SOLAR IMPRINT ON ICMES, THEIR MAGNETIC CONNECTIVITY, AND HELIOSPHERIC EVOLUTION

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Abstract. Interplanetary outflows from coronal mass ejections (ICMEs) are structures shaped by their magnetic fields. Sometimes these fields are highly ordered and reflect properties of the solar magnetic field. Field lines emerging in CMEs are presumably connected to the Sun at both ends, but about half lose their connection at one end by the time they are observed in ICMEs. All must eventually lose one connection in order to prevent a build-up of flux in the heliosphere; but since little change is observed between 1 AU and 5 AU, this process may take months to years to complete. As ICMEs propagate out into the heliosphere, they kinematically elongate in angular extent, expand from higher pressure within, distort owing to inhomogeneous solar wind structure, and can compress the ambient solar wind, depending upon their relative speed. Their magnetic fields may reconnect with solar wind fields or those of other ICMEs with which they interact, creating complicated signatures in spacecraft data.

1. Introduction

How do the properties of interplanetary coronal mass ejections (ICMEs) relate to their origins on the Sun, and how do the kinematics and dynamics of propagation into the heliosphere affect ICMEs and their environment? These two questions structure the content of this paper. The first concerns internal structure and magnetic connection to the Sun and is addressed in Section 2. The second concerns external processes and is addressed in Section 3.

2. Internal Structure and Connectivity

As reviewed by Zurbuchen and Richardson (2006, this volume), ICMEs range in complexity from fairly simple magnetic clouds characterized by smooth field rotations, high magnetic field strength, and low temperature (e.g., Burlaga, 1988) to complicated, compound structures with signatures that have non-matching boundaries. This section focuses on the simple structures, magnetic clouds, whose magnetic parameters, usually calculated from flux rope model fits, can be classified and related to solar parameters. Sections 2.1, 2.2, and 2.3, respectively, address

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the imprint of solar magnetic fields on clouds, the remote connections of magnetic field lines in clouds, and the relation between cloud properties and solar features observed in coronagraphs.

2.1. Solar Magnetic Field Imprint

Various aspects of solar magnetic structures are reflected in the structure of magnetic clouds. Section 2.1.1 discusses how CME formation under the helmet streamer belt can create ICMEs that blend into the heliospheric sector structure, and Section 2.1.2 discusses how the chirality, leading magnetic field orientation, and axis orientation of magnetic clouds reflects magnetic properties of filaments and the helmet streamer belt.

2.1.1. *ICMEs and Sector Boundaries*

Coronagraphs have long shown that CMEs arise from the predominantly closed field line regions of the Sun under the umbrella of the helmet streamer belt (e.g., Hundhausen, 1993). The helmet streamer belt, in turn, forms the base from which stems the boundary between sectors of oppositely directed magnetic fields in the heliosphere, or the heliospheric current sheet (HCS) (Figure 1a).If field lines from the arcade of loops comprising the streamer belt rise, shear, and reconnect to form a CME flux rope, as pictured in Figure 1a and commonly modeled (e.g., Mikic

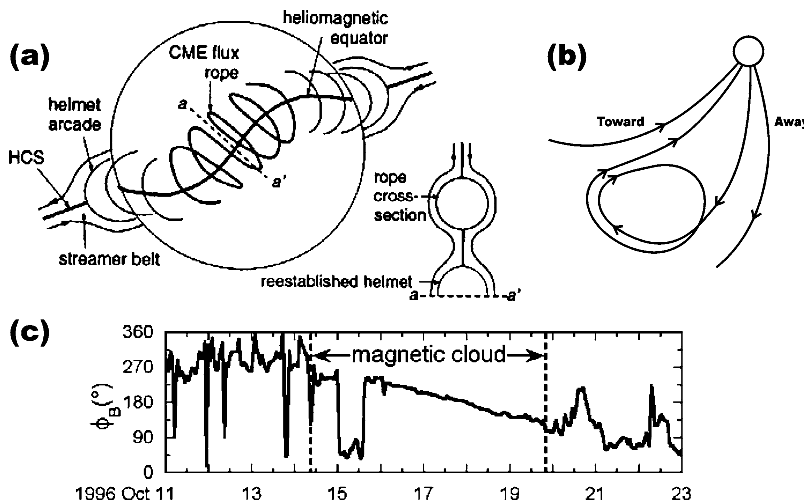

Figure 1. Relationship between magnetic clouds and sector boundaries. (a) A CME flux rope forms from the helmet arcade at the base of the heliospheric current sheet (HCS) separating sectors of opposite magnetic polarity (Crooker *et al.*, 1998). (b) Fields in flux rope legs match away and toward polarity of adjacent sectors. (c) Magnetic azimuth angle measured by Ulysses rotates from away to toward polarity across a magnetic cloud (flux rope) at a sector boundary (Forsyth *et al.*, 1997).

and Lee, 2006, this volume), it follows that the field lines comprising the flux rope will match the surrounding sector structure. Further into the heliosphere, Figure 1b illustrates how the fields in the legs of the flux rope and the sides of its loops will have the same local polarity as the true polarity of the adjacent open field lines on either side. Moreover, the current that creates the flux rope configuration embeds itself in the HCS so that the CME constitutes a bulge of distributed current in what is otherwise a current sheet.

