longer time scales of the corona results in a time profile that integrates and smooths out the variations of the impulsive energy release. In this picture we ascribe extended or gradual emissions at higher energies to some form of particle acceleration closely related to the reconnection process. Such emissions include Type I noise storms [*Lantos et al.*, 1981], stationary type IV emission [*Kahler et al.*, 1982; *Cliver*, 1983], delayed microwave peaks [*Cliver*, 1983], and gradual hard X-ray bursts [*Cliver et al.*, 1986].

Various non-CME manifestations of outwardly moving material also suggest the ejection of mass from the corona. These include Hα "flare sprays" [*Warwick*, 1957], which have speeds greater than the escape velocity, prominence eruptions [*Smith and Ramsey*, 1964; *Munro et al.*, 1979; *Webb et al.*, 1976], and moving Type IV bursts [*Boischot*, 1958]. Note that some ejections [flare-associated surges, *McMath and Pettit*, 1937; see also *Smith and Smith* 1963] may return to the solar surface. We survey the evolution of the early models in the series of cartoons in Figure 1 which begins with Carmichael's prescient schematic from 1963. Collectively this paradigm has been referred to as the CSHKP model [*Švestka and Cliver*, 1991], recognizing the contributions of the various authors.

Figure 1

Figure 1

4. Survey of new observational results

4.1. White light

The observations by the LASCO coronagraphs on board SOHO certainly have revolutionized our knowledge of directly-observed CMEs, with our choices for the main novelties listed below:

1. Early observations of CMEs showing concave-outward features [*Illing and Hundhausen*, 1983; *Cliver*, 1989; *Webb and Cliver*, 1995] have been confirmed by *St. Cyr et al.* [2000], who now find that 30-50% of LASCO events may have this structure. However the favored interpretation has now changed from "disconnection" to a 3-dimensional flux-rope structure [*Dere et al.*, 1999].

2. CMEs may show very large size scales, frequently involving both E and W limbs, e.g. the "global coronal disturbances" of *Brueckner* [1997].

3. *Wang et al.* [1999] point out the occurrence of infalling material, in the form of small cusps, in the trains of CMEs at great radial distances. They interpret these features as the results of magnetic reconnection in the middle corona (i.e., distinguishable from the site of the arcade).

4. "Halo CMEs" [*Howard et al.*, 1982], interpreted as events formed near disk center (either the front or back hemisphere of the Sun), prove to be numerous, as many as 10% of all events [*St. Cyr et al.*, 2000], a result attributed to improved observational sensitivity.

5. Based upon height-time plots, using both limb and "halo" views, *Sheeley et al.* [1999] distinguished two classes of CMEs, based upon their acceleration profiles, identifiable with origins in active-region flares and in quiet-Sun arcades, respectively (*cf. MacQueen and Fisher* [1983]).

In the sections below we discuss non-coronagraphic signatures. As noted above, these signatures do not apply to all CMEs. Even for the most energetic events, any given signature may not be detectable, so they are not reliable proxies – only a coronagraph observation can definitively detect a CME. At the same time, these non-coronagraphic observations may be critical to deciphering the basic physics of CMEs.

4.2. Non-coronagraphic observations

4.2.1. X-rays and EUV. Beginning with *Skylab*, and now with *Yohkoh* [*Acton et al.*, 1992], SOHO, and TRACE, we have effective means for observing the corona *against the disk of the Sun*. These observations include not only the natural plasma emissions of the hot corona, but also HeII 304 Å, which shows cold inclusions (prominences). The association of CMEs with "transient coronal holes" [*Rust*, 1983], and especially with arcade systems of soft X-ray loops [*Kahler*, 1977], had been known since *Skylab*. But the new observations brought higher photometric precision, better dynamic range, and more frequent sampling, and have confirmed in detail the gradual-phase energy release that provides one of the best pieces of evidence for large-scale reconnection [*Schmieder et al.*, 1994; *Balch*, 1999]. Accordingly we can follow eruptive events in much greater detail than before. For example, the huge arcades discovered by *Yohkoh* [*Tsuneta et al.*, 1992b; *McAllister et al.*, 1996] differ quantitatively, if not qualitatively, from the similar events seen by *Skylab*. We list the principal results from *Yohkoh* soft X-ray and SOHO EUV observations in Table 2, in the order in which they were reported, before discussing them below.

Table 2 Table 2

The most eye-catching new phenomenon found to be associated with CMEs during the past decade would have to be the coronal EIT waves discovered by SOHO [*Thompson et al.*, 1998]. These events originate in volumes comparable to that of the associated flare or active region. This suggests a flare origin, but the EIT waves also appear to be highly associated with CMEs [*Thompson et al.*, 1999]. Moreover, *Dere et al.* [1997] reported a CME that originated in a compact ($<10^5$ km) source. These results argue against the view that the large angular extents of CMEs preclude their origins in small-scale magnetic structures. Clearly there is a need for a detailed calibration study between EIT waves and CMEs.

The soft X-ray observations frequently show material ejections [*Klimchuk et al.*, 1993], typically in association with flares [*Hudson et al.*, 1996a; *Manoharan et al.*, 1996; *Ohyama and Shibata*, 1998]. *Nitta and Akiyama* [1999] have shown that these flare ejecta are associated with CMEs. The X-ray observations also sometimes show faint large-scale global brightenings [*Hudson et al.*, 1996a, *Manoharan et al.*, 1996]; see *Gopalswamy et al.* [1999c], who attribute them to the skirt of the CME itself.

The *Yohkoh*/SOHO observations of "X-ray dimmings," both above the limb and on the disk [*Hudson et al.*, 1995; *Hudson and Webb*, 1997], have probably led to the greatest new insight into the origins of CMEs in the low corona. The dimmings have the same interpretation as the "depletions" seen in the white-light corona by *Hansen et al.* [1974] or the "transient coronal holes" detected by *Skylab* [*Rust*, 1983]. Dimmings may have various morphologies and can occur above the limb as well as on the disk; they also appear clearly in EUV observations [*Thompson et al.*, 1998; *Harrison and Lyons*, 2000]. The X-ray dimmings usually consist of amorphous darkenings with no obvious magnetic restructuring, but sometimes also result from directly-observed outflows. The amorphous dimmings nevertheless probably also represent unresolved mass motions, since cooling in place to explain the dimming would have too long a time scale [*Hudson et al.*, 1996a].

