AN INTRODUCTION TO THE PRE-CME CORONA

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Abstract. Coronal mass ejections provide a gateway to understanding the physics of energy release and conversion in the solar corona. While it is generally accepted that the energy required to power a CME is contained in the pre-eruption coronal magnetic field, the pre-CME state of that field and the conditions leading up to the release of the magnetic energy are still not entirely clear. Recent studies point to various phenomena which are common to many, if not all, CME events, suggesting that there may be identifiable characteristics of the pre-CME corona which signal the impending eruption. However, determining whether these phenomena are necessary or even sufficient has yet to be achieved. In this paper we attempt to summarize the state of the solar corona and its evolution in the build up to a CME.

Keywords: corona, CMEs, magnetic field

1. Introduction

One of the greatest challenges in understanding the energy release process resulting in a coronal mass ejection (CME) is to separate "the gold from the dross"[1] and to determine which of all of the observable characteristics of a CME source region are key in driving the corona to erupt. Given the sheer number of studies characterizing pre-CME conditions and the limited space available in this paper we adopt a breadth over depth approach to discuss some of the more recent results pertaining to the state of the corona prior to a CME.

To understand the energy build-up, storage and release processes which govern CME initiation one must understand the magnetic field and its variations before, during, and after an eruption. Several advances have been made in recent years in measuring, modeling, interpreting, and understanding the development of the source region magnetic field both as a photospheric boundary condition and as a 3D topological system. How this field manifests itself in the corona and how the corona responds to its evolution provides the main focus for this paper.

2. Energy Requirements for CMEs

CMEs have many characteristics signifying the conversion of the free magnetic energy (the difference between the total energy in the magnetic field and that in

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[1] Or "the wheat from the chaff" for a less Scottish version

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the corresponding potential field) in the pre-CME corona to other forms, the most notable of which is the rapid acceleration of some 10^{16} g of material. Energy is not only required to accelerate the plasma but also to combat solar gravity, open magnetic field, heat in situ plasma to temperatures in excess of 10 MK, and to accelerate particles to GeV energies. These individual components all have comparable energy budgets of around 10^{30-32} ergs.

The energy to power these various CME phenomena comes from the free energy available in the magnetic field, which must, by necessity, contain significant electric currents. These electric currents are generally expected to be field-aligned in order to satisfy the force-free field environment assumed for the solar corona. For the energy requirement of order 10^{32} ergs, the solar corona must convert a 100 G field over a volume of $\sim 10^{29}$ cm^3, which is equivalent to about 100 post-flare loop structures.

The association between current distributions and coronal energy release is further strengthened by the fact that current concentrations, determined from vector magnetic field measurements, are found to be connected by extrapolated coronal field lines that extend along separatrices (e.g. Mandrini *et al.*, 1995). This suggests that the energy released during CMEs is stored in these field-aligned currents and that the energy release takes place when the currents are interrupted by reconnection either at a separator or on separatrix surfaces (see section 5).

Many of these issues are studied in their own right as part of the CME/flare initiation process. However, we are primarily concerned here with the state of the corona which determines the amount of free magnetic energy available and the temporal evolution which serves to release it as a CME.

3. Photospheric and Chromospheric Fields

The solar photospheric magnetic field is routinely measured with constantly improving instrumentation allowing the full magnetic vector to be determined. Recently, Leka and Barnes (2003a,b) have used the photospheric vector magnetic field data from the Mees Imaging Vector Magnetograph (Mees/IVM) in an attempt to identify pre-eruption signatures in parameters derived from the magnetic field. These authors concentrated on solar flares but many of the results apply directly to active region CMEs. While there are many reported correlations between certain field parameters and associated flare phenomena, the correlations are not perfect nor was much attention paid to the diverse array of similar behavior exhibited in active regions which do not produce flares and/or CMEs (e.g. Mandrini *et al.*, 1995; Song *et al.*, 2002).

