AN INTRODUCTION TO THEORY AND MODELS OF CMES, SHOCKS, AND SOLAR ENERGETIC PARTICLES

Z. MIKIĆ[1,*] and M. A. LEE[2]
[1]*Science Applications International Corporation, 10260 Campus Point Drive, San Diego, CA 92121, USA*
[2]*Institute for Earth, Oceans, and Space, 39 College Rd., University of New Hampshire, Durham, NH 03824, USA*
*(*Author for correspondence: E-mail: mikicz@saic.com)*

(Received 1 February 2006; Accepted in final form 12 June 2006)

Abstract. We present a brief introduction to the essential physics of coronal mass ejections as well as a review of theory and models of CME initiation, solar energetic particle (SEP) acceleration, and shock propagation. A brief review of the history of CME models demonstrates steady progress toward an understanding of CME initiation, but it is clear that the question of what initiates CMEs has still not been solved. For illustration, we focus on the flux cancellation model and the breakout model. We contrast the similarities and differences between these models, and we examine how their essential features compare with observations. We review the generation of shocks by CMEs. We also outline the theoretical ideas behind the origin of a gradual SEP event at the evolving CME-driven coronal/interplanetary shock and the origin of "impulsive" SEP events at flare sites of magnetic reconnection below CMEs. We argue that future developments in models require focused study of "campaign events" to best utilize the wealth of available CME and SEP observations.

1. Introduction

One of the primary focuses of present theoretical coronal mass ejection (CME) research is the initiation problem. Many of the theoretical interpretations of observations in the lower corona and inner heliosphere, including radio emission, shock acceleration of particles, and the structure and properties of interplanetary CMEs (ICMEs) and flux ropes, and their relationship to their solar source regions, hinge on the details of the CME initiation mechanism.

Modern observations, starting with Skylab in the 1970s, the Solar Maximum Mission (SMM) in the 1980s, and with Yohkoh, SOHO, and TRACE in the 1990s and present decade, have provided a rich source of observations to classify the morphology and characteristics of CMEs. Why, then, has the solution to the CME initiation problem remained elusive, in light of this wealth of observations? It is fair to say that we strongly suspect we know the key phenomena involved in CME initiation, and several candidate models, but no confirmation yet. Alexander *et al.* (2006, this volume) have provided a brief historical review of CME observations in the last century and a half. During this time period we have gradually come to the realization, which is universally held today, that CMEs are magnetically driven

Space Science Reviews (2006) 123: 57–80
DOI: 10.1007/s11214-006-9012-2

phenomena. That is not to say that pressure and gravity forces do not play a role in the destabilization of CMEs (they very well may). Indeed, the solar wind itself is a phenomenon driven by pressure and gravity forces (Parker, 1963). The role of non-magnetic forces will most likely grow in importance as our understanding of CMEs improves.

One of the principal reasons why the CME initiation problem has not been solved is because it is not possible (in general) to measure coronal magnetic fields in detail. We therefore have to rely on photospheric (and sometimes chromospheric) measurements, extrapolated using models, to infer the magnetic field in the corona. Furthermore, we routinely only measure the line-of-sight (longitudinal) component of the magnetic field, and not the transverse component, even though the energization of the coronal field (the very energy that drives the CME) can only be quantified with vector magnetic field measurements. Because measured coronal emission (e.g., in white light, EUV, and X-rays) is optically thin, it is necessary to deconvolve the effect of line-of-sight integration to interpret the emission, complicating the situation further. Radio emission measurements also need to be deconvolved in a non-trivial way to infer the coronal magnetic field (e.g., Lee *et al.*, 1998a,b, 1999). In-situ measurements of ICMEs afford limited ability to diagnose the 3D structure of CME ejecta but nevertheless provide important constraints. In Section 3 we list observations that are useful in characterizing the properties of CMEs.

In addition to these observational difficulties, there are considerable theoretical difficulties: the models are too idealized; they cannot address realistic geometry; they don't include fine-scale structure; they are too dissipative; they are not fully self-consistent (e.g., energy transport is neglected, prominences are not included, parallel flows are not modeled); and they don't produce the quantities that are measured (e.g., EUV, X-ray, and H-α images).

We are therefore forced to deduce the structure and topology of the pre-CME and post-CME plasma from indirect measurements and interpret them with incomplete models, which explains why it has been difficult to unravel the mystery of CME initiation.

1.1. A Brief History of CME Models

CME models have evolved from the early "cartoon" models, in which the description was qualitative and imprecise, to simple analytic and semi-analytic models, to idealized 2D and 3D numerical models. The next generation of 3D numerical models that are being implemented on massively parallel computers will be able to directly address observations, as discussed in Section 9. It is evident that CMEs are driven by the energy in the magnetic field. The main question that remains is: how is this energy released, and, most importantly, how is it released rapidly enough to explain fast CMEs that are observed to travel at speeds exceeding 1,000 km/s? Explaining fast CMEs has remained a difficulty of present models.

Barnes and Sturrock (1972) examined the energy stored in a twisted force-free field in order to explain how a magnetic field configuration could release energy while the field is opening (and presumably leading to an eruption). In subsequent work, Yang *et al*. (1986) found that the energy in the open field appears to be an upper limit to the magnetic energy, a result that has been formalized into a conjecture (Aly, 1991; Sturrock, 1991). This key development in the theory of CME initiation is worth restating: a fully open magnetic field provides an upper limit to the energy in a force-free field with the same normal magnetic field distribution on the solar surface (Aly, 1984, 1991; Sturrock, 1991). Therefore, in a model in which all the energy is stored in the magnetic field, it does not appear to be energetically possible for a closed magnetic field configuration to spontaneously make a transition to an open field. This seemingly implies that magnetic fields cannot open dynamically. However, there are many ways in which CMEs can open the magnetic field, including *partial* opening of the field (Wolfson and Low, 1992; Wolfson, 1993; Mikić and Linker, 1994), and by including the effect of pressure and gravity forces (Low, 1993; Low and Smith, 1993; Wolfson and Dlamini, 1997, 1999; Wolfson and Saran, 1998). See the review by Forbes (2000) for a discussion.

Early theory (e.g., Low, 1977, 1981; Birn and Schindler, 1981) examined the properties of equilibria using "generating function" solutions of the Grad-Shafranov equation in which the variation of a parameter was taken to represent evolution through a sequence of equilibria. In these models, it was presumed that "loss of equilibrium" would occur when solutions ceased to exist. However, Klimchuk and Sturrock (1989) cautioned against interpreting loss of equilibrium due to an artificial parametric specification as evidence of dynamical evolution.

Aly (1984, 1985, 1988, 1990) has investigated the mathematical properties of magnetic field configurations to deduce limits on their energy, stability, and the existence of solutions. In the highly conducting solar corona, the footpoints of the magnetic field lines are dragged by motions in the dense photosphere, a situation that is referred to as "line tying." Although line tying provides a stabilizing effect, it also allows the convective motions on the Sun to deform the coronal magnetic field, leading to the possibility of eruptive behavior.

The evolution of line-tied 2D magnetic arcades deformed by shearing photospheric motions has been studied by Mikić *et al*. (1988), Biskamp and Welter (1989), Finn and Chen (1990), Finn and Guzdar (1993), Choe and Lee (1996a,b) and Amari *et al*. (1996). When converging motions are applied at the neutral line, the arcade ejects a plasmoid (Inhester *et al*., 1992) due to reconnection. Manchester (2003) studied the disruption of buoyant 2D arcades. Arcade models have also been extended to spherical geometry (Mikić and Linker, 1994; Antiochos *et al*., 1999), including the effect of the solar wind (Linker and Mikić, 1995; Wu *et al*., 2001). Recently, models have been extended to study idealized 3D magnetic configurations (e.g., Amari *et al*., 2003a,b; Linker *et al*., 2003a,b; Roussev *et al*., 2003, 2004; Manchester *et al*., 2004a b).

In another class of semi-analytic models, the CME problem is formulated as loss of equilibrium due to a catastrophe (Forbes and Isenberg, 1991; Isenberg *et al.*, 1993; Forbes *et al.*, 1994; Forbes and Priest, 1995). Recent improvements to this "catastrophe model" (Lin *et al.*, 1998, 2001, 2002; Forbes and Lin, 2000; Lin and Forbes, 2000; Lin and van Ballegooijen, 2002) have significantly extended its applicability to the CME initiation problem. There is a close relationship between the catastrophe model and the flux cancellation model discussed in Section 5.1.

2. The MHD Model

Most large-scale theories of CMEs in the corona are based on the resistive magnetohydrodynamic (MHD) equations and their simplifications (e.g., zero-β, force-free, etc.), although kinetic extensions are needed to study the evolution in the inner heliosphere and especially to model the acceleration of solar energetic particles (SEPs), as described in Sections 7 and 8. In its most comprehensive form, the MHD model includes equations for mass, momentum, and energy conservation as well as the resistive Ohm's law. Energy transport includes parallel thermal conduction (along the magnetic field lines), radiation loss, coronal heating, and acceleration by Alfvén waves, usually treated according to a WKB formalism (Jacques, 1977; Usmanov *et al.*, 2000). For a description of these equations and their application to coronal modeling, see, for example, Mikić *et al.* (1999). Early models considered a simple polytropic energy equation (e.g., Linker and Mikić, 1995) with a reduced polytropic index (Parker, 1963) to model the solar wind. The realism needed to model campaign events (as discussed in Section 9) is pushing the models toward an improved description of energy transport.

