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Coronal Mass Ejections at High Temperatures

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Abstract

We now have extensive X-ray (*Yohkoh*) and EUV observations of the behavior of coronal mass ejections (CMEs) at high temperatures in the lower corona. We also now have coronagraph observations from space with which to make identifications of the related phenomena. This paper reviews theories and observations of CMEs in this new context.

Key words: Corona. Flares. X-rays. Coronal Mass Ejections.

1. Introduction

The beautiful events detected by *Skylab* and other white-light coronal observations define what we mean by "Coronal Mass Ejection" (CME), observed largely via photospheric radiation Thomson-scattered by coronal electrons. This process directly shows the existence of new mass as it appears in the solar corona, hence the name CME.

White-light observations only show that part of the corona above the limb, and so until the recent era we have had little detailed knowledge of the actual antecedents of the CMEs. Now we have routine X-ray observations from *Yohkoh* and EUV observations from SOHO and TRACE, and these show us a great deal more about the behavior of the low corona during a CME launch even when projected against the disk. With the LASCO coronagraphs to identify the CMEs, we now have much better tools with which to fix the relationships among the different phenomena.

A CME prototypically consists of a bright front, a void that follows it outward, and a rising filament. The front may or may not accelerate, and within the body of the CME there may be a complicated velocity field continuing long after the original eruption. The identification of the front with (a) a magnetic loop structure, or (b) with a more 3-dimensional bubble, immediately posed a problem during the Skylab days, and differing opinions still remain (3.3). The legs of the structure normally appear to remain open (or cusp-like; Kahler and Hundhausen, 1992). The extent of subsequent flows (tens of minutes to hours later), and the location of their sources, remain difficult observational questions.

In the low corona, as discussed below, we now can see several earmarks of CME launching: various kinds of X-ray dimming; large-scale EUV waves as observed by SOHO EIT; X-ray arcade formation often below the sensitivity of the GOES photometry; and of course the most direct signature, actual eruptive motions. These phenomena all contribute information that was generally not available before, and the community is in the process of digesting this information and incorporating it into a fuller picture of the CME physics. We are extremely fortunate to have the SOHO LASCO data available so that we can "calibrate" these signatures against the real thing.

Please refer to the proceedings of the 1996 Chapman Conference on CMEs *Coronal Mass Ejections* (Crooker *et al.*, 1997) for full background information, including some of the new material from SOHO. In particular the articles by Amari *et al.*, Chen, Démoulin, Gosling, Hundhausen, Low, and Wu and Guo in that volume provide theoretical opinions from a good fraction of the community of CME theorists. These papers precede some of the "calibration" we are doing with *Yohkoh* and SOHO data, so in the conclusion of this paper I will try to update one major misconception in some of the *Coronal Mass Ejections* collection. The main purpose here thus is to survey the theories in the context of this calibration activity. See Webb (1998) or Gopalswamy (1999) for more extensive discussions of the observations. My special interest is in observations of natural coronal radiation (hence "high temperatures") rather than on the white-light observations.

2. Basic Principles

2.1. *Coronal structure*

We recognize that coronal magnetism has large-scale organization, as represented by coronal holes and filament cavities, as well as small-scale structure (the "salt-and-pepper" or "solar magnetic carpet"), with the latter continually in a transient state because of the photospheric convective motions (Schrijver *et al.*, 1997; Title and Schrijver, 1998). Superposed on this one has the active regions in which flares usually appear. Thus in principle one might consider three separate systems of magnetism in the corona – the small-scale fields, the large-scale fields, and the active-region fields (see also Brueckner, 1997).

Other than the forces at the photospheric boundary, the long-lived parts of the corona also must have structure imposed on it by the solar wind. In between these interfaces (note that the solar-wind interface must be highly asymmetric, unlike the "source surface" models (Altschuler and Newkirk, 1969), the solar-wind force must be exerted over an extended volume (Munro and Jackson, 1977). The coronal field evolves from small-scale structure, normally in the form of loops on all scales, through helmet-streamer geometries (cusps), and thence to the essentially bipolar solar-wind magnetic field.

We recognize a filament channel from the Hα image morphology, for example (Martres *et al.*, 1966; Engvold, 1989); on the limb such a channel often projects as the base of a helmet streamer, with a cavity above the prominence (filament) location. The systematic coronal views by SOHO during the recent solar minimum have clarified the roles of the streamers: there appears to be a basic quadrupolar streamer structure at the limb, *i.e.* in the simplest cases one has one helmet streamer at each quadrant. These then tilt azimuthally towards the solar equator as one goes further outwards radially, until the north and south branches converge to form the heliospheric neutral sheet. The association of the slow component of the solar wind with streamers has now been confirmed by SOHO direct imaging of coronal motions (Sheeley *et al.*, 1997) and by IPS observations (Habbal *et al.*, 1997).

