CORONAL MASS EJECTIONS

Cover illustration:

Drawing of the corona as it appeared to Temple at Torreblanca, Spain during the total solar eclipse of 18 July 1860 showing what may be the first observation of a CME (see Eddy, J. A.: 1974, *Astron. Astrophys.* **34**, 235).

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CORONAL MASS EJECTIONS

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FOREWORD

Coronal Mass Ejections are a spectacular an violent phenomenon of the solar atmosphere with repercussions throughout the entire heliosphere. They are a spectacular sight when seen to erupt from the Sun with the aid of a coronagraph such as LASCO on the Solar and Heliospheric Observatory SoHO. They are a violent phenomenon when arriving at Earth, pounding on our magnetosphere, and sometimes disrupting all kinds of achievements of the industrial and information age. CMEs have been with us ever since the existence of the solar system, yet only in the past century and a half they make themselves known to us in that way. They are a continuously observable phenomenon only since the Skylab and SoHO era, save for some very brief periods of solar eclipses, one of which is pictured on the front cover. The flare that was observed live through the telescope by Lord Carrington in 1859 led to a gigantic CME that, would it happen today, could easily cause a global blackout. Understanding CMEs is thus a first step in protecting ourselves from their potentially devastating effects.

This volume is the result of a series of workshops during the years 2000–2004 to study in detail origin, development, and effects of coronal mass ejections (CMEs). An international team of about sixty experimenters, ground observers, and theoreticians worked on interpreting the observations and developing new models for CME initiations, development, and interplanetary propagation. Under investigation were also effects on charged particles and related phenomena like energetic particle acceleration, interaction with ambient solar wind and other CMEs, as well as the internal structure of CMEs and its time variation. Fundamental questions concerning CMEs (e.g., CME initiation) and many detailed observations are still not understood. The workshops helped to jointly investigate these questions with scientists from all scientific areas involved.

The workshops were subdivided into eight working groups with always four of them held in parallel. Each participant attended two different working groups. While in the first four working groups (A-D) scientists from the same field discussed and described the topics from their own point of view, the second four (E-H) were topic-oriented with participants from all relevant areas attending. Their goal was to investigate all aspects of the phenomenon and to present a comprehensive interpretation. Occasionally this working scheme led to duplications in different working groups, however, this was intended and helped to further clarify the topic, especially in the case of conflicting statements.

The eight working group reports constitute the main body of the book. In addition, seven introductory chapters describe the state of knowledge prior to the first workshop and serve as introduction to the topics discussed later in more detail. The

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volume is rounded off with a historical overview to start with and with a paper on geoeffectiveness and a summary to conclude.

We are happy to complement with this volume an earlier ISSI book that has been conceived and compiled in a very similar manner. Volume 7 in the *Space Sciences Series of ISSI* was dealing with Corotating Interaction Regions (CIRs), which are shaping the heliosphere at times of solar minimum activity. CMEs, conversely, are an important phenomenon mainly at solar maximum activity. Thus the two volumes now form a nice pair covering the entire solar cycle.

It is a pleasure to thank all those who have contributed to this volume and to the workshops in general. First of all, we thank the authors for writing up their contributions, in particular the Working Group co-chairs for compiling the massive WG reports. All papers were peer reviewed by referees, and we thank the reviewers for their critical reports. We also thank the directorate and staff of ISSI for selecting this topic for a workshop and for their support in making it happen, in particular Roger M. Bonnet, Brigitte Fasler, Vittorio Manno, Saliba F. Saliba, Irmela Schweizer, and Silvia Wenger.

July 2006

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A BRIEF HISTORY OF CME SCIENCE

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Abstract. We present here a brief summary of the rich heritage of observational and theoretical research leading to the development of our current understanding of the initiation, structure, and evolution of Coronal Mass Ejections.

Keywords: CMEs, corona, history

1. Introduction

The key to understanding solar activity lies in the Sun's ever-changing magnetic field. The potential role played by the magnetic field in the solar atmosphere was first suggested by Frank Bigelow in 1889 after noting that the structure of the solar minimum corona seen during the eclipse of 1878 displayed marked equatorial extensions, called 'streamers'. Bigelow (1890) noted that the coronal streamers had a strong resemblance to magnetic lines of force and proposed that the Sun must, in fact, be a large magnet. Subsequently, Henri Deslandres (1893) suggested that the forms and motions of prominences seen during solar eclipses appeared to be influenced by a solar magnetic field. The link between magnetic fields and plasma emitted by the Sun was beginning to take shape by the turn of the 20th Century. The epochal discovery of magnetic fields on the Sun by American astronomer George Ellery Hale (1908) signalled the birth of modern solar physics. This realization led to the modern emphasis on solar transient activity and its relationship to the solar magnetic field and its reconfiguration.

2. Historical Observations

The first terrestrial phenomena recognized to be of solar origin were geomagnetic disturbances. Colonel Sabine, in the middle of the 19th century (Sabine, 1852), noted that the frequencies of both geomagnetic storms and sunspots followed an 11-year cycle. The first step in associating geomagnetic storms with transient solar activity – what later became known as solar flares – rather than simply with the associated spot regions, was the memorable observations in 1859 by British amateur

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astronomers Richard Carrington and Richard Hodgson (Carrington, 1860). They independently witnessed a rapid intense flash of two bright ribbons on the Sun in visible light accompanied, essentially simultaneously, by a marked disturbance of the Earth's magnetic field detected at Kew Observatory in London. Some 17.5 hours later, one of the largest magnetic storms on record occurred. While Carrington was reluctant to suggest a physical connection between the visible event at the Sun and the geomagnetic storm, Balfour Stewart, the Director of Kew Observatory, claimed that they had caught the Sun in the act of producing a terrestrial event. The first systematic evidence for a flare-storm connection, however, didn't come until the work of Hale (1931) (see Cliver, 1994a,b, 1995 for a detailed history). Over a century and a half later, solar and space physicists are revisiting the remarkable event of 1859 in a concerted effort to apply 21st Century tools to model its solar and terrestrial effects (e.g. Tsurutani *et al.*, 2003).