Leka and Barnes (2003a,b) identify, and quantify, such parameters as horizontal field gradients, vertical current density, measure of field twist, current helicity density and magnetic shear angles, together with their moments, as potential examples of field quantities related to coronal energy storage and release. They concluded that no obvious flare-imminent signatures were evident in the active regions studied and that to ensure a flare-unique signature one must simultaneously consider numerous field parameters since many candidate parameters can be excluded because of similar behavior in flare-productive and flare-quiet regions. *In other words, considering parameters one at a time, as is often done for specific events, is inadequate.*

While photospheric vector magnetic field measurements generally provide the boundary condition for force-free extrapolations into the corona one must consider the fact that the photosphere is demonstrably not force free and hence may be physically disconnected from chromospheric/coronal sites of magnetic reconnection. Moreover, because of the forced nature of the photosphere, the free magnetic energy available for a CME may not be accurately determined. Metcalf *et al.* (1995) have shown, using the Na I D-line, that chromospheric fields become essentially force free some 400 km above the photosphere (see Figure 1). It has been shown that force-free field extrapolations starting with a chromospheric boundary provide better agreement with coronal structures than those using a photospheric boundary (Leka and Metcalf, 2003).

Solar eruptive phenomena such as CMEs are ultimately driven by energy released from the magnetic field. While infrared and radio techniques for determining the magnetic field in the corona are rapidly being developed, the detail to which we understand the coronal field relies entirely on how well we understand the photospheric and chromospheric boundary condition for that field and the validity of the physical assumptions made to extrapolate the observed boundary field into the region of interest. The ability to measure all three components of the magnetic

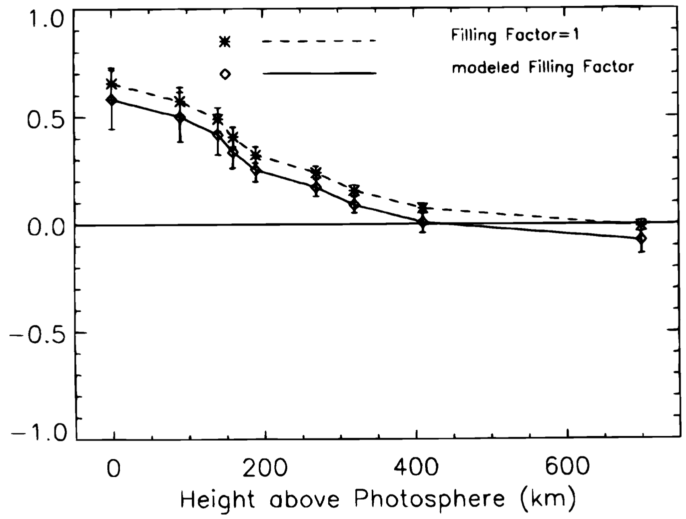

Figure 1. Scaled z-component of net Lorentz force measured in AR7216 as a function of height above the photosphere (from Metcalf *et al.*, 1995, courtesy of T. R. Metcalf).

field in the photosphere and, more interestingly, the chromosphere with increasing resolution (spatial and temporal) and accuracy is making an impact on our understanding of the role of the magnetic field in developing the conditions necessary for a CME to occur.

4. Energy Budgets from Field Measurements

The release of the non-potential magnetic energy required to drive transient activity must be accompanied by a change in the magnetic field topology as it relaxes to a more potential state. One major reconfiguration frequently invoked to describe CMEs is the opening of previously closed field lines. It has been conjectured that, for simple geometries, the energy stored in pre-eruption closed force-free fields can never exceed that of a fully open coronal magnetic field with the same boundary conditions (Aly, 1991; Sturrock, 1991). This has been confirmed by numerical experiments (e.g. Mikic and Linker, 1994). Thus, if a CME was required to open all of the field then the energy source could not be solely magnetic in nature. The Aly-Sturrock conjecture has also been found to apply to more complex magnetic topologies, most notably ones which contain a current-carrying fluxrope of the type often used to model filaments (e.g. Lin *et al.*, 1998). The impact of the Aly-Sturrock conjecture has led many authors to develop schemes with which to maintain the purely magnetic nature of the free-energy released in a CME. Three popular approaches are to assume that

(a) the corona is not, in fact, force-free and that significant energy is stored in cross-field currents (Wolfson and Dlamini, 1997; Gary and Alexander, 1999; Georgoulis and LaBonte, 2004),
(b) the coronal field is only partially opened and that the energy required from the non-potential field need only be sufficient to open part of the closed field (Wolfson, 1993; Antoichos, DeVore and Klimchuk, 1999), or
(c) non-ideal MHD processes, such as magnetic reconnection, are an integral part of the eruption process (e.g. Lin and Forbes, 2000; MacNiece *et al.*, 2004).