Some observations clearly support the Figures 1a and 1b views (e.g., Crooker *et al*., 1998). Figure 1c gives an example of the time variation of the magnetic azimuth angle across a magnetic cloud at a sector boundary encountered by Ulysses at 4.4 AU (Forsyth *et al*., 1997). Instead of a sharp change from 270° marking polarity away from the Sun to 90° marking polarity toward the Sun, as expected for an HCS crossing, the polarity change is accomplished through the days-long field rotation intrinsic to the cloud. As noted by Forsyth *et al*. (1997), "The HCS is neither pushed aside nor draped around the CME but is replaced locally by the CME."

Many ICMEs are not encountered at sector boundaries, presumably because ICMEs are large and orbits through them skim the vicinity of the HCS rather than pass through it. Supporting this view, Kahler *et al*. (1999) found that the "polarity" of ICMEs, assuming passage through one leg rather than the apex of an ICME loop (cf. Figure 1b), is 10 times more likely to match than not to match the surrounding sector polarity. In their study, ICME leg "polarity" was determined not from local magnetic fields, which can turn back on themselves, but from the direction of the strongest counterstreaming suprathermal electron beam relative to the magnetic field direction (see Section 2.2). The fact that one beam is usually stronger supports the assumption that passage is through one leg, since the stronger beam presumably comes from the nearest solar connection point (Pilipp *et al*., 1987). The Kahler *et al*. (1999) study is the most thorough confirmation to date that ICMEs blend into the sector structure, consistent with the expected solar imprint.

2.1.2. *Magnetic Cloud Flux Rope Parameters, Filaments, and the Heliomagnetic Equator*

A magnetic flux rope expanding into the heliosphere as a loop of nested coils connected to the Sun at both ends (Figure 2 in Zurbuchen and Richardson, 2006, this volume) can be characterized by the directions of its axial and leading fields at the apex of the loop, which together determine the handedness of the twist (Bothmer and Schwenn, 1998). These parameters carry the imprint of both high- and low-altitude solar features (see review by Crooker (2000) and references therein).

From Figure 1a one might expect the direction of the magnetic field at the leading edge of an ICME flux rope or magnetic cloud to reflect the dipole component of the solar magnetic field inherent in the helmet streamer belt, pointing south (north) from the maximum of an even (odd) cycle to the maximum of an odd (even) cycle. Observations show this to be true for 77% of a total of 79 clouds tested

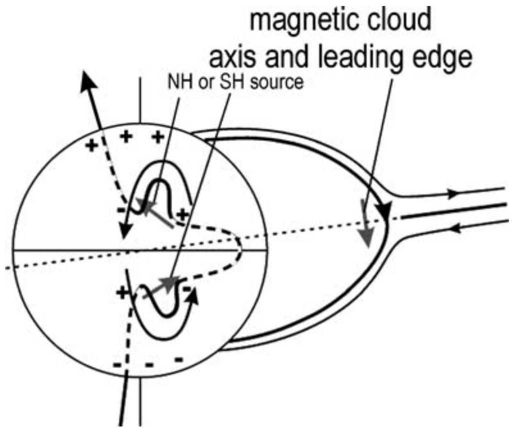

Figure 2. Schematic diagram of solar magnetic features that control magnetic cloud parameters. The direction of the field line distorted by differential rotation gives the direction of the cloud axis, depending upon its hemisphere of origin, and the direction of the dipole component (with a phase lag, see text) gives the direction of the leading field.

in the period spanning 1974 to 1991 (Bothmer and Rust, 1997; Mulligan *et al.*, 1998), with the caveat that the sign change expected at solar maximum shifts to the declining phase. This phase shift may reflect higher-order field components lower in the solar atmosphere, where arcades over filaments retain the old cycle polarity until presumably they are shed as CMEs (cf. Gopalswamy *et al.*, 2003). Although (Leamon *et al.*, 2002) report no correspondence between the solar dipolar component and the leading field direction in magnetic clouds arising from sigmoids in active regions, when the phase shift is taken into account, 65% of their 34 cases fit the pattern.