The importance of the "chromospheric eruptions", as the early flares were known, for the Earth's space environment came through the study of these events and their apparent association with geomagnetic storms. Lindemann (1919) suggested that geomagnetic storms were caused by ejections of magnetically neutral matter from the Sun impacting the Earth's magnetic field several days afterwards, as illustrated in the top panel of Figure 1. The statistical association of large flares and

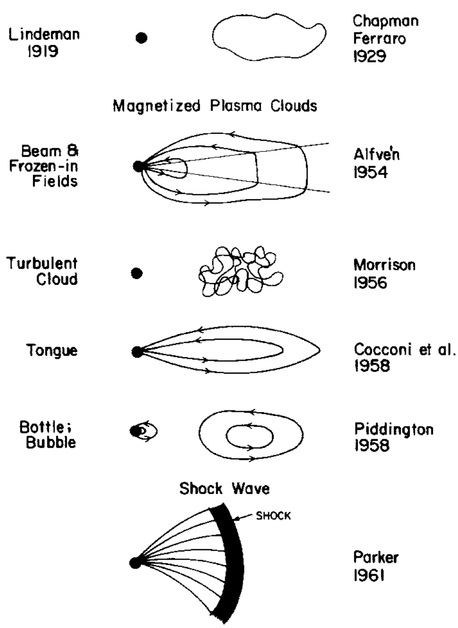

Figure 1. Early concepts of the structure of ICMEs, showing (from the top): unmagnetized material; a plasma cloud including frozen-in magnetic field loops; plasma including turbulent magnetic fields; a "tongue" of magnetic field loops rooted at the Sun; a disconnected "plasmoid" or "bubble"; and a shock wave ahead of a region of enhanced turbulence (Burlaga, 1991).

storms was solidified by Newton (1943), who surveyed all the large flares observed since 1892 and found a significant correlation between those flares and subsequent geomagnetic storms.

The expulsion of hydrogen was also observed near the time of peak intensity of the majority of bright flares. These emissions occurred in specific directions, usually along nearly vertical trajectories, and exhibited all the characteristics of the well-known eruptive prominences. The initial velocity of a mass expulsion was around 500 km/s and, while its H brightness was several times that of normal quiescent prominences, it was still much fainter than the flare emission itself. The physical relationship between solar flares and prominences dates back to the *disparition brusques* phenomena catalogued in the late 1940s by researchers at Meudon Observatory. The factors which cause this relationship are important since filament eruptions appear to have a role in many of the coronal transients that make up the most energetic solar activity. However, despite the fact that solar prominences have been observed for several hundred years, they were not thought to play a role in geomagnetic storms. A relationship was suggested by Greaves and Newton (1928); but Hale disagreed, pointing out three years later (Hale, 1931) that erupting prominences generally fall back to the Sun. The connection between prominence eruptions and geomagnetic storms, while hinted at by Newton (1936), was not fully appreciated until the work of Joselyn and McIntosh (1981).

It was pointed out by Kiepenheuer (1953) that the sudden disappearance of a prominence could result as the prominence rises into the corona with an increasing velocity that may eventually exceed the velocity of escape. This process was studied in detail with the conclusion that the ejected plasma is accelerated as it rises. Such studies were the precursors to present-day investigations into the relationship between filament eruptions and flares, and preceded by as much as three decades the discovery of coronal mass ejections.

Combined with the apparently clear association between geomagnetic disturbances and solar flares, the observed acceleration of material associated with prominence eruptions suggested a physical mediator for the transfer of energy from the solar atmosphere to the Earth's. Given the incontrovertible evidence for the existence of corpuscular radiation from the Sun, a major effort to detect the particles in transit was performed. Waldmeier (1941) and Ellison (1943) independently detected a strong asymmetry in the wings of the H emission line of flares. Ellison interpreted this as being due to the absorption by hydrogen atoms expelled in all directions from the flare site. This asymmetry was subsequently confirmed with spectrohelioscopes at observatories around the world. Ellison did caution, however, that: "While these asymmetric profiles provide the strongest possible evidence for the general expulsion of hydrogen during flares, we must await further work in order to prove that this constitutes the initial departure of the geomagnetic storm particles". Coinciding with large flares, sudden increases in cosmic ray intensity were occasionally detected (e.g., Forbush, 1946; Meyer *et al.*, 1956), suggesting that flares were also able to accelerate charged particles to energies in excess of

5 GeV. The notion that the particles could be accelerated en route did not occur to researchers at the time.

Early cosmic ray studies also provided evidence for ejections of material from the Sun that are related to geomagnetic storms, and strongly suggested that this material was magnetized. Decreases in the galactic cosmic ray intensity that accompany some storms were reported by Forbush (1937), and these were later explained by the exclusion of the cosmic rays from "magnetic bottles" formed when the ejection of highly-conducting coronal material drags solar magnetic fields into interplanetary space. Such bottles may remain connected to the Sun (Cocconi *et al.*, 1958) or be disconnected plasmoid-like structures (Piddington, 1958), as illustrated in Figure 1. An alternative, a turbulent cloud with tangled magnetic fields, also shown in Figure 1, was proposed by Morrison (1956).

Gold (1955) noted that many geomagnetic storms have remarkably abrupt onsets and suggested that shocks generated ahead of fast ejections cause the sudden onsets as they arrive at the Earth. The possibility that a large solar flare could drive a hydrodynamic blast wave to the Earth in 1–2 days was demonstrated by Parker (1961) (Figure 1). This idea was subsequently "confirmed" by a series of calculations on interplanetary shocks and was supported by observations of shocks which became available with the advent of in-situ measurements of the interplanetary plasma and magnetic fields in the space era (e.g., Sonnet *et al.*, 1964). Nevertheless, Hundhausen (1972) noted a number of apparent discrepancies between shock wave models and observations, expressing some reservations about the association between large flares and interplanetary shocks. Thus, by this time, one year prior to the launch of Skylab, the physics of storm-causing interplanetary shocks was understood but the shocks themselves could not be directly related to any coronal events.

While there had been indications of large, transient disturbances traveling through the Sun's outer corona in solar radio records and coronagraph observations from earlier unmanned spacecraft, it took the as-then unprecedented sensitivity of the Skylab coronagraph to put these observations in perspective. Skylab observations showed "gargantuan loops rushing outwards from the Sun at remarkable speeds" with the frequently observed "expulsion from the Sun of an eruption bigger than the disk of the Sun" (see Eddy, 1979, chapter 7). The first quantitative summary of the Skylab coronal disturbances (Gosling *et al.*, 1974) strongly indicated that these transients were the long-sought eruptions of coronal material required to produce the high-speed solar wind flows responsible for geomagnetic storms: measured speeds ranged from <100 km/s to >1200 km/s (Gosling *et al.*, 1976). These events came to be known by a variety of names such as "plasma clouds", "solar mass ejections", "mass ejection coronal transients", "coronal mass ejection events" and then simply "coronal mass ejections".

The detailed observations of CMEs by Skylab led Eddy (1974) to scour eclipse records for evidence of similar phenomena. The paucity of reports of such coronal transients was readily explained by the combination of the Skylab CME occurrence rate, the typical CME speed and the short duration of eclipse totality, resulting in

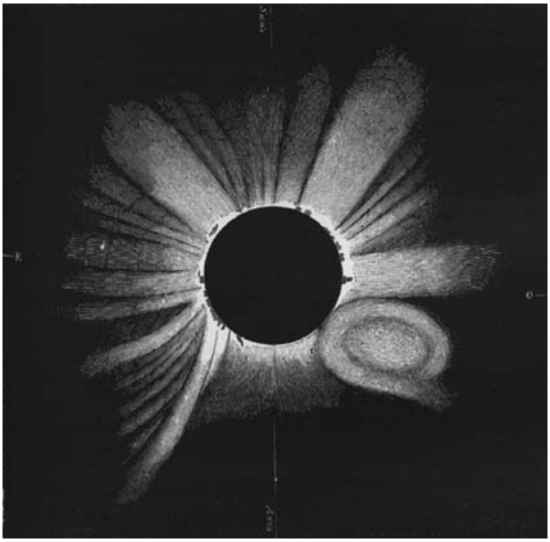

Figure 2. Drawing of the corona as it appeared to Tempel at Torreblanca, Spain during the total solar eclipse of 18 July 1860 showing what may be the first observation of a CME (see Eddy, 1974).

the expectation of one chance per century of capturing a CME during an eclipse. Despite these slim odds, Eddy (1974) found signs of a transient, very similar in form to the Skylab CMEs (see Figure 2) in a drawing of the Spanish eclipse of July 18, 1860, made by the Italian astronomer Gugliemo Tempel with supporting evidence from other observers. Other examples include a disconnection event from 16 April 1893 (Cliver, 1989) and a 3-part structure observation from an eclipse on 29 May 1919[1].