For a more detailed discussion on the implications for the Aly-Sturrock conjecture for solar eruptions see Lin *et al.* (2003). One must also note that in addition to the energy required to open the field, the magnetic field must also provide the energy to heat the corona, generate energetic particles, lift the ejected material against the Sun's gravity and accelerate this material into the interplanetary medium.

To fully understand the role played by the magnetic field in powering CMEs, one must be able to determine the available 'free' energy in the magnetic field and to measure how much of this free energy is released during an event. Recently, Metcalf *et al.* (2002) performed an interesting analysis of NOAA Active Region 8299 observed in the Na I 5896 Å spectral line by the Mees/IVM on 1998 August

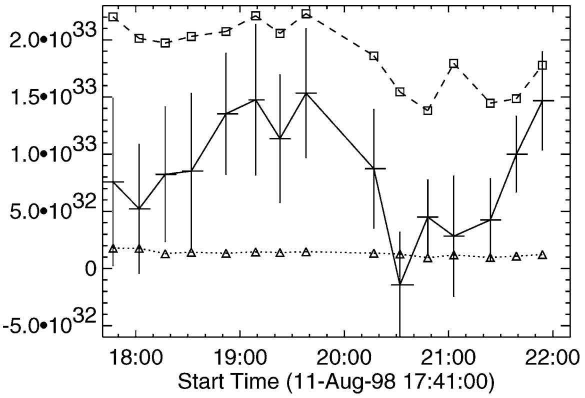

Figure 2. The total magnetic energy in ergs above the chromosphere in AR8299 (*solid line*). The dotted line shows the energy of the equivalent potential field and the dashed line shows the equivalent open field energy. Courtesy of T. R. Metcalf.

11. Using the magnetic Virial theorem, the total (force-free) magnetic energy was calculated as a function of time (Figure 2).

The total magnetic energy shows a rapid decrease beginning around 19:40 UT, falling to the potential field value at ~20:30 UT before rising again more slowly over the remainder of the observation time. This drop in energy corresponds to approximately $\sim 10^{33}$ ergs, more than enough to power a substantial CME. A similar analysis has been performed more recently for the active region 10486 (Metcalf *et al.*, 2005).

5. Role of Multipolar Flux Systems

One of the most vibrant debates over the last few years has been the role of magnetic complexity in the CME process. The magnetic breakout model of Antiochos *et al.* (1999) requires a multi-polar flux configuration as a pre-requisite for a CME eruption. In this scenario, the energy for the eruption builds up in one flux system, evidenced, for example, as shearing of a magnetic arcade, while the presence of a second flux system serves to regulate the coronal response to this build-up in energy by providing a magnetic tension force which restricts the natural expansion of the sheared system. The interaction between these two flux systems then triggers a reconnection in the overlying field allowing the sheared field to erupt.

In recent years, significant advances have been made in understanding the role of the three-dimensional magnetic topology in providing the conditions for the energy release associated with CMEs. In particular, the development of theoretical models of separatrices, separators, and quasi-separatrix layers, coupled to observational studies, have led to the notion that these topological structures, defined by the magnetic field, are the natural locations for current sheets to form and for magnetic reconnection to occur (e.g. Longcope and Silva, 1998).

One clear manifestation of magnetic complexity is that of δ spot active regions which have been found to be directly related to flare and CME productivity (Innes *et al.*, 1999). A δ-configuration active region has two sunspot umbra with a shared penumbra and is frequently observed to have strong localized shear between the two sunspot umbra, providing the conditions for the presence of substantial free magnetic energy. Recently, Tian *et al.* (2005a) performed a statistical study on 104 δ active regions and found that those active regions violating the Hale-Nicholson and Joys Laws but following the hemispherical helicity rule have a much stronger tendency to produce X-class flares, CMEs and strong proton events. There is, therefore, clear observational evidence that increasing magnetic complexity results in more and stronger solar transient activity.

