IN-SITU SOLAR WIND AND MAGNETIC FIELD SIGNATURES OF INTERPLANETARY CORONAL MASS EJECTIONS

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(Received 16 March 2004; Accepted in final form 4 May 2005)

Abstract. The heliospheric counterparts of coronal mass ejections (CMEs) at the Sun, interplanetary coronal mass ejections (ICMEs), can be identified in situ based on a number of magnetic field, plasma, compositional and energetic particle signatures as well as combinations thereof. We summarize these signatures and their implications for understanding the nature of these structures and the physical properties of coronal mass ejections. We conclude that our understanding of ICMEs is far from complete and formulate several challenges that, if addressed, would substantially improve our knowledge of the relationship between CMEs at the Sun and in the heliosphere.

Keywords: interplanetary coronal mass ejections, solar wind plasma, interplanetary magnetic field

1. Introduction

We review the signatures observed by spacecraft that are currently used for the in-situ identification of interplanetary coronal mass ejections (ICMEs), the interplanetary manifestations of coronal mass ejections (CMEs) at the Sun. The emphasis is on near-Earth phenomena. These signatures are summarized in Table I together with a few key references that further define and/or use a specific signature. We separate the ICME identifiers into magnetic field, plasma dynamics, plasma composition, plasma wave and suprathermal particle signatures. See, also, the reviews by Gosling (1990, 2000) and Neugebauer and Goldstein (1997).

2. ICME Signatures

2.1. MAGNETIC FIELD SIGNATURES, MAGNETIC CLOUDS

Magnetic field signatures are perhaps the most studied because, if a particular model is assumed, the three-dimensional magnetic field structure may be inferred from a single pass through an ICME. An interesting subset of ICMEs (Klein and Burlaga, 1982) have enhanced magnetic fields (>10 nT) that rotate slowly through a large

Space Science Reviews (2006) 123: 31–43
DOI: 10.1007/s11214-006-9010-4

TABLE I

In-situ signatures of ICMEs (description applies to ∼1 AU heliospheric distance) in the magnetic field (B), plasma dynamics (P), plasma composition (C), plasma waves (W), and suprathermal particles (S)

Signature	Description	Selected references
B1: B Rotation	$\gg 30^\circ$, smooth	Klein and Burlaga (1982)
B2: B Enhancement	>10 nT	Hirshberg and Colburn (1969); Klein and Burlaga (1982)
B3: B Variance decrease		Pudovkin *et al.* (1979); Klein and Burlaga (1982)
B4: Discontinuity at ICME boundaries		Janoo *et al.* (1998)
B5: Field line draping around ICME		Gosling and McComas (1987); McComas *et al.* (1989)
B6: Magnetic clouds	(B1, B2 and $\beta = \frac{\sum nkT}{B^2/(2\mu_0)} < 1$)	Klein and Burlaga (1982); Lepping *et al.* (1990)
P1: Declining velocity profile/expansion	Monotonic decrease	Klein and Burlaga (1982); Russell and Shinde (2003)
P2: Extreme density decrease	≤ 1 cm^{-3}	Richardson *et al.* (2000a)
P3: Proton temperature decrease	$T_p < 0.5 T_{\text{exp}}$	Gosling *et al.* (1973); Richardson and Cane (1995)
P4: Electron temperature decrease	$T_e < 6 \times 10^4$ K	Montgomery *et al.* (1974)
P5: Electron Temperature increase	$T_e \gg T_p$	Sittler and Burlaga (1998); Richardson *et al.* (1997)
P6: Upstream forward shock/“Bow Wave”	Rankine-Hugoniot relations	Parker (1961)
C1: Enhanced α/proton ratio	$\text{He}^{2+}/\text{H}^{+} > 8\%$	Hirshberg *et al.* (1972); Borrini *et al.* (1982a)
C2: Elevated oxygen charge states	$\text{O}^{7+}/\text{O}^{6+} > 1$	Henke *et al.* (2001); Zurbuchen *et al.* (2003)
C3: Unusually high Fe charge states	$\langle Q \rangle_{\text{Fe}} > 12$; $Q_{\text{Fe}}^{>15+} > 0.01$	Bame *et al.* (1979); Lepri *et al.* (2001); Lepri and Zurbuchen (2004)
C4: Occurrence of He^{+}	$\text{He}^{+}/\text{He}^{2+} > 0.01$	Schwenn *et al.* (1980); Gosling *et al.* (1980); Gloeckler *et al.* (1999)
C5: Enhancements of Fe/O	$\frac{(\text{Fe/O})_{\text{CME}}}{(\text{Fe/O})_{\text{photosphere}}} > 5$	Ipavich *et al.* (1986)
C6: Unusually high ^{3}He/^{4}He	$\frac{(^3\text{He}/^4\text{He})_{\text{CME}}}{(^3\text{He}/^4\text{He})_{\text{photosphere}}} > 2$	Ho *et al.* (2000)
W1: Ion acoustic waves		Fainberg *et al.* (1996); Lin *et al.* (1999)
S1: Bidirectional strahl electrons		Gosling *et al.* (1987)
S2: Bidirectional ∼MeV ions	2nd harmonic >1st harmonic	Palmer *et al.* (1978); Marsden *et al.* (1987)
S3: Cosmic ray depletions	Few % at ∼ 1GeV	Forbush (1937); Cane (2000)
S4: Bidirectional cosmic rays	2nd harmonic >1st harmonic	Richardson *et al.* (2000b)

