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A SURVEY OF INTERPLANETARY CORONAL MASS EJECTIONS IN THE NEAR-EARTH SOLAR WIND DURING 1996 - 2005

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ABSTRACT

We have extended our comprehensive survey of interplanetary coronal mass ejections (ICMEs) in the near-Earth solar wind since 1996 up to near-present, and have incorporated solar wind compositional data from ACE/SWICS into the identification of these events. We discuss the variations in the ICME occurrence rate, including evidence for a ~160 day periodicity, the average properties of the ICMEs, the fraction that are magnetic clouds, and the relationship between ICME properties and geomagnetic storms.

1. INTRODUCTION: ICME IDENTIFICATION

In Cane and Richardson (2003; hereafter CR03), we reported on a comprehensive survey of interplanetary coronal mass ejections (ICMEs), the interplanetary manifestations of coronal mass ejections at the Sun, from 1996 (approximately the launch of the SOHO spacecraft) until 2002. The 214 ICMEs were identified principally from their characteristic solar wind magnetic field and plasma signatures, with reference to additional data such as shock passages, cosmic ray modulations (e.g., Forbush decreases) and other energetic particle data. See CR03 for further discussion of the event identification, and Zurbuchen and Richardson (2005) for a summary of the in-situ signatures of ICMEs.

More recently (Richardson and Cane, 2004a), we compared intervals of anomalous solar wind composition and ion charge states observed by the ACE/SWICS instrument with the ICMEs identified by CR03, finding excellent agreement. For example, Figure 1 summarizes the occurrence rates of O^7/O^6, Mg/O, Ne/O, Fe charge states ≥16, and mean Fe charge measurements that are anomalously enhanced relative to values in normal solar wind (to be discussed further below), during the passage of all the CR03 ICMEs. Vertical dashed lines indicate the ICME leading and trailing edges. The occurrence of solar wind He/proton ratio > 6% is also shown. The ICMEs are divided into those with or without magnetic cloud signatures (enhanced (>10 nT) magnetic field intensity with a smooth rotation in direction through a large angle, e.g., Klein and Burlaga, 1982). Thus, ~70-80% of the SWICS observations inside the CR03 ICMEs show enhanced O^7/O^6 or Fe charge states. Lower occurrence rates are found for enhanced Mg/O and Ne/O. The occurrence rates tend to increase in the vicinity of the ICME leading edge, and decrease near the trailing edge, indicating that the regions identified by CR03 do closely correspond to CME-associated source material that has been heated near the Sun. In some events, charge states remain high for a short distance after the trailing edge.

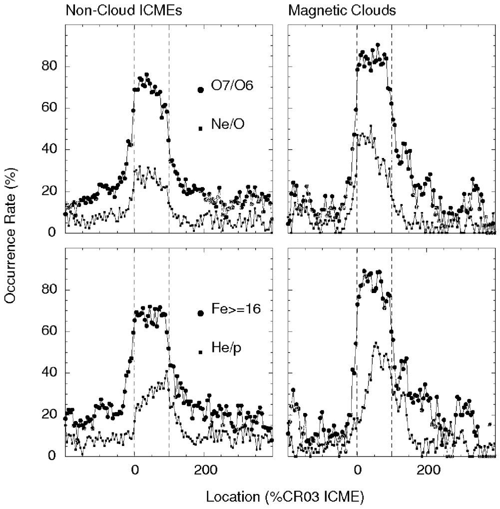

Figure 1. Summary of the occurrence of various compositional anomalies with respect to the boundaries of the Cane and Richardson (2003) ICMEs (dashed vertical lines) (after Richardson and Cane, 2004a).

Enhanced He/proton ratios have long been recognized as associated with ICMEs (e.g., Hirshberg et al., 1972). However, only ~30 - 40% of the observations inside the CR03 ICMEs have values >6%. Interestingly, enhanced *He/p* tends to occur more frequently towards and outside the ICME trailing edge. We finally note that compositional anomalies tend to be more common in magnetic clouds than non-cloud ICMEs.