On the theoretical side, the 3D characteristics of magnetic reconnection are highly complex and are only just beginning to be understood. A theoretical understanding of CMEs requires knowledge of the magnetic topology of the parent active region. Given this, CME models must explain not only how and where magnetic energy is released but also the link between the release site and the various CME signatures. Recent developments on the role of separators, separatrices (Mandrini *et al.*, 1995; Longcope and Silva, 1998), and quasi-separatrix layers (Bagalá *et al.*, 2000) in the solar corona, and their application to solar flares and CMEs, have shed new light on the coronal energization story. However, details of how and where the energy storage, release and response occur are still unclear.

6. Role of Filaments

6.1. FILAMENT/CME ASSOCIATION

The relationship between filament/prominence eruptions and CMEs is difficult to fully assess. Many studies typically show a strong but not perfect correlation between the two phenomena with a large spread due to the various data and filament eruption definitions used as well as when in the solar cycle and over what time duration the study was performed. Munro *et al.* (1979) used *Skylab* data to determine that $\sim$55% of CMEs were associated with erupting filaments, while SMM data showed $\sim$45% association (Webb and Hundhausen, 1987; St. Cyr and Webb, 1991). Conversely, Gilbert *et al.* (2000) found from Mauna Loa H_α data that 94% of eruptive prominences had an associated CME. A more recent study by Subramanian and Dere (2001), which concentrated on CMEs emanating from source regions near disk center, found that:

- 44% of CMEs were associated with filament eruptions in active regions
- 15% are associated with filament eruptions outside of active regions

– 41% are associated with active regions with no filament eruptions

giving a total association in the same range as previous studies.

The filament/CME relationship issue is complicated by the fact that filaments only form above the parts of the magnetic polarity inversion line which are also filament channels. Filament channels are chromospheric regions defined by the approximately parallel alignment of fibrils along the magnetic neutral line. In models of CME initiation it is the magnetic configuration of the filament channel which is more important than any mass loading which may serve to define a filament (see, for example, Lin, 2004). The filament/CME relationship studies quoted above do not take into account the possible contribution from filament channel eruptions and so there may be a larger correspondence between the filament-related magnetic configuration and CME initiation. Such as study has yet to be performed.

Recent work by Zhang *et al.* (2001) has looked more closely at the physical connection between the filaments and flares/CMEs with the principal conclusion being that both the magnetic eruption traced by the erupting filament and the impulsive energy release are driven by a destabilization of the overall magnetic field configuration in which the filament and flare are embedded.

6.2. PRE-ERUPTION FILAMENT ACTIVATION

The magnetic field configuration in the solar atmosphere plays a crucial role in the formation and subsequent evolution of filaments. The interaction of a filament/filament channel with the small scale evolution of the nearby magnetic field frequently results in dynamic activation of the filament material, often including counter-streaming bulk flows. While it has often been argued that dips in the magnetic field are required to support the filament material against gravity, recent results (Karpen *et al.*, 2001) have also suggested that the dynamic motions, observed to occur in filaments, can serve to create a high density cool filament in the corona without recourse to dipped field geometries. The importance of this dynamic nature of filaments to the potential for eruption and CME initiation is still being explored but the interaction between the filament magnetic field and the dynamical motions is such that any external disturbance, such as emerging or canceling flux in the filament vicinity, could have dramatic consequences for the filament itself (e.g. Romano, Contarino, and Zuccarello, 2005).