angle, low proton temperatures and low plasma β (ratio of the thermal and magnetic field energies), features that are evident in the event in Figure 1(a). Such ICMEs are termed “magnetic clouds” (MCs). Although spheromak-like plasmoid models have been proposed for magnetic clouds (Vandas *et al.*, 1993), work has focused on flux ropes (Lepping *et al.*, 1990; Osherovich and Burlaga, 1997; Cid *et al.*, 2002; Mulligan and Russell, 2001; Lynch *et al.*, 2003, and references therein). Figure 3 shows a schematic of an ICME with a magnetic flux-rope structure.

It should be emphasized that MC-like features are only present in a subset of all ICMEs. The magnetic field configurations of non-cloud-like ICMEs may be more complicated, leading Burlaga *et al.* (2002) to name them “complex ejecta”. Two non-cloud ICMEs are shown in Figures 1(b) and (c). Signatures B1 and B2 (Table I) are not observed even though each ICME includes a number of the other characteristic signatures to be discussed below. Gosling (1990) concluded that $\sim$30% of ICMEs in 1978–1982 were MCs. Other estimates (Bothmer and Schwenn, 1996; Richardson *et al.*, 1997; Cane *et al.*, 1997; Mulligan *et al.*, 1999) range from $\sim$15 to 60%, while Marubashi (2000) has claimed that up to $\sim$80% of the set of ICMEs studied were flux rope encounters, arguing that the absence of MC signatures frequently occurs when the observing spacecraft makes only a glancing encounter with the MC. There is also evidence of a solar cycle effect, ranging from $\gtrsim$60% MCs for the few ICMEs near solar minimum to $\sim$15% around solar maximum (Cane and Richardson, 2003). Non-MC-like configurations may arise if an ICME is a conglomerate of several individual ICMEs (cf. Figure 2(c)), or if the magnetic field configuration of the original CME was more complex than a simple flux rope (Figure 2(b) may be an example). Even an apparently simple MC may consist of several flux tubes (Fainberg *et al.*, 1996).

Magnetic field observations can help identify the boundaries of the ICME. In principle, the boundary between the ICME and ambient solar wind should be a tangential discontinuity, which magnetic field lines do not cross. While in some cases such discontinuities can be identified with little ambiguity, in other cases the boundaries are less distinct and may include complex structures perhaps indicative of waves or field-line reconnection (Vasquez *et al.*, 2001).

Another common feature within ICMEs is a reduction in the magnetic field variability. This is most evident from inspection of field observations with time resolutions of $\sim$5 minutes or less (Figure 1). The relatively smooth magnetic fields within ICMEs are in marked contrast to those in the turbulent “sheaths” found ahead of fast ICMEs.

The southward interplanetary magnetic field component is a dominant parameter governing the intensity of geomagnetic activity (Tsurutani and Gonzalez, 1997). Because this is strongly enhanced within some ICMEs or the associated sheaths, the majority of major geomagnetic storms are ICME-related (Richardson *et al.*, 2001). In Figure 2, the Dst index (increasingly negative values indicate increased activity) illustrates the geomagnetic response to variations in the southward magnetic field intensity during each event (cf. B, and $\theta_B \ll 0°$).