The central role of the magnetic field, combined with a desire to simplify the problem, has led theorists to focus on force-free models of the corona, in which all forces other than magnetic forces are neglected. In this model, the equilibrium force-balance condition simplifies to

$$\mathbf{J} \times \mathbf{B} = 0 \tag{1}$$

where $\mathbf{J} = c\nabla \times \mathbf{B}/4\pi$ is the electric current density and $\mathbf{B}$ is the magnetic field intensity, which implies that $\mathbf{J} = \alpha\mathbf{B}$, with α, the torsion, an (unknown) function of position. Much theoretical research has focused on the study of equilibria satisfying Equation (1), which in itself is a difficult nonlinear problem.

3. Relevant Observations

Observations that help to determine the magnetic field topology in the pre-eruptive state (Gopalswamy, 2003) include the orientation of flows along filaments in H-α, X-ray and EUV loops (as beautifully seen in TRACE images), radio emission, longitudinal and vector magnetograms, the history of **B** in the photosphere as determined from sequences of magnetograms, and limb measurements of prominences. Magnetograph measurements can help to estimate the magnetic energy (Klimchuk *et al.*, 1992; Metcalf *et al.*, 2005). For details on how these observations can be used to determine the properties of the pre-CME corona see Gopalswamy *et al.* (2006) in this volume.

In the post-eruptive state, clues to the topology of the magnetic field can be obtained from H-α flare ribbons, EUV and soft-X-ray emission in post-flare loops and post-CME coronal dimmings, hard X-ray footpoint emission, measurements of bidirectional electrons and heat flux dropouts (Gosling *et al.*, 1987), and estimates of field line length (Larson *et al.*, 1997). Coronagraph measurements can help to estimate CME velocities and masses, and hence kinetic energies (Vourlidas *et al.*, 2000, 2002), as well as their morphology. Radio signatures (Reiner *et al.*, 2001; Bastian *et al.*, 2001; Cliver *et al.*, 2004) and solar energetic particle (SEP) measurements can probe the properties of shocks in the corona. Composition and charge state measurements can help to relate *in situ* plasma to its solar sources. Interplanetary measurements can be used to estimate flux rope helicity and twist. For details on how these observations can be used to determine the properties of CMEs see Schwenn *et al.* (2006, this volume) and Pick *et al.* (2006, this volume).

4. Classification of Models

There have been several reviews of the theory of CME initiation (Low, 1994, 1996, 1999, 2001; Forbes, 2000; Klimchuk, 2001; Linker *et al.*, 2003b), including a recent comprehensive review (Lin *et al.*, 2003) to which the reader is referred for more detailed discussions; see also Forbes *et al.* (2006, this volume) for a detailed presentation of the various models. Klimchuk (2001) has presented a classification of models into two broad classes: “storage and release” models and “directly driven” models. The class of directly driven models, in which the energy released during CME eruption is injected into the corona during the eruption, includes dynamo models (Chen, 1989; Chen *et al.*, 1997, 2000; Krall *et al.*, 2000) and thermal blast models, in which a pressure pulse is used to initiate the eruption (Dryer, 1982; Wu *et al.*, 1982). These are presently not considered as viable CME initiation models since they are not supported by observations (Forbes, 2000; Lin *et al.*, 2003). We therefore restrict our attention to storage and release models.

5. Examples of “Storage and Release” Models

In storage and release models, the CME is driven by the energy stored in the magnetic field, which is built up over a long period of time (days to weeks) and is released in a short time (minutes to hours). Rough estimates indicate that the coronal magnetic field can store sufficient energy to power even the largest flares and CMEs (Forbes, 2000). Here we will only touch on the essential principles and broadly survey the relevant phenomena, with specific references to two particular models with which we are familiar, the flux cancellation model and the breakout model. The catastrophe models mentioned in Section 1.1 are closely related to the flux cancellation model. See Forbes *et al*. (2006, this volume) for a more detailed discussion of these models.

In equilibrium, if gravity can be neglected (when very strong magnetic fields are present), the momentum equation expresses a balance between the tension in magnetic field lines that are line-tied in the photosphere and magnetic and thermal pressure: $\mathbf{B} \cdot \nabla\mathbf{B} = \nabla(4\pi p + B^2/2)$. Eruption involves forcing the system to evolve into a state in which this delicate balance can no longer be maintained. The two models differ in the way that this balance is upset, as described below.

5.1. The Flux Cancellation Model

Detailed observations of magnetic fields in and around active regions indicate that the emergence of new magnetic flux, especially in the vicinity of pre-existing magnetic fields (Gaizauskas *et al*., 1983; Zwaan, 1985; Feynman and Martin, 1995), and flux cancellation (Martin *et al*., 1985; Livi *et al*., 1985, 1989; Zwaan, 1987, 1996; Gaizauskas, 1993), are connected with solar eruptions (flares and CMEs). This led to the development of models that incorporate flux cancellation and magnetic field diffusion in the neighborhood of polarity inversion lines as a key ingredient in prominence formation and eruption (Pneuman, 1983; van Ballegooijen and Martens, 1989, 1990; Mackay *et al*., 1998; Litvinenko and Martin, 1999; Amari *et al*., 1999; Mackay and van Ballegooijen, 2001, 2005; Lionello *et al*., 2002; Mackay and Gaizauskas, 2003). Flux cancellation has been identified as a key element in the formation of prominences, which are also known as filaments (Gaizauskas *et al*., 1997; Martin, 1998; van Ballegooijen *et al*., 2000; Martens and Zwaan, 2001). Démoulin (1998) has reviewed the structure of magnetic fields in filaments.

Flux cancellation has been studied in prominence formation, eruption, and CME initiation with simulations of the large-scale corona (Linker *et al*., 2001; Linker *et al*., 2003a,b; Roussev *et al*., 2004) and also on active-region scales (Amari *et al*., 1999, 2000, 2003a,b; Lionello *et al*., 2002; Welsch *et al*., 2005). When the amount of cancelled flux does not exceed a threshold value, a magnetic flux rope forms above the neutral line in 3D arcades. This structure is stable and can support prominence material (Linker *et al*., 2001; Lionello *et al*., 2002). If flux cancellation is continued beyond this threshold, the configuration erupts (Amari *et al*., 2000, 2003a,b). The eruption converts a significant fraction of the magnetic energy into kinetic energy. When the configuration is close to the critical state, even a small amount of flux cancellation can trigger a violent eruption. The crossing of the threshold is unremarkable as far as the photospheric field is concerned, and it is likely to be missed in magnetograph observations. This critical behavior resembles that seen in the catastrophe models (e.g., Forbes and Isenberg, 1991).

5.2. The Breakout Model

Syrovatskii (1982) first noted the possible importance of multipolar configurations in explaining eruptive behavior. The breakout model, which describes the eruption of multipolar configurations, was developed by Antiochos (1998), Antiochos *et al.* (1999), MacNeice *et al.* (2004), Lynch *et al.* (2004), and DeVore and Antiochos (2005). Like the flux cancellation model, breakout requires strongly sheared fields near the neutral line, as observed in filament channels. A key feature of the model is that it requires a multipolar flux distribution and a magnetic null to be present. When the central arcade is sheared, causing the field lines to rise, slow reconnection at the null point transfers overlying flux in the central arcade to the neighboring arcades, eventually destabilizing the central arcade. An application of the breakout model to flare observations is given by Gary and Moore (2004).

5.3. Similarities and Differences

In our opinion, the flux cancellation and breakout models have more fundamental similarities than differences. Both models require build-up of significant parallel electric current (shear, twist) prior to eruption; the magnetic field is highly aligned along the neutral line; eruption requires build up of magnetic pressure within the central arcade and/or release of tension in the overlying field lines. The exact mechanism by which this occurs is different in the two models. In the flux cancellation model, magnetic pressure is built up in the flux rope by the slow reconnection of magnetic field lines at the neutral line, which at the same time relieves the tension in the overlying field lines by severing connections to the photosphere. In the breakout model, the reconnection of the high field lines in the arcade with the overlying field lines in the surrounding flux systems releases the magnetic tension that holds down the central arcade. In both cases, reconnection in the lower corona within the arcade completes the eruption process and ejects a flux rope. Any prominence material that happens to be trapped in the dips of magnetic field lines is also ejected.

The models also have differences. For example, the photospheric magnetic field has a different character before eruption (the flux cancellation model has a flux rope whereas the breakout model does not). Flux cancellation requires converging flows and cancellation of flux at the neutral line, combined with (slow) magnetic reconnection there. Flux cancellation can occur in a simple dipolar configuration, whereas breakout requires a more complex topology. In the flux cancellation mechanism, prominence material can become trapped on the flux-rope magnetic field line dips as they form and rise into the corona, leading to the natural formation of a prominence within the arcade. This material is observed to be ejected together with the streamer. In contrast, in the breakout model the prominence material needs to condense in the corona or be siphoned from the chromosphere.

It is important to note that the idealizations inherent in axisymmetric (2D) geometry tend to emphasize the differences between the two models. In a fully 3D geometry it is more difficult to distinguish between these two models; there is a continuum between dipolar and multipolar configurations as the relative orientation between the overlying field and a bipolar active region is changed. Furthermore, the distinctions between the two topologies may be blurred by the similarities in behavior of magnetic field configurations that have true separatrices versus quasi-separatrix layers (Démoulin *et al*., 1996, 1997; Titov *et al*., 2002). In addition, in 3D it is difficult to distinguish between a “flux rope” with a fraction of a turn of twist, whose legs are attached to the photosphere, and a highly-sheared, dipped field line (e.g., as depicted in the prominence support model of Antiochos *et al*., 1994).