Song *et al.* (2002) found that the observed evolution of the magnetic field in relationship to filament activation implied a continuous transport of magnetic energy and complexity from the lower atmosphere to the corona. In their interpretation, slow magnetic reconnection and helicity re-distribution appeared to play a key role in the energy build-up process resulting in the initiation of a halo CME. Sterling *et al.* (2001) used observations of H_α filament activation in the build-up to a flare and associated CME to demonstrate that while, in this case, the filament itself did not appear to erupt, it underwent significant dynamic motion and morphological changes in the early stages of the CME initiation. The cospatial and cotemporal association with flare-associated brightenings at other wavelengths allowed these authors to conclude that models which allow reconnection high above the core region are more relevant to the CME initiation process. The role played by reconnection in erupting filaments has important consequences for models of CME initiation (see below).

7. Existence of Pre-CME Fluxropes

The existence of fluxropes in the pre-CME corona and the role they play in the CME process is a topic of much debate. There is significant observational and theoretical evidence to support the idea that the coronal cavity surrounding a prominence is an example of a large-scale twisted fluxrope (see Gibson and Low, 2000). In this scenario, the fluxrope geometry is required to support the filament mass against gravity. However, it has been argued from force-free and MHD simulations that dips in the magnetic field form as a result of shearing motions near the neutral line and that such dips can readily support the mass in a filament with no need to resort to the helical structure of a fluxrope (e.g. DeVore and Antiochos, 2000).

The arguments in favor of a fluxrope topology preceding the eruption is based on a combination of modeling and observations. The presence of X-ray sigmoids, the observed three-part structure in CMEs, and observations of twisted fluxropes emerging through the photosphere all point to the presence of a fluxrope configuration in the solar corona prior to any CME eruption with fluxrope models naturally explaining many of the observed phenomena. Lites (2005) concluded, from a study using high angular resolution data with high polarimetric precision from the Advanced Stokes Polarimeter, that low-lying filaments have a profound influence on the photospheric magnetic field and thereby supports the idea of the emrgence of a fluxrope from the solar interior (see also Fan and Gibson, 2004; Tian *et al.*, 2005b).

8. Role of Sigmoids

In recent years the role of helicity injection has been a focal point in the discussion of eruptive events. The attractiveness of magnetic helicity for such studies lies in the fact that it is a globally conserved quantity in ideal MHD and can also be considered to be conserved in resistive MHD on time scales shorter than the global diffusion time scale. This property opens up an array of possibilities for exploring the CME process both theoretically and observationally (see articles in Brown, Canfield, and Pevtsov, 1999).

An observational manifestation of the connection between helicity and CME production is the soft X-ray sigmoid. Sigmoids may indicate the presence of twisted magnetic structures and it has been shown that active regions exhibiting S shapes exhibit a greater tendency to erupt (Canfield, Hudson, and McKenzie, 1999). It is important to understand more about the formation and evolution of sigmoid structures in active regions and to explore the conditions that drive them to eruption if we are to fully understand the conditions leading to solar eruptive events. A key issue here is how the helicity injection is driven: via shearing or direct emergence of twisted flux.

Recent results have been confusing about this issue. On the one hand, Devore (2000) has argued that a significant quantity of magnetic helicity is injected by the action of differential rotation over the lifetime of an active region; enough to explain the total ‘ejected’ helicity detected in interplanetary magnetic clouds. This assertion has been contested by Démoulin *et al.* (2002) and Green *et al.* (2002) who argue that the helicity injected by differential rotation is 5 to 50 times smaller than that inferred to be carried away in CMEs, leaving these authors to conclude that the bulk of the helicity injection is provided by the twist in the sub-photospheric part of the magnetic fluxtubes forming active regions.

In the debate over the role of differential rotation, the strong local shearing often observed near the magnetic neutral line(s) of flare-productive active regions is frequently neglected. Such strong local shear may contribute significantly to the helicity injection into large but otherwise local structures associated with the active region. Recent studies by Kusano *et al.* (2002) have shown that the shearing motions can contribute as much, if not more, helicity as the flux emergence. Converging motions and the subsequent magnetic reconnection at coronal loop footpoints also contribute to the injection of magnetic helicity into the corona from below (e.g. MacKay and van Ballegooijen, 2005).