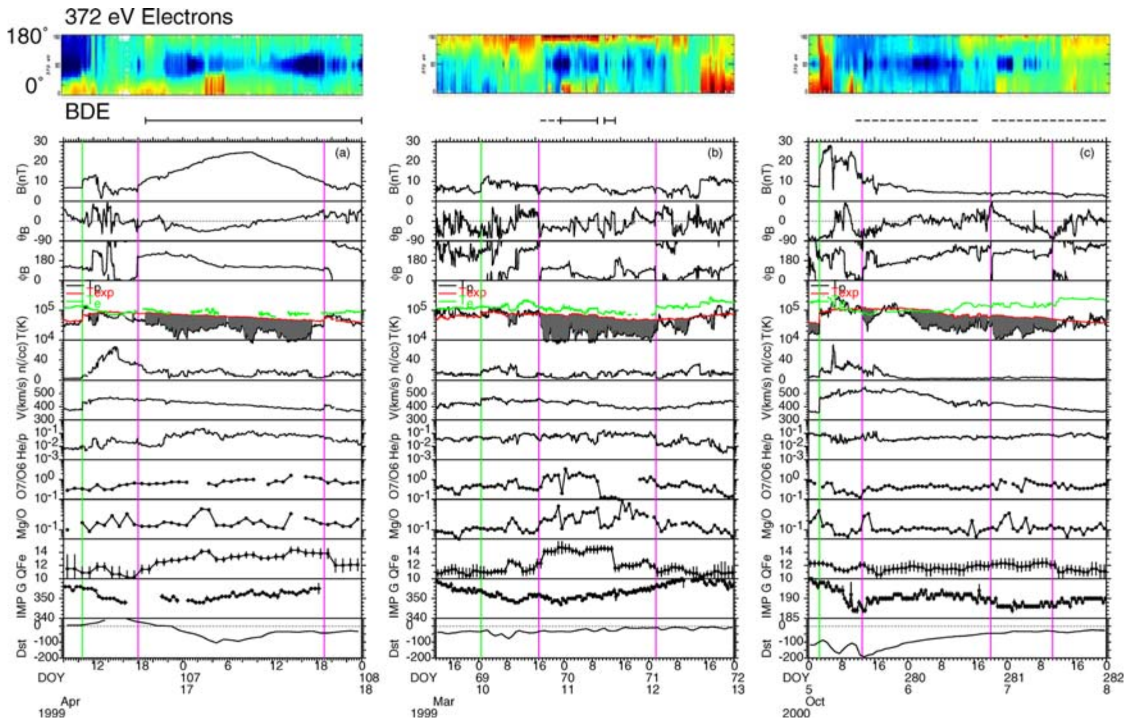

Figure 1. Examples of ICMEs observed by ACE following interplanetary shocks (green vertical lines). ICME boundaries are based on a consensus of plasma/field signatures (Cane and Richardson, 2003). Event (a) is a "classic" magnetic cloud, showing an enhanced, smoothly-rotating magnetic field; (b) has a more irregular and weaker field; (c) may be divided into two regions, possibly separate ICMEs, each with weak but rotating fields. Other ICME characteristics which may be evident and may not necessarily occupy the same regions include: depressed proton temperatures (grey shading indicates $T_p \leq 0.5T_{\mathrm{exp}}$); electron temperatures $>T_p$; declining solar wind speed profiles; He/proton abundance enhancements; enhanced oxygen and iron charge states and Mg/O ratio; cosmic ray depressions (IMP 8 GME guard $\gtrsim$60 MeV particle count rate) commencing in the vicinity of shock passage; and geomagnetic storms (indicated by the *Dst* index). The top panels show 0–180° 372 eV electron pitch-angle distributions, with BDEs at the times indicated (dashed = weak/questionable).