Below each helmet may lie one of the filament channels, centering on a magnetic inversion line in the photosphere. If the horizontal field at this inversion line is concave-up, we call it a *bald patch* (Titov *et al.*, 1993), and Bungey *et al.* (1996) suggest that a prominence may form preferentially in such a region. Streamers may disrupt and form a CME (the "streamer blowout" or "bugle" phenomenon), and this type of CME often does not involve an active region except peripherally. The channel core at the base of the streamer, even at the limb, may contain a hot active component even without eruption (Hudson *et al.*, 1999).

2.2. *Theories and models*

2.2.1. *The hard problems*

I will begin the review of models by stating what I think are the difficult problem areas (*cf.* Sturrock, 1989). The list only contains three items, but Gosling (1997) lists as many as 25, including many dealing with CME propagation in the interplanetary medium. So we do not have a clear theoretical understanding of these phenomena, and there is no lack of scope for future research. In the following discussion we do not distinguish between theories of "pure" CME antecedents and eruptive flares.

1. Instability. Under what conditions does a coronal structure become unstable and create a CME; in particular, what role does reconnection play? See for example Sakurai (1989) for a general discussion.

2. Reconnection. How do the fields opened by the CME reconnect, thus averting the problem of interplanetary field buildup (*e.g.* McComas *et al.*, 1991; see also Low, 1997 and Van Aalst *et al.*, 1999)?

3. Particle acceleration. At event onset, how does so much energetic particle acceleration occur?

The last item needs explanation in a CME context. We know that impulsive-phase particle acceleration may contain a predominant part of the impulsive-phase energy release of a flare: *e.g.* Lin and Hudson (1976) for electrons, or Ramaty *et al.* (1995) for ions. We don't know for a fact that CME events involve this kind of particle acceleration. However even slowly-developing eruptive flares do (Dennis and Zarro, 1993; Hudson *et al.*, 1994; see also Rieger, 1998), and there is no clear dividing line between the event types, for example in the sense of some bimodal distribution function. There is clear evidence for powerful CME-associated shock acceleration in the outer corona (*e.g.* Reames, 1992); this appears to represent a different phenomenon.

Table 1. Models for CMEs/Eruptive flares.

Model	Description	Proponents
Enhanced wind	High-temperature coronal base	Parker, Lin-Hudson
Blast wave	Pressure pulse from the flare drives the CME	Nakagawa, Steinolfson, Wu, Dryer
Quadrupolar	3-D reconnection in a complex mixed-polarity region	Sweet, Uchida, Antiochos
Buoyancy	Gravitational potential energy	Sturrock, Low, Wolfson
Ideal MHD	Flux-rope ejection (Standard model A)	Carmichael, Sturrock, Hirayama, Anzer-Pneuman, Gosling, Van Ballegooijen-Martens, Priest-Forbes, Mikić-Linker
Tether-cutting	Reconnection from emerging flux below the flux rope (Standard model B)	Sturrock, Anzer-Pneuman, Gosling, Moore-LaBonte, Shibata, Yokoyama-Shibata
Current injection	Sigmoid current ramps up, driving the flux rope	Amari, Chen
Twist	Large-scale Alfvén wave	Piddington
Kink	Beyond a certain limit (∼2.5π twist), instability	Rust, Vršnak
Breakout	Reconnection above the flux rope, in a complex field	Antiochos
Non-force-free	The corona supports cross-field currents	Low, Wolfson
Open fields	Adjacent open-field regions close	

2.2.2. The models

CME models fall into two broad categories (Table 1)[1]. Early ideas associated the presence of the interplanetary shock waves, associated with CMEs and flares, with the possibility of a pressure pulse (Nakagawa *et al.*, 1978; Steinolfson *et al.*, 1978; Wu *et al.*, 1978; Dryer, 1994). This made sense because of the early recognition of truly coronal shock fronts, via meter-wave type II bursts (*e.g.* Wild *et al.*, 1963) or chromospheric Moreton waves (Athay and Moreton, 1961) possibly associated with the interplanetary shocks. It now seems much likelier that in fact the CME itself drives the interplanetary shock, which does not represent an extension of the coronal shock (*e.g.* Gopalswamy *et al.*, 1998). This would be consistent with the energetics of CMEs, as well as with the direct interplanetary measurement of probable CME material, which imply magnetic driving of the whole phenomenon (Anzer, 1978). Coronal magnetic energy storage of course is also generally accepted as the source of flare energy, including the eruptive flares known to occur with CME launches. However theorists continue to think in terms of non-magnetic factors, in part because of the energetics (see 2.2.3).