9. Rotating Sunspots and Sigmoids

Recent observations of rotating sunspots in TRACE white light images and their apparent association with soft X-ray sigmoids have led to the possibility sunspot rotation is a key component in driving sigmoid formation and evolution. A number of rotating sunspot events have now been observed; many associated with some of the largest solar flares of this solar cycle (Brown *et al.*, 2003; Tian *et al.*, 2005a). Tian and Alexander (2006a) found for NOAA AR 9684 that the whole sunspot-group rotated in the same direction as the main sunspot implying that sunspot rotation is a primary driver of helicity production and injection into the corona (see also Tian and Alexander, 2006b).

The role of helicity injection in driving the corona to eruption has been explored by several authors. Rust and Kumar (1994) calculated that a fluxrope becomes unstable when the injected helicity exceeds a critical value, $H_{\mathrm{crit}} > 1.85\phi^2$, where ϕ is the magnetic flux. These instability conditions are supported by recent numerical simulations of fluxrope emergence by Fan and Gibson (2004).

A recent analysis of a long-lived active region (AR 9632) by Tian *et al.* (2005b) finds that the active region exhibited a prolonged period of clockwise rotation. The best-fit twist parameter observed from vector magnetic fields was found to be positive suggesting that the fluxtube making up the active region had a right-handed twist. Coupled with the clockwise group rotation, it is argued that AR 9632 was comprised of a magnetic configuration with the same-handedness of twist and writhe helicity. This points to an active region formation process involving the emergence of a highly twisted and kinked fluxtube through the photosphere.

The close association between soft X-ray sigmoids and CMEs has been established as a possible driver in understanding the physical connection between active region magnetic topology and the potential for eruption. What remains less clear, however, are the physical processes governing this association and the conditions that determine whether an eruption will occur. The rotating sunspot phenomena allows us insight into the formation of the active regions and the source of the observed dynamics while providing crucial diagnostic information on the energization of the corona in the build-up to an eruption.

10. Models of the Pre-CME Sun

A variety of models exist for exploring the CME formation and initiation. The evolution of magnetic flux from the solar interior to the corona is being addressed by several models (e.g. Abbett, and Fisher, 2003) and the results are being coupled to theoretical developments on helicity injection, atmospheric current distributions and magnetic topology (see Lin, Soon, and Baliunas, 2003, for an excellent review).

Distinguishing between the various models of CME initiation is extremely difficult and, to date, has only been performed for very specific cases. Critical to many of them is the pre-eruption conditions of the ambient magnetic field and the subsequent development of the field through the coronal destabilization. The presence, or lack thereof, of a fluxrope geometry in the pre-eruption corona, the location and drivers for magnetic reconnection, the complexity of the magnetic configuration all play significant roles in the various models and all are difficult to measure quantitatively. As theoretical developments progress in tandem with improved models and observations, we should be able to focus on the key physical conditions in the pre-CME Sun which lead to an eruption and understand how variations in these key conditions influence the subsequent initiation and evolution of the CME.

11. Concluding Remarks

Understanding the pre-CME corona is clearly a crucial step in defining the physics which govern CME initiation. It is important in providing the necessary inputs to theoretical models, to increase the accuracy of event prediction and forecasting, and to better understand the physical interaction between magnetic field and plasma in astrophysical systems. As we have stressed in this brief introductory paper, the pre-CME corona cannot be considered in isolation from the pre-CME photosphere and the pre-CME solar interior. The build-up to a CME involves the dynamic coupling between a wide range of phenomena in a wide range of physical environments. Knowing the ‘correct’ combination of parameters required to initiate a CME involves many different facets and, at present, remains elusive.

Many studies have pointed to the apparent importance of a number of individual factors related to CME production. However, the detailed analysis by Leka and Barnes (2003a,b) gives a glimpse of the complexity involved in trying to determine which aspects are CME /flare specific and which are the day-to-day behavior of the parent active region.

Techniques for observing chromospheric and coronal magnetic fields are continuously improving (STEREO, Solar-B and the Solar Dynamics Observatory are all due for launch within the next 2–3 years), while computational and data access and handling resources are rapidly being developed. Thus, in the near-term we can expect significant advances in a number of areas which will significantly improve our chances of identifying key characteristics of the pre-CME corona.

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