Following Skylab, several space-based coronagraphs were flown to study the transient Sun. The Solar Maximum Mission (SMM), launched in 1980, significantly advanced our knowledge of solar flares and coronal mass ejections. The nine years of SMM coronagraph observations resulted in a dramatic shift in the paradigm of the Sun-Earth interaction and brought CMEs to the fore of solar-terrestrial research. A complete summary of the contribution of SMM to our understanding of solar transients can be found in Strong *et al.* (1998). The theme of solar-terrestrial interactions continued into the 1990's with the launches of the Yohkoh and SOHO satellites. Observations by Yohkoh/SXT have demonstrated that CMEs typically produce a response in the hot corona even when this response does not include typical flare emissions. In particular, intriguing "dimmings" of the X-ray corona preceding arcade formation suggest that a significant volume (and mass) of gas is ejected from the flare site, consistent with coronagraph observations in white light. The quantitative relationship between this ejected mass and that seen in the CME, however, has yet to be established.

[1]Memoirs of the RAS, 64, plates 18 and 19, 1929; E. W. Cliver personal communication

Coronal mass ejections returned to the fore of solar activity research with the launch of SOHO in 1995. The combination of three white light coronagraphs, collectively known as LASCO, together with a full disk EUV imager (known as the Extreme Ultraviolet Imaging Telescope, EIT) has demonstrated the coronal consequences of these large-scale magnetic reconfigurations. While the characteristics of the CMEs observed by LASCO are similar to those observed in previous coronagraphs, there are several new aspects: (i) many CMEs are accompanied by a global response of the solar corona, (ii) many show acceleration to the edge of the LASCO field of view (32 R_s), (iii) partial disconnection is a frequent occurrence, (iv) CMEs are occurring more frequently than had been expected at solar minimum, and (v) CMEs undergo extensive internal evolution as they move outward. (see Howard *et al.*, 1997) In addition, LASCO has a greater ability to detect CMEs moving well out of the plane of the sky, in particular 'halo' CMEs which may be directed towards the Earth. The dimming events, discovered by Yokhoh, have been confirmed in EUV observations by EIT and also by the TRACE spacecraft. (e.g. Thompson *et al.*, 1998; Wills-Davey and Thompson, 1999)

CME research also extends to their interplanetary and heliospheric effects, with significant effort being devoted to identifying and measuring in-situ the characteristics of the material ejected into interplanetary space during CMEs. Such material was first identified in the early space era through regions of plasma with unusual characteristics, such as enhanced helium abundances (Hirshberg *et al.*, 1970) commencing a few hours following some interplanetary shocks. These regions extended over periods of ∼1 day, suggesting scale sizes of ∼0.2 AU, and were initially referred to by terms such as "shock driver", "piston", "plasma cloud", "solar mass ejection", and "ejecta", under the supposition that this plasma was the material ejected from the Sun that generated the shock. At the time of these first observations, it was assumed that the ejected material originated, or at least contained a component, from solar flares that was accelerated through some explosion, or piston process. Subsequent combined CME observations by coronagraphs and in-situ measurements made by spacecraft off the limbs of the Sun (e.g., Schwenn, R. 1983; Sheeley *et al.*, 1985; Lindsay *et al.*, 1999) or near the Earth (e.g., Webb *et al.*, 2000) have demonstrated the clear association (though not necessarily one-to-one, e.g., Cane *et al.*, 2000)) between CMEs launched in the general direction of the observing spacecraft and the subsequent detection of shocks and the related ejected material. The interplanetary manifestations of CMEs are currently frequently termed "Interplanetary Coronal Mass Ejections" (ICMEs), although this does imply an association with CMEs that is arguably not completely proven.

ICMEs are characterized by an array of signatures, most of which had been identified by the early 1980's with the exception of certain compositional signatures which are only observable under all solar wind conditions with the later generation of specialized instruments, such as the Solar Wind Ion Composition Spectrometer (SWICS) on the Advanced Composition Explorer (ACE) satellite. The in-situ signatures of ICMEs are summarized by Zurbuchen and Richardson (this volume).

It was also clear from early in-situ observations (e.g., Bryant *et al.*, 1962) that CME-driven shocks can accelerate particles as they move out through the heliosphere such that major solar energetic particle events include, and may even be dominated by, shock-accelerated particles (e.g., Cane *et al.*, 1988). See the papers in this volume by Cane and Lario, and by Klecker *et al.* for further discussion of this topic.

3. Theories

The observational developments, as in any scientific field, progressed hand-in-hand with theoretical considerations. The development of theoretical models of solar activity has as rich a history as the observational side of solar physics (see Alexander and Acton, 2001 for a more complete discussion of the early developments in flare theory). However, it was realized very early that most solar phenomena had something to do with the magnetic field and its variability. Consequently, the major improvements in our theoretical understanding of solar activity has come about through our ability to investigate the interplay between the plasma and the magnetic field. An important series of models worth mentioning briefly here appeared in the 1960s and 1970s. The first of these, by Carmichael in 1964, proposed that magnetic field lines high above the photosphere could be forced open by the solar wind. Developments of this line of thinking appeared from Sturrock and Coppi (1966), Hirayama (1974) and Kopp and Pneuman (1976) earning this class of the models the sobriquet of the CSHKP model. Since these early models, there have been major advancements in the development of theories to explain the initiation and evolution of solar eruptive transients (Forbes *et al.*, this volume). The development of theoretical models is a small but vibrant area of solar research and the synergy with observation only helps to improve the subtlety and relevance of the theoretical ideas.

4. Overview

As this volume indicates, the study of the formation and development of Coronal Mass Ejections at the Sun and their impact on the heliosphere is a burgeoning field of research with important consequences for our understanding of the Sun and its interaction with the interplanetary medium and planetary magnetospheres. The recent ubiquitous interest in Space Weather is a fitting testament to the heritage provided by the 150 year effort to understand the Sun-Earth connection.

There is still much to learn about solar eruptive events, but it is clear that flares, CMEs, and ICMEs are all important components of the Space Weather system. Studies of these phenomena will continue to drive our need to understand solar variability and increase our ability to predict these events and their potential terrestrial effects.