The more general idea now current seeks a full MHD explanation of a CME, and although 2.5-D numerical simulations continue to be interesting, this requires a true flux rope anchored to the photosphere. Such anchored flux ropes do appear in the interplanetary medium in the form of "magnetic clouds" (Marubashi, 1986; Burlaga *et al.*, 1987), and these structures fit naturally into our view of filaments or filament cavities if not so obviously into active regions. The 2-D predecessors of this idea (Carmichael, 1964; Sturrock, 1966) envisioned a flare/CME process in the form of a plasmoid of detached magnetic field lines; Hirayama (1974) sketched a three-dimensional view, in which a true plasmoid field remains rooted in the photosphere. This picture is called the "sheared core" picture by Moore (1988; *cf.* Moore and LaBonte, 1980) and the "plasmoid-driven reconnection" picture by Shibata (1997; *cf.* Yokoyama and Shibata, 1997)

The flux rope could in principle rise unstably either for mechanical reasons, in an ideal MHD instability, or because of dissipative reconnection in the process of its formation (Anzer and Pneuman, 1982; Gosling, 1990). If either way were theoretically possible, the flare loops could form as a result of reconnection, but in the former case there might be a substantial time delay. The large-scale reconnection needed to free the flux rope could supply energy, via advection of magnetic energy into the reconnection point and resulting slow shocks (*e.g.* Tsuneta, 1996; Tsuneta *et al.*, 1997), to power the flare radiation. Based on Skylab observations, such models have become the standard for interpretation of the gradual phase of a flare (*e.g.* MacCombie and Rust, 1979), and have many attractive features.

The flux rope could also conceivably pre-exist in the solar atmosphere, fully formed over a "bald patch" inversion line, and simply rise intact (Chen and Garren, 1993; Chen, 1996); Kumar and Rust (1996) point out that helicity

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[1] These models often deal with specific problems, rather than overall solutions, so the papers may omit consideration of some features of the theory (for example, the energetics issue discussed in Section 2.2.3.)

conservation could account for the heating experienced by the flux rope during its interplanetary expansion. Observationally, as noted by Rust and Kumar (1996), *Yohkoh* SXT observes sigmoid structures easily interpretable as flux ropes waiting to erupt (but see Hudson *et al.*, 1999, for a non-eruptive case). Gibson and Low (1998) show analytically that a flux-rope model can reproduce the sigmoidal structure. Canfield *et al.* (1999) find that the flux-rope (sigmoid) signature in soft X-rays strongly favors eruption from an active region, consistent with the idea that helicity plays a role in the instability (*e.g.* Pevtsov *et al.*, 1996; Kusano and Nishikawa, 1996).

Finally, Antiochos (1998; *cf.* Antiochos *et al.*, 1999) has recently proposed a "breakout" model, akin to the quadrupolar configurations discussed by Sweet (1958) and by Uchida *et al.* (1998) (see Longbottom, 1997, for a description of the topology). Here a stressed field domain finds itself held down by overarching fields; because of the complexity of the field this domain cannot erupt by an ideal MHD process. Accordingly the stress builds up until reconnection occurs *above* the structure; afterwards normal arcade-forming reconnection can also occur if needed and possible. This model allegedly does not have a conflict with the Aly-Sturrock limit (see below).

An eruptive flare or CME presents a major modeling problem, and current numerical simulations cannot handle all aspects of the important physics. For example, no MHD model can self-consistently deal with particle acceleration, hence the "action at a distance" of energetic particles has to remain a mystery. CME propagation models, to cite another example, often start only outside the critical point of the flow, so they cannot consistently explain the eruption itself. At the present time we should probably view the simulations as experiments, rather than theories; they have little predictive power in terms of the hard problems we need to explain, and at best they serve to link one set of observations with another in a limited framework.

2.2.3. The Aly-Sturrock theorem

It seems intuitively obvious that open field lines require extra energy; here "open" means of a scale large enough to pass the critical point of the solar-wind flow. Aly (1991) and Sturrock (1991) proved that, in the force-free approximation, the open state for the coronal magnetic field has the highest energy - the "Aly Conjecture". In Sturrock's proof, there is a requirement that the source surface of the open field be simply-connected, but the existence of a current sheet does not invalidate the theorem. A fully-detached plasmoid could bypass it because of the simple-connection requirement. Taken at face value, the theorem basically states that a CME cannot happen as the result of an instability that opens all of the solar magnetic field, but a partial opening could be possible.