With the possible exception of the early declining phase, magnetic fields high in the solar atmosphere appear to be systematically related to those in the lower atmosphere (Martin and McAllister, 1997; McAllister *et al.*, 2002), with the result that magnetic cloud parameters reflect filament as well as streamer belt characteristics. Filaments align with neutral lines which are convoluted at low altitudes owing to the influence of higher-order fields but map up to the smoother HCS, which serves as the heliomagnetic equator (Figure 1a). Thus there is some correspondence between the tilts of cloud axes and HCS tilt with respect to the ecliptic plane (Mulligan *et al.*, 1998) as well as the tilts of filament axes (Marubashi, 1997). Zhao and Hoeksema (1997) have shown that on average cloud axes are less tilted than filament axes by a factor of 0.7, consistent with the influence of higher-order fields on filaments (cf. Section 2 of Forsyth *et al.* (2006, this volume)).

In addition to tilt angle, the handedness of twist determined from filament structure is reflected in magnetic clouds. Although filaments may not be flux ropes themselves (Martin and McAllister, 1997), the pattern of magnetic fields surrounding filaments, consisting of barbs and fibrils, displays a skew. Martin *et al.* (1994) found the skew to be dextral in the northern hemisphere and sinistral in the southern hemisphere for 89% of 73 quiescent filaments, independent of solar cycle, although no pattern was found for 31 active-region filaments. At higher altitudes, the coronal arcades overlying quiescent filaments have the opposite skew (Martin and McAllister, 1997). When these arcade fields reconnect to form a CME flux rope, the rope will tend to have left-handed twist if it emerges from the northern hemisphere and right-handed twist if it emerges from the southern hemisphere. Rust (1994) found this to be true for 13 out of 16 magnetic clouds. Somewhat surprisingly, for 36 clouds arising from active regions, (Leamon *et al.*, 2002) found the same hemispheric pattern for 75% of them.

Figure 2 summarizes the solar magnetic imprint patterns on magnetic clouds. The predicted direction of the axial field of a cloud, marked by a short gray arrow in each hemisphere, is the direction of a field line distorted by differential rotation, as in the Babcock model and in the filament pattern low in the solar atmosphere (cf. Bothmer and Schwenn, 1998). At higher altitudes, one can imagine the tilt of the axis lowering toward the dotted line representing the heliomagnetic equator as the neutral line of the filament channel maps up to the HCS. The bipolar field line arched over each filament axis, as in the Babcock view of sunspot formation, represents a low-level arcade. At higher altitudes, the skew of the arcade fields increases until they point in the direction of the solar dipole component, at least until solar maximum. This is the predicted direction of the leading field of a magnetic cloud, as indicated. For the subsequent cycle, when the dipolar fields have the opposite sign, the directions of both the cloud axes and their leading fields will be reversed, which maintains the observed hemispheric pattern of handedness. While the Figure 2 sketch does not capture the lag between filament and polar fields during the declining phase that can account for the phase shift in the sign change of leading fields, it is physically accurate for the ascending phase and serves as a mnemonic device for most of the solar cycle between maxima.

2.2. Magnetic Connectivity to the Sun

Sketches of ICMEs usually show their magnetic field lines connected to the Sun at both ends, as in Figure 1b. The degree to which this is true, our understanding of how connections change, and implications for the heliospheric magnetic flux budget are the respective topics of Sections 2.2.1, 2.2.2, and 2.2.3.

2.2.1. *Tracing ICME Field Connections*

Particles with energies higher than those that constitute the core of solar wind distributions act as field line tracers. Like core particles, they are confined to gyrating motions about field lines; but their considerably higher velocity components result not only in larger gyroradii but in high field-aligned speeds that create particle beams that give nearly instant information about solar connections. For example, solar energetic particle (SEP) events observed inside magnetic clouds give incontrovertible evidence of field lines connected to the Sun at least on one end, as opposed to field lines detached at both ends or closing upon themselves in plasmoids (e.g., Richardson, 1997; Malandraki *et al.*, 2003; and references therein). Further discussion of ICME tracing with particles in the SEP energy range can be found in Section 4.6 of Wimmer-Schweingruber *et al.* (2006, this volume). This section focuses primarily on the lower-energy suprathermal electrons ($E \gtrsim 80$ eV) as ICME field-line tracers.

Because fluxes are higher at lower energies, suprathermal electrons constitute a continuous source of field-aligned particles from the Sun. They focus into beams as their pitch angles decrease owing to decreasing magnetic field strength with distance from the Sun. While scattering processes, shocks, and other inhomogeneities in the heliospheric magnetic field alter these beams as they propagate outward (Wimmer-Schweingruber *et al.*, 2006, this volume), informed use of suprathermal electron data have yielded a large body of information about ICME connections. Counterstreaming beams, used as one of the first widely-accepted signatures of ICMEs (Gosling *et al.*, 1987), are interpreted as a signature of closed field lines, connected to the Sun at both ends. Unidirectional beams signal open field lines, connected at only one end. The lack of beams, called a "heat flux dropout" (HFD) because suprathermal electrons carry heat flux away from the Sun, is a necessary but unfortunately not sufficient signature of field lines disconnected from the Sun at both ends (Crooker *et al.*, 2002; Crooker *et al.*, 2003; Pagel *et al.*, 2005; and references therein). Studies of counterstreaming suprathermal electrons as well as higher-energy particles conclude that ICMEs contain a mixture of open, closed, and, on rare occasions, disconnected field lines (Bothmer *et al.*, 1996; Larson *et al.*, 1997, 2000; Malandraki *et al.*, 2003; Crooker *et al.*, 2004). For example, in a study of 48 magnetic clouds at 1 AU, Shodhan *et al.* (2000) found counterstreaming only 59% of the time, on average, leaving the clouds 41% open.