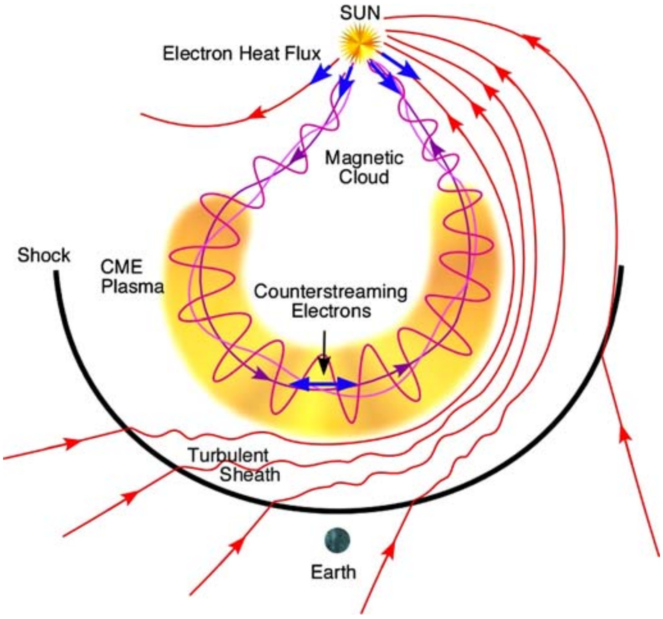

Figure 2. Schematic of the three-dimensional structure of an ICME and upstream shock, relating magnetic field, plasma, and BDE signatures.

2.2. PLASMA DYNAMICS

The solar wind velocity signatures of some ICMEs indicate expansion in the solar wind rest frame (cf. Figure 2). The ICME leading edge moves at a speed $V_{\text{ICME}} + V_{\text{EXP}}$, with a smooth transition during passage of the ICME to a speed of $V_{\text{ICME}} - V_{\text{EXP}}$ at the trailing edge. The expansion speed V_{EXP} is typically around half the Alfvén speed in the ICME (Klein and Burlaga, 1982). Not all ICMEs exhibit expansion signatures, however, and similar speed variations in coronal-hole-associated solar wind may lead to false identifications.

In the ambient (non-ICME) solar wind, there is an empirical correlation between the solar wind speed (V_{sw}) and plasma proton temperature (T_p) (Lopez, 1987, and references therein). Gosling *et al.* (1973), however, pointed out occasional intervals of unusually low T_p that do not follow this correlation. These intervals were attributed to magnetically isolated, ejected material expanding at a higher rate than the ambient solar wind. They also tended to follow interplanetary shocks by a few hours, suggesting that they were related to the drivers of these shocks that we now associate with ICMEs. Richardson and Cane (1995) found that ICMEs typically have $T_p < 0.5T_{ex}$, where T_{ex} is the "expected T_p" determined from the empirical $V_{sw} - T_p$ correlation and the simultaneously observed solar wind speed. Grey shading in Figure 1 denotes intervals when this criterion is met. They also noted that the fraction of the solar wind having $T_p < 0.5T_{ex}$ increases from $\sim$4%

at solar minimum to $\sim$12% around solar maximum, consistent with an association with ICMEs. In a similar vein, Neugebauer and Goldstein (1997) defined a thermal index $I_{th} = (500V_p + 1.75 \times 10^5)/T_p$ such that if $I_{th} > 1$, the plasma is likely to be associated with an ICME, while this may or may not be the case when $I_{th} < 1$. Other authors have simply defined an upper threshold for T_p (e.g., thermal speed $\leq$20 km/s; Russell and Shinde, 2003). ICME identification based on T_p has the advantages that observations are available since the beginning of the space era (with some gaps), and T_p depressions are generally present in ICMEs (Richardson and Cane, 1995; Mulligan *et al.*, 1999). Nevertheless, other solar wind structures, such as the heliospheric plasma sheet, may include depressed T_p, so the solar wind context should also be examined.

Montgomery *et al.* (1974) reported that solar wind electron temperatures (T_e) were temporarily depressed for intervals of 10 to >40 hours commencing 10–20 hours following around half of the interplanetary shocks they studied, concluding that these were regions of closed field lines that were magnetically isolated from the hot corona. Other studies, however, indicate that T_e tends to be enhanced relative to T_p in some magnetic clouds (Osherovich *et al.*, 1993; Fainberg *et al.*, 1996; Sittler and Burlaga, 1998) and non-cloud ICMEs (Richardson *et al.*, 1997), suggesting efficient transport of electron thermal energy along field lines connected to the corona. Richardson *et al.* (1997) proposed $T_e/T_p > 2$ as a more appropriate indicator of an ICME than one based on T_e alone. When $T_e/T_p > 1$, the Landau damping constraint on the excitation of ion acoustic waves is removed, so these waves may accompany ICMEs (Lin *et al.*, 1999). We note that, when this criterion holds, the plasma pressure is dominated by the electron component.