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CORONAL MASS EJECTIONS: OVERVIEW OF OBSERVATIONS

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Abstract. We survey the subject of Coronal Mass Ejections (CMEs), emphasizing knowledge available prior to about 2003, as a synopsis of the phenomenology and its interpretation.

Keywords: sun, corona, CMEs

1. Background

A Coronal Mass Ejection (CME) is "...an observable change in coronal structure that (1) occurs on a time scale of a few minutes and several hours and (2) involves the appearance and outward motion of a new, discrete, bright, white-light feature in the coronagraph field of view" (Hundhausen *et al.*, 1984; Schwenn, 1996). With a kinetic energy that may exceed 10^{32} ergs, it is one of the most energetic forms of solar activity. We believe a CME in essence to be the eruption of a magnetically closed volume of the lower and middle corona.[1] The CMEs are interesting in their own right; they also have substantial effects on the Earth's environment. In this chapter we give an overview of the CME phenomenon, touching on all of its manifestations – traceable now from the photosphere into the distant heliosphere as far as human exploration has extended. This chapter summarizes the basic knowledge available prior to 2003. Figure 1 shows representative examples.

Originally termed "coronal transients," CMEs entered the modern era (but Figure 1 also shows one historical observation) with the Skylab observations (Gosling *et al.*, 1974; Munro *et al.*, 1979). Detailed records from the P78-1 coronagraph (Howard *et al.*, 1985) provided an early comprehensive view, including the discovery of the "halo CME" (Howard *et al.*, 1982; see also Alexander *et al.*, 2006, this volume) now known to be mainly responsible for terrestrial effects.

The modern view of CMEs has broadened considerably as the result of observations made by instruments other than coronagraphs at visual wavelengths. The Chapman Conference of 1997 (Crooker *et al.*, 1997) provides an excellent set of papers covering both the classical and the newer material available then.

[1]In our usage the lower and middle corona are below and above, respectively, the projected height of a typical coronagraphic occulting edge.

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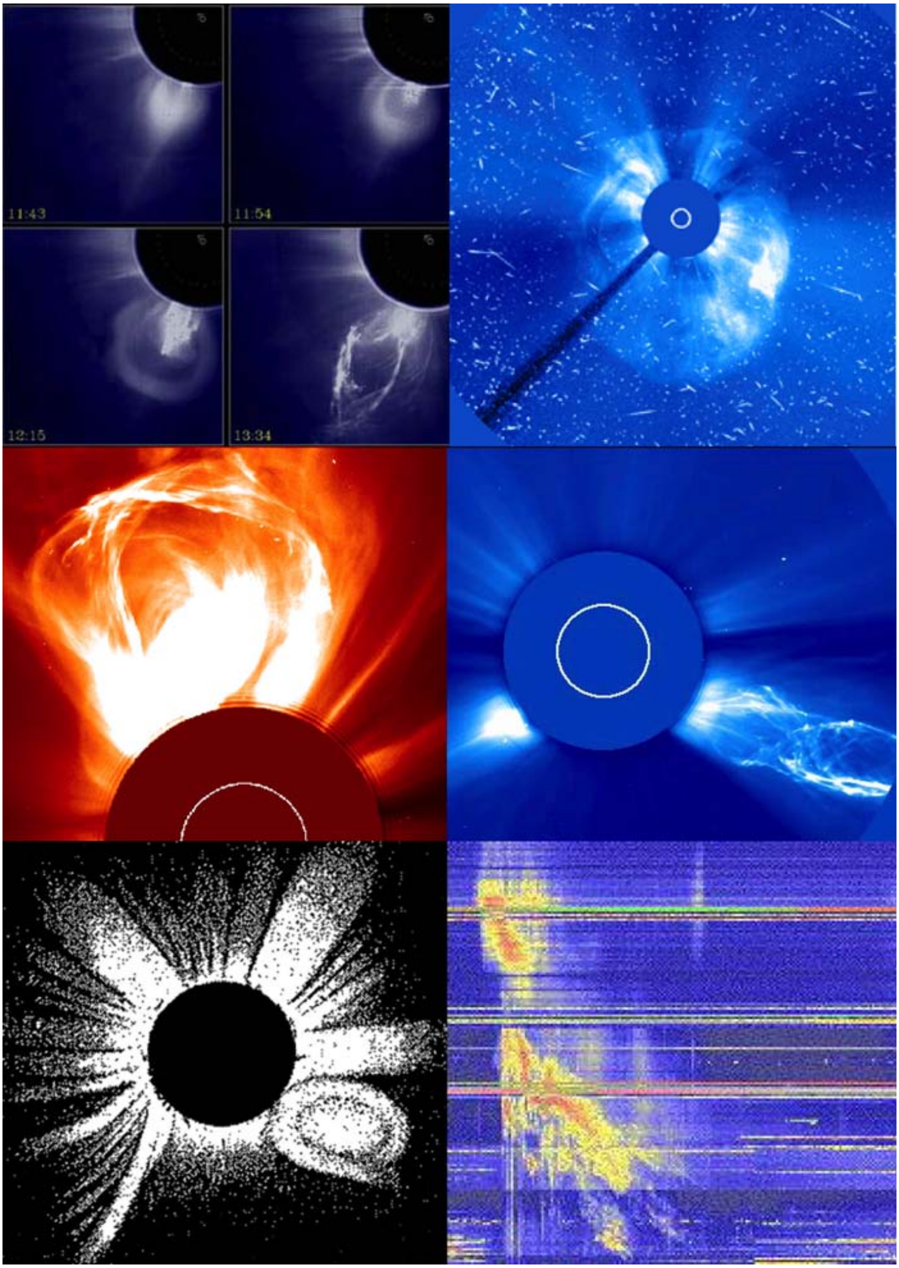

Figure 1. Six views of coronal mass ejections. Top: Prototypical "3-part CME" as observed by SMM; halo CME from LASCO. Middle: two views of flux-rope CMEs (LASCO). Bottom: Historical eclipse observation of possible CME; type II radio burst (Culgoora spectrogram).