5.4. Comparison with Observations

Several features of these models agree with observations. A magnetic field topology that can support a filament (i.e., dipped field lines) is formed naturally and erupts together with the streamer in the flux cancellation mechanism, as seen in many CME observations. Also, CMEs tend to occur in decaying active regions with dispersing magnetic flux, in accordance with the flux cancellation scenario. Converging flows and the disappearance of magnetic elements of opposite polarity are also observed at neutral lines. Breakout requires a complex topology, a feature that is consistent with flare-productive regions.

Other features do not agree with observations. In particular, it has been difficult to show that fast CMEs can be produced with the models, although this may be related to the geometrical simplicity of the models and because they have not been able to simulate the strong localized magnetic fields in active regions. Additionally, the large-scale shear flows that have been used to energize the models are typically not observed, although a large part of the twist in the active regions is present when they emerge from below the photosphere (Leka *et al*., 1996). In Section 9 we discuss future improvements to these models that will greatly enhance their ability to address observations.

6. Connecting the Corona to the Heliosphere: The CME–ICME Connection

CMEs that are observed in the corona produce signatures in interplanetary space which can be measured by *in-situ* spacecraft (Wimmer *et al*., 2006, this volume). These signatures often reveal a great deal about their properties and origin. Many studies have attempted to link observations of magnetic clouds to their inferred active-region sources (e.g., Webb *et al.*, 2000; Leamon *et al.*, 2004). Simulations have shown that CMEs can undergo a significant amount of distortion as they expand and encounter solar wind streams with different velocities (Riley *et al.*, 1997, 1998; Odstrcil and Pizzo, 1999a,b,c).

Odstrcil *et al.* (2002) and Riley *et al.* (2003) have followed a CME from its eruption in the corona to 5 AU. A 2D CME was initiated in the corona by the flux cancellation mechanism (Linker *et al.*, 2003a). Significant distortion and "pancaking" of the ICME is observed as it propagates away from the Sun. This simulation was used to test several flux-rope fitting techniques (Riley *et al.*, 2004) and to interpret the global context of a CME that was observed by ACE and Ulysses (Riley *et al.*, 2003). Simulations of an idealized 3D eruption have also been performed (Odstrcil, 2003; Luhmann *et al.*, 2004). Although these are promising first steps, we are just beginning to explore the detailed relationship between CMEs and ICMEs. Little is known about the relationship between CME initiation mechanisms and ICME signatures, so that it is difficult to use these signatures to discriminate between the models. Furthermore, the topology of the magnetic field lines that connect the magnetic cloud with the Sun and the heliosphere is not well known (e.g., Gosling *et al.*, 1995; Crooker *et al.*, 2002). Adressing these issues will have to await improvements to the models.

7. CME-Driven Shock Propagation

An immediate consequence of a fast CME is a magnetic field and pressure enhancement ahead of it. If the ejected mass is or becomes superalfvénic, then the enhancement forms a bow shock that drapes around the CME and propagates ahead of it into the heliosphere. The flanks of the bow shock/wave may extend to the base of the corona (Sheeley *et al.*, 2000) and be observed as a Moreton wave (Moreton, 1960) or an EIT-wave (Brueckner *et al.*, 1998). However, this picture is probably oversimplified. Multiple shock waves may be produced low in the corona, where the Alfvén speed is small, due to a complex release of magnetic energy during the eruption process. Thus, the interpretation of the observed disturbances and type II radio bursts indicating shock formation in a given event may be difficult.

The governing equations for the macroscopic behavior of waves and shocks in the corona and solar wind are generally taken to be the 1-fluid ideal MHD equations supplemented by an adiabatic equation of state with $\gamma = 5/3$. They specify the time evolution of the fluid velocity $\mathbf{V}$, magnetic field $\mathbf{B}$, pressure P, and mass density ρ. These equations are not valid at shocks since non-ideal terms involving viscosity, heat flux, and electrical resistivity are important there. However, for the macroscopic behavior of the fluid, it is sufficient to impose the Rankine-Hugoniot jump conditions at the discontinuity that forms in the flow. There are several algorithms available for this purpose (Hundhausen, 1985; Pizzo, 1985; Powell *et al.*, 2003). The linearized equations describe the "fast," "slow" and Alfvén modes of homogeneous MHD and their generalizations in a solar wind with inhomogeneous velocity $\mathbf{V}_0$ and magnetic field $\mathbf{B}_0$. The "fast" and "slow" modes are compressive and form shocks. However, the "slow" shock is indeed slow with subalfvénic flows both upstream and downstream of the shock in the shock frame (Hundhausen, 1985). The shocks observed in the solar wind and predicted in the corona are generally "fast" shocks (but see Whang *et al.*, 1996).

The two simplest solutions of these equations, assuming spherically symmetric, hydrodynamic flows ($\mathbf{B} = 0$), and neglecting gravity, are the blast wave with constant total energy (created, say, by an impulsive enhancement in solar wind speed) and the driven shock with increasing energy content (created, say, by a sudden and persistent increase in wind speed). Under further simplifying assumptions, these two cases may be described by analytical "self-similar" solutions (Rogers, 1957; Sedov, 1959; Parker, 1961, 1963; Chevalier, 1982). The blast wave is a single forward shock, whereas the driven configuration involves a forward shock propagating into the solar wind ahead and a reverse shock propagating backwards into the ambient wind behind, but swept outwards by the flow. These two simple cases provide a framework for interpreting shock propagation in the corona and solar wind in more general cases. The CME-associated shock is initially driven, since CMEs appear to retain their high speeds for tens of R_s. However, as CME speeds decay with a spatial scalelength of $r \sim 50R_s$ (Reiner *et al.*, 2003) and assimilate into the solar wind as interplanetary CMEs (ICMEs), the shocks probably transform into blast waves. The simple models omit many features which are important in the solar wind and corona. Inhomogeneity, particularly in coronal active regions and the streamer belt, causes refraction of the shock waves (Vainio and Khan, 2004). Beyond Earth orbit, shocks may interact and coalesce (Pyle *et al.*, 1984). Numerous simulations over three decades have revealed various aspects of interplanetary shock propagation (e.g., Dryer, 1974; Steinolfson, 1985; Whang and Burlaga, 1985; Tsurutani *et al.*, 2003).

The US National Space Weather Program has revitalized studies of CME-driven shock propagation, since these shocks contribute to geomagnetic disturbances. Odstrcil and Pizzo (1999c,a,b) developed a 3-D hydrodynamic and an MHD code to investigate how a CME, simulated by a localized pressure and velocity enhancement at the inner boundary, interacts with a solar wind that includes a tilted magnetic dipole configuration with streamer belt and stream structure. Odstrcil *et al.* (2002) combined the heliospheric MHD code of Odstrcil and Pizzo (1999a) with the coronal MHD code of Mikić and Linker (1994) to treat a 2-D axisymmetric eruption of a CME into the heliosphere beyond Earth orbit. A competing 3-D MHD code with adaptive mesh refinement has been developed by the U. Michigan group (Powell *et al.*, 2003). Groth *et al.* (2000) and Manchester *et al.* (2004c) presented results of the Michigan code, which described the eruption of a CME into a structured solar wind. The CME was modeled as a 3-D flux rope with initial force imbalance, resulting in rapid outward acceleration.

A crucial issue for particle acceleration at a CME-driven shock (see Section 8.1(5)) is the formation time and strength of the shock close to the Sun. These features depend primarily on CME speed and the spatial distribution of the Alfvén speed, V_A. Although V_A clearly depends on local coronal structure, generally, away from active regions V_A is low in the chromosphere and low corona where the density is high, increases with height as the density decreases, and finally decreases in the solar wind as $V_A \propto r^{-1}$ inside Earth orbit. We expect a maximum of V_A ~500 km/s at a heliocentric radial distance of $r \sim 3 - 5R_s$ (Gopalswamy *et al.*, 2001; Mann *et al.*, 2003). Thus, we expect CMEs that accelerate to speeds ~500 km/s to form bow shocks at $r \sim 3 - 5R_s$. This expectation is consistent with the onset time of energetic ion acceleration to GeV energies (Kahler, 1994) and the strong correlation of energetic ion intensity and CME speed (Reames *et al.*, 1997).

A recent simulation by Roussev *et al.* (2004) initiates a CME based on the evolution of the observed photospheric and coronal magnetic fields for the event of 2 May 1998. They find that the nose of the driven shock reaches a speed of ~1200 km/s at $r \sim 4R_s$, with a compression ratio ~3. Assuming that the scattering mean free path of protons is approximately their gyroradius, this shock is predicted to have an energetic particle cutoff energy ~10 GeV, consistent with the observation that this event was a "ground-level event" (Lopate, 2001, but see Section 8.1(5)).

8. Acceleration of Energetic Particles

An important product of CMEs are energetic particles, which are detected either directly in space or by secondary electromagnetic and neutron emissions. Energetic particles generally contain a small fraction of the energy released by a CME. Nevertheless, by virtue of their high speed and energy, they can have deleterious effects on humans and assets in space and may be utilized in space weather forecasting (Reames, 1999; Feynman and Gabriel, 2000; Tóth *et al.*, 2005).