2.3. PLASMA COMPOSITION SIGNATURES

Observations since the 1970s have identified regions following some interplanetary shocks with helium (He^{2+}) abundances (e.g., He^{2+}/protons >6%) that exceed normal solar wind values, leading to the suggestion that this unusual composition is indicative of ejected solar material (Hirshberg *et al.*, 1971). Helium enhancements are not detected following every shock because they are only present in a subset of the ICMEs identified by other signatures (Zwickl *et al.*, 1983; Mulligan *et al.*, 1999; Richardson and Cane, 2004), and ICMEs are typically less extended than the shocks they generate (Figure 3). Figures 1a and 1b show ICMEs with enhanced He/p. Neugebauer and Goldstein (1997) ascribe the enhanced helium abundances to "a sludge removal phenomenon," whereby helium that has settled at the footpoints of solar wind flow tubes is cleared out by the CME. The predictions from such chromospheric evaporation models with collisional transport, however, have not been tested in the context of the complete set of compositional data now available.

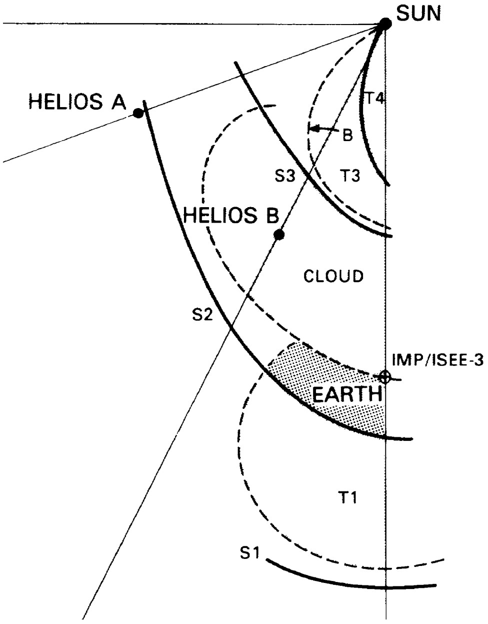

Figure 3. The configuration of interplanetary shocks (S1–S3) and ICMEs (T1–T4) at 2200 UT on April 3, 1979, inferred from multi-spacecraft observations (Helios and IMP 8/ISEE-3) (Burlaga *et al.*, 1987).

Although some observations were available from earlier spacecraft, detailed measurements of solar wind composition other than He/p have only been routinely available since the launch of Ulysses in 1990, and more recently from the ACE spacecraft (Galvin, 1997; Zurbuchen *et al.*, 2003; Richardson and Cane, 2004, and references therein). The relationship of compositional anomalies to ICMEs is an active area of current research (Wimmer *et al.*, 2006, this volume). ICMEs generally show elemental abundances that are fractionated relative to the First Ionization Potential (FIP) in a similar manner to those in slow solar wind associated with streamers (Neukomm, 1998). There are also reports that some ICMEs exhibit substantial mass fractionation, as opposed to FIP fractionation (Gloeckler *et al.*, 1999; Wurz *et al.*, 2000; Zurbuchen *et al.*, 2004). Isotopic fractionation has been observed in ICMEs in the case of ^{3}He/^{4}He (Ho *et al.*, 2000) but not conclusively for other elements, probably because of the limited precision of current experiments (Wimmer *et al.*, 1999; Wimmer *et al.*, 2006, this volume). Relative to the ambient solar wind, ICMEs may include enhancements in heavy ion abundances (in particular iron) (Mitchell *et al.*, 1983; Ipavich *et al.*, 1986) and enhanced ion charge states. The ionic charge state of heavy ions is a sensitive measure of the thermal environment of CMEs and their interplanetary counterparts (Hundhausen *et al.*, 1968; Buergi and Geiss, 1986). Generally, ICME-associated plasma charge states suggest a CME source that is "hot" relative to the ambient solar wind. Examples were reported by Bame *et al.* (1979) and Fenimore (1980), and more complete surveys have been made by Neukomm (1998), Henke *et al.* (2001) and Rodriguez *et al.* (2004) based on O and C charge states, which freeze in relatively close to the Sun (within $\sim 1 R_s$ above the solar surface). Lepri *et al.* (2001) and Lepri and Zurbuchen (2004) have discussed Fe charge states, which become frozen in during the CME expansion in the outer corona where ICME plasma seems to be well-differentiated from plasma of the ambient solar wind. Roughly 50% to 70% of all ICMEs have enhanced Fe charge states as defined by the criteria in Table I. This fraction is much smaller for $\mathrm{O}^{7+}/\mathrm{O}^{6+} > 1$, though a relative enhancement of $\mathrm{O}^{7+}/\mathrm{O}^{6+}$ might be a more reliable ICME indicator (Richardson and Cane, 2004). Compositional signatures relying on "hot" ionic charge states appear to be some of the best indicators of ICMEs currently available, with remarkably few false identifications (Lepri *et al.*, 2001). In particular, they are more generally present in ICMEs than, for example, magnetic cloud signatures. The ICMEs in Figures 1(a) and (b) show enhancements in the helium/proton, $\mathrm{O}^{7+}/\mathrm{O}^{6+}$, and Mg/O ratios, and Fe charge states, while these features are essentially absent in the ICME in Figure 1(c). Richardson and Cane (2004) have made a comprehensive survey of enhancements in these compositional signatures during 1996–2002 and demonstrate their close association with ICMEs (see Figure 2 in Wimmer *et al.*, 2006, this volume).