2.2.2. *Conceptual Modeling of ICME Connections*

An explanation for how a coherent flux rope in the solar wind can contain a mix of open and closed field lines, as pictured in Figure 3a, has been provided by Gosling *et al.* (1995). The conceptual model is based upon an MHD simulation of flux rope release in Earth's magnetosphere (Hesse and Birn, 1991) in which reconnection between differently-connected field lines occurs seemingly randomly yet progressively disconnects closed field lines. The steps leading to disconnection are illustrated in Figure 3b: (1) closed loops with sheared footpoints reconnect to form a flux rope that is still connected to the Sun at both ends (i.e., closed); (2) an open field line reconnects with a field line in one leg of the flux rope to form an open coil; (3) an open field line reconnects with a field line in the other leg of the flux rope to form a disconnected coil; (4) two open field lines reconnect to form a U-shaped disconnected field line encasing the disconnected coil. Since

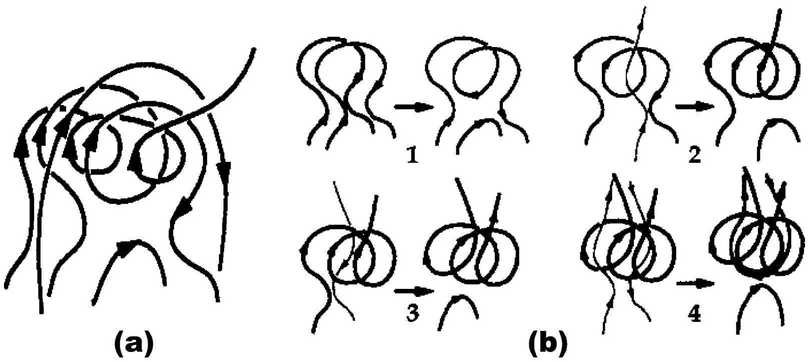

Figure 3. Schematic drawings of magnetic field lines in CME flux rope (Gosling *et al.*, 1995). (a) Coherent flux rope with open coil nested in a closed coil. (b) Four steps to disconnection: 1. partial disconnection, two closed loops reconnect to form coil; 2. interchange reconnection, open field line reconnects with closed coil to form open coil; 3. open field line reconnects with open coil to disconnect coil; 4. two open field lines reconnect to form U-shaped disconnected field line.

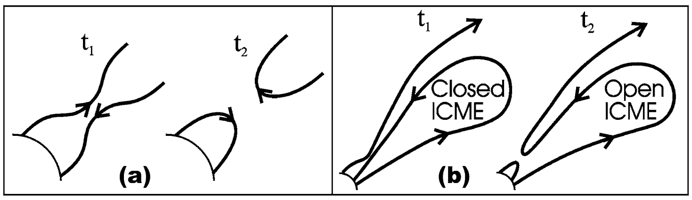

Figure 4. Before (t1) and after (t2) solutions to the problem of magnetic flux build-up from CMEs: (a) disconnection and (b) interchange reconnection (Crooker *et al.*, 2002).

observations show that disconnected field lines in ICMEs are rare, steps 3 and 4 are not important for CMEs. Steps 1 and 2, respectively called "partial disconnection" and "interchange reconnection," result in the configuration in Figure 3a and play an important role in the heliospheric magnetic flux budget (Crooker *et al.*, 2002), discussed in the following section.

2.2.3. *Heliospheric Magnetic Flux Budget*

Without some mitigating process, the closed flux that CMEs introduce to the heliosphere would result in a continuous build-up of magnetic flux, which is not observed. McComas (1995) argues that the only means of preventing flux build-up from CMEs is to disconnect fields elsewhere through reconnection of open field lines back at the Sun. Figure 4a illustrates the resulting U-shaped field with no connection to the Sun (cf. step 4 in Figure 3b). The problem with this solution is that true signatures of disconnection are rare, as mentioned in Section 2.2.1, not only within ICMEs but throughout the solar wind. About 90% of HFDs at time scales > 1 hr show electrons with reduced intensities and/or at higher energies still streaming from the Sun along what must be connected field lines (Lin and Kahler, 1992; Pagel *et al.*, 2005).