A bipolar "double dimming" often appears during a flare in an active region that contains an S-shaped or *sigmoid* structure visible in soft X-rays [*Rust and Kumar*, 1996; Sterling and Hudson, 1997]; this pattern suggests the footprints of a large-scale loop ejection (a flux rope; see the cartoons in Figure 1 and the example in Figure 2). Such a flux-rope ejection might lead to an interplanetary "magnetic cloud" morphology, as discussed below in the context of *in-situ* observations. These observations have added a significant feature to the standard model, namely the *magnetic helicity* $H = \int_V \mathbf{A} \cdot \mathbf{B} dV$, where $\mathbf{A}$ is the magnetic vector potential. For a tutorial, see *Canfield et al.* [2000]. The magnetic helicity is a global property of the field that helps to guide theoretical considerations [*Low*, 1995]; according to Taylor's hypothesis, the magnetic helicity H remains invariant within a flux tube. The *Yohkoh* soft X-ray imaging data reveal a relationship between the coronal X-ray sigmoids and eruptivity [*Canfield et al.*, 1999]. Note that the inclusion of the flux rope in the standard model was anticipated by *Hirayama* [1974] from the frequent involvement of filaments in two-ribbon flares.

Figure 2 Figure 2

Often the counterpart of a CME in the low corona does not seem to fit the sigmoid flux-rope pattern. The CME does not rise symmetrically from an active region, and the associated flare tends to occur at one side of an extended dimming region and the CME in such cases [*Harrison*, 1990; *Kahler*, 1991; *Harrison*, 1995; *Khan and Hudson*, 2000; *Thompson et al.*, 2000b]. *Khan and Hudson* [2000] recently presented evidence that a flare can destabilize an adjacent transequatorial loop structure, thus launching a CME. We illustrate their new finding in Figure 3.

Figure 3

Figure 3

It is important to note that X-ray dimming does not always appear prominently, even in events definitely associated with a CME (*e.g.* *Kahler et al.* [1998]). Nor are strong interplanetary events always accompanied by intense soft X-ray events in GOES photometry. This was shown by *Webb et al.* [1998] for the well-studied CME on January 6, 1997, and by *McAllister et al.* [1996] for the source of the "problem storm" of April, 1994. A "problem storm" is a geomagnetic storm with no associated Hα flare, and the *Yohkoh* soft X-ray images associated with this one show a weak but physically large X-ray arcade event. These events demonstrate that a major coronal disturbance can happen without a soft X-ray burst at high temperatures as defined by the GOES passbands – but nevertheless involving elevated temperatures [*Alexander et al.*, 1996] and generally flare-like properties [*Tsuneta et al.*, 1992b; *McAllister et al.*, 1996]; *cf.* *Harvey et al.* [1986].

4.2.2. Radioheliography. Radio observations in general show non-thermal effects of particles (fast electrons) accelerated in and around solar flares and CMEs. These data thus help in understanding the connectivity of the magnetic field and its dynamics (see the recent review by *Bastian, Benz, and Gary* [1998]). The particle motions may also illuminate coronal magnetic structures and determine their densities precisely via coupling (through plasma oscillations) to radiation at the local plasma frequency and its harmonics, uniquely determined by the ambient density. The non-thermal emission of particles trapped within CME structures may also reveal the CME motions (*e.g.* *Gopalswamy and Kundu* [1990]).

We can detect CMEs via the dimming of thermal (free-free) radiation at longer radio wavelengths [*Gopalswamy and Kundu*, 1992], and somewhat surprisingly, a microwave dimming has now also been detected [*Gopalswamy et al.*, 2000b]. After the CME eruption, the LDE soft X-ray burst implies the existence [*Hudson and Ohki*, 1972] of a corresponding long-duration microwave burst [*Sheeley et al.*, 1975], of the type classified as a "post-burst increase" or a "gradual rise and fall" [*Kundu*, 1964]. This kind of observation contains essentially the same information as the observation of an X-ray arcade, since both come from thermal emission processes.

At microwave frequencies, the Nobeyama radioheliograph data frequently show filaments and their eruptions [*Hanaoka et al.*, 1994], and even entire CME structures [*Gopalswamy*, 1999; *Gopalswamy et al.*, 1999a]. This offers new capability in terms of time resolution and visibility; *Hanaoka and Shinkawa*, [1999] directly observed the apparent heating of a rising filament, a phenomenon long inferred indirectly. The heating changes the ionization and excitation of the typical chromospheric lines used to detect filaments (Hα, HeI 10830Å, Ca K, HeII 304Å). The microwave observations thus give an independent window on the physical conditions in the filament, and one that is much less model-dependent because of the weak temperature dependence of the free-free opacity at long wavelengths.

4.2.3. Particles and fields. The interplanetary observations seem almost perfectly complementary to the astronomical (imaging) observations – they show us particle distribution functions and actual field properties *in situ* at single points, whereas the remote-sensing observations with telescopes are relatively blind to these specific properties of the plasmas. On the other hand the telescopic data show us the global structures near the Sun and how they evolve in time. The many signatures of a CME in the heliosphere include Burlaga's "magnetic cloud" pattern and Gosling's bidirectional streaming of electrons in the tail of the solar-wind velocity distribution (*cf. Richardson et al.* [2000], who discuss bidirectionality at higher energies). Figure 4 shows the bidirectional-streaming pattern in two events observed at high latitudes by *Ulysses*

[*Gosling et al.*, 1994], as well as clearly-defined forward and reverse shocks driven by the expanding ejection.

Figure 4 Figure 4

The interplanetary electron observations establish the existence of CME-related structures that remain rooted, either partially or completely [*Larson et al.*, 1997], at the solar surface. This would seem a perfect match to the bipolar coronal-hole pattern noted by *Sterling and Hudson* [1997] and *Hudson et al.* [1998] to associate with a halo CME [*St. Cyr et al.*, 2000]. Moreover, the (rare) presence of low ionization states of Fe in the solar-wind plasma strongly suggests that at least in some cases, traces of the erupted filament accompany the CME into the heliosphere [*Burlaga et al.* 1998], and may even fill a major part of the volume of a flare-associated magnetic cloud [*Skoug et al.*, 1999]. This links the "magnetic cloud" morphology to another element of the classical three-part CME as seen in a coronagraph, and leaves little doubt regarding the close association of these interplanetary signatures with at least some CMEs.

One of the most interesting peculiarities of the interplanetary observations is the similarity of signatures from event to event for the *Ulysses* high-latitude events. *Hudson et al.* [1995] note that the two events of Figure 4 were associated (a) with an impulsive solar flare (February 20, 1994) at low heliographic latitude, and (b) with a polar-crown arcade excitation (April 15, 1994) at high latitude in the opposite hemisphere, respectively. Nevertheless these had almost identical interplanetary signatures [*Gosling et al.*, 1994].