There is also a very small subset of unusually "cold" events with low ion charge states and unusual fractionation patterns that are uncharacteristic of the majority of ICMEs. These were first identified by the presence of singly-charged helium abundances well above solar wind values (Schwenn *et al.*, 1980; Gosling *et al.*, 1980). Zwickl *et al.* (1982) reported only three cases in eight years of observations. Additional cold ICMEs have been reported (Yermolaev *et al.*, 1989; Burlaga *et al.*, 1998; Gloeckler *et al.*, 1999; Skoug *et al.*, 1999). Singly-charged He and other low charge states suggest that the plasma originated in low temperature material at the Sun, possibly the cool, dense prominence material which is observed rising above the solar surface following some CMEs. None of the events in Figure 1 have this signature. Under special circumstances, both unusually "hot" and unusually "cold" ion charge states have been observed within the same ICME, even with simple electrostatic analyzers (see Bame, 1983, and references therein).

2.4. ENERGETIC PARTICLE SIGNATURES

Bidirectional beams of suprathermal ($\gtrsim$100 eV) electrons (BDEs), which normally focus into a single field-aligned "strahl" directed away from the Sun, are typically associated with other ICME signatures (Zwickl *et al.*, 1983; Gosling *et al.*, 1987). The physical interpretation is that the electrons are flowing in opposite directions along magnetic field loops within ICMEs that are rooted at the Sun (Figure 2). BDEs are one of the more widely-used signatures for identifying ICMEs, and the primary signature in some studies. Some care, however, is required in interpreting the electron distributions (Gosling *et al.*, 2001; Wimmer *et al.*, 2006, this volume). Furthermore, BDEs may occur intermittently, or even be absent, within an ICME (Shodhan *et al.*, 2000). Their absence may indicate ICME field lines that have reconnected in the legs of the loops with open interplanetary magnetic field lines (Gosling *et al.*, 1995). Electron flows are also usually stronger in one direction, possibly corresponding to flow away from the field line footpoint that is closer to the observer. Intervals of bidirectional electron flows observed by ACE/SWEPAM are indicated in Figure 1 together with angular distributions of 372 eV electrons.

Other particle signatures of ICMEs include short-term (few day duration) depressions in the galactic cosmic ray intensity, bidirectional energetic particle flows, and unusual flow directions during solar energetic particle onsets. See Cane and Lario (2006, this volume) for an overview of energetic particle phenomena associated with ICMEs.

2.5. ASSOCIATION WITH INTERPLANETARY SHOCKS

Fast mass ejections, exceeding the magnetosonic speed in the solar wind, generate fast forward shocks ahead of them. Studies suggest that shocks can be observed over $\sim 90^\circ$ in longitude from the location of energetic solar events, compared with up to $\sim 50^\circ$ (i.e., a total extent of $\sim 100^\circ$) for the related ICMEs (Borrini *et al.*, 1982b; Cane, 1988; Richardson and Cane, 1993). ICMEs from less energetic events may be narrower. For example, remarkably few ICMEs were observed at both the Helios 1 and 2 spacecraft even when separated by only $\sim 40^\circ$ in longitude (Cane *et al.*, 1997).