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The excellent association between the CR03 ICMEs and compositional anomalies suggests that compositional data can be used to reassess and refine the ICME identifications. We have therefore updated our original survey by incorporating SWICs compositional data, available from 1998, and identifying events since 2002. We conclude that the vast majority of the original identifications remain reliable, and the revisions have been modest. In the 1996 - 2002 interval, ~20 events have been added, and ~10 weak events removed. The ICME list, currently with ~280 events, can be obtained from the authors.

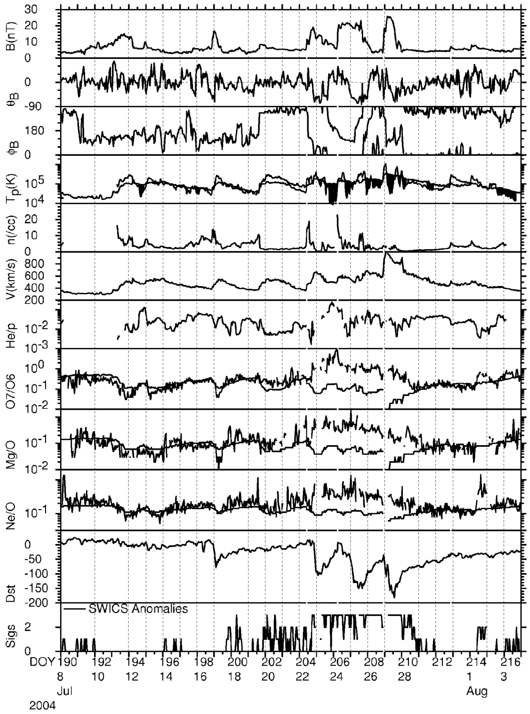

Figure 2. ACE solar wind plasma, field and compositional parameters during a 27-day interval in July-August 2004. "Expected" values are shown in red.

Fig. 2 shows a 27-day interval of ACE plasma/field and composition data in mid-2004 (from the ACE Science Center) that illustrates how potential ICME periods can be identified by comparing the "expected values" of the proton temperature (T_p), O^7/O^6, *Mg/O*, and *Ne/O*, indicated by the red graphs, with the observed values. The expected values are inferred from the observed solar wind speed (*V*) using the *V*-dependences found in normal solar wind (e.g., Lopez, 1987; Richardson and Cane, 2004a, Table 1). In particular, T_p is correlated with V, while O^7/O^6, *Mg/O* and *Ne/O* are anti-correlated. Fortuitously, these relationships appear to be independent of the phase of the solar cycle. Regions of abnormally low T_p ($\leq 0.5T_{exp}$, shaded black in Fig. 2), are frequently potential ICMEs (Richardson and Cane, 1995), though they may be associated with other structures, such as the heliospheric current sheet. Otherwise, T_p and T_{exp} generally track each other, suggestive of ambient (non-ICME) solar wind. The conspicuous interval on July 22-28 with SWICS compositional signatures far exceeding expected values (the bottom panel indicates the number of signatures ≥ twice expected values) also encompasses the low temperature regions. These signatures suggest a candidate ICME interval that can then be studied using higher resolution data to evaluate the structures present. We conclude that during the 22-28 July interval, there were four ICMEs. These produced an extended magnetic storm with three main peaks in the *Dst* index. At least three shocks (vertical green lines) passed ACE.