4.2.4. Other. Observations of interplanetary scintillation confirm the existence of continued flows following a CME, as can be seen in the LASCO movies, and establish that solar active regions (as well as normal coronal holes) can act as sources of solar-wind flow [*Hick et al.*, 1999; *Švestka et al.*, 1998]. This finding legitimizes the term "transient coronal hole" in the sense that the dimming it represents must in fact correspond to the opening of substantial areas of field lines in the vicinity of an active region undergoing an eruption.

5. Cartoons

5.1. Why we need them

CMEs involve phenomena that occur in domains covering a wide range of physical conditions. It had been well understood, even prior to the current epoch, that CMEs involve larger spatial scales and longer time scales than their chromospheric/low-coronal counterparts. The LDE flares ("gradual rise and fall" or "post-burst increase" at radio wavelengths [*Sheeley et al.*, 1975; *Kahler*, 1977; *Pallavicini et al.*, 1977]) and filament eruptions outside active regions [*Webb et al.*, 1976] had known associations with CMEs, but involved more limited spatial scales. The CMEs themselves have large angular extent (on the order of 45 degrees) and a distribution function of mass, size, or inferred energy with a well-defined average (an exponential distribution) [*Jackson and Howard*, 1993] – unlike flares, for which the distribution of energy follows a power law with no known scale [*Hudson*, 1991; but see also *Kucera et al.*, 1997]. Other known signatures of CMEs included the Type IV/I "storm continuum" at meter wavelengths [*Cliver*, 1983], and long-duration hard X-ray events which implied gradual non-thermal energy release [*Cliver et al.*, 1986; *Kiplinger*, 1995; *Hudson and McKenzie*, 2000].

To relate the small scales and large scales in a solar event, and to link different observing regimes to one another, we need a conceptual model that allows us to visualize the all-important magnetic geometry. The main value of such a model seems to lie in its ability to leap schematically across the boundaries between different pieces of a theory, in the absence of a self-consistent framework. One such boundary would be the relationship between particle acceleration and MHD evolution – in the MHD approximation, there are no particles, and so there can be no self-consistent theory embracing both domains if the particles represent a major component of the energy release (see *Lin and Hudson* [1976] and *Ramaty et al.* [1995]).

5.2. The standard model

We reproduce some well-known cartoon models in Figure 1, all showing variations of the standard model. Note that these cartoons are often two-dimensional representations. The "double dimming" events observed by *Yohkoh* and SOHO [*Sterling and Hudson*, 1997; *Hudson and Webb*, 1997; *Thompson et al.*, 1998] played a critical role in the widespread acceptance of the standard model, incorporating the third dimension in a fundamental manner. Theoretical work by *Chen and Garren* [1993] and by *Low* [1995], for example, anticipated this requirement [see also the discussion and references in *Low* 1997]. The standard model could currently be described as including the following steps:

- The CME originates from a sigmoidal structure, usually within an active region but sometimes outside, and usually compact relative to the CME angular scale that develops later on.
- A flux rope moves outward. The rope often incorporates an erupting filament, and bipolar "transient coronal hole" dimming regions appear within the arms of the sigmoid.
- The physical motion of the magnetic field (or gas heating) launches and drives global waves.
- An arcade, usually the gradual phase of a flare, develops following the eruption, apparently resulting from large-scale magnetic reconnection.

Figure 5 shows two cartoons from *Moore et al.* [1999] that schematically capture the new aspects of the standard model – sigmoid, flux rope, and double dimming – while retaining the geometry for reconnection essential to the model. While there is general agreement that the arcade excitation results from large-scale reconnection, the role of reconnection in creating the flux rope remains unclear: are the concave-outward features seen in CMEs true disconnections, or are they flux ropes that had existed prior to the eruption? For a discussion of both sides of this question, which remains unresolved at present, see *Rust* [1997] and *Martin and McAllister* [1997] in the proceedings of the Chapman Conference on Coronal Mass Ejections [*Crooker et al.*, 1997].

Figure 5

Figure 5

Certain aspects of the 2D version of this model (see Figure 1) have generally been accepted since the interpretation of two-ribbon flares in the 1960s [*Bruzek* 1964] (of course, at this early time little was known of CMEs, and the only forms of ejection easily identifiable were those seen in Hα and via meter waves). The modern data have abundantly confirmed and extended this scenario: *Yohkoh* sees streamer-like cusp structures [*Hiei* et al., 1993] that may have hot edges [*Tsuneta et al.*, 1992a]; *Yohkoh* hard X-ray observations suggest coronal particle acceleration above the soft X-ray loops [*Masuda et al.*, 1994; *Aschwanden et al.*, 1999]; SOHO spectroscopic data clearly show flow in the outer edges of flare ribbons, consistent with chromospheric ablation [*Czaykowska et al.*, 1999] in newly-reconnected flux tubes; and most conclusively the soft X-ray data now show downflows above the soft X-ray arcade [*McKenzie and Hudson*, 1999] in many events [*McKenzie*, 2000]. In view of this mass of evidence, it seems clear that an eruptive flare consists of an ejection of mass via an opening of magnetic fields that subsequently can close to form a cusped arcade structure. An eruption of this type appears to consist basically of the outward motion of a flux rope, whose footprints remain attached to the solar surface for some extended period of time. This might lead naturally to an interplanetary magnetic cloud, as is frequently observed in conjunction with a CME.

6. Discussion

6.1. Critique of the standard model

The description above – essentially the CSHKP model, also seen in the "core field explosion" model of *Moore and LaBonte* [1979], or the "grand unified theory" of [*Shibata*, 1998] – more or less successfully resembles the observations across all domains for some events, but we should point out some apparent difficulties. There is no comprehensive theory of the model, for example. Certainly parts of the standard model are understood theoretically; the sigmoid structure, for example, has a natural interpretation in terms of force-free equilibrium [*Low*, 1995; *Gibson and Low*, 1998; *Titov and Démoulin*, 1999; *Canfield et al.*, 2000]. However we do not have a successful theory for the eruption itself. A full theory, even one based on ideal MHD, is beyond an analytic treatment. The numerical techniques that have been used (see *e.g. Mikić and Linker* [1994], for a 2.5-D simulation) generally do not have adequate spatial resolution to match the observations. These simulations need to make restrictive assumptions, and their results often depend upon many free parameters. Many CMEs appear to erupt naturally from a bipolar magnetic environment, but this may not be possible theoretically; accordingly the complex field geometries suggested by *Giovanelli* [1949] and *Sweet* [1958] have always attracted interest [*Uchida and Jockers*, 1979; *Antiochos*, 1998; *Uchida et al.*, 1999].