The present observational situation conceals the nature of the instability. First, the CME instability has an intimate timing relationship with flare energy release, even to the extent that clear signatures of filament acceleration often occur during the impulsive phase (see the figures in Kahler *et al.*, 1988). This means that the CME instability needs to find the resources not only to go to an apparently higher-energy state of the field, but also to accelerate mass, to elevate it against gravity, to radiate all of the flare energy and to accelerate all of the flare particles (see Wolfson and Saran, 1998, who do not list the radiation and particle acceleration as requirements on the energetics). Second, we have almost no observational evidence for inward motions that would mark field restructuring on compact scales that might compensate for the field opening on larger scales[2]. Most flare-associated mass motions detected by *Yohkoh* SXT seem to go outwards (*e.g.* Hudson and Khan, 1996) rather than inwards.

Current theoretical papers on CME eruption take the Aly-Sturrock theorem seriously, but its applicability to a limited eruption remains somewhat questionable because of the difficulty of the theory. My opinion here is purely intuitive – to expand the field absorbs energy, so it seems doubly difficult to form a CME while radiating and dissipating other forms of energy as well, and at the same time not producing obvious signatures of contraction. Others have different opinions, but the simple theoretical question of the instability of a sheared arcade still seems open.

3. Behavior of the Low Corona during CMEs

We now proceed to examine some data, emphasizing *Yohkoh* and SOHO images. Much has already been published, at least informally, and need not be repeated; also several other papers at this conference deal with particular examples.

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[2] But see Forbes and Acton, 1996, for discussion of "shrinkage" (Švestka *et al.*, 1982) or dipolarization.

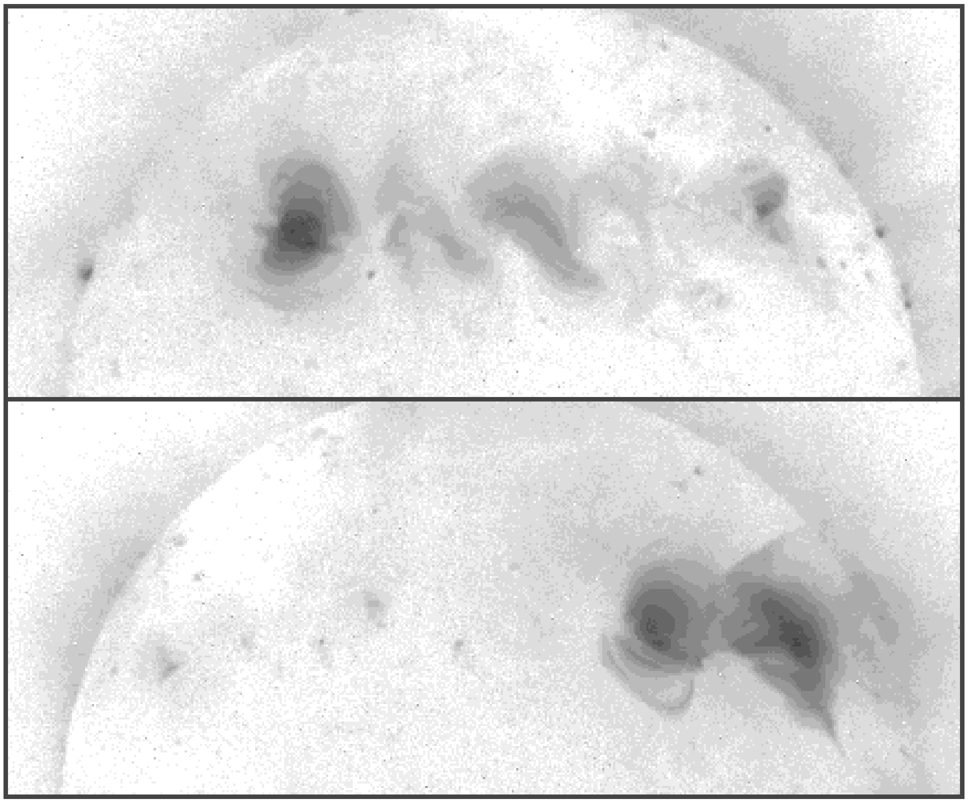

Fig. 1.. An example of the "sigmoid → arcade" pattern for a minor LDE event occurring on May 19, 1998. The upper panel shows a set of active regions in the northern hemisphere, including a sigmoidal region near central meridian, five days prior to the LDE. The LDE image (lower) shows cusps extending NW and SW, at the ends of the arcade, and a typical bright bar along the loop tops of the arcade itself. The non-sigmoidal active region (NOAA 8222), at the left, did not erupt.