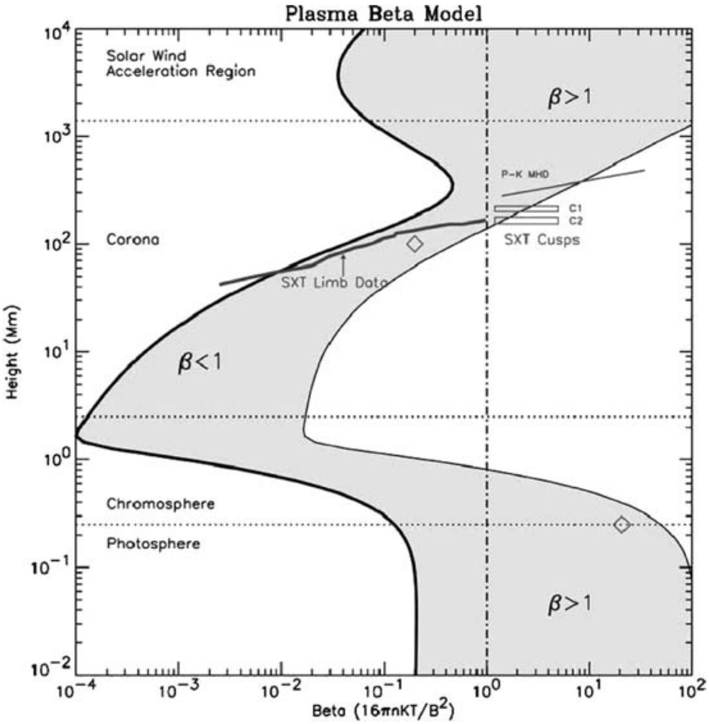

Figure 2. Survey of coronal plasma β, from Gary (2001), as a function of height above the photosphere. Note that this display ignores non-radial variation. A similar plot for Alfvén speed would show a radial decrease outward, followed by a rise to a local maximum in the upper corona, then a monotonic decline into the heliosphere.

The solar corona consists mainly of hot (10^6 K) and ionized plasma, bounded above by the solar wind and below by atmospheric layers at much lower temperatures. The magnetic field dictates the structure of the corona, according to its generally low plasma beta (the ratio of gas to magnetic pressure; see Figure 2). CME movies give the impression that a sector of the coronal field simply expands and opens out into the solar wind. It thus (temporarily, at least) must increase the open-field fraction of the photospheric field. The corona (to $10R_\odot$) contains 10^{18-19} g according to the semi-empirical models of Withbroe (1988). The mass content above $3R_\odot$, representative of the domain of coronagraphic observations, would not amount to 10^{15} g in the angular domain of a large CME, so that (as the images show) most of the CME mass typically originates in or below the lower corona.

Figure 2 shows estimates of the distribution of β with height (Gary, 2001); note that this survey ignores non-radial structure. Large local variations of plasma β occur in active regions because of the presence of dense loops. Our direct knowledge of the coronal magnetic field is extremely limited because of observational difficulties. As a result one must use representative ranges (as presented in Figure 2) or extrapolations from the photospheric Zeeman-splitting observations, usually based on the force-free condition $\nabla \times \mathbf{B} = \alpha\mathbf{B}$ (where α generally would be a function of position as determined by subphotospheric conditions). These extrapolations have systematic errors, the most obvious of which is that the photospheric observations refer to a layer that is not itself force-free.

In general the corona supports a system of currents, and so potential-field representations based upon data at the lower boundary cannot exactly represent the geometry. The "potential field source surface" (PFSS) method ingeniously sidesteps this problem (Altschuler and Newkirk, 1969; Schatten *et al.*, 1969), at least for the large-scale structure. In this approach one uses a potential representation from the photosphere out to an optimum spherical "source surface," almost universally now set at $2.5 R_\odot$. A fictitious current flows at this surface with such a distribution that the field external to it is strictly radial. Several groups pursue this practical approach, which (for example) appears to do a good job in defining coronal holes and open field for heliospheric applications (e.g., Wang *et al.*, 1996). Unfortunately it cannot be used to represent magnetic energy storage within the coronal domain itself, so it is of little use in studying the details of flare or CME evolution.

The photospheric magnetic field does not reflect CME occurrence in any obvious way, although observations of subtle flare effects do exist, especially in limb observations where a small tilt in the field may affect the line-of-sight component (Cameron and Sammis, 1999). This absence of strong effects is consistent with the general idea of coronal energy storage and release to explain the transients, but this conclusion must be understood more quantitatively. It is also consistent with the important idea (Melrose, 1995) that the vertical currents responsible for coronal magnetic energy storage must have their origin deep in the convection zone, and not vary appreciably during the transient.

CMEs usually come from active regions in close association with major solar flares, but they also can come from filament channels in the quiet Sun. The three-part structure for the quiet-Sun events, often associated with filament eruptions from the polar crown, can be directly identified with the appearance of a streamer cavity seen on the limb in white light or soft X-rays. Quiet-Sun events correspond to weak flare-like effects seen in chromospheric observations (Harvey *et al.*, 1986); such events often have slow, low-temperature soft X-ray emissions that do not produce recognizable GOES[2] signatures (e.g., Hudson *et al.*, 1995).

2. Techniques of Observation

CMEs are observed directly by white-light coronagraphs, mostly via photospheric light Thomson-scattered by coronal electrons. Eclipse images show coronal structure definitively well, and in spite of their infrequency have shown CMEs in rare historical cases (see Figure 1). Phenomena related to CMEs appear at virtually

[2]Geostationary Operational Environmental Satellite.

every observable wavelength (the "non-coronagraphic" observations; see Hudson and Cliver, 2001) as well as in many interplanetary signatures (e.g., Gosling, 1991).

2.1. Optical/UV

Bernard Lyot's invention of the coronagraph permitted time-series observations of changes in coronal structure. A coronagraph is a special-purpose telescope that images only the corona, suppressing the bright photosphere by either internal or external occultation; stray-light levels can now be reduced to the order of 10^{-15} of disk brightness at an elongation of 18° (Buffington *et al.*, 2003). The essential point of the visible-light observations is that they show the electron-scattered emission of the K-corona; the intensity thus determines the line-of-sight column density of the corona, which is optically thin outside prominences. The high temperature of the corona smears out the photospheric Fraunhofer line spectrum, but an emission-line component appears prominently at short wavelengths.

2.2. Radio

Within the vast spectral range of ground-based radio techniques (roughly 3×10^6 Hz to 10^{12} Hz) one finds a variety of emission mechanisms and observing techniques. The meter-decimeter wavelength ranges show us the corona mainly via coherent emission mechanisms; because these are bright at the plasma frequency one gets a rough measure of the density. At shorter wavelengths the optical depth decreases until at submillimeter wavelengths one sees right into the upper photosphere. Free-free emission can be detected from either over-dense coronal loops following flares or the quiet lower solar atmosphere; gyrosynchrotron radiation comes from high-energy electrons. Below about 10 MHz radio receivers in space allow us to study solar-wind phenomena as far down as the local plasma frequency at 1 AU, normally at $\sim 3 \times 10^4$ Hz.

2.3. EUV/X-ray

The EUV and X-ray wavelengths show us the K-corona directly in emission. The emissivity of the hot corona decreases rapidly at short wavelengths, but the extreme temperature dependence ($\propto e^{-h\nu/kT}$ in the limit) results in large image contrast for X-rays at $h\nu > kT$. Focusing optics (grazing incidence for soft X-rays to a few keV; normal incidence for narrow-band imaging longward of about 100 Å) with good angular resolution led to many discoveries. The first systematic X-ray and EUV observations were those from Skylab, and showed coronal holes, flares, CME-related ejecta and dimmings, and in general many counterparts of phenomena previously studied only at other wavelengths. The normal-incidence TRACE observations have revolutionized our views of coronal dynamics, owing to their high resolution (0.5″ pixels; see Handy *et al.*, 1999).