An alternative solution to the problem of magnetic flux build-up is that the closed field lines within ICMEs open through interchange reconnection (Gosling *et al.*, 1995; Crooker *et al.*, 2002). As illustrated in Figure 4b (cf. step 2 in Figure 3b), an open field line can reconnect with a closed field line in one leg of an ICME back at the Sun with the result that the closed loop in the heliosphere is exchanged for a closed loop in the solar atmosphere. This alternative solution is attractive because interchange reconnection generates no disconnected field lines, in agreement with the observation that they are rare, and it can continue to open CMEs well after they have left the Sun, until they are completely open and add no flux to the heliosphere.

If interchange reconnection is the means by which the flux budget is balanced, one might expect that ICMEs observed by Ulysses beyond 1 AU would be more open than those at 1 AU, but this seems not to be the case. Using counterstreaming electrons as a signature of closed fields, Riley *et al.* (2004) could detect no radial trend in the degree of openness in ICMEs encountered on the way to Jupiter, and (Crooker *et al.*, 2004) found that magnetic clouds near 5 AU were not significantly more open on average than those at 1 AU. Both papers conclude that the rate at which a CME opens by interchange reconnection must slow significantly as its leading edge moves out into the heliosphere and that it may take months to years rather than days to open completely, leading to a temporary flux build-up that is consistent with the factor of two solar cycle variation in heliospheric magnetic flux (e.g., Wang *et al.*, 2000). On the other hand, as discussed in detail by Crooker (2005), after months to years, closed loops moving out into the heliosphere will likely lose their counterstreaming signature and be indistinguishable from open field lines in spacecraft measurements. The interchange reconnection that eventually opens them will then give the signature of open field lines reconnecting, or disconnection, which reopens the problem of finding sufficient disconnection signatures. A different problem arises if one argues that ICMEs should be completely open by the time they reach 5 AU based upon estimates of the rate of interchange reconnection at the Sun (Reinard and Fisk, 2004). Although this eliminates the need for disconnection signatures, it casts doubt upon the relatively robust and widely-used interpretation of counterstreaming suprathermal electrons as signatures of closed fields. Clearly current understanding of these issues leads to dilemmas that remain to be resolved.

2.3. Imprint of Plasma Origins

Progress in understanding plasma characteristics of ICMEs in terms of what we know about CMEs has been limited owing to a number of constraints on observations. Two topics of interest concern the interpretation of elemental and ionic composition data from ICMEs and ICME manifestations of the three-part structure of CMEs observed in coronagraphs. The first is treated by Wimmer-Schweingruber *et al*. (2006, this volume), von Steiger and Richardson (2006, this volume), and Gazis *et al*. (2006, this volume). Here, relevant to the discussion in section 2.2.2, we note that the high charge state of heavy ions characteristic of ICMEs and indicative of high-temperature origins may well be a signature of magnetic fields reconnecting during CME liftoff, as argued by Lepri and Zurbuchen (2004).

The second topic, ICME manifestations of CME three-part structure, still raises more questions than it answers. The classic three parts are the bright outer rim, the dark cavity, and the bright core (see, e.g., Schwenn *et al*., 2006, this volume). These have been loosely associated with the pile-up of plasma or streamer material at the leading edge, the flux rope, and the filament, respectively, but these associations raise unsettled issues, particularly about flux rope formation and filament structure. What is assumed to be evidence of cool filament material from low in the solar atmosphere, for example, the presence of He+, is only rarely found in the solar wind (Zurbuchen and Richardson, 2006, this volume; Wimmer-Schweingruber *et al*., 2006, this volume), yet sometimes the bright core is a substantial fraction of the volume of an ICME. Suleiman *et al*. (2005) illustrate such a case and argue that although the bright core may be filament material, it may no longer reside on filament field lines. Through partial disconnection the filament material may gain access to the much larger flux rope formed by that process and thus lose both its magnetic coherence and the imprint of its cold origins (Crooker, 2005).

3. External Forces and Structures

The interaction of ICMEs with the ambient solar wind through which they propagate can significantly alter their properties as well as change the solar wind plasma itself. These interactions need to be understood in order to relate ICME properties to properties at their solar origins and thereby learn about what causes their generation and ejection. These interactions also tend to make ICMEs harder to identify and study. Significant additional effects of solar wind/ICME interactions include the energisation of particles by shocks (e.g., Reames, 1999), increased geoeffectiveness (e.g., Webb *et al*., 2000; Siscoe and Schwenn, 2006, this volume), and the enhanced blocking of energetic particle propagation (e.g., Ifedili, 2004).

The study of ICMEs over the last few decades has led to an increasing appreciation of the complexity that can arise from the dynamics of ICME interactions. These interactions result in extremely structured objects which are highly undersampled with in situ spacecraft data, and it is therefore challenging to deduce their 3D structure. Nevertheless, considerable progress has been made. Increasingly sophisticated simulations of ICME dynamics have shown what behaviours are possible and help interpret in situ data (see Forsyth *et al*., 2006, this volume). Advances have also been made in analytical models of magnetic flux ropes to take into account the effects of dynamical deformation.