The observations also have features that do not fit comfortably within the standard model. The field lines anchored in the double dimming regions do not seem to re-form into the arcade (see Figure 2 and *Zarro et al.* [1999]), as the standard model implies (*cf. van Driel-Gesztelyi et al.* [2000]). The dimming regions may remain dark for longer than the existence of the arcade. So, any reconnection following the eruption may be partial or slow; the standard model does not predict the rate of reconnection. An arcade may have a spiky pattern of cusps above it [*Švestka et al.*, 1998], and in fact such arcades often provide excellent evidence for flows consistent with large-scale reconnection [*McKenzie and Hudson*, 1999]. But we normally interpret a cusped X-ray structure as evidence for the slow shocks responsible for energy release in the reconnection picture [*Forbes and Malherbe*, 1986; *Tsuneta*, 1992a; *Tsuneta*, 1996; *Forbes and Acton*, 1996]; what would the geometry of these shocks and their flows look like in the case of multiple cusps?

Flare effects are often discussed as secondary processes following the CME, and the literature even uses circumlocutions such as "post-CME loop" and "eruptive event" rather than "flare" in the normal usage. This shift in emphasis is partly due to early timing studies (*e.g. Harrison et al.*, [1990]). The peak soft X-ray flux often lags behind the CME onset, but the post-flare loop system also lags other flare phenomena. One reason for this is the prolonged late-phase heating attributed to reconnection, but another contribution to this effect is simply that the cooling time scale exceeds the duration of the impulsive phase. This means that the soft X-ray sources *integrate* the input energy in time and hence necessarily must lag behind it (the Neupert effect; see *Neupert* [1968], *Balch*, [1999], and *McTiernan et al.*, [1999]). Current (more sensitive) soft X-ray data usually show simultaneity between soft X-ray brightening and mass motion, either directly observed in X-ray image motion or indirectly via X-ray dimming patterns [*Hudson*, 1997; *Zarro et al.*, 1999].

The standard model is not very clear concerning particle acceleration. Flare particle acceleration, as distinguished from the shock acceleration seen in the corona and in the interplanetary medium, could happen in any of several different locations. The inferred particle numbers imply that the flare particles mainly reside on closed field lines [the "thick-target model"; *Lin and Hudson*, 1996]. In the standard model the energy for this acceleration ultimately derives from the effects of reconnection, but the fundamentals remain unknown. The Type III bursts provide another puzzle for the standard model. These require open or at least large-scale field lines to exist prior to the eruption, and their timing and inferred plasma densities suggest a close involvement in the primary energy release associated with the eruption. The standard model does not allow for these field lines in a self-consistent manner, although some of the cartoons of Figure 1 show open field lines existing before the eruption.

The role of the filament in the standard model also seems awkward. We have evidence that in some cases the filament heats strongly as it rises. There seems to be no ready explanation for this in the standard model, which identifies the filament with the rising plasmoid, since the reconnection and/or slow shocks do not directly involve the rising filament.

Finally, the standard model does not envisage a magnetic implosion to supply the energy from its local storage in the magnetic field [*Hudson*, 2000]; *cf. Melrose* [1995]. An implosion should result from the fact that virtually all manifestations of a CME or flare are *exoergic*, and in a low-β corona, on a short time scale, with no extraneous energy inputs (such as gravity), only the magnetic field can supply the necessary energy. In some volume of the corona, the field lines must therefore systematically shorten during a flare or CME launch to supply the energy (Figure 6). We feel that this constraint presents a major problem in understanding, because in the impulsive phase of a flare (near the time of the main acceleration phase of a CME) one typically sees only outward explosive motions. A related difficulty for CMEs comes from the Aly-Sturrock theorem [*Aly*, 1991; *Sturrock*, 1991]. This theorem establishes that an open-field configuration contains more energy than a closed one, under certain conditions. This suggests a conflict with the observation that CMEs appear to cause field lines to become open, since this process would tend to add energy to the field, rather than extract it. The theorem as proven does not apply to limited parts of the field, but rather to the entire corona. This is often cited as evidence that there is no real constraint. Nevertheless numerical experiments [*Klimchuk*, 1990; *Sturrock et al.*, 1994] generally show that adding stress to the coronal field (increasing its stored energy) causes it to inflate, so that the converse (implosion) would be required to extract energy.

Figure 6

Figure 6

Some CMEs simply do not fit the standard model; *Harrison* [1995] noted that the associated flare often appears near one footpoint of the CME structure, rather than in a symmetrical position underneath it [see also *Kahler* 1991]. *Khan and Hudson* [2000] and *Thompson et al.* [2000a] report soft X-ray and EUV observations that show this pattern clearly.

6.2. The role of large-scale waves

How do coronal global waves (Moreton, EIT, Type-II-burst) fit into the standard model? Our feeling is that such global wave disturbances probably do not show us the CME itself; instead they represent secondary processes caused by the flare and/or CME explosion. However recent work suggests that slowly-moving diffuse EIT waves and stationary emitting structures may actually trace the CME material, presumably displaced from the dimming regions [*Gopalswamy et al.*, 1999c; *C. Delannée* personal communication, 2000], in other words representing the "ground track" of the CME.

We do not presently understand the source of the metric type II bursts, which *Klassen et al.* [2000], in a good example of a cross-calibration study, have shown to correlate strongly with EIT waves: Are such waves primarily due to a flare (blast wave or simple wave) [*Gopalswamy et al.*, 1998] or a CME (driven wave) [*Cliver et al.*, 1999] phenomenon? If the latter, the observation of waves and their high-frequency precursors by *Klassen et al.* [1999], as well as high-resolution X-ray and EUV imaging, may help guide us to an understanding of the initial eruption and/or implosion. What we really need is a calibration of metric type II bursts against the new LASCO observations of CMEs, with due account taken of the low-coronal counterparts seen by *Yohkoh* and SOHO.

6.3. Puzzles in the outer corona

Gosling et al. [1994] reported the presence of reverse as well as forward shocks in high-latitude *Ulysses* interplanetary events. These can be seen in Figure 4. *Gosling et al.* argue that this requires an explosion *outside* the critical point of the solar-wind flow, because otherwise the reverse shock would not escape from the Sun. Such an explosion could not be directly related to flare processes in the low corona, nor even to the CME-launching instability which we infer observationally to occur inside the critical point. Thus the solar-wind counterpart of a CME can include distinct physical processes and not merely represent the direct consequence of a driver in the low corona.