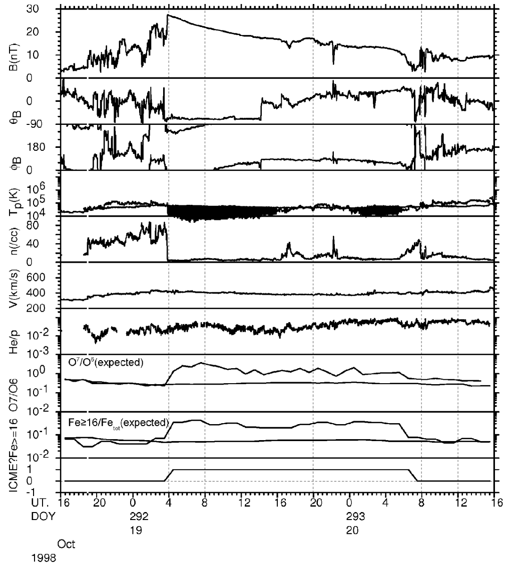

Figure 3. An ICME with good agreement between the compositional and plasma/field boundaries (the bottom panel indicates the CR03 ICME). Note that the "magnetic cloud" is a substructure of this region.

In many cases, compositional data help confirm the ICME boundaries. In Fig. 3, the compositional boundaries (*Fe* charge states from S. Lepri and O^7/O^6 are shown) are in excellent agreement with the boundaries inferred by CR03 (bottom panel) based predominantly on plasma/field observations. In other cases, compositional boundaries may differ significantly from those suggested by plasma/field data. The ICME in Fig. 4 associated with the Bastille Day (July 14), 2001 solar event is an extreme example. Enhanced ion charge states persisted for more than half a day beyond the CR03 ICME trailing edge and ~1.5 days beyond the "magnetic cloud" identified by the WIND magnetometer team (http://lepmfi.gsfc.nasa.gov/mfi/

mag_cloud_S1.html), indicated by blue shading. Thus, the magnetic cloud in Fig. 4 (likewise in Fig. 3) was only a substructure (determined principally by the region giving the best fit to a force-free flux-rope model) of the CME-related plasma indicated by the enhanced charge states. In Fig. 4, this plasma extended for ~ 0.5 AU in the wake of the magnetic cloud.

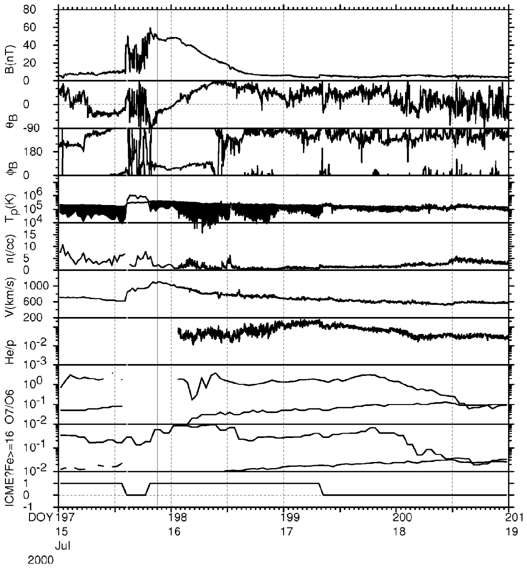

Figure 4. The ICME associated with the "Bastille Day" 2000 solar event (ACE solar wind plasma data are from R. Skoug). Enhanced O and Fe charge states extended ~1½ days following the "magnetic cloud".

2. ICME OCCURRENCE RATE

Fig. 5 shows 3-solar (Carrington) rotation running averages of the ICME occurrence rate/rotation during 1996 (solar minimum) – early 2005 in the CR03 (red) and revised lists. As noted above, the difference in the number of events in the lists is modest. Through much of this solar cycle, since early 1997 up to the present, enhancements in the ICME rate associated with the presence of major active regions have been superposed on a background rate of ~1-2 ICMEs/rotation. Even late in the solar cycle, the most recent data suggests that the ICME rate can be as high as during intervals of higher solar activity.