We consider some of the most important consequences of dynamics in this paper. A number of related issues such as ICME deceleration and multi-spacecraft observations are discussed by Forsyth *et al*. (2006, this volume).

3.1. Kinematic Evolution

Kinematic aspects of the propagation of an ICME into interplanetary space result in changes to its shape, independent of any interaction with the ambient plasma. ICMEs are typically extended objects and cover a finite solid angle near the Sun. The propagation of the ICME plasma radially away from the Sun results in a preservation of this solid angle and a consequent increase in the extent of the ejecta perpendicular to the radial direction. Therefore, if the ICME retains its radial extent, it will expand into a "pancake" shape far from the Sun. This kinematic effect is shown schematically in Figure 5(a). Riley and Crooker (2004) show that this effect is significant by 1 AU for typical ICMEs. Radial expansion and the interaction with the ambient solar wind will obviously also alter the ICME shape, but this simple

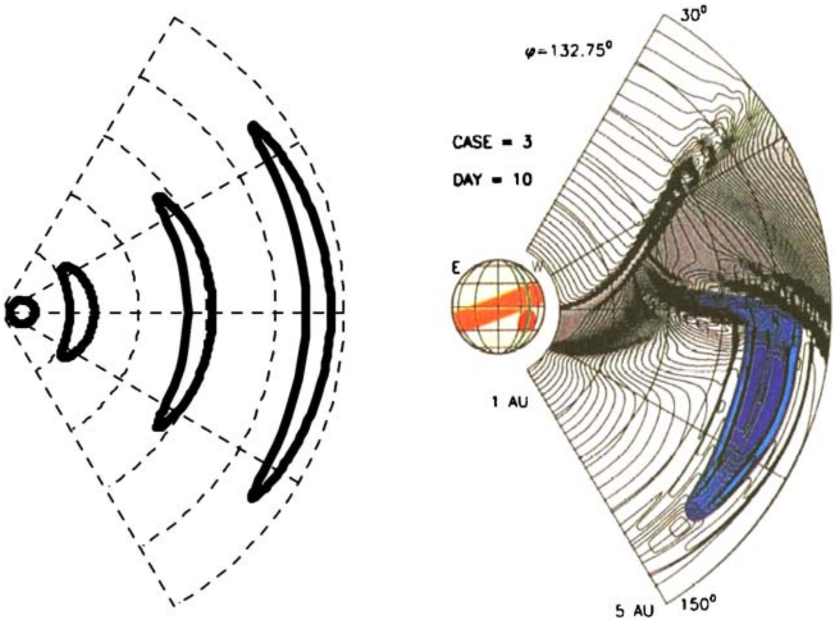

Figure 5. (a) Schematic of the kinematic effects of the radial expansion of ICMEs, leading to a "pancake" shape. (b) Results of a 3D simulation of an ICME propagating through a structured solar wind: the ICME is greatly distorted by its interaction with slow solar wind at low latitudes (after Odstrčil and Pizzo, 1999b).

geometrical effect implies that it is never possible to assume that ICMEs propagate unchanged into interplanetary space.

3.2. Dynamic Evolution

3.2.1. *Overexpanding ICMEs*

The simplest interplanetary signatures of ICMEs were in fact the last to be identified. Ulysses observations within steady, high-speed solar wind at high latitudes at several AU revealed (e.g., Gosling *et al.*, 1998) a class of transients lasting a few days, bounded by a forward and reverse shock, the latter being uncommon for low-latitude ICMEs. Their internal structure was remarkably uniform, and all the events were similar in their gross form. As with low-latitude ICMEs, around 1/3 contained magnetic flux ropes. Perhaps most surprisingly, these events tended to have a lower pressure inside than the ambient wind, although they were bounded by compressions and shocks. Gosling *et al.* (1998) showed that these signatures were consistent with ejecta with an initial overpressure relative to the ambient solar wind: this pressure drives the expansion of the ICME, producing a lower density cavity. In addition, simulations (e.g., Schmidt and Cargill, 2001) show that at least parts of ICMEs can propagate in latitude from the streamer belt into polar solar wind (see Section 3.2.3), so the observation of overexpanded ICMEs in high-speed wind does not imply that they originate in coronal holes. The magnetic field of flux rope ICMEs can act to prevent disruption of the large scale ICME structure (Cargill *et al.*, 2000).

The remarkable similarity of the observed events implies that, in the presence of uniform solar wind conditions, many or all ICMEs will exhibit this profile. Some events exhibit less symmetric time profiles than others: Gosling *et al.* (1998) showed that this was due to differences in the relative speeds of the solar wind and ejecta.