3.1. General

We find ourselves in the midst of a calibration of the low-coronal signatures against true CME observations, the latter as provided mainly by LASCO. We would like to know how the corona restructures itself as it launches a CME; this information would resolve our confusion about the Aly conjecture, for example, by showing where the field lines open. And we have many other unresolved questions lingering because of the past difficulty of observation of this domain. From the *Yohkoh* perspective, the first step in this calibration was undertaken by Klimchuk *et al.* (1993). At that time no space observations of CMEs were available. Now that they are, what do we see? The following sections describe the evidence for eruptions of simple bipolar configurations, and also the evidence for magnetic complexity. We also survey various related topics such as "disconnection."

3.2. Evidence for bipoles: the sigmoids

One of the striking features of the new soft X-ray and EUV observations is the beautiful pattern of the "sigmoid → arcade" development during a CME launch. Sterling and Hudson (1997) first described the formation of "transient coronal holes"[3] in the context of a halo CME event well-observed by SOHO both as a CME and as a large-scale coronal wave (Thompson *et al.*, 1999). The sigmoid pattern occurs frequently, even to the point of aiding in predictions of CME occurrence (Canfield *et al.*, 1999). Hudson *et al.* (1998) found a general pattern of dimmings of the "transient coronal hole" (*cf.* Watanabe *et al.* 1992) type, appearing near the end of each arm of the sigmoid spiral, for most or all of a set of halo CME antecedents.

Interpretatively, we recognize that the sigmoid pattern results from currents flowing through the corona along the magnetic field. This provides the environment necessary for a kink instability (Vršnak *et al.*, 1986; Matsumoto *et al.*,

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[3] This name may be misleading; we have no reason yet to assume that the physics of these dimmings and the formation of true coronal holes has anything in common.

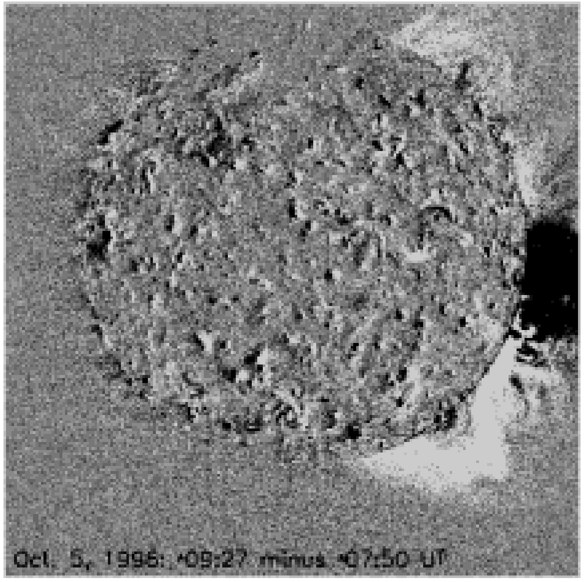

Fig. 2.. A large-scale *Yohkoh* view of the coronal changes during the CME launch of Oct. 5, 1996. This shows a before/after difference over a five-hour time span: the dark region is the result of dimming, and the bright regions show the excitation of both N and S streamers. This illustrates, with SXT observations, Brueckner's view from LASCO of a global coronal participation in the CME process.

1998), and Kumar and Rust (1996) have shown that the *Yohkoh* soft X-ray images tend strongly to display sigmoid shapes in eruptive regions (Sterling and Hudson, 1997; Hudson *et al.*, 1998; Canfield *et al.*, 1999; see Manoharan *et al.*, 1996, for a particularly well-observed example, including meter-wave coronal observations). The fact that the sigmoid pattern is inherently bipolar lends credence to the idea that an eruptive flare/CME can unstably occur in such a field geometry, even if the theory remains unclear.

3.3. Evidence for multipoles

Recent work suggests that more complicated magnetic geometries may also play a major role in CME formation. Harrison (1995) points out that the associated flare may occur at one extreme end of a CME appearing above the limb. This paper incidentally clarifies the earlier work of Harrison *et al.* (1990) which had also suggested (based on onset times) a time-relationship between CMEs and associated flares that suggested that CMEs *caused* flares (hence the term "post-CME loops"). Feynman and Hundhausen (1994) note that the timing of great flares and CMEs does not confirm this causal relationship, nor do the modern data described by Hudson and Webb (1997) and shown in this review.