An interesting feature of Fig. 5 is the suggestion of periodic variations in the ICME rate at intervals of ~5-6 solar rotations. Consistent with this, CR03 found a dominant period of ~163 days in the rate for 1996-2002, and noted that this is similar to that of the "~150 day periodicity" that has been reported to be intermittently present in solar phenomena during cycle 21 and earlier solar cycles (e.g., Lean, 1990). The top centre panel of Fig. 6 (Richardson and Cane, 2005) shows the results of a wavelet analysis of the ICME rate in 1996 – 2004. A dominant ~160 day component, evident from ~1999 to 2002, is indicated by the arrow. Similar, though less persistent, components are evident in the 19-28 MeV proton intensity (from the WIND spacecraft), geomagnetic storm sudden commencement (SSC) rate, and northern hemisphere sunspot number. Interestingly, the interplanetary magnetic field (IMF) strength and the southern hemisphere sunspot number show little evidence of similar features.

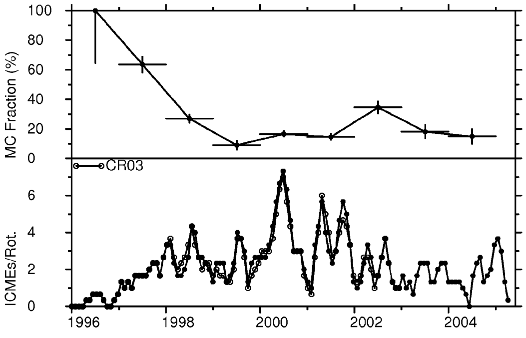

Figure 5. The yearly fraction of ICMEs that are magnetic clouds (top panel) and the ICME rate/solar rotation (3-rotation running averages) for 1996 (solar minimum) - early 2005. The CR03 rate is shown in red.

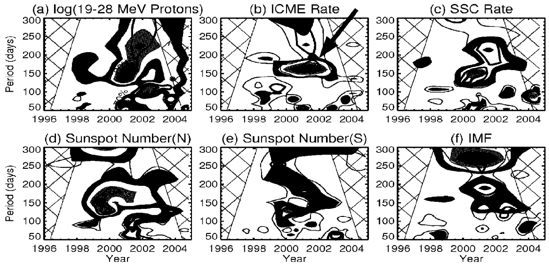

Figure 6. Wavelet analysis of the 19-28 MeV proton intensity, ICME rate, SSC rate, northern and southern sunspot numbers, and IMF strength. The interval of ~160 periodicity in the ICME rate is indicated (Richardson and Cane, 2005).

Figure 5 also shows the yearly fraction of ICMEs with clear magnetic cloud signatures (e.g., as reported by the WIND magnetometer team). As noted by Richardson and Cane (2004b), the cloud fraction decreased from ~100% at solar minimum to ~20% around solar (sunspot) maximum, which occurred in 2000. The cloud fraction in 2004 shows no sign of recovering.

Considering average values, ICME speeds were lowest (360 km/s) in 1996 and highest (563 km/s) in 2003, principally because of the exceptionally fast "Halloween" events and the higher background solar wind speeds due to the presence of high-speed streams from coronal holes. Average ICME magnetic fields were also strongest (13 nT) in 2003, again because of the contribution of the Halloween events. The largest number of ICMEs (54) occurred in 2000, the year of solar maximum.

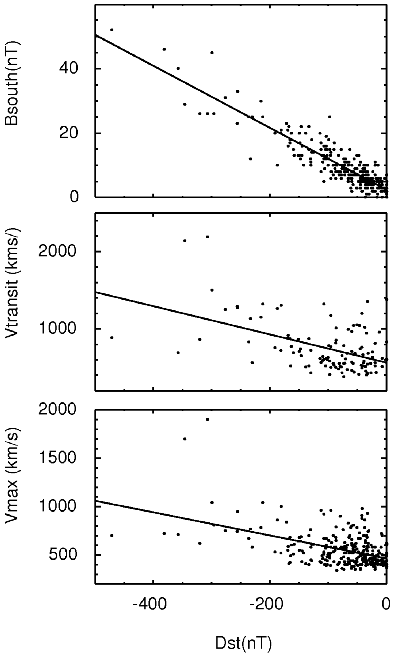

Figure 7. Variation of the peak Dst associated with ICMEs in 1996 – 2005 with (top) maximum B_s in the ICME or upstream sheath, (middle) the disturbance transit speed, and (bottom) maximum solar wind speed in the ICME or sheath.