2.4. Interplanetary

The interplanetary data mostly consist of *in-situ* measurements of particles and fields, in which one characterizes the bulk parameters (speed, density, temperature, magnetic field) of the solar wind, plus the distribution functions and abundances (ionization states, elements, isotopes) within the plasma (Zurbuchen and Richardson, 2006, this volume; Wimmer *et al.*, 2006, this volume). These include solar energetic particles resulting ultimately from flares and CMEs; the interplanetary shock waves have a close association with CMEs (Sheeley *et al.*, 1985), and these shock waves cause SEP (Solar Energetic Particle) events (e.g., Reames, 1999; Klecker *et al.*, 2006, this volume; Cane and Lario, 2006, this volume). Most of the interplanetary observations are from near-Earth space, but Helios, Ulysses, and the Voyagers have now explored as far in as $0.3R_{\odot}$, out of the ecliptic plane, and out to the heliopause (Gazis *et al.*, 2006 his volume).

3. Coronagraphic Observations

3.1. White Light

CMEs are unambiguously identified in white light coronal observations as outward-moving density structures (Tousey, 1973; Gosling *et al.*, 1974). The rate at which they occur correlates well with the solar activity cycle (Webb and Howard, 1994); (St. Cyr *et al.*, 2000); their appearance does not significantly differ between sunspot minimum and sunspot maximum. CMEs often appear as a "three-part" structure comprised of an outer bright front, and a darker underlying cavity within which is embedded a brighter core as shown in Figure 1 (Hundhausen, 1987). The front may contain swept-up as well as primary material (Hildner *et al.*, 1975; Illing and Hundhausen, 1985). The cavity is a region of lower plasma density but probably higher magnetic field strength. The cores of CMEs can often be identified as prominence material on the basis of their visibility in chromospheric emission lines (Sheeley *et al.*, 1975; Schmieder *et al.*, 2002) and often appear to have helical structure.

In addition to the familiar 3-part CMEs, other types commonly occur – narrow CMEs and CMEs with clear flux-rope morphology, in particular (Howard *et al.*, 1985). Halo CMEs (Figure 1) have special properties resulting from projection effects (see Burkepile *et al.*, 2004).

Five different coronagraphs have contributed substantial information about CME properties in a statistical sense: those on Skylab, Solwind, SMM, and SOHO from space, and the MK3 coronagraph at Mauna Loa Solar Observatory. These instruments have different properties (sampling, radius of occulting edge, epoch of observation) but a consistent picture generally prevails. We can distinguish the observational properties of CMEs into morphological (geometry, kinematics) and

TABLE I
CMEs: average properties.

	MK3[a]	SMM[b]	Skylab[c]	Solwind[d]	LASCO[e]
Period of observation	1980–99	1980 1984–89	1973–1974	1979–1980 1984–85	1996– present
Field of view ($R_\odot$)	1.15–2.24	1.8–$\sim$5	2–6	3–10	1.1–32
Angular Size (deg)	37	47	42	43	72
Speed (km/s)	390	349	470	460	424
Mass (g)		3.3×10^{15}	4.7×10^{15}	4.0×10^{15}	1.7×10^{15}
K. E. (erg)		6.7×10^{30}	3.1×10^{30}	3.4×10^{30}	4.3×10^{30}
P. E. (erg)		7.1×10^{30}	8.0×10^{30}		

[a] St. Cyr *et al.* (1999).
[b] Hundhausen (1993).
[c] Gosling *et al.* (1976), Rust (1979) and Hundhausen (1993).
[d] Howard *et al.* (1985) and Howard *et al.* (1986).
[e] St. Cyr *et al.* (2000) and Vourlidas *et al.* (2002).

physical (mass, energy) categories. For reference we quote the average properties from the different sources in Table I; these are roughly consistent among the different data sets.

It is important to note that these are measurements of CME apparent properties as seen projected in two dimensions in an optically thin medium. This projection introduces systematic distortions in the appearance of the object and makes the determination of point properties more difficult and generally model-dependent. The distortions are small for structures close to the "plane of the sky" (i.e., the plane containing the solar limb) but can be severe elsewhere. Objects located away from the plane of the solar limb appear at higher apparent latitudes, have larger apparent widths and lower apparent heights than their true values (Hundhausen, 1993; Burkepile *et al.*, 2004). In addition, the lower apparent heights lead to underestimates of CME speeds (Hundhausen *et al.*, 1994). The underestimation of the height also impacts the brightness and, hence, the mass estimate.

3.2. Morphological and Kinematical Properties

3.2.1. *Position Angles*

The apparent latitude of a CME is typically determined from the position angle of its projected angular centroid (Howard *et al.*, 1985). Hundhausen (1993) showed that this depends strongly upon the CME source location. They also found the distribution of apparent latitudes of CMEs to be unimodal and to center at the heliomagnetic equator. There is a systematic variation with the solar cycle.