Charged particles are accelerated by **E**, the electric field. The fact that the accelerated electrons are very effective in canceling electric field enhancements generally ensures that $\mathbf{E} \approx 0$ in the plasma frame of reference. Thus, acceleration in space plasmas generally depends on relatively subtle effects. These involve variations of the plasma velocity $\delta\mathbf{V}$ in a particular configuration so that both $\mathbf{E} \approx -c^{-1}\delta\mathbf{V} \times \mathbf{B}_0$ and the motion of the particles allows a nonzero average value of $\mathbf{v} \cdot \mathbf{E}$. Here **v** is particle velocity, and $|\mathbf{E}|/|\mathbf{B}_0| \sim |\delta\mathbf{V}|/c \ll 1$.

Observations of solar energetic particles (SEPs) in space provide some guidance in determining the relevant configuration for acceleration. SEPs appear in two fairly distinct classes of events: "impulsive" and "gradual." Impulsive events are small, last for hours, occur at a rate of ~10^3/y during solar maximum, are rich in electrons, ^{3}He and heavy ions, and have relatively high charge states. In contrast, gradual events are large, last for days, occur at a rate of ∼10/y during solar maximum, have approximately solar wind or coronal ion composition, are electron poor, and have relatively low charge states (Lee, 1991). Although this classification has become blurred by recent measurements of elemental and ionic charge composition as described in detail by (Cane and Lario, 2006, this volume) and (Klecker *et al.*, 2006, this volume), nevertheless it implies distinct acceleration mechanisms for impulsive and gradual events.

8.1. Gradual Events and Shock Acceleration

The characteristics of gradual events are generally consistent with their origin at a coronal/interplanetary shock driven by a CME. In addition to those characteristics listed above, these events are strongly correlated with fast CMEs and type II radio bursts and have a broad extent in heliographic solid angle. All of these features are expected for a shock origin.

Figure 1 is a schematic diagram of a CME-driven coronal/interplanetary shock as it propagates toward Earth and into the solar wind across the Archimedes-spiral magnetic field. The dots indicate the SEPs. They are accelerated by criss-crossing the shock and, in the process, both drifting in the inhomogeneous shock magnetic field parallel to **E** in the shock frame and scattering between the convergent

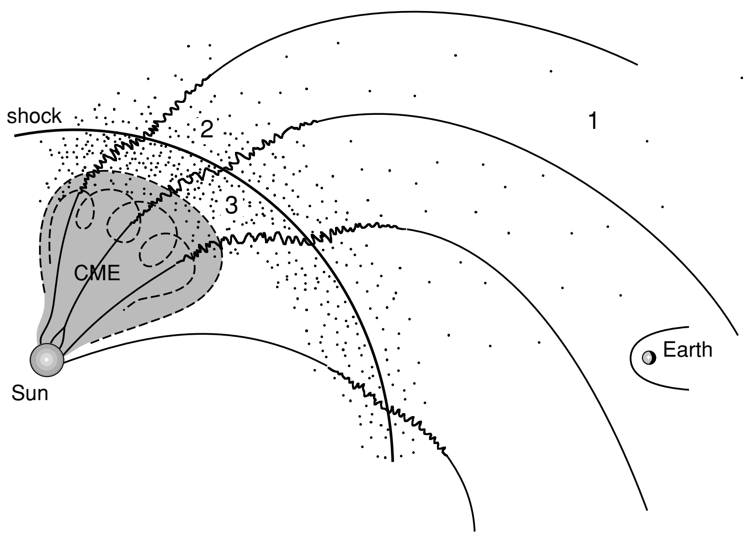

Figure 1. Schematic snapshot of an evolving coronal/interplanetary shock driven by a CME. Accelerated ions are denoted by dots. Magnetic field lines are shown, with wiggles denoting magnetic fluctuations. The spatial domain accessible to the ions is divided into solar wind (1), a proton-excited turbulent sheath upstream of the shock (2), and the turbulent shock-heated solar wind downstream of the shock (3).

electromagnetic irregularities on either side of the shock. These two aspects of shock acceleration are known as "shock drift" acceleration (Hudson, 1965; Sarris and VanAllen, 1974) and "first-order Fermi" acceleration (Fermi, 1954). Their relative contributions are dependent on the chosen frame of reference. Both aspects are combined in the theory of diffusive shock acceleration (Jokipii, 1982).

Figure 1 draws attention to the possible temporal and spatial complexity of the shock acceleration process. The solar wind is inhomogeneous, the shock evolves in strength and shape, and the magnetic connection between observer and shock can be complicated. Another complication is that the ion scattering mean free path λ in the solar wind (Region 1 in Figure 1) is too large ($\sim$0.1–1 AU) to yield the rapid multiple traversals of the shock required for particles to attain the observed SEP energies. However, the accelerating ions excite hydromagnetic waves to form a turbulent sheath upstream of the shock. Within this sheath, denoted by Region 2 in Figure 1 with its fluctuating magnetic field components, λ is small and acceleration is rapid. Region 3, adjacent to and downstream of the shock, is also turbulent. There the upstream turbulence is compressed and enhanced by the shock. These three regions are distinct and require different ion transport equations for the ion distribution function.

The basic particle transport equation for application to SEPs is the focused transport equation (Roelof, 1969; Skilling, 1971; Earl, 1976, 1981; Isenberg, 1997; Forbes *et al.*, 2006, this volume), which describes the convection, adiabatic deceleration, magnetic focusing and pitch-angle diffusion (with diffusion coefficient D_μ) of particles confined to a magnetic flux tube. Although the equation treats particles with $v \sim |\mathbf{V}|$ and accommodates large anisotropy, it neglects drift transport, which is generally negligible for SEPs. If scattering is efficient ($D_\mu \gg |\mathbf{V}|/r$), the particle distribution is nearly isotropic, and $v \gg |\mathbf{V}|$, then the focused transport equation may be integrated over pitch-angle to yield the spatial diffusion equation with diffusion coefficient $\kappa_\parallel$ (Parker, 1965; Gleeson and Axford, 1967; Forbes *et al.*, 2006, this volume). The spatial diffusion equation may be readily generalized to include drift transport and diffusion perpendicular to **B** (Jokipii and Levy, 1977) and is the basis for the theory of diffusive shock acceleration. The perpendicular diffusion $\boldsymbol{\kappa}_\perp$ is generally small and negligible for SEP transport. A possible exception is the region close to a quasi-perpendicular shock with large magnetic fluctuation intensities (Dwyer *et al.*, 1997). The parallel spatial diffusion coefficient $\kappa_\parallel$ may be expressed in terms of D_μ, and D_μ in terms of the fluctuation intensity, I (Lee, 1983; Gordon *et al.*, 1999). In principle, then, a wave kinetic equation for I is required, which describes wave excitation by the accelerated protons and closes the nonlinear system of equations.

Early theoretical work on shock acceleration proceeded in two directions. Firstly, following the development of the theory of diffusive shock acceleration (Axford *et al.*, 1978; Krymsky, 1977; Blandford and Ostriker, 1978; Bell, 1978), there were applications of the theory to SEPs by Achterberg and Norman (1980), Lee and Fisk (1982) and Lee and Ryan (1986). These were simplified in both geometry and the form of the diffusion coefficient. There were also applications of the theory to energetic storm particle (ESP) enhancements observed at Earth orbit (Forman, 1981; Lee, 1983; Gordon *et al.*, 1999). An ESP event is actually one phase of a gradual event, which occurs if the shock still accelerates ions when it passes Earth. With the planar geometry appropriate for ESP events, Lee (1983) was able to include wave excitation in the theory. These models provided a reasonable description of the ion (and wave) enhancements near the shock.

Secondly, there were many applications of the focused transport equation to the nearly scatter-free transport of SEPs in interplanetary space early in an event when ion anisotropy may be large (Heras *et al.*, 1992, 1995; Kallenrode, 1993; Ruffolo, 1995; Kallenrode and Wibberenz, 1997; Lario *et al.*, 1998). These particles constitute an important phase of the event for space weather forecasting and usually include the most energetic particles. These models include the shock acceleration heuristically as a source term, which is chosen with a power-law energy spectrum appropriate to a moving shock that is weaker on the flanks. They provide a reasonable description of the early phase of gradual events.

Other studies have attempted to combine the advantages of these two research directions in order to accommodate more realistic geometry, wave excitation, and the transition from scatter-dominated to nearly scatter-free ion transport with increasing distance upstream of the shock. Ng *et al.* (1999) have combined the focused transport and wave kinetic equations describing the upstream propagation of all ion species, including the wave excitation essential to the turbulent sheath adjacent to the shock. Although this approach cannot describe the acceleration process, it does predict the upstream fractionation of different ion species. For the event of 20 April 1998 they find excellent agreement with observed abundance ratios (Tylka *et al.*, 1999). Zank *et al.* (2000) used a "hybrid" approach to calculate the proton time profiles expected in gradual events. They combined the shocked plasma flow from hydrodynamic numerical simulations, the upstream ion/wave configuration from Gordon *et al.* (1999) assuming a free-escape boundary at a prescribed position upstream of the shock, and a numerical calculation of the ion distribution downstream of the shock. In spite of this patchwork approach, the predicted time profiles provide a good match to observations. Lee (1999, 2005) combined the wave kinetic equation with the two-stream moments of the focused transport equation to accommodate large streaming anisotropy in the theory of diffusive shock acceleration combined with wave excitation. Although this model is effectively stationary, assumes a simple geometry, and neglects adiabatic deceleration and drift of ions, it does describe analytically the extraction of ions from the turbulent sheath adjacent to the shock by magnetic focusing and the resulting cutoff in the power-law energy spectrum.