However the geometrical complexity of the large-scale coronal disruptions observed by LASCO (*e.g.* Brueckner, 1997) underscores the suggestion that complex magnetic structure may be required to permit an eruption to take place at all. This conflicts with the simple view the sigmoids offer, but the soft X-ray images sometimes do not show us the outer corona very well and the geometry may not be clearly seen.

From the *Yohkoh* movie one can see many hints of very large-scale coronal phenomena, and one of the first large-scale ejections described showed possibly correlated disturbances in both polar regions (Hudson *et al.*, 1996; see also Manoharan *et al.*, 1996). We show a much clearer example in Figure 2, a difference image between 150-sec summed exposures over a time gap of about five hours, spanning the time of the remarkable CME-related event reported by Watari *et al.*, (1997).

Another recently-reported CME event observed by SXT to have complex structure occurred on Sep. 20, 1992, with "calibration" from the Mauna Loa Mark III observations (Webb *et al.*, 1999). Figure 3 shows that the bright front of this event corresponds, by overlay, with a structure *apparently connecting two cusped arcades!* The CME void lies between the arcades. Uchida (1996) had previously noted that flare cusps seen in soft X-rays may not extend outwards towards the outer corona, but instead may connect back, apparently to the photosphere. This implies a bipolar (current-sheet) structure in the expanding front of a CME, if this identification can be made.

The event shown in Figure 2 and another discussed by Webb *et al.* (1999), have global morphologies quite different from the bipolar appearance of the sigmoid CME antecedents. Perhaps the corona can become unstable in more than one way, but if we want to keep theories simple, we might want to look for a common theme. From the point of view of Aly-Sturrock and intuition about energetics, it would seem preferable to have some sort of complex magnetic structure playing a role even in the apparently simple sigmoids. Is this possible?

3.4. Disconnection

The search for "disconnection events", inspired by a literal interpretation of the 2-D reconnection cartoons, reached a plateau in the survey of Webb and Cliver (1995). Illing and Hundhausen (1983) had reported one good example from *Skylab* data, showing a concave-up structure interpreted as the disconnected plasmoid rising into the corona - here "plasmoid" means a region totally disconnected from the solar surface. The disconnection point would represent the magnetic null separating the outwards-bound plasmoid and the reconnected arcade. The Webb-Cliver work found that approximately 10% of CME events had image morphology consistent with the concave-up structures expected in the 2-D reconnection picture. Then SOHO happened, and one now can see many examples of concave-up structures rather clearly resulting from the coils of a flux-rope configuration, rather than a disconnection at a 2-D neutral point. Moreover Klimchuk (1996) reminds us that the legs of a CME normally do not show any tendency for moving together after the eruption, as true "disconnection" would imply. Simnett *et al.* (1997) however do present an extremely convincing view of a Y-shaped structure following a CME, a "plasmoid" that resembles that of the Feb. 21, 1992 X-ray observations (Hudson *et al.*, 1995b; Tsuneta, 1996; but see also Uchida, 1996). Nevertheless the rarity of clear examples of "disconnection" seems to prove that the reconnection process does not normally occur as expected from the 2-D models, at least within the coronagraph fields of view.

3.5. Dimming and motions

The depletion of the corona during a CME launch can often be detected at the limb by a coronagraph (Hansen *et al.*, 1974); with *Yohkoh* SXT observations we could detect dimming not only in limb events, but also on the disk. Hudson and Webb (1997) suggested four categories of X-ray dimming: the bulk outward motion of a cloud, "transient coronal holes", dimming enveloping a streamer seen at the limb; and dimming above the site of a flare arcade forming at the limb. In each case the preferred interpretation is that of mass ejection, which invariably occurs when the dimming source can be seen to move. Tsuneta (1996) incidentally gave an alternative interpretation of one event, noting that the dimming volume (assuming *inflow*, rather than the apparent *outflow* (Hudson *et al.*, 1995b) would have about the right size to provide the source region for a reconnection inflow. Even though in apparent conflict with the data, such an interpretation must be taken quite seriously, because there is still no other evidence for the inflow required by this class of theories. Because of the importance of this alternative, we would like to see much more detailed data analysis, including correlation tracking if possible, to characterize the flow fields from *Yohkoh*, SOHO, or TRACE images. The success of observations of transverse flows will depend upon the existence of *tracers* in the medium, rather than on line-of-sight Doppler motions.