Relating shocks, ICMEs and solar events can be particularly complicated at times when several ejections are moving away from the Sun. For example, Figure 3 shows the configuration of shocks (S1–S3) and ICMEs (T1–T4) inferred from Helios and IMP 8 observations in early April 1979 (Burlaga *et al.*, 1987). Observations from multiple, well-separated spacecraft are of immense value when studying such structures. Reliable associations between shocks/ICMEs and the related solar event are also important. For energetic events, energetic particle intensity-time profiles or interplanetary type II radio emissions can be helpful. For less energetic events, it can be difficult to make an unambiguous association, in particular if there are several candidate solar events. Based on the estimates of typical ICME longitudinal extents referred to above, it is probably reasonable to treat claimed ICME associations with solar phenomena much beyond $\sim 50^\circ$ longitude from the observer with a degree of skepticism.

3. Summary and Discussion

Despite the plethora of signatures associated with ICMEs and improvements in spacecraft instrumentation, ICME identification "is still something of an art" (Gosling, 1997). The main reasons are that the various signatures do not necessarily occur simultaneously and define precisely the same regions of the solar wind, and they show little event-to-event organization (Zwickl *et al.*, 1983; Crooker *et al.*, 1990; Richardson and Cane, 1995; Neugebauer and Goldstein, 1997; Mulligan *et al.*, 1999). This is not too surprising since they arise from different physical circumstances. For example, plasma composition reflects abundances and electron temperatures near the Sun, depressed proton temperatures result from expansion of the ICME in the solar wind, and suprathermal electrons indicate field line connectivity to the Sun. The most practical approach is to examine as many signatures as possible and reach a consensus based on the grouping of several signatures within a certain region of the solar wind. This region may have distinct boundaries in plasma, magnetic field and other signatures, while in other cases, the boundaries may be more ambiguous. Differences in instrumentation, data analysis and selection criteria will also influence when certain ICME signatures are reported by different researchers. There are also ICMEs that lack some of the characteristic signatures, even those that are relatively ubiquitous, such as a depressed proton temperature. Hence, the most important conclusion of this paper is that a necessary and sufficient condition that defines the presence of an ICME or provides a crisp definition of an ICME remains elusive and is most likely unattainable.

Further progress is necessary in relating the properties of ICMEs to coronal phenomena. One limitation is that most data analysis has been limited to single-point observations whereas ICMEs are three-dimensional structures that can only be disentangled through multi-point observations. Recent three-dimensional simulations of CME propagation into the heliosphere (Riley *et al.*, 2003; Manchester *et al.*, 2004) can provide a context for interpreting observations, but their physical realism is still insufficient to answer many of the questions posed by observers. Second, our limited understanding of the underlying physical processes governing ICME signatures makes it difficult to know how to interpret observations or combine signatures that are intrinsically related. We therefore suggest four challenges, which, if addressed, may provide breakthroughs in our understanding of ICMEs and their signatures:

- Investigate the thermodynamic state of CMEs and ICMEs, based on a combination of theoretical and observational studies, and hence advance our understanding of the physical interpretation of the various ICME signatures and the relationship of compositional signatures to other in-situ observables.
- Develop a theoretical framework for the interpretation of compositional data from ICMEs that can address elemental, isotopic, and charge composition in concert, and relate them to the plasma properties observed in situ. Although compositional data teach us something about the source of ICME material, currently we do not know how to interpret that information.
- Using models and multi-point observations of critical signatures, such as BDEs, magnetic fields, and energetic particles, investigate the three-dimensional topology of ICMEs and their effects on the space environment.

– Provide wider access to ICME models, allowing observers to address questions of specific interest, such as the effect of changing intersection geometries.

Acknowledgements

The authors acknowledge ISSI and the workshop organizers for making this workshop possible. THZ was supported, in part, by NASA Grants NAG–12893 and NAG5–11000, while IGR was supported by NASA Grant NCC5–180. We thank Ruth Skoug and Jack Gosling for providing and interpreting the BDE data in Figure 1.

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