This kind of independence might be expected from the structure of the outer corona. The inner corona is basically a magnetic region with low plasma β, in an approximately force-free equilibrium that balances the stresses imposed from below the photosphere, the acceleration of the solar wind, and rotation. In the solar wind the gas component of the plasma is also important energetically. In the Parker models, the solar-wind velocity varies only slowly with radial distance outside the critical point of the flow. The density ρ therefore falls roughly as r^{-2}, cancelling the volume increase in the integral giving the mass of the solar wind, $M = \int 4\pi r^2 \rho dr$. The mass of the solar wind thus decreases only slowly outwards by comparison with a corona in hydrostatic equilibrium. This change in the nature of the medium suggests the possibility CMEs might change their character as they propagate from the low-β corona into the solar wind.

Finally we speculate about a practical problem that CMEs pose: some mechanism is required to regulate the intensity of the magnetic fields in the solar wind [*Gold*, 1962]. Without such a mechanism, the field lines observed to open (extend great distances from the low corona) during CME eruptions would gradually add to the solar-wind magnetic flux, which in fact does not change substantially over the solar cycle. The site of this regulating mechanism currently remains unknown, but the discovery in streamers of numerous blob-like ejecta [*Sheeley et al.*, 1997; *van Aalst et al.*, 1999], and inflowing material [*Wang et al.*, 1998] offers some possibilities. *Moldwin et al.* [2000] point out the existence of small-scale flux ropes formed near one A. U., similar to those associated with CMEs but much smaller. We speculate that these formation of small-scale flux ropes occurs analogously with CME flux-rope formation and may be related to the physics of the regulation mechanism.

6.4. Flares and CMEs

Within the past decade, the coronal mass ejection has emerged as a key object for study in solar and solar-terrestrial physics. Whereas previously flares were often thought to cause CMEs via explosive heating of the atmosphere, the loop arcades of gradual flares are now recognized as consequences of CMEs via the reconnection paradigm. The relationship of the impulsive phase of eruptive flares to CMEs is less certain (*cf. Kahler* [1992]; *Cliver* [1995]). Several new observations serve both to challenge and to refine our view of the relationship between early flare brightening and mass motions in solar eruptions. These include: the close timing relationship between ejecta and the onset of X-ray emission [*Hudson et al.*, 1996; *Hudson*, 1997; *Zarro et al.*, 1999]; the possible triggering of CMEs by flares [*Khan and Hudson*, 2000]; the origins of EIT waves and some CMEs in compact sources [*Thompson et al.*, 1998; *Dere et al.*, 1997]; and the rapid acceleration of active region CMEs [*Sheeley et al.*, 1999]. Both the impulsive flare (i.e., impulsive phase of a fully-developed two-ribbon flare) and the CME result from catastrophic instabilities of the coronal magnetic field but the nature of these instabilities as well as the difference between eruptive and compact flares remain open questions.

7. Conclusions and open questions

In this review we have attempted to fold new kinds of observation into a better understanding of CMEs. Glancing again at Tables 1 and 2 will convince the reader that we have a great deal of material to integrate, but that much more work in calibration of signatures needs to be done. Although LASCO data have been available for four years at the time of writing, many of the important non-coronagraphic data sets have not been calibrated against these new and superior coronagraphic observations except in individual case descriptions.

In interpreting the combined data now available, we have first checked to see whether a single standard model basically can explain most of the observed phenomena. We find that for a certain class of CME events, a modern interpretation of the standard model of an eruptive flare fits well enough. This does not mean that a theory exists, simply that we can see considerable evidence for the cartoon that has evolved around this scenario. On the other hand, some CMEs do not fit the standard model, specifically the ones involving transequatorial loops and extended dimming regions [*Khan and Hudson*, 2000; *Thompson et al.*, 2000b].

We conclude with some open practical questions, in principle answerable with the current data:

- What is the relationship between the flare X-ray ejecta and Hα flare sprays and erupting prominences?
- Does the flux rope, in the standard model, form via large-scale reconnection *during the eruption*, or does it exist fully-formed beforehand?
- Which coronal field lines reconnect during the sigmoid-to-arcade eveolution, based upon the direct mapping of their photospheric footpoints?
- What is the explanation of the recently-discovered CME infalling material?

- What fraction of events resemble the standard model?
- What is the nature of Brueckner's global coronal disturbances, which apparently can involve activity in the streamer belt on opposite solar limbs?
- Do the different velocity profiles of active-region CMEs and those originating outside active regions imply substantially different physics?
- Do EIT waves actually show us the CME itself? What is the relationship of the waves to the large-scale dimmings?
- How do the various interplanetary signatures of CMEs relate in detail to structures in the lower corona?
- What is the fate of the open field lines in transient coronal holes? When and where do they reconnect with opposite-polarity field lines to prevent flux build-up in the heliosphere?

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Figure 1. Representative cartoons from the history of the modeling of eruptive events. Clockwise from upper left: *Carmichael* [1963], *Sturrock* [1966], *Hirayama* [1974], *Kopp and Pneuman* [1976], *Cliver et al.* [1986], and *Shibata et al.* [1995]. All show variants on what we term the "standard model" of an eruptive flare or CME, which is magnetically bipolar. The cartoon of *Hirayama* [1974], on the center right, introduces the flux-rope configuration; the model of *Cliver et al.* [1986], on the lower left, includes hints about the origin of many non-coronagraphic phenomena. See also Figure 5.

Figure 2. A quiet-Sun bipolar X-ray dimming and arcade event (October 23, 1997) observed in soft X-rays by *Yohkoh* (reversed color table). The panel on the upper left shows the pre-event sigmoid (arrow), and the final panel on lower right shows the resulting arcade as seen from almost directly above. Although not a flare event, this quiet-Sun arcade involved double dimmings (arrows in lower-right panel) similar to those discovered in the eruptive flare of April 7, 1997 [*Sterling and Hudson* 1997].

Figure 3. The dimming associated with the conversion of a large-scale NS interconnecting loop system into a CME front [*Khan and Hudson* 2000]; from *Yohkoh* SXT observations from May 6, 1998. The flare occurred in NOAA AR 8210 (south of the equator, which passes underneath the large loop structure). Left, pre-flare; middle, post-flare; right, difference (reversed color table so that the dimmed region shows as white). This was the first of a series of three homologous events, spread over three days, in which the NS loop structure re-formed and then became destabilized, apparently as a result of a powerful flare near its southern footpoint.

Figure 4. *Ulysses* particles-and-fields observations of two similar interplanetary events identified with CMEs [*Gosling et al.*, 1994]). The label "CME" on each figure refers to the time range of bidirectional electron streaming, not to the CME itself. Left, an event associated with an impulsive flare in at (N09,W02); right, an event associated with a giant polar-crown arcade event stretching across the entire southern hemisphere (*cf. Kahler et al.* [1998]). Both events show the interesting forward/reverse shock-pair structure seen especially well in the high-latitude events (see text).