In attempting to develop a theory that can account for the characteristics of any given event, several challenging issues must be recognized:

(1) The geometry of the magnetic field, the shock, and the connection to the observer are crucial to a quantitative prediction of the event characteristics, yet it

is generally unknown, particularly near the Sun, and most models are restricted to spherical or simplified geometry. Ironically it was the dependence of gradual event morphology on the solar longitude of the flare/CME which was one of the strongest arguments in favor of a shock origin of these events (Cane *et al.*, 1988). Also, the obliquity of the shock (the angle θ_{bn} between the upstream magnetic field and the shock normal) is crucial in determining the appropriate injection rate Q into the acceleration process (see Point 2 below) and the acceleration rate, yet the appropriate value of θ_{bn} for the observer's field line is variable and difficult to determine. These aspects of the problem present severe challenges to a predictive theory.

(2) The traditional transport equations cannot describe the extraction of particles from the ambient plasma at the shock front to create a population of energetic particles satisfying $v \gg |\mathbf{V}|$ or gyrotropy for which the equations are valid. Accordingly, there is no rigorous way to determine Q as a function of v and species. This is a particularly challenging issue for SEPs since the composition of different events may be largely determined by the relative injection rates of solar wind, the suprathermal tail of the solar wind, the "inner source" pickup ions, ambient gradual event material, and ambient impulsive event material (Gloeckler *et al.*, 2000; Mason *et al.*, 1999; Desai *et al.*, 2003). Not only is Q expected to be different for these populations, it also is expected to depend on the shock Mach number and very sensitively on θ_{bn}. The unknown nature of Q makes compositional predictions difficult.

(3) The traditional transport equations depend on quasilinear theory, whose accuracy in general is difficult to assess. Certainly at Earth's bow shock, for example, "shocklets" are observed to form as large-amplitude upstream waves steepen; this nonlinear process modifies the power spectrum markedly (Hoppe *et al.*, 1981; Hada *et al.*, 1987). In addition, the models employ approximate solutions of the wave kinetic equation even though the coupled configuration of ions and waves is expected to be very sensitive to I.

(4) Gradual events, which are magnetically well-connected to the observer when the CME/flare is near the Sun, may also contain energetic particles that originate at the flare (see Section 8.2). The resulting admixture of impulsive event material should have important spectral and compositional signatures. There is a tendency for Fe/O to be enhanced, as in typical impulsive events, early in well-connected gradual events (Cane *et al.*, 1991). This enhancement, however, can also be explained by rigidity-dependent propagation of ions from the shock to the observer (Tylka *et al.*, 1999) or by a combination of shock geometry and accessible seed particles (Tylka *et al.*, 2005). The possible admixture of flare-accelerated ions in gradual events remains a controversial topic.

(5) Although the formation of a CME-driven shock at $r \sim 3$–$5\ R_s$ is in principle consistent with the onset times of GeV protons (Kahler, 1994), these onset times require scattering mean free paths on the order of the proton gyroradius to achieve the required acceleration rate (Roussev *et al.*, 2004). It is unclear whether such

small scattering mean free paths exist parallel to the shock normal upstream of the shock in this region of the corona.

8.2. Impulsive Events and Magnetic Reconnection

The characteristics of impulsive events imply that they originate in solar flares low in the corona. Flare electromagnetic emissions indicate that most of the energetic particles accelerated in the flare remain in the low corona; only a small fraction find their way to magnetic field lines open to interplanetary space. Many or most impulsive events are not associated with CMEs. However, since most CMEs are associated with large flares, it is reasonable to suppose that the energetic particles in gradual events have an "impulsive" component (see Section 8.1(4)).

The acceleration mechanism of impulsive events is unknown. The two leading candidates are direct acceleration by **E** at the site of magnetic reconnection, where the reconnecting component of **B** normal to **E** is small (Litvinenko, 1996). This field configuration is able to accelerate both electrons and ions. However, it is unclear how it can lead to the remarkable enhancements and variability in ^{3}He. These enhancements appear to require stochastic acceleration by plasma waves which can resonate selectively with different ion species. Fisk (1978) suggested electrostatic ion-cyclotron waves because they selectively resonate with ^{3}He if the ^{4}He/H ratio is enhanced. Others have suggested that the waves are excited by the electric-field-accelerated electrons (Temerin and Roth, 1992; Miller and Viñas, 1993). Several authors (e.g., Ramaty, 1979; Möbius *et al.*, 1982; Miller *et al.*, 1990; Ryan and Lee, 1991) have constructed models for the stochastic acceleration of impulsive event ions based on the diffusion equation including an energy diffusion term. However, these models are limited by unknown geometry, origin of the turbulence, and particle escape rates.

Although these two mechanisms are the leading candidates for particle acceleration in impulsive events, shock acceleration is also possible, either at the shock produced by the downward reconnection jet (Tsuneta and Naito, 1998) or a shock generated by impulsive plasma heating at the reconnection site. Clearly, the current theoretical framework for impulsive events is more rudimentary and challenging than for gradual events.

9. Future Directions: Confronting Models with Observations

Presently, there exist a broad spectrum of models for CME initiation that address selected aspects of the observations, though not in a consistent and complete manner. Progress in CME theory will most likely be achieved by confronting models with observations. Although the present complement of CME observations is rich and abundant, the models are too idealized to address them in detail. Modeling an actual

CME event and producing quantities that are observed is presently not possible. Once the models improve sufficiently, these observations will serve to distinguish the various models. In this sense, the observations are ahead of the models. Impending advances in CME and active region observations, especially those from the upcoming Solar-B and STEREO missions, will not only present further challenges to the models but will also undoubtedly provide additional insight into the CME initiation problem.

In our opinion, an effective way to resolve which physical mechanism initiates CMEs from among the many proposed possibilities will require the models to be refined until they can directly address observations, i.e., by producing as output measured observables, such as white light coronagraph images, radio, EUV and X-ray emission images, shock and particle signatures, and predicted in-situ ICME properties. The following improvements are presently being considered:

1. Extension of the models to 3D, including the effect of the strong magnetic fields that characterize active regions;
2. Modeling active-region length scales while at the same time including the coupling to large-scale (global) fields;
3. Models that are driven by observed boundary conditions, such as photospheric line-of-sight magnetic fields (e.g., from SOHO/MDI magnetograms) and transverse magnetic fields from vector magnetograms;
4. Use of time-dependent photospheric magnetic field boundary conditions to follow the evolution of the coronal magnetic field and the triggering of eruptions;
5. A more sophisticated treatment of energy transport in the corona;
6. Improved coupling of coronal and heliospheric models to follow the propagation of a CME into the heliosphere;
7. Improved modeling of the quasi-steady solar wind structure to better track the trajectory of a CME and to describe its evolution;
8. Direct comparison of model outputs with X-ray and EUV emission images;
9. Relating observed ICME characteristics to their solar source regions;
10. Focused study of specific CME events.

The requirement that models directly address observations in order to make progress also holds for the configuration of the ICME in interplanetary space, the behavior of the CME-driven shock, and the distribution of energetic ions and excited waves throughout the inner heliosphere. This challenge is being faced in part by global heliospheric MHD codes (Odstrcil *et al.*, 2002; Manchester *et al.*, 2004c). The SEP models are not yet ready for the severe challenges posed by energy spectra, anisotropies and time profiles for electrons and multiple ion species, and charge states for a complex variety of events with a variety of magnetic connection geometries. However, this bewildering array of particle data is slowly achieving some level of organization through consideration of multiple seed populations (Mason *et al.*, 1999; Desai *et al.*, 2003) and shock geometry (Tylka *et al.*, 2005). Insights gained through these considerations should lead to a predictive class of models.

This prospect is particularly exciting since SEPs are in principle a very effective probe of the CME/shock configuration in the inner heliosphere and even close to the Sun for magnetically well-connected events.

The realization that detailed simulations of specific events is needed to advance our understanding further has been espoused by the CME community. For example, the "Solar, Heliospheric, and INterplanetary Environment" group (SHINE) has selected a set of "Campaign Events" for detailed coordinated study (Gopalswamy, 2005). The list of events can be accessed at the group website (`http://www.shinegroup.org`). One of these, perhaps the simplest for modeling purposes, is the CME that occurred on May 12, 1997. We expect that such detailed studies will solve the CME initiation problem and establish the behavior of the ICME and its driven shock in interplanetary space.

Acknowledgements

The authors are grateful for the patience and hospitality of the Workshop organizers at Schloss Elmau and ISSI. ZM acknowledges support from NASA's Sun-Earth Connection Theory, Supporting Research and Technology, and Living With a Star Programs, and NSF's Center for Integrated Space Weather Modeling. The computations were performed at NSF's San Diego Supercomputer Center. ML acknowledges support from NASA grant NNG05GL40G, NSF grant ATM-0091527, and the DoD MURI grants to the University of Michigan and the University of California at Berkeley (subcontracts to the University of New Hampshire).

