TOTAL PRESSURE SIGNATURE AS A QUALITATIVE INDICATOR OF THE IMPACT PARAMETER DURING ICMES ENCOUNTERS

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ABSTRACT

We have used total perpendicular pressure to distinguish ICMEs from other solar wind disturbances such as stream interactions without examining the direction of the magnetic field or its temporal behavior. We compare our identifications with those of other groups and conclude that this identifier is quite effective. The pressure signature gives a quantitative signature of the strength of the ICME and a qualitative indicator of how close the spacecraft came to the magnetic rope that forms the core of the ICME. By using such signatures we improve our ability to match ICMEs with the causative CMEs back at the Sun. We also find a very characteristic and expected variation in the strength of ICMEs through the solar cycle.

1. INTRODUCTION

Interplanetary Coronal Mass Ejections (ICMEs) are the interplanetary manifestations of Coronal Mass Ejections (CMEs) (Klein and Burlaga, 1982), seen in light scattered from enhanced electron densities in the solar corona (*e.g.* Gosling, 1990 and references therein). Our perhaps overly simplified paradigm of an ICME is shown in Fig. 1. The ICME has a leading shock and, at the center of the disturbance, there is a well formed, perhaps force-free flux rope. Since at 1 AU the density enhancement of the mass ejection becomes not so evident, the identification of ICMEs is usually based on patterns of change in the individual components of the magnetized plasma: a stronger than ambient magnetic field, a rotating magnetic field, low beta, low ion temperature, declining velocity profile and others. Based on the somewhat subjective criteria, several observers have compiled lists of ICMEs, which are not a little different from each other (Russell *et al.*, 2005a; Zurbuchen and Richardson, 2005).

A magnetic field exerts no pressure along its length, but magnetic field and plasma both contribute to the pressure force perpendicular to the field direction. We define total perpendicular pressure P_{tpp} as the sum of the magnetic pressure and thermal pressure ($B^2/2\mu_0$+nkT) (Russell *et al.*, 2005b). Since it is force that drives the evolution of solar wind structures and the force is the gradient of total perpendicular pressure P_{tpp}, we obtain much simpler and also more reasonable signatures in P_{tpp} than in the signatures of the constituent components.

If magnetic field lines are straight (no magnetic curvature force), through the action of compressional waves, P_{tpp} should tend to be constant in the absence of an interaction with an obstacle. If there is a collision of the plasma with an obstacle, a gradient in the pressure will occur that will deflect the plasma around the obstacle. In addition, the pressure exerted by the twisted field in plasma may be significant and recognizable. Therefore, the P_{tpp} is an effective diagnostic parameter of interplanetary solar wind structures, an important one of which is the ICME.

Ideally the identification of solar wind structures should be undertaken with the minimum set of parameters necessary for an unambiguous identification. There are many solar wind properties that change during stream interactions and ICMEs, and only a few of these occur sufficiently regularly to be

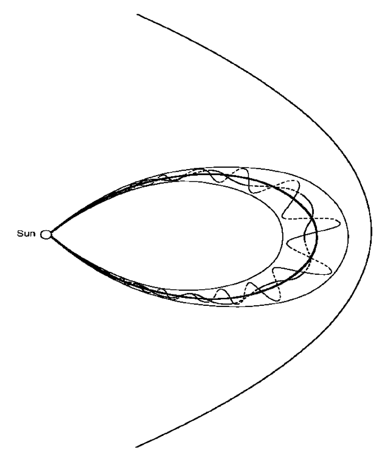

Figure 1. Simplified paradigm of Interplanetary Coronal Mass Ejection (ICME).

necessary and sufficient identifiers of these two solar wind disturbances. Two such identifiers are the total perpendicular pressure and the solar wind speed. Supplemented with the solar wind flow direction and the magnetic field direction, we have an over-determined set of identifiers that can robustly characterize all solar wind disturbances with pressure perturbations over 40 pPa.

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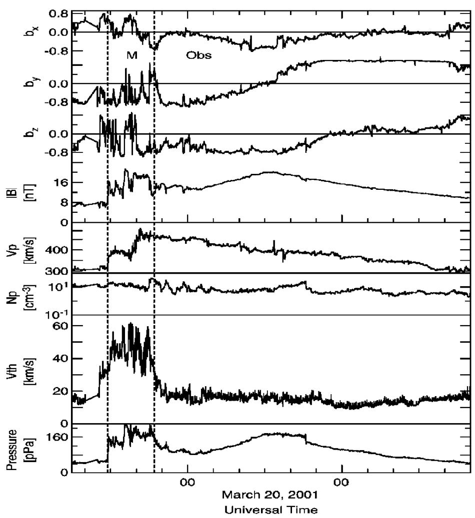


Figure 2. Group 1 ICME. From top to bottom: direction cosines of IMF in GSM coordinates, magnetic field strength, solar wind speed, proton density, proton thermal speed, and total perpendicular pressure

This approach can lead to: 1) real time event characterization; 2) event characterization when only limited solar wind diagnostics are available; 3) studies of the statistical occurrence of infrequent conditions that are used as identifiers by other schemes; 4) reliable solar-cycle variation studies; 5) characterization approaches that are objective and independent of observer training; 6) deeper insight into the physics of both stream interactions and ICMEs. This approach does not identify relic ICMEs, the remains of once active ICMEs that are no longer exerting pressure on the surrounding solar wind but are in equilibrium with it.

2. SIGNATURES IN THE TOTAL PRPENDICULAR PRESSURE P_{TPP}

Assuming a constant solar wind electron temperature 150,000 K and a constant 4% alpha number fraction, we have calculated the total perpendicular pressure for the entire WIND solar wind data set (GSFC/MIT). Figs 2, 3 and 4 show examples of ICMEs we have classified as group 1, group 2 and group 3 ICMEs according to their temporal variation of pressure as the ICMEs cross the spacecraft. The ICME in Fig. 