Figure 5. Simple cartoons, from *Moore et al.* [1999], which depict the geometry of the current standard model in a clear manner. These cartoons show individual field lines, but the supposed field geometry consists of a single smoothly-distributed bipolar structure. We believe that this geometry is well-established by a large number of observations across all observing regimes, for certain events. This particular representation does not show the open field lines resulting from the CME (compare with Figure 1), but they would include all of the ones projecting above the limb in the right-hand sketch.

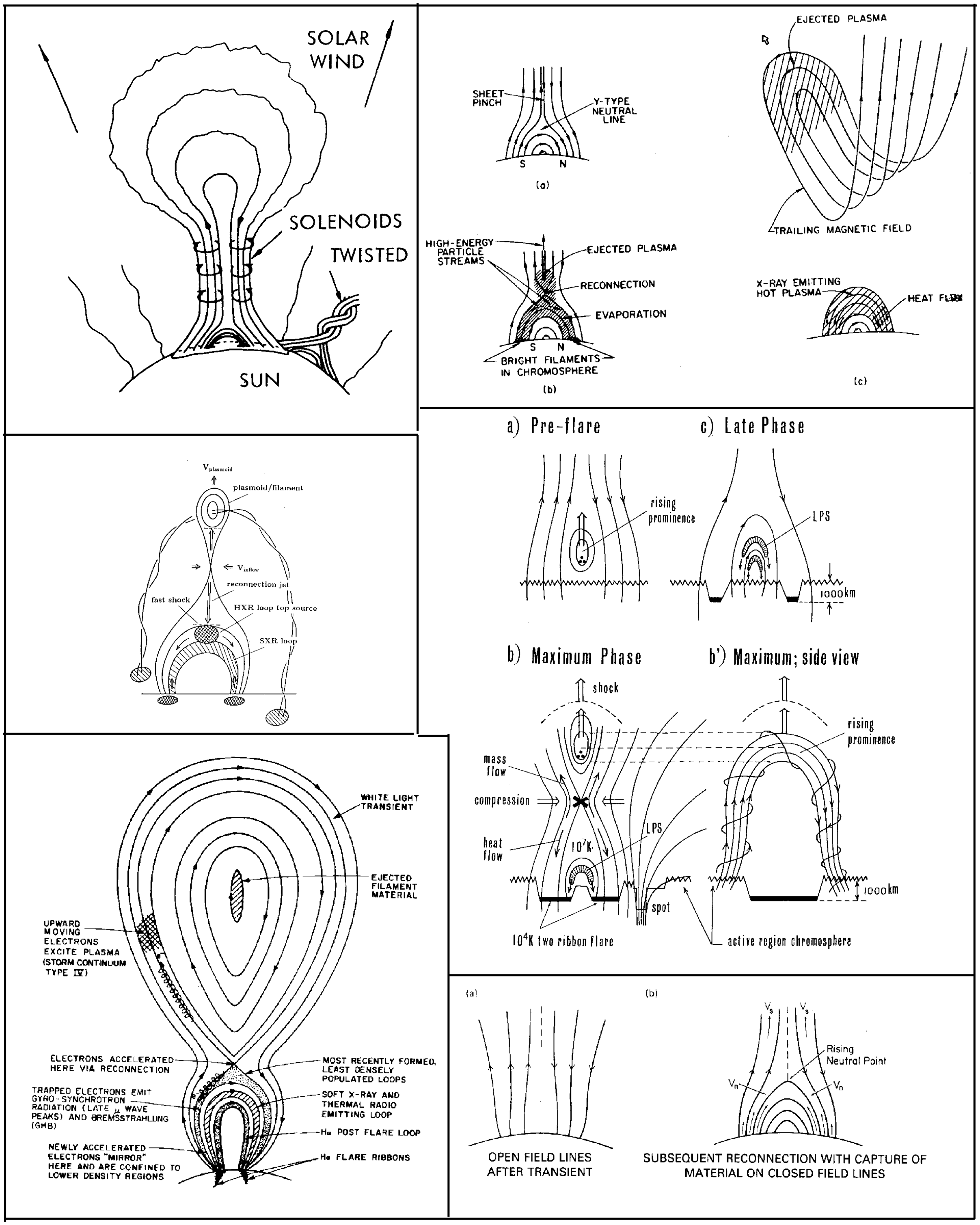
Figure 6. Sketch of the theoretical problem imposed by the impulsive phase of a flare or the acceleration phase of a CME. The lines represent the magnetic field of an active region (solid, prior to the event; dotted, after); the heavy dashed lines represents level surfaces (contours) for the magnetic energy density $B^2/8\pi$, showing how a magnetic implosion would provide energy for the magnetic explosion a CME represents [*Hudson* 2000].

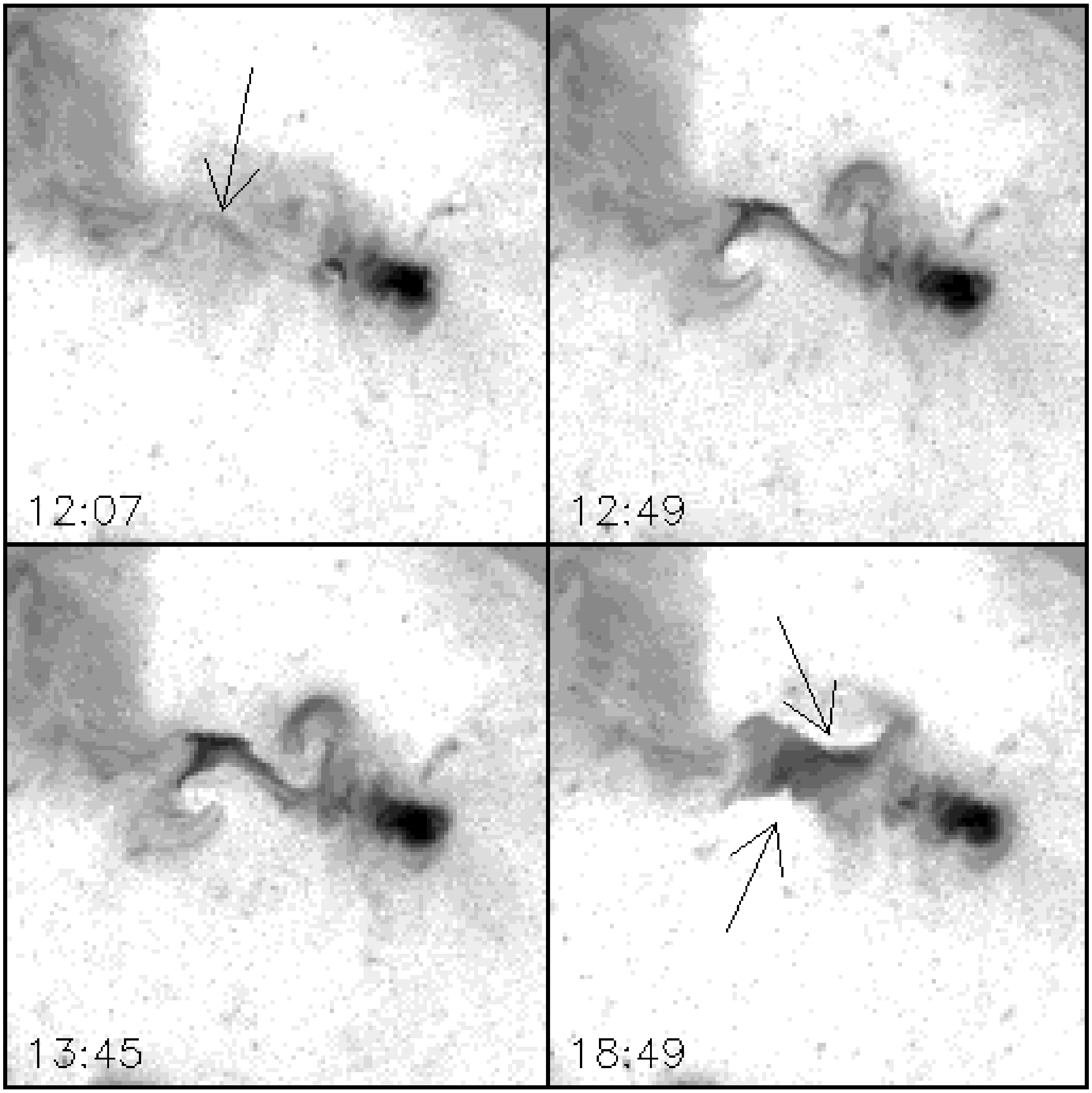
Table 1. Literature on Calibration of Non-Coronagraphic CME Signatures with LASCO observations