References

Achterberg, A., and Norman, C. A.: 1980, *Astron. Astrophys.* **89**, 353.
Alexander, D., Richardson, I., and Zurbuchen, T. H.: 2006, *Space Sci. Rev.*, (this volume), doi: 10.1007/s11214-006-9008-y.
Aly, J. J.: 1984, *ApJ* **283**, 349–362.
Aly, J. J.: 1985, *A&A* **143**, 19–22.
Aly, J. J.: 1988, *A&A* **203**, 183–188.
Aly, J. J.: 1990, *Physics of Fluids B* **2**, 1928–1935.
Aly, J. J.: 1991, *ApJ* **375**, L61–L64.
Amari, T., Luciani, J. F., Aly, J. J., Mikić, Z., and Linker, J.: 2003a, *ApJ* **585**, 1073–1086.
Amari, T., Luciani, J. F., Aly, J. J., Mikić, Z., and Linker, J.: 2003b, *ApJ* **595**, 1231–1250.
Amari, T., Luciani, J. F., Aly, J. J., and Tagger, M.: 1996, *A&A* **306**, 913–923.
Amari, T., Luciani, J. F., Mikić, Z., and Linker, J.: 1999, *ApJ* **518**, L57–L60.
Amari, T., Luciani, J. F., Mikić, Z., and Linker, J.: 2000, *ApJ* **529**, L49–L52.
Antiochos, S. K., Dahlburg, R. B., and Klimchuk, J. A.: 1994, *ApJ* **420**, L41–L44.
Antiochos, S. K.: 1998, *ApJ* **502**, L181–L184.
Antiochos, S. K., DeVore, C. R., and Klimchuk, J. A.: 1999, *ApJ* **510**, 485–493.

Axford, W. I., Leer, E., and Skadron, G.: 1978, *Proceedings of the International Conference Cosmic Rays 15th*, vol. 11, pp. 132–137.
Barnes, C. W., and Sturrock, P. A.: 1972, *ApJ* **174**, 659.
Bastian, T. S., Pick, M., Kerdraon, A., Maia, D., and Vourlidas, A.: 2001, *ApJ* **558**, L65–L69.
Bell, A. R.: 1978, *Mon. Not. R. Astr. Soc.* **182**, 147.
Birn, J., and Schindler, K.: 1981, in Priest, E. R. (ed.), *Solar Flare Magnetohydrodynamics*, Gordon and Breach, New York. pp. 337–378.
Biskamp, D., and Welter, H.: 1989, *Sol. Phys.* **120**, 49–77.
Blandford, R. D., and Ostriker, J. P.: 1978, *Astrophys. J.* **221**, L29–L32.
Brueckner, G. E., Delaboudiniere, J.-P., Howard, R. A., Paswaters, S. E., St. Cyr, O. C., Schwenn, R., *et al*.: 1998, *Geophys. Res. Lett.* **25**, 3019–3022.
Cane, H. V., and Lario, D.: 2006, *Space Sci. Rev.*, (this volume), doi: 10.1007/s11214-006-9011-3.
Cane, H. V., Reames, D. V., and von Rosenvinge, T. T.: 1988, *J. Geophys. Res.* **93**, 9555–9567.
Cane, H. V., Reames, D. V., and von Rosenvinge, T. T.: 1991, *Astrophys. J.* **373**, 675–682.
Chen, J.: 1989, *ApJ* **338**, 453–470.
Chen, J., Howard, R. A., Brueckner, G. E., Santoro, R., Krall, J., Paswaters, S. E., *et al*.: 1997, *ApJ* **490**, L191+.
Chen, J., Santoro, R. A., Krall, J., Howard, R. A., Duffin, R., Moses, J. D., *et al*.: 2000, *ApJ* **533**, 481–500.
Chevalier, R. A.: 1982, *Astrophys. J.* **258**, 790.
Choe, G. S., and Lee, L. C.: 1996a, *ApJ* **472**, 360–371.
Choe, G. S., and Lee, L. C.: 1996b, *ApJ* **472**, 372–388.
Cliver, E. W., Nitta, N. V., Thompson, B. J., and Zhang, J.: 2004, *Sol. Phys.* **225**, 105–139.
Crooker, N. U., Gosling, J. T., and Kahler, S. W.: 2002, *J. Geophys. Res.* **107**, 1028.
Démoulin, P.: 1998, Webb, D., Rust, D., and Schmieder, B. (eds.), *ASP Conference Series: New Perspectives on Solar Prominences*, Vol. 150, pp. 78–85.
Démoulin, P., Bagala, L. G., Mandrini, C. H., Henoux, J. C., and Rovira, M. G.: 1997, *A&A* **325**, 305–317.
Démoulin, P., Henoux, J. C., Priest, E. R., and Mandrini, C. H.: 1996, *A&A* **308**, 643–655.
Desai, M. I., Mason, G. M., Dwyer, J. R., Mazur, J. E., Gold, R. E., Krimigis, S. M., *et al*.: 2003, *Astrophys. J.* **588**, 1149–1162.
DeVore, C. R., and Antiochos, S. K.: 2005, *ApJ* **628**, 1031–1045.
Dryer, M.: 1974, *Space Sci. Rev.* **15**, 403.
Dryer, M.: 1982, *Space Sci. Rev.* **33**, 233–275.
Dwyer, J. R., Mason, G. M., Mazur, J. E., Jokipii, J. R., von Rosenvinge, T. T., and Lepping, R. P.: 1997, *Astrophys. J.* **490**, L115.
Earl, J. A.: 1976, *Astrophys. J.* **205**, 900.
Earl, J. A.: 1981, *Astrophys. J.* **251**, 739–755.
Fermi, E.: 1954, *Astrophys. J.* **119**, 1–6.
Feynman, J., and Gabriel, S. B.: 2000, *J. Geophys. Res.* **105**, 10543–10564.
Feynman, J., and Martin, S. F.: 1995, *J. Geophys. Res.* **100**, 3355–3367.
Finn, J. M., and Chen, J.: 1990, *ApJ* **349**, 345–361.
Finn, J. M., and Guzdar, P. N.: 1993, *Physics of Fluids B* **5**, 2870–2876.
Fisk, L. A.: 1978, *Astrophys. J.* **224**, 1048–1055.
Forbes, T. G.: 2000, *J. Geophys. Res.* **105**, 23153–23166.
Forbes, T. G., Linker, J. A., *et al*.: 2006, *Space Science Reviews*, (this volume), doi: 10.1007/s11214-006-9019-8.
Forbes, T. G., and Isenberg, P. A.: 1991, *ApJ* **373**, 294–307.
Forbes, T. G., and Lin, J.: 2000, *J. Geophys. Res.* **62**, 1499–1507.
Forbes, T. G., and Priest, E. R.: 1995, *ApJ* **446**, 377–389.

Forbes, T. G., Priest, E. R., and Isenberg, P. A.: 1994, *Sol. Phys.* **150**, 245–266.
Forman, M. A.: 1981, *Adv. Space Res.* **1**(3), 97.
Gaizauskas, V.: 1993, *Adv. Space Res.* **13**, 5–14.
Gaizauskas, V., Harvey, K. L., Harvey, J. W., and Zwaan, C.: 1983, *ApJ* **265**, 1056–1065.
Gaizauskas, V., Zirker, J. B., Sweetland, C., and Kovacs, A.: 1997, *ApJ* **479**, 448–457.
Gary, G. A., and Moore, R. L.: 2004, *ApJ* **611**, 545–556.
Gleeson, L. J., and Axford, W. I.: 1967, *Astrophys. J.* **149**, L115.
Gloeckler, G., Fisk, L. A., Geiss, J., Schwadron, N. A., and Zurbuchen, T. H.: 2000, *J. Geophys. Res.* **105**, 7459–7464.
Gopalswamy, N.: 2003, *Adv. Space Res.* **31**, 869–881.
Gopalswamy, N.: 2005, *EOS Trans. AGU* **86**(50), 525.
Gopalswamy, N. *et al.*: 2006, *Space Sci. Rev.*, (this volume), doi: 10.1007/s11214-006-9020-2.
Gopalswamy, N., Lara, A., Kaiser, M. L., and Bougeret, J.-L.: 2001, *J. Geophys. Res.* **106**, 25,261–25,277.
Gordon, B. E., Lee, M. A., Moebius, E., and Trattner, K. H.: 1999, *J. Geophys. Res.* **104**, 28263–28277.
Gosling, J. T., Baker, D. N., Bame, S. J., Feldman, W. C., Zwickl, R. D., and Smith, E. J.: 1987, *J. Geophys. Res.* **92**, 8519–8535.
Gosling, J. T., Birn, J., and Hesse, M.: 1995, *Geophys. Res. Lett.* **22**, 869–872.
Groth, C. P. T., de Zeeuw, D. L., Gombosi, T. I., and Powell, K. G.: 2000, *J. Geophys. Res.* **105**, 25053–25078.
Hada, T., Kennel, C. F., and Terasawa, T.: 1987, *J. Geophys. Res.* **92**, 4423–4435.
Heras, A. M., Sanahuja, B., Lario, D., Smith, Z. K., Detman, T., and Dryer, M.: 1995, *Astrophys. J.* **445**, 497–508.
Heras, A. M., Sanahuja, B., Smith, Z. K., Detman, T., and Dryer, M.: 1992, *Astrophys. J.* **391**, 359–369.
Hoppe, M. M., Russell, C. T., Frank, L. A., Eastman, T. E., and Greenstadt, E. W.: 1981, *J. Geophys. Res.* **86**, 4471–4492.
Hudson, P. D.: 1965, *Mon. Not. R. Astr. Soc.* **131**, 23–49.
Hundhausen, A. J.: 1985, *AGU Geophys. Monogr.* **34**, 37–58.
Inhester, B., Birn, J., and Hesse, M.: 1992, *Sol. Phys.* **138**, 257–281.
Isenberg, P. A.: 1997, *J. Geophys. Res.* **102**, 4719–4724.
Isenberg, P. A., Forbes, T. G., and Démoulin, P.: 1993, *ApJ* **417**, 368–386.
Jacques, S. A.: 1977, *ApJ* **215**, 942–951.
Jokipii, J. R.: 1982, *Astrophys. J.* **255**, 716–720.
Jokipii, J. R., and Levy, E. H.: 1977, *Astrophys. J.* **213**, L85–L88.
Kahler, S.: 1994, *Astrophys. J.* **428**, 837–842.
Kallenrode, M. B.: 1993, *J. Geophys. Res.* **98**, 19037–19047.
Kallenrode, M. B., and Wibberenz, G.: 1997, *J. Geophys. Res.* **102**, 22311–22334.
Klecker, H., Kunow, H., *et al.*: 2006, *Space Science Reviews*, (this volume), doi: 10.1007/s11214-006-9018-9.
Klimchuk, J. A.: 2001, *Space Weather*, Song, P., Singer, H., and Siscoe, G. (eds.), AGU, Washington DC, Geophys. Monograph, Vol. 125, pp. 143–158.
Klimchuk, J. A., Canfield, R. C., and Rhoads, J. E.: 1992, *ApJ* **385**, 327–343.
Klimchuk, J. A., and Sturrock, P. A.: 1989, *ApJ* **345**, 1034–1041.
Krall, J., Chen, J., and Santoro, R.: 2000, *ApJ* **539**, 964–982.
Krymsky, G. F.: 1977, *Dokl. Akad. Nauk SSSR* **234**, 1306.
Lario, D., Sanahuja, B., and Heras, A. M.: 1998, *Astrophys. J.* **509**, 415–434.
Larson, D. E., Lin, R. P., Ergun, R. E., McTiernan, J. M., McFadden, J. P., Carlson, C. W., *et al.*: 1997, *Adv. Space Res.* **20**, 655–658.
Leamon, R. J., Canfield, R. C., Jones, S. L., Lambkin, K., Lundberg, B. J., and Pevtsov, A. A.: 2004, *J. Geophys. Res.* **109**, 5106.