3.6. Filaments

Hα filaments at least provide fascinating markers for the evolution of coronal structure in one of the CME/eruptive flare events. Theorists also often wish to make use of the gravitational potential energy of the prominence material trapped high up in the corona. As is well-known to observers, filaments often begin to writhe and rise well in advance of the impulsive phase of an eruptive flare. As the filament activates, one often sees heating, and curiously linear ejecta (Kano, 1994) often accompany the ejections. In the regular cadence of the best EIT movies at 195Å, one can sometimes see a large-scale twisting motion of the rising filament and directly view its heating (*e.g.* Hanaoka *et al.*, 1994; Khan *et al.* 1998; Hanaoka and Shinkawa, 1999; Gopalswamy *et al.*, 1999). We interpret these ejecta as heated filament material, and note that EIT provides spectacular views of both the hot and cold forms in movie representations.

3.7. Coronal waves as seen by EIT

The large-scale coronal waves seen by EIT represent one of the most fascinating new observations, not well-recognized at the time of the Chapman conference (Crooker *et al.*, 1997). No extensive literature yet exists, but Thompson *et al.* (1998 and 1999) report two excellent examples. These waves probably show us the coronal shock propagation anticipated from observations of Moreton waves (Athay and Moreton, 1961). Since the latter famously accompanied powerful impulsive flares, they provided impetus for the "pressure pulse" theories (see Table 1). However the EIT waves, although closely associated with flare onsets (the impulsive phase), often occur even if the flare seems weak and not impulsive. We clearly need further theoretical work on the wave physics, but in the meanwhile these observations underscore the importance of compact source regions in the low corona. The EIT waves have a strong relationship with halo CMEs (St. Cyr *et al.*, 1997), for which LASCO has provided a new rich data set.

4. Particles and fields

Because CMEs involve the *opening* of magnetic field lines, in the sense the solar wind carries a field line beyond the critical point of the flow, we cannot fully understand the physics without observations in the heliosphere. The interplanetary observations show many features of the heliospheric propagation of CMEs far beyond the critical point. *Ulysses* in particular has given an extremely clean view of several solar-minimum events associated with CMEs (Gosling *et al.*, 1994). Weiss *et al.* (1996) traced five events backwards to the Sun, and found two flare associations plus three X-ray arcade associations, noting that the arcades were not hot enough or bright enough to produce GOES signatures (see also Lemen *et al.*, 1995). This confirms the general conclusion that flare-like signatures (heating, arcade formation, and chromospheric "ribbons") accompany most CMEs, even those not directly associated with active regions.

We note also that the calibration of the many interplanetary signatures, even the bidirectional electron streaming (*e.g.* Gosling, 1990) remains imperfect. The occurrence of "magnetic clouds" (Marubashi, 1986; Burlaga *et al.*, 1987) matches what one might expect from the flux-rope creation of bipolar X-ray dimmings noted by Sterling and Hudson (1997). However many puzzles remain: how could two extremely different X-ray events in 1994 – one a northern-hemisphere impulsive LDE flare, and one a distinctly gradual southern-hemisphere giant arcade (Hudson *et al.*, 1995a; Kahler *et al.*, 1998) – have produced almost identical *Ulysses* signatures?

Data from *Ulysses* suggest (Bothmer *et al.*, 1997) that the 3-D reconnection scenario envisaged by Gosling *et al.* (1995) may actually be detectable via particle tracers within a magnetic cloud. Larson *et al.* (1997) come to similar conclusions from WIND observations.

5. Flares and CMEs

A great deal of controversy had arisen over misinterpretations of the relationships between flares and CMEs, and the new observations have allowed us to straighten some of this out. We now know much more solidly than before (a) that flares and CMEs usually have an extremely tight temporal relationship, with extensive common physics; (b) that however CMEs may occur with minimal low-coronal (flare-like) manifestations – we did not know this for sure until the modern era (see below), because of sensitivity limits and because of behind-the-limb confusion; and (c) that timing arguments do not point to CME/flare causal relationships one way or the other. McAllister *et al.* (1996) discuss a particularly beautiful example of a "problem" CME without an active-region flare signature (*cf.* Hudson *et al.* 1995a; Kahler *et al.* (1998).

Regarding item (a) above: hot coronal ejecta occur in almost every flare (Shibata *et al.*, 1995), but not all (de la Beaujardiére *et al.*, 1995). The common ejecta may or may not be related to CME launching.

Regarding item (b) above: Hundhausen (1997) has noted the existence of a poor correlation between GOES flux and CME kinetic energy. In extreme cases (his Figure 3) the scatter can exceed four decades! Burkepile (1997) however found definite improvement in the correlations by including source flare locations, which Hundhausen had disregarded. Over-the-limb flares may accompany energetic CMEs but could have no correlation at all because the limb occults them. This point has often been neglected, even though a large fraction of half of all CMEs must originate beyond the limb. Although the geometrical circumstances of the Thomson scattering favor the "plane of the sky," a CME can of course start from any location it chooses to.