3. GEOMAGNETIC ACTIVITY

Figure 7 summarizes the geomagnetic activity (peak *Dst* index) produced by the ICMEs, plotted versus (top) the maximum southward magnetic field strength in the ICME or upstream "sheath" (B_s), (middle) the 1 AU transit speed of the associated shock or upstream disturbance (where the related solar event can be identified), and (bottom) the maximum solar wind speed in the sheath or ICME (V_{max}). The excellent anti-correlation between *Dst* and B_s ($cc = -0.904$) is given by $Dst(\mathrm{nT}) = -8.49B_s + 5.6$. The smaller correlation coefficients for Dst-$V_{transit}$ (-0.488) and Dst-V_{max} (-0.478) indicate that geomagnetic (*Dst*) activity is more weakly dependent on these speeds (and on the in-situ ICME speed, not shown) than on B_s.

4. SUMMARY

Inclusion of compositional data has led only to a modest reassessment of the ICME identifications proposed by CR03, though the boundaries suggested by the compositional data may occasionally differ significantly. In some cases, "magnetic clouds" are substructures of the ICME regions indicated by the compositional data. The fraction of ICMEs including magnetic cloud signatures remains low (~15%) up to the most recent data, and has not returned to the higher levels of the previous solar minimum. The ICME rate also has not yet declined to solar minimum values. The size of a geomagnetic storm produced by an ICME continues to be better correlated with the maximum southward field in the ICME or upstream sheath than with transit or in-situ speeds. In closing, we acknowledge the many researchers who have contributed to the data included in this study.

5. REFERENCES

Cane, H. V., and I. G. Richardson, Interplanetary coronal mass ejections in the near-earth solar wind during 1996-2002, *J. Geophys. Res., 108*, No. 4, 10.1029/2002JA009817, 2003 (CR03).

Hirshberg, J., S. J. Bame, and D. E. Robbins, Solar flares and solar helium enrichments: July 1965 – July 1967, *Sol. Phys. 23*, 467, 1972.

Klein, L. W., and L. F. Burlaga, Interplanetary magnetic clouds at 1 AU, *J. Geophys. Res., 87*, 613, 1982.

Lean, J. L., Evolution of the 155 day periodicity in sunspot areas during solar cycles 12 to 21, *Astrophys. J., 363*, 718, 1990.

Lopez, R. E., Solar cycle invariance in solar wind proton temperature relationships, *J. Geophys. Res. 92*, 11,189, 1987.

Richardson, I. G., and H.V. Cane, Regions of abnormally low proton temperature in the solar wind (1965-1991) and their association with ejecta, *J. Geophys. Res., 100*, 23397, 1995.

Richardson, I. G., and H. V. Cane, Identification of interplanetary coronal mass ejections at 1 AU using multiple solar wind composition anomalies, *J. Geophys. Res., 109*, A09104, doi:10.1029/2004JA010598, 2004a.

Richardson, I. G, and H. V. Cane, The fraction of interplanetary coronal mass ejections that are magnetic clouds: Evidence for a solar cycle dependence, *Geophys. Res. Lett., 31*, L18804, doi:10.1029/2004GL020958, 2004b.

Richardson, I. G., and H. V. Cane, The ~150 day quasi-periodicity in interplanetary and solar phenomena during cycle 23, *Geophys. Res. Lett., 32*, L02104, doi:10.1029/2004GL021691, 2005.

Zurbuchen, T. H., and I. G. Richardson, In-situ solar wind and magnetic field signatures of interplanetary coronal mass ejections, *Space Sci. Rev.*, in press, 2005.