Lee, J., McClymont, A. N., Mikić, Z., White, S. M., and Kundu, M. R.: 1998a, *ApJ* **501**, 853–865.
Lee, J., White, S. M., Kundu, M. R., Mikić, Z., and McClymont, A. N.: 1998b, *Sol. Phys.* **180**, 193–211.
Lee, J., White, S. M., Kundu, M. R., Mikić, Z., and McClymont, A. N.: 1999, *ApJ* **510**, 413–421.
Lee, M. A.: 1983, *J. Geophys. Res.* **88**, 6109–6119.
Lee, M. A.: 1991, *22nd International Cosmic Ray Conference*, Vol. 5, pp. 293–312.
Lee, M. A.: 1999, *EOS* **80**, S255. abstract.
Lee, M. A.: 2005, *Astrophys. J. Suppl.* **158**, 38–67.
Lee, M. A., and Fisk, L. A.: 1982, *Space Sci. Rev.* **32**, 205–228.
Lee, M. A., and Ryan, J. M.: 1986, *Astrophys. J.* **303**, 829–842.
Leka, K. D., Canfield, R. C., McClymont, A. N., and van Driel-Gesztelyi, L.: 1996, *ApJ* **462**, 547–560.
Lin, J. and Forbes, T. G.: 2000, *J. Geophys. Res.* **105**, 2375–2392.
Lin, J., Forbes, T. G., and Isenberg, P. A.: 2001, *J. Geophys. Res.* **106**, 25053–25074.
Lin, J., Forbes, T. G., Isenberg, P. A., and Démoulin, P.: 1998, *ApJ* **504**, 1006–1019.
Lin, J., Soon, W., and Baliunas, S. L.: 2003, *New Astron. Rev.* **47**, 53–84.
Lin, J., and van Ballegooijen, A. A.: 2002, *ApJ* **576**, 485–492.
Lin, J., van Ballegooijen, A. A., and Forbes, T. G.: 2002, *J. Geophys. Res.* **107**, 3–1.
Linker, J. A., Lionello, R., Mikić, Z., and Amari, T.: 2001, *J. Geophys. Res.* **106**, 25165–25176.
Linker, J. A., and Mikić, Z.: 1995, *ApJ* **438**, L45–L48.
Linker, J. A., Mikić, Z., Lionello, R., Riley, P., Amari, T., and Odstrcil, D.: 2003a, *Phys. Plasmas* **10**, 1971–1978.
Linker, J. A., Mikić, Z., Riley, P., Lionello, R., and Odstrcil, D.: 2003b, *AIP Conference Proceedings: Solar Wind Ten*, Velli, M., Bruno, R., and Malara, F. (eds.), American Institute of Physics, New York, Vol. 679, pp. 703–710.
Lionello, R., Mikić, Z., Linker, J. A., and Amari, T.: 2002, *ApJ* **581**, 718–725.
Litvinenko, Y. E.: 1996, *Astrophys. J.* **462**, 997–1004.
Litvinenko, Y. E., and Martin, S. F.: 1999, *Sol. Phys.* **190**, 45–58.
Livi, S. H. B., Martin, S., Wang, H., and Ai, G.: 1989, *Sol. Phys.* **121**, 197–214.
Livi, S. H. B., Wang, J., and Martin, S. F.: 1985, *Australian J. Phys.* **38**, 855–873.
Lopate, C.: 2001, *Proceedings of the International Conference Cosmic Rays 27th*, Vol. 8, pp. 3398–3400.
Low, B. C.: 1977, *ApJ* **212**, 234–242.
Low, B. C.: 1981, *ApJ* **251**, 352–363.
Low, B. C.: 1993, *Adv. Space Res.* **13**, 63–69.
Low, B. C.: 1994, *Phys. Plasmas* **1**, 1684–1690.
Low, B. C.: 1996, *Sol. Phys.* **167**, 217–265.
Low, B. C.: 1999, *AIP Conference Proceedings: Solar Wind Nine*, Habbal, S. R., Esser, R., Hollweg, J. V., and Isenberg, P. A. (eds.), American Inst. Phys., New York, Vol. 471, pp. 109–114.
Low, B. C.: 2001, *J. Geophys. Res.* **106**, 25141–25164.
Low, B. C., and Smith, D. F.: 1993, *ApJ* **410**, 412–425.
Luhmann, J. G., Solomon, S. C., Linker, J. A., Lyon, J. G., Mikić, Z., Odstrcil, D., *et al*.: 2004, *J. Atmos. Terrestrial Phys.* **66**, 1243–1256.
Lynch, B. J., Antiochos, S. K., MacNeice, P. J., Zurbuchen, T. H., and Fisk, L. A.: 2004, *ApJ* **617**, 589–599.
Mackay, D. H., and Gaizauskas, V.: 2003, *Sol. Phys.* **216**, 121–142.
Mackay, D. H., Priest, E. R., Gaizauskas, V., and van Ballegooijen, A. A.: 1998, *Sol. Phys.* **180**, 299–312.
Mackay, D. H., and van Ballegooijen, A. A.: 2001, *ApJ* **560**, 445–455.
Mackay, D. H., and van Ballegooijen, A. A.: 2005, *ApJ* **621**, L77–L80.