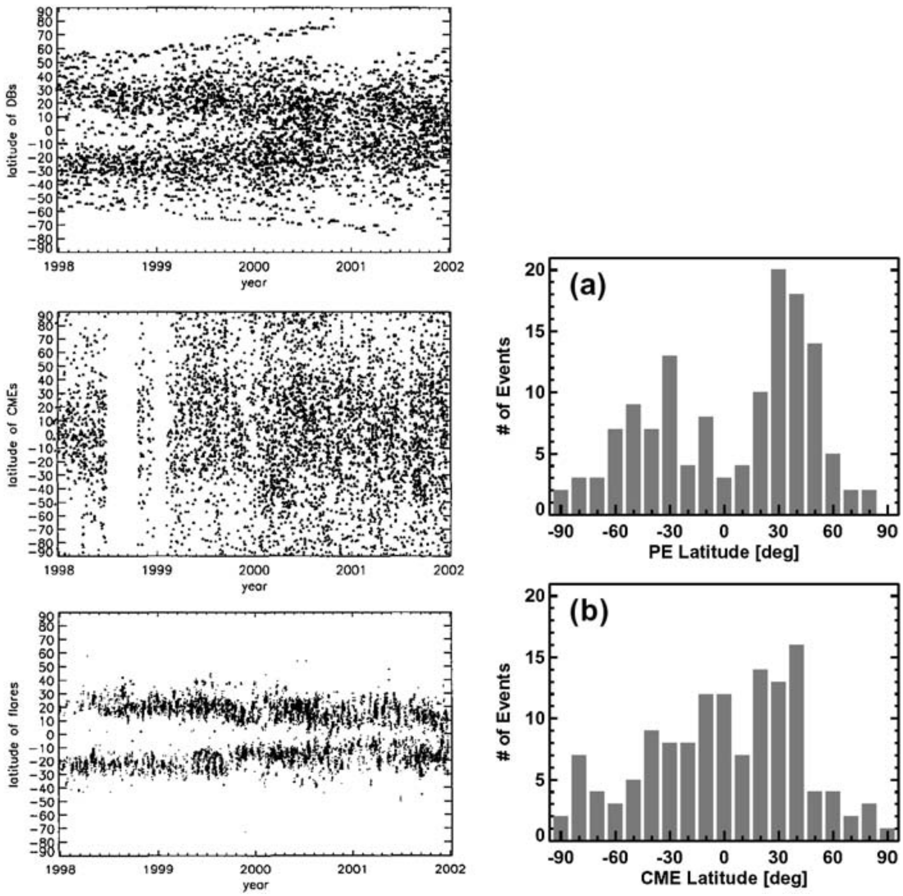

Figure 3. Left: Apparent latitudes (position angles) of CME occurrence, as observed by SOHO (center panel) compared with disappearing filaments (*top*) and flares (*bottom*) (from Pojoga and Huang (2003)). *Right*: Similar comparison between microwave-observed filament locations (*top*) and their corresponding CMEs (Gopalswamy *et al.*, 2003). The statistical views show that CME origins in the low corona (flares or CME eruptions) have a bimodal distribution in latitude, whereas the CMEs have a unimodal distribution concentrated at the equator.

Around solar minimum the CMEs tend to occur at lower latitudes, and as the rise to maximum occurs, the apparent latitudes increase. The CME apparent latitudes are well-correlated with the latitude distribution of the helmet streamers (Hundhausen, 1993) rather than with the "butterfly diagram" latitudes of active regions. The LASCO observations of the current cycle (St. Cyr *et al.*, 2000) confirm this observation (Figure 3).

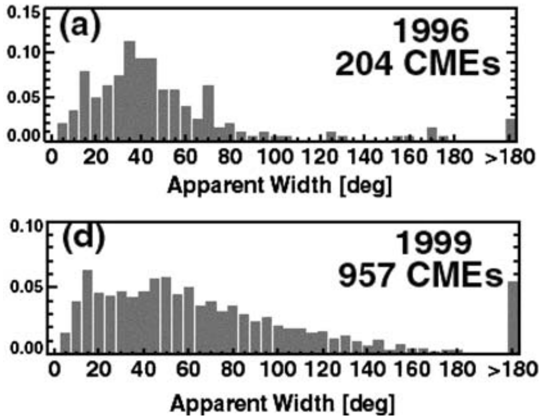

Figure 4. Angular sizes of CMEs vs. phase in the solar cycle, based upon LASCO observations (St. Cyr *et al.*, 2000). The number of wider CMEs increases towards solar maximum (Hundhausen, 1993).

3.2.2. *Angular Sizes*

The smallest average CME angular size in Table I is measured in the low coronal measurements from MK3 (St. Cyr *et al.*, 1999). This suggests that some CMEs may expand in the early stages of their formation and propagation, particularly those events (the majority; see (Subramanian and Dere, 2001) that originate in and near active regions (Dere *et al.*, 1997). The higher average angular sizes determined from the outer coronal observations from LASCO (St. Cyr *et al.*, 2000) probably result from projection, since the LASCO coronagraphs are able to detect many disk-centered CMEs with large apparent widths. Figure 4 compares CME apparent widths between states of low and high solar activity (St. Cyr *et al.*, 2000). The data generally indicate a decrease in the percentage of wide CMEs during the descending or minimum phases of the solar cycle for each of the three datasets.

3.2.3. *Speeds*

The average CME speeds determined from the various datasets do not vary significantly (see Table I). This speed, however, does have a solar-cycle dependence, though not a simple one. Both SMM and Solwind report very low speeds for CMEs in 1984, during the declining phase of activity. However, the average SMM CME speeds are higher in 1985 and 1986, at solar minimum, due to the appearance of new active regions which are associated with a handful of high-speed CMEs. The lowest average LASCO CME speed occurs at solar minimum (1996) and gradually increases through 1998 with the appearance of a high-speed tail in the distribution which may be associated with the occurrence of new-cycle active regions. CMEs associated with active regions have higher average speeds than CMEs associated with eruptive prominences located away from active regions (Gosling *et al.*, 1976).

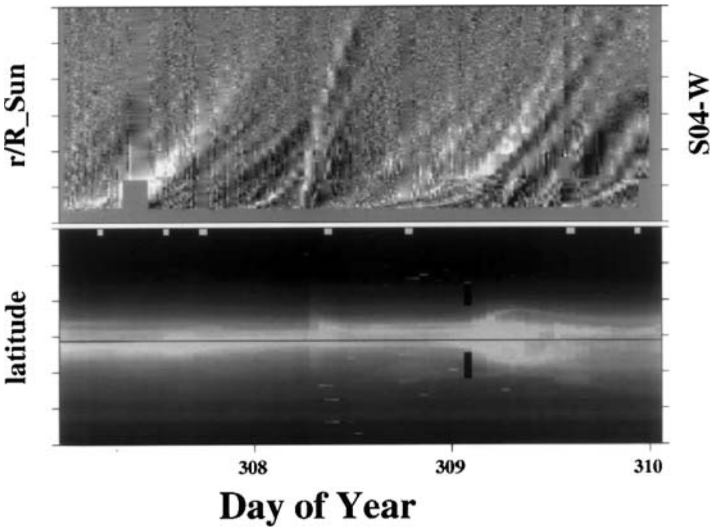

Figure 5. Illustration of the two types of CME motion suggested by Sheeley *et al.* (1999). The upper panel shows brightness distribution along a radial line (in this case 4° N of W, or a position angle of 274°). The decelerating event of Nov. 4, 1997, occurs early on Day 308 and was associated with an X2.1 flare at S14, W33. Many accelerating events can be seen as well.

3.2.4. *Accelerations*

MacQueen and Fisher (1983) found that CMEs associated with flares had more rapid accelerations. Sheeley *et al.* (1999), on this basis, argue for the existence of two types of CMEs: those associated with flares, which tend to appear at full speed and then decelerate, and the filament-eruption CMEs, which slowly accelerate (see Figure 5 for examples).

3.3. Physical Properties

3.3.1. *Masses*

The excess brightness of a given image relative to a pre-event image gives a "snapshot" estimate of CME mass via the plane-of-the-sky assumption. This represents a lower limit, and a snapshot also does not capture the continuing enhanced flow often seen long after the initial eruption. Standard assumptions are (1) that all of the CME material is located in the plane of the sky, and (2) that the corona is a completely ionized plasma consisting of 90% hydrogen and 10% helium (Vourlidas *et al.*, 2000).

3.3.2. *Energies*

The kinetic and potential energies of a CME can be determined from the inferred masses and velocities, subject to the projection biases. The total mechanical energy of a major CME obtained in this manner is of order 10^{31-32} ergs, with the potential energy dominating for flux-rope CMEs (Vourlidas *et al.*, 2000). The magnetic energy of a CME is the dominant factor; it is widely agreed that CMEs result from a conversion of magnetic energy into the other forms, but we have no direct observations and cannot confirm this. The energetics estimates of Vourlidas *et al.* (2000) suggest that the magnetic energy does in fact diminish as the kinetic and potential energies increase.