Signature	Early description	Calibration	Number
Hα two-ribbon flare	*Munro et al.* [1979]	None	–
Hα post-flare loops	*Bruzek* [1964]	None	–
λ10830Å two-ribbon flare	*Harvey et al.* [1986]	None	–
Filament eruption	*Munro et al.* [1979]	*Delannée et al.* [2000]	7
Moreton wave	*Smith & Harvey* [1971]	None	–
EIT wave	*Thompson et al.* [1998]	None	–
X-ray eruptive flare	*Rust & Hildner* [1978]	*Nitta & Akiyama* [1999]	17
X-ray dimming	*Rust* [1983]	*Thompson et al.* [2000]	7
Radio dimming	*Gopalswamy & Kundu* [1992]	None	–
Long-Decay Event/X-ray arcade	*Kahler* [1977]	*McKenzie* [2000]	12
Microwave gradual event	*Sheeley et al.* [1975]	None	–
Hard X-ray gradual event	*Cliver et al.* [1986]	None	–
Noise storm (Type I)	*Lantos et al.* [1981]	None	–
Stationary Type IV burst	*Cliver* [1983]	None	–
Moving Type IV burst	*Boischot* [1958]	None	–
Type II burst	*Sheeley et al.* [1984]	None	–
Bidirectional electrons	*Gosling et al.* [1987]	None	–
Magnetic cloud	*Burlaga* [1987]	None	–

Table 2. Results from EUV/X-ray Observations

Result	Reference
Extended arcade	[*Tsuneta et al.* 1992a]
Common X-ray ejection	[*Klimchuk et al.* 1993]
Coronal sigmoids	[*Rust and Kumar* 1996]
X-ray dimming above the limb	[*Hudson and Webb* 1997]
Compact CME origins	[*Dere et al.* 1997]
X-ray double dimming	[*Sterling and Hudson* 1997]
EIT wave	[*Thompson et al.* 1998]
X-ray global brightening	[*Gopalswamy et al.*, 1999b]
Erupting trans-equatorial loop	[*Khan and Hudson* 2000]