MacNeice, P., Antiochos, S. K., Phillips, A., Spicer, D. S., DeVore, C. R., and Olson, K.: 2004, *ApJ* **614**, 1028–1041.
Manchester, W.: 2003, *J. Geophys. Res.* **108**, 10–1.
Manchester, W., Gombosi, T., DeZeeuw, D., and Fan, Y.: 2004a, *ApJ* **610**, 588–596.
Manchester, W. B., Gombosi, T. I., Roussev, I., De Zeeuw, D. L., Sokolov, I. V., Powell, K. G., Tóth, G., and Opher, M.: 2004b, *J. Geophys. Res.* **109**, 10.1029/2002JA009672.
Manchester, W. B., Gombosi, T. I., Roussev, I. I., Ridley, A., de Zeeuw, D. L., Sokolov, I. V., *et al.*: 2004c, *J. Geophys. Res.* **109**, CiteID A02107 DOI 10.1029/2003JA010150.
Mann, G., Klassen, A., Aurass, H., and Classen, H.-T.: 2003, *Astron. Astrophys.* **400**, 329–336.
Martens, P. C., and Zwaan, C.: 2001, *ApJ* **558**, 872–887.
Martin, S. F.: 1998, *Sol. Phys.* **182**, 107–137.
Martin, S. F., Livi, S. H. B., and Wang, J.: 1985, *Australian Journal of Physics* **38**, 929–959.
Mason, G. M., Mazur, J. E., and Dwyer, J. R.: 1999, *Astrophys. J.* **525**, L133–L136.
Metcalf, T. R., Leka, K. D., and Mickey, D. L.: 2005, *ApJ* **623**, L53–L56.
Mikić, Z., Barnes, D. C., and Schnack, D. D.: 1988, *ApJ* **328**, 830–847.
Mikić, Z., and Linker, J. A.: 1994, *ApJ* **430**, 898–912.
Mikić, Z., Linker, J. A., Schnack, D. D., Lionello, R., and Tarditi, A.: 1999, *Phys. Plasmas* **6**, 2217–2224.
Miller, J. A., Guessoum, N., and Ramaty, R.: 1990, *Astrophys. J.* **361**, 701–708.
Miller, J. A., and Vinas, A. F.: 1993, *Astrophys. J.* **412**, 386–400.
Moebius, E., Scholer, M., Hovestadt, D., Klecker, B., and Gloeckler, G.: 1982, *Astrophys. J.* **259**, 397–410.
Moreton, G. E.: 1960, *Astron. J.* **65**, 494–495.
Ng, C. K., Reames, D. V., and Tylka, A. J.: 1999, *Geophys. Res. Lett.* **26**, 2145–2148.
Odstrcil, D.: 2003, *Adv. Space Res.* **32**, 497–506.
Odstrcil, D., Linker, J. A., Lionello, R., Mikić, Z., Riley, P., Pizzo, V. J., *et al.*: 2002, *J. Geophys. Res.* **107**, 10.1029/2002JA009334.
Odstrcil, D., and Pizzo, V. J.: 1999a, *J. Geophys. Res.* **104**, 28225–28239.
Odstrcil, D., and Pizzo, V. J.: 1999b, *J. Geophys. Res.* **104**, 483–492.
Odstrcil, D., and Pizzo, V. J.: 1999c, *J. Geophys. Res.* **104**, 493–504.
Parker, E. N.: 1961, *Astrophys. J.* **133**, 1014.
Parker, E. N.: 1963, *Interplanetary Dynamical Processes*, New York, Interscience Publishers.
Parker, E. N.: 1965, *Planet. Space Sci.* **13**, 9.
Pick, M., Forbes, T. G., Mann, G., *et al.*: 2006, *Space Sci. Rev.*, (this volume), doi: 10.1007/s11214-006-9021-1.
Pizzo, V. J.: 1985, *AGU Geophys. Monogr.* **35**, 51–68.
Pneuman, G. W.: 1983, *Sol. Phys.* **88**, 219–239.
Powell, K. G., Gombosi, T. I., deZeeuw, D. L., Ridley, A. J., Sokolov, I. V., Stout, Q. F., *et al.*: 2003, *SOLAR WIND TEN: Proceedings of the Tenth International Solar Wind Conference, AIP Conference Proceedings*, Vol. 679, pp. 807–814.
Pyle, K. R., Simpson, J. A., Barnes, A., and Mihalov, J. D.: 1984, *Astrophys. J.* **282**, L107–L111.
Ramaty, R.: 1979, in *Particle Acceleration Mechanisms in Astrophysics: Proceedings of the Workshop held at La Jolla, Calif., January 3–5, 1979*, AIP, New York, pp. 135–154.
Reames, D. V.: 1999, *Space Sci. Rev.* **90**, 413–491.
Reames, D. V., Kahler, S. W., and Ng, C. K.: 1997, *Astrophys. J.* **491**, 414–420.
Reiner, M. J., Kaiser, M. L., and Bougeret, J.-L.: 2001, *J. Geophys. Res.* **106**, 29989–30000.
Reiner, M. J., Kaiser, M. L., and Bougeret, J.-L.: 2003, *Solar Wind Ten, Proceedings of the Tenth International Solar Wind Conference, AIP Conference Proceedings*, Vol. 679, pp. 152–155.
Riley, P., and Gosling, J. T.: 1998, *Geophys. Res. Lett.* **25**, 1529–1532.
Riley, P., Gosling, J. T., and Pizzo, V. J.: 1997, *J. Geophys. Res.* **102**, 14677–14686.

Riley, P., Linker, J. A., Lionello, R., Mikić, Z., Odstrcil, D., Hidalgo, M. A., *et al.*: 2004, *J. Atmos. Terrestrial Phys.* **66**, 1321–1331.

Riley, P., Linker, J. A., Mikić, Z., Odstrcil, D., Zurbuchen, T. H., Lario, D., *et al.*: 2003, *J. Geophys. Res.* **108**, 1272.

Roelof, E. C.: 1969, *Lectures in High Energy Astrophysics*, Ogelmann, H., and Wayland, J. R. (eds.), NASA Spec. Publ. SP-199, p. 111.

Rogers, M. H.: 1957, *Astrophys. J.* **125**, 478.

Roussev, I. I., Forbes, T. G., Gombosi, T. I., Sokolov, I. V., DeZeeuw, D. L., and Birn, J.: 2003, *ApJ* **588**, L45–L48.

Roussev, I. I., Sokolov, I. V., Forbes, T. G., Gombosi, T. I., Lee, M. A., and Sakai, J. I.: 2004, *ApJ* **605**, L73–L76.

Ruffolo, D.: 1995, *Astrophys. J.* **442**, 861–874.

Ryan, J. M., and Lee, M. A.: 1991, *Astrophys. J.* **368**, 316–324.

Sarris, E. T., and Van Allen, J. A.: 1974, *J. Geophys. Res.* **79**, 4157–4173.

Schwenn, R., Raymond, J. C., *et al.*: 2006, *Space Sci. Rev.*, (this volume), doi: 10.1007/s11214-006-9016-y.

Sedov, L.: 1959, *Similarity and Dimensional Methods in Mechanics*, Academic Press, New York.

Sheeley, N. R., Hakala, W. N., and Wang, Y.-M.: 2000, *J. Geophys. Res.* **105**, 5081–5092.

Skilling, J.: 1971, *Astrophys. J.* **170**, 265.

Steinolfson, R. S.: 1985, *AGU Geophys. Monographs* **35**, 1–12.

Sturrock, P. A.: 1991, *ApJ* **380**, 655–659.

Syrovatskii, S. I.: 1982, *Sol. Phys.* **76**, 3–20.

Temerin, M., and Roth, I.: 1992, *Astrophys. J.* **391**, L105–L108.

Titov, V. S., Hornig, G., and Démoulin, P.: 2002, *J. Geophys. Res.* **107**, 1164.

Tóth, G., Sokolov, I. V., Gombosi, T. I., Chesney, D. R., Clauer, C. R., De Zeeuw, D. L., *et al.*: 2005, *J. Geophys. Res.* **110**, CiteID A12226, DOI 10.1029/2005JA011126.

Tsuneta, S., and Naito, T.: 1998, *Astrophys. J.* **495**, L67–L70.

Tsurutani, B., Wu, S. T., Zhang, T. X., and Dryer, M.: 2003, *Astron. and Astrophys.* **412**, 293–304.

Tylka, A. J., Cohen, C. M. S., Dietrich, W. F., Lee, M. A., Maclennan, C. G., Mewaldt, R. A., *et al.*: 2005, *Astrophys. J.* **625**, 474–495.

Tylka, A. J., Reames, D. V., and Ng, C. K.: 1999, *Geophys. Res. Lett.* **26**, 2141–2144.

Usmanov, A. V., Goldstein, M. L., Besser, B. P., and Fritzer, J. M.: 2000, *J. Geophys. Res.* **105**, 12675–12696.

Vainio, R., and Khan, J. I.: 2004, *Astrophys. J.* **600**, 451–457.

van Ballegooijen, A. A., and Martens, P. C. H.: 1989, *ApJ* **343**, 971–984.

van Ballegooijen, A. A., and Martens, P. C. H.: 1990, *ApJ* **361**, 283–289.

van Ballegooijen, A. A., Priest, E. R., and Mackay, D. H.: 2000, *ApJ* **539**, 983–994.

Vourlidas, A., Buzasi, D., Howard, R. A., and Esfandiari, E.: 2002, *ESA SP-506: Solar Variability: From Core to Outer Frontiers*, pp. 91–94.

Vourlidas, A., Subramanian, P., Dere, K. P., and Howard, R. A.: 2000, *ApJ* **534**, 456–467.

Webb, D. F., Lepping, R. P., Burlaga, L. F., DeForest, C. E., Larson, D. E., Martin, S. F., *et al.*: 2000, *J. Geophys. Res.* **105**, 27251–27260.

Welsch, B. T., DeVore, C. R., and Antiochos, S. K.: 2005, *ApJ* **634**, 1395–1404.

Whang, Y. C., and Burlaga, L. F.: 1985, *J. Geophys. Res.* **90**, 10,765–10,778.

Whang, Y. C., Zhou, J., Lepping, R. P., and Ogilvie, K. W.: 1996, *Geophy. Res. Lett.* **23**, 1239–1242.

Wimmer-Schweingruber, R. F., Crooker, N. U., *et al.*: 2006, *Space Science Reviews*, this volume.

Wolfson, R.: 1993, *ApJ* **419**, 382–387.

Wolfson, R., and Dlamini, B.: 1997, *ApJ* **483**, 961–971.

Wolfson, R., and Dlamini, B.: 1999, *ApJ* **526**, 1046–1051.

Wolfson, R., and Low, B. C.: 1992, *Apj* **391**, 353–358.

Wolfson, R., and Saran, S.: 1998, *ApJ* **499**, 496–503.
Wu, S. T., Andrews, M. D., and Plunkett, S. P.: 2001, *Space Sci. Rev.* **95**, 191–213.
Wu, S. T., Hu, Y. Q., Wang, S., Dryer, M., and Tandberg-Hanssen, E.: 1982, *Ap&SS* **83**, 189–194.
Yang, W. H., Sturrock, P. A., and Antiochos, S. K.: 1986, *ApJ* **309**, 383–391.
Zank, G. P., Rice, W. K. M., and Wu, C. C.: 2000, *J. Geophys. Res.* **105**, 25079–25095.
Zwaan, C.: 1985, *Sol. Phys.* **100**, 397–414.
Zwaan, C.: 1987, *ARA&A* **25**, 83–111.
Zwaan, C.: 1996, *Sol. Phys.* **169**, 265–276.