Regarding item (c) above: Figure 3 shows an example of the simultaneity of flare brightening and mass ejection (Zarro *et al.*, 1999). It is well-known that gradual filament motions may substantially precede the impulsive phase of a flare, but examples such as this and many others from *Yohkoh* (*e.g.* Hudson and Webb 1997) show that in general there is no clear delay between motion and brightening (but see Ohyama and Shibata, 1998).

None of these factors can conceal the conclusion from events such as January 6, 1997 (Webb *et al.*, 1998), where in spite of the sensitive X-ray observations from *Yohkoh* and EUV observations from SOHO, a major "geo-effective" CME happened with only the subtlest visible manifestations in the low corona (in this case, a faint sigmoid dimming). So, a given solar eruptive event may have flare and CME properties, but in different measures.

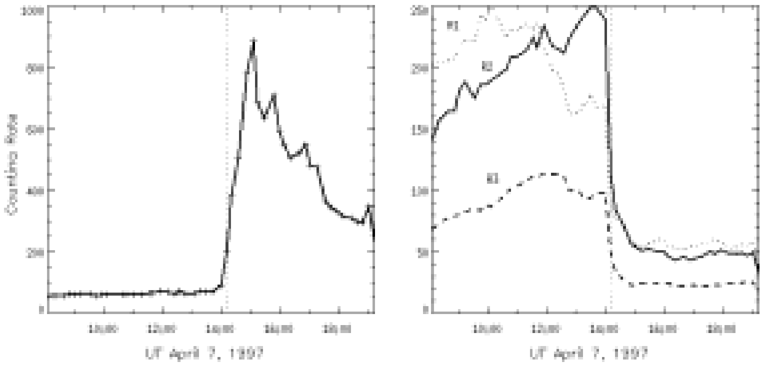

Fig. 3.. Illustration of the relative simultaneity of flare brightening and mass ejection (adapted from Zarro *et al.*, 1999; see the original paper for definition of the photometric regions R1, R2, R3). The vertical dotted lines provide a time reference for the simultaneous onset. Here we interpret the “dimming” of the transient coronal holes as evidence for outward mass flow (Sterling and Hudson, 1997).

6. Conclusions

The story of CMEs as viewed in detail in the low corona has provided some unexpected twists and turns. Whereas we often see simple sigmoids, either in active regions or in the quiet Sun, we have the event shown in Figure 3, and the general view of LASCO in which the coronal consequences of a CME extend broadly. Is magnetic complexity a crucial feature permitting the eruption to occur, and if so where is it to be found within a normal, simple, sigmoidal active region that erupts? The standard large-scale reconnection model describes many aspects of the observations quite well, but does not tackle the hard problems mentioned at the beginning in Section 2.

I would like to speculate that the presence of open-field areas in active regions might offer the necessary complexity. The central field line of a round, symmetrical sunspot of course may open to the solar wind, but there would be no mathematical need for the open area to have any finite measure. However type III bursts occur in good correlation with the impulsive phases of solar flares (*e.g.* Kundu, 1964), and especially the flare-related type III bursts may have high starting frequencies. This implies the existence of open field lines reaching to densities in excess of 10^9 cm^{-3} (a starting frequency of $\sim$300 MHz) an order of magnitude larger than that normally assumed for “the base of the corona” in solar-wind models. This suggests the existence of open structures in active regions, with low visibility because of low density, reaching down to the high-density transition region and chromosphere. A CME formation thus might involve a transition from a partially-open configuration to another partially-open configuration, somewhat analogous to the “autoionization” phenomenon in atomic physics.

Finally, for those who have read right through this paper, or for those who start from the end, I would like to correct one of the misconceptions in the papers found in some of the *Coronal Mass Ejections* (Crooker *et al.*, 1997), as promised in the Introduction (see especially Low, 1997). This has to do with the hypothetical sequential relationship between CMEs and flares. In fact we see a close time correspondence between the ejecta from the low corona and the flare brightening, with obvious links (*e.g.* Thompson *et al.*, 1998) to the impulsive phase. Therefore it no longer seems reasonable to think only in terms of a distinct ideal MHD instability that opens the field lines, followed by a subsequent phase of dissipation that we would term a “flare” (see Cliver, 1995, for a full discussion of the terminology here). Instead we see brightening (energy dissipation, heating, and non-thermal particle acceleration) right along with the mass motions. This does not seem to rule out ideal MHD instabilities, *i.e.* those without dissipative magnetic reconnection, as long as they can be shown to be consistent with the energetics (see Section 2.3.3).

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