There are inherent inaccuracies in the estimates of CME energetics. CME masses are underestimated, due to the assumption that all of the material lies in the plane containing the solar limb. CME mass and speed underestimations become significant for CME components more than $\sim$30 degrees from the plane of the solar limb (see Hundhausen, 1993, Appendix A and Hundhausen *et al.*, 1994).

3.3.3. *Energy or Mass Distribution*

Because of the lack of direct estimates of the dominant component, the magnetic energy, it is doubtless premature to draw conclusions from the distribution of CME total energies; but the masses and kinetic energies are available. Vourlidas *et al.* (2002) suggest power-law distributions for the mass and kinetic energy, rather than the exponential distribution of Jackson and Howard (1993). The inferred power laws are flatter than those observed for flares (e.g., Hudson, 1991).

3.4. UV and EUV Limb Spectroscopy

The UV and EUV spectrographic observations of CMEs provide diagnostic information but suffer from limited sensitivity. SOHO carries two UV spectrographs (UVCS for coronal observations, and SUMER for disk observations, but operated for most of the mission with its slit positioned above the limb in a coronagraphic mode).

Raymond *et al.* (2003) discuss three well-observed CMEs, each associated with an X-class flare near the limb. The UVCS observing slit was positioned approximately tangent to the limb at a height of 1.64 $R_\odot$ above it, and with an observing cadence of 120 s for spectra of a variety of UV emission lines, including some with high formation temperatures (notably Fe XVIII above 6×10^6 K). This high-temperature emission occurs in narrow structures the authors identify with the current sheets expected to form after the eruption (Ciaravella *et al.*, 2002; Ko *et al.*, 2003).

SUMER has provided observations that may be more directly related to flare energy release in large-scale reconnection. The original observation of downflows in soft X-rays by McKenzie and Hudson (1999) suggested reconnection outflow with a complex structure and clearly sub-Alfvénic velocities. SUMER observations have confirmed that the principal components of these downflows have low densities, being undetectable in any temperature regime (Innes *et al.*, 2003).

4. Non-Coronagraphic Observations

Much of the interesting development of a CME takes place in the lower corona, below the coronagraph's occulting edge. Even if this edge could be placed exactly at the solar limb, a halo CME originating at disk center would be at a large radial distance from the Sun before any part of it became visible. Luckily there are many wavebands, ranging from radio to X-ray, that in principle reveal the CME development from the photosphere outwards. One must be cautious interpreting these non-coronagraphic observations, however, because they show aspects of the CME disturbance that may not be directly identifiable with the mass distribution as seen in a coronagraph. Radio observations, in particular, normally show only non-thermal particles and thus give a picture of the overall structure that is biased towards those parts containing energetic particles, specifically electrons far out in the tail of the velocity distribution function. The "calibration" of these different kinds of observation presents problems to the extent that we may need to rely upon theory and modeling (or even cartoon descriptions) to link one feature with another observed by very different means (Hudson and Cliver, 2001).

4.1. X-Ray and EUV Imaging

We have now had more than a decade of systematic exploration of the solar corona via soft X-ray and EUV imaging from Yohkoh, SOHO, and TRACE. These new data have gone far beyond the pioneering observations from Skylab, especially in terms of sensitivity and of sampling. The essential contributions of these new observations lie in several domains: the direct observation of ejecta (Klimchuk *et al.*, 1994; Nitta and Akiyama, 1999); the detailed observation of coronal dimming (Hudson and Webb, 1997); and the observation of EIT waves (Moses *et al.*, 1997); Thompson *et al.* (1999). Such observations show that the coronal restructuring underlying the CME phenomenon in fact extends throughout the corona, consistent with the simple idea that the CME simply opens the coronal magnetic field into an enhanced solar-wind flow. Spectroscopic observations from SOHO (Harra and Sterling, 2001; Harrison *et al.*, 2003) confirm that the X-ray dimmings do represent material depletions rather than a temperature effect (Hudson *et al.*, 1996).

The X-ray and EUV observations of eruptions should be considered in the context of the behavior of filaments observed in Hα emission. Filaments give a different glimpse at coronal behavior during the CME process. The onset of filament activity, together with a gradual rising motion presumably related to streamer swelling, may precede the actual eruption by tens of minutes. In some cases the erupting filament continues into the outer corona, where it forms the dense core of a classical three-part CME structure; in other cases the filament appears to stop ("confined explosion" or failed eruption"; (see, e.g., Moore *et al.*, 2001; Ji *et al.*, 2003), and in some CMEs there appears to be no filament involvement at all. The

X-ray observations (Kano, 1994; Hanaoka *et al.*, 1994) show that the filament matter may heat rapidly during the eruption, and the EUV observations often show both cool and hot phases of the filament during its eruption.

The direct observations of CME counterparts in the low corona help greatly with understanding the time sequence of the eruption. The X-ray dimmings could be directly interpreted as a part of the coronal depletion required for a CME (Hudson *et al.*, 1996; Sterling and Hudson, 1997; Hudson and Webb, 1997). The dimmings turn out to coincide with the flare brightening, suggesting that the flare energization and CME acceleration can be identified (Zarro *et al.*, 1999). This close timing relationship has also been found with the LASCO C1 observations, which have the lowest occulting edge and hence the least timing ambiguity (Zhang *et al.*, 2001).

Large-scale shock waves in the corona and heliosphere play a major role in any discussion of CMEs (Schwenn, 1986); indeed the CME disturbance itself is describable in terms of MHD waves (e.g., Chen *et al.*, 2002). The type II bursts provided the first evidence for the passage of global waves through the corona and heliosphere, and the Moreton waves in the chromosphere (e.g., Athay and Moreton, 1961) were put into the same context by the Uchida (1968) theory of weak fast-mode MHD shock emission from solar flares. Interplanetary shocks and geomagnetic impulses (e.g., Chapman and Bartels, 1940), on the other hand, have a natural interpretation in terms of bow shocks driven ahead of the CME ejecta.

4.2. Radio Signatures

Radio-frequency observations provided some of the first clues of large-scale restructuring of the solar corona during a CME. The metric wavelength band (30–300 MHz) led to the well-known event classification (the type I–V bursts; see Kundu, 1965). Space-borne receivers extended the observational domain down to $\sim$30 kHz, and at shorter wavelengths ground-based observations have generally improved in resolution and coverage. These bursts tell us about energetic electrons either trapped in large-scale coronal magnetic structures or propagating through them on open field lines. In particular, the type II bursts reveal MHD shock waves propagating away from coronal disturbances such as flares and CMEs. We also now have clear observations of the elements of the classical 3-part CME structure via gyrosynchrotron emission at decimetric wavelengths and via free-free emission at centimetric wavelengths (Bastian *et al.*, 2001).

The radio observations provide key information about the connectivity of the coronal magnetic field. The type III bursts show that open (i.e., heliospheric) magnetic fields can originate in active regions as well as in coronal holes; the exciter (an electron beam) can be traced over at least four decades in frequency or 8 decades of density.