3.2.2. *Interaction with the Ambient Solar Wind*

While overexpanded ICMEs represent a particularly simple and regular class of ejecta signatures, most observed events are more complex. This is largely due to the complicated interactions between the ejecta and the ambient solar wind plasma. Since many ICMEs do not travel at the same speed as the solar wind in which they are embedded, compressions and rarefactions develop at the edges of the events. Even simple 1D simulations (e.g., Gosling and Riley, 1996) of solar wind dynamics show some of the possible consequences of these interactions, such as shocks and the acceleration or deceleration of ICMEs. The ICME shape can also be greatly distorted. Some of the consequences of these interactions are discussed in the remainder of this paper.

3.2.3. *Low- and High-Latitude Manifestations of the Same ICME*

The observation of relatively simple overexpanded ICMEs in high-latitude fast wind and much more complex structures at low latitudes raises the question as to whether these are two different classes of events or simply different manifestations of the same phenomenon. Observations of the same ICME at high and low latitudes (Hammond *et al*., 1995) show that these can be the same phenomenon, highlighting the importance of the ambient solar wind in determining the in situ signature of an ICME. As mentioned in Section 3.2.1, simulations (Riley *et al*., 1997; Schmidt and Cargill, 2001) show that ICMEs launched from within the streamer belt can partially penetrate the stream interface and enter high-speed polar wind, resulting in an ICME with different signatures in fast and slow wind, as observed (see Section 4.3 of Forsyth *et al*., 2006, this volume). When an ICME propagates within streams of different speeds, shear of the structure results from the effect of drag to bring speeds closer to that of the ambient solar wind.

The complexity that can arise from ICME-solar wind interactions, and the different character of a single ICME at different locations, is shown in the 3D simulation result in Figure 5(b), taken from Odstrčil and Pizzo (1999b). At high latitudes, the ICME resembles the kinematic ICME in Figure 5(a), although with a larger extent due to expansion caused by internal overpressure. At lower latitudes, the ICME is heavily distorted by solar wind interactions. Such simulations highlight the difficulties in interpreting in situ ICME data.

3.2.4. *Folded Flux Ropes*

If the footpoints of an ICME flux rope are rooted in the Sun, as sketched in Figure 2 of Zurbuchen and Richardson (2006, this volume), then solar rotation would be expected to cause distortion in the structure, just as the large scale magnetic field tends to form Archimedean (Parker) spirals. Such effects are seen in 3D simulations (Vandas *et al*., 2002). Consistent with this view, Owens *et al*. (2004) suggested that west flank passages through ICMEs were around twice as common as east flank. In principle, it could be possible for a single spacecraft to pass through both legs of the same magnetic cloud, as suggested by Crooker *et al*. (1998) on the basis of mirror symmetric patterns in magnetic field elevation angle coincident with counterstreaming electrons trailing magnetic clouds. However, since several ICMEs often exist close to each other, it is difficult unambiguously to distinguish two encounters with one cloud from two separate events. A necessary but not sufficient test is for both events to exhibit the same handedness. Rees and Forsyth (2004) describe two such examples in Ulysses data, while Kahler *et al*. (1999) found only one in 8 possible cases in ISEE 3 data.

3.2.5. *Modelling Dynamic Effects: Non-Circular Flux Rope Models*

Analysis of ICMEs has often concentrated on magnetic flux ropes, despite their occurrence in only around 1/3 to 1/2 of apparent events, for a number of reasons: the relative simplicity of identifying flux ropes; their presumed relation to magnetic structures at the Sun; and because by fitting analytical models to their profiles, it is possible to estimate parameters such as the location and orientation of the rope's axis. The earliest models of flux ropes (e.g., Burlag, 1988) assumed circular cross sections: these often result in good agreement with observations, but deformation from this shape will occur as a result of both kinematics and dynamics. There is evidence that this deformation can lead to systematic errors in estimates of flux rope parameters derived from circular cross section models. As a result, considerable efforts have been made to extend models to include elliptical cross sections (e.g., Mulligan *et al*., 2001; Hidalgo *et al*., 2002). A more generalised fitting method (Hu and Sonnerup, 2002), assuming $2\frac{1}{2}$D variations, has recently been developed and shows considerable promise. These models are discussed further by Forbes *et al.* (2006, this volume).

3.3. Sheaths and Shocks

Both ICME propagation at a speed different from the ambient solar wind and elevated internal pressure result in compressions and rarefactions. Passage of compressed solar wind plasma and magnetic field in sheath regions upstream of ICMEs at 1 AU can last for many hours. If this compression is strong, the magnetic field can be much larger than typical and, hence, geoeffective (e.g., Tsurutani *et al*., 1999; Siscoe and Schwenn, 2006, this volume). The orientation of the plane of compression in which the magnetic field in the sheath is forced to lie can be determined by minimum variance analysis and used to estimate the local orientation of the leading edge of an ICME (Jones *et al*., 2002; Section 4.3 of Wimmer-Schweingruber *et al*., 2006, this volume).