SOLAR WIND
SOLENOIDS
TWISTED
SUN
SHEET PINCH
Y-TYPE NEUTRAL LINE
S N
(a)
HIGH-ENERGY PARTICLE STREAMS
EJECTED PLASMA
RECONNECTION
EVAPORATION
BRIGHT FILAMENTS IN CHROMOSPHERE
(b)
EJECTED PLASMA
TRAILING MAGNETIC FIELD
X-RAY EMITTING HOT PLASMA
HEAT FLUX
(c)
V plasmoid
plasmoid/filament
V inflow
reconnection jet
fast shock
HXR loop top source
SXR loop
a) Pre-flare
c) Late Phase
rising prominence
LPS
1000km
b) Maximum Phase
b') Maximum; side view
shock
mass flow
compression
heat flow
10⁷K
spot
10⁴K two ribbon flare
active region chromosphere
WHITE LIGHT TRANSIENT
EJECTED FILAMENT MATERIAL
UPWARD MOVING ELECTRONS EXCITE PLASMA (STORM CONTINUUM TYPE IV)
ELECTRONS ACCELERATED HERE VIA RECONNECTION
MOST RECENTLY FORMED, LEAST DENSELY POPULATED LOOPS
TRAPPED ELECTRONS EMIT GYRO-SYNCHROTRON RADIATION (LATE μ WAVE PEAKS) AND BREMSSTRAHLUNG (GHB)
SOFT X-RAY AND THERMAL RADIO EMITTING LOOP
Hα POST FLARE LOOP
NEWLY ACCELERATED ELECTRONS "MIRROR" HERE AND ARE CONFINED TO LOWER DENSITY REGIONS
Hα FLARE RIBBONS
(a)
(b)
Rising Neutral Point
OPEN FIELD LINES AFTER TRANSIENT
SUBSEQUENT RECONNECTION WITH CAPTURE OF MATERIAL ON CLOSED FIELD LINES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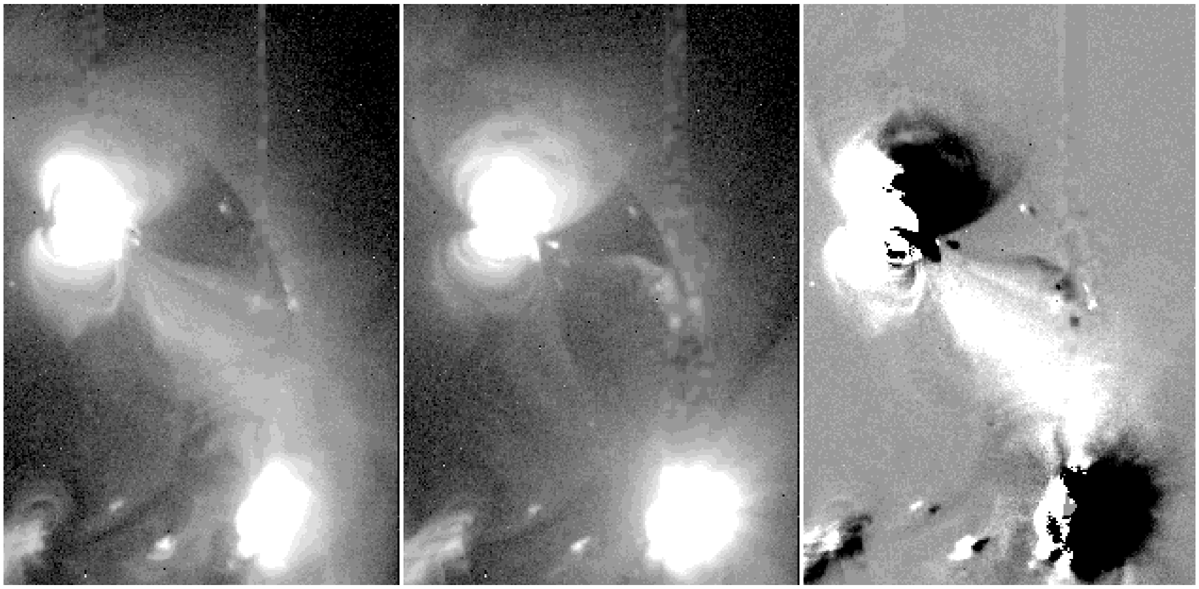
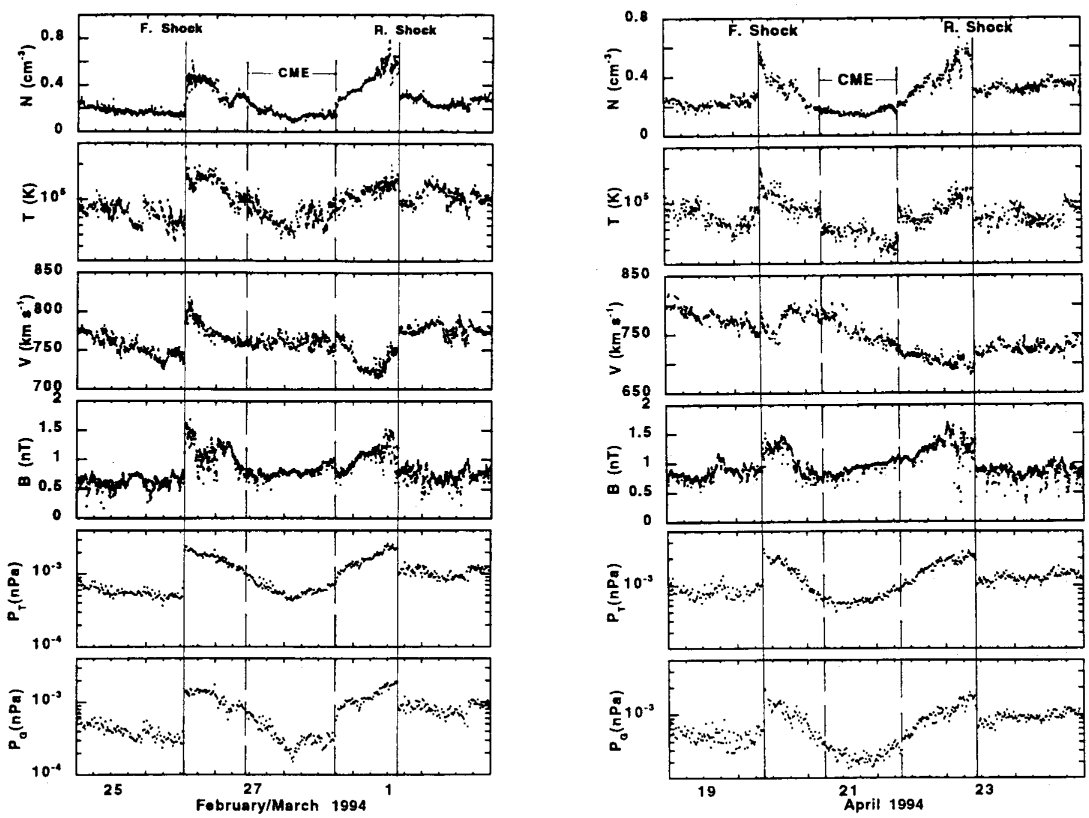
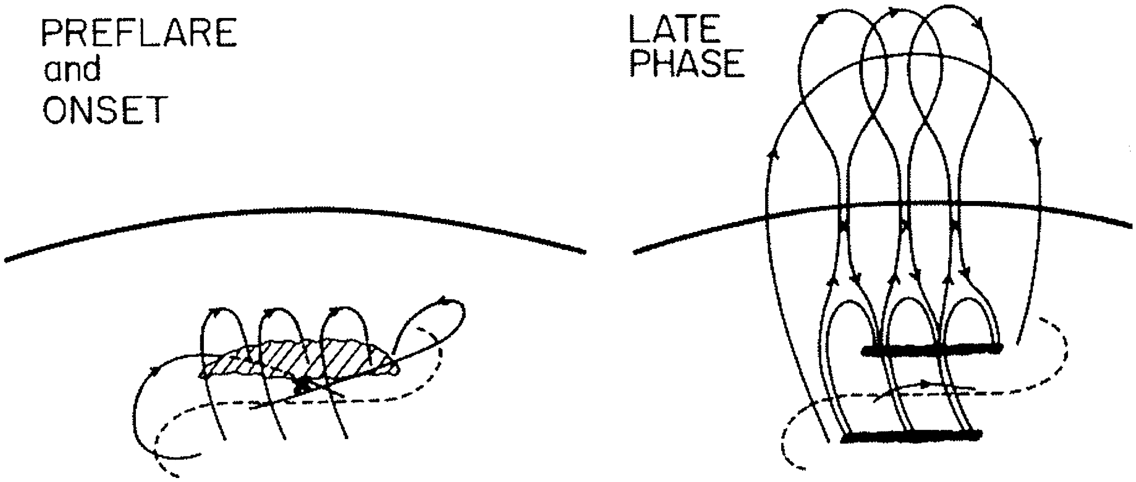




F. Shock
R. Shock
CME
N (cm⁻³)
T (K)
V (km s⁻¹)
B (nT)
P_T (nPa)
P_G (nPa)
25
27
1
February/March 1994
19
21
23
April 1994


PREFLARE
and
ONSET
LATE
PHASE