The shocks driven by speed and pressure differences between the ICME and the surrounding solar wind can propagate significant distances away from the ejecta itself, both radially and perpendicular to the flow. Simulations (e.g., Odstrčil and Pizzo, 1999a) show that the shock and resulting compression can result in profiles in the solar wind which might be mistaken for passage through the ejecta itself. This may explain events such as that reported by Richardson *et al*. (1994) when two spacecraft encountered a shock but only one entered ejecta material. In principle, composition signatures can help to distinguish these cases, since the sheath, being compressed solar wind, should retain solar wind composition. For example, Borrini *et al*. (1982) used enhancements of He/H to identifiy ejecta following shocks and explained the large number of shocks without this marker (48 out of 91) in terms of the much larger extent of shocks compared to ejecta. It is highly likely, however, that some ejecta went undetected owing to the variability of composition patterns in ICMEs (Wimmer-Schweingruber *et al*., 2006, this volume; Crooker, 2005).

3.4. Reconnection

Both simulations and some limited observations suggest that reconnection occurs around and within ICMEs. The large compression ahead of some ICMEs would be expected to trigger reconnection between ICME and sheath magnetic field if their orientations were favourable. McComas *et al*. (1994) presented suprathermal electron data which could be interpreted as signatures of reconnection ahead of an ICME. Simulations (Cargill and Schmidt, 2002) show that reconnection can occur at the flanks of ICMEs, particularly if they are traveling through the streamer belt. Simulations also imply that reconnection can occur within ICMEs owing to shear by background solar wind inhomogeneity (Schmidt and Cargill, 2001). (See Sections 4.2 and 4.3 of Forsyth *et al*. (2006, this volume) for examples of simulation results.) Farrugia *et al*. (2001) have discussed one possible signature of such an event, and more direct evidence has been reported recently by Gosling *et al*. (2005). Behind ICMEs, simulations by Riley *et al*. (2002) indicate that the in situ signatures of partial reconnection back at the Sun (section 2.2.2) would be a slight velocity and density increase trailing an ICME as a result of an outward reconnection jet. Such signatures have been seen in spacecraft data, but only rarely (Riley *et al*., 2002).

3.5. Interactions of Multiple ICMEs

The ejection of multiple CMEs from the vicinity of individual active regions over several days, combined with their variable velocities and large angular extent, makes it inevitable that ICMEs will sometimes interact. Indeed, as ICMEs propagate into the outer heliosphere, they merge and interact with CIRs and other ICMEs to form global merged interaction regions (GMIRs) – these effects are discussed by Gazis *et al*. (2006, this volume). Like ICME/solar wind interactions, ICME/ICME interactions can also result in complicated structures and spacecraft signatures. For example, Kahler *et al*. (1999) used bidirectional electron fluxes to argue that some magnetic clouds are in fact multiple events. Hu *et al*. (2003) used the reconstruction technique of Hu and Sonnerup (2002) to infer a double rope structure of a magnetic cloud at 1 AU.

Burlaga *et al*. (2002) discussed three sets of multiple halo CMEs and their associated ejecta at 1 AU. They showed that the ejecta were “complex,” being fast (> 600 km/s) events that were not magnetic clouds. These events typically showed substructure in parameters such as composition and density, suggesting that they were formed from several structures. They emphasised the challenges in quantitatively describing such events.

Simulations, again, reveal some of the possible consequences of multiple ICME interactions, such as shocks propagating through ejecta (Odstrčil *et al*., 2003) – and, if two flux ropes are of the same chirality and polarity, the merging and reconnection of ICMEs (Schmidt and Cargill, 2004).

3.5.1. *Interacting ICMEs as Particle Accelerators*

Gopalswamy *et al*. (2002a) showed that radio emission occurred at around 10 solar radii when two CMEs came into contact and argued that this was due to either reconnection or the formation of a shock at this location. Gopalswamy *et al*. (2002b) argued that when one CME overtakes a second, slower event, solar energetic particle acceleration is significantly increased. However, this conclusion was recently disputed by Richardson *et al*. (2003) and remains controversial.

4. Conclusion

There is little question that ICMEs are the interplanetary manifestations of CMEs, but both simulations of their propagation and observations of their complicated signatures indicate that they evolve substantially as they move out into the heliosphere. Magnetic field lines change their connections, the imprint of the magnetic field at their source weakens, shapes and structures distort, and particles accelerate. It appears that many aspects of that evolution can be understood in terms of phenomenological models – a first step toward the long-term goal of understanding in terms of fundamental physical processes – but a number of basic questions remain. Some of the more important of these questions concern how long field lines remain connected to the Sun at both ends, the fate of filament plasma, and the degree to which simulations represent the actual distortion of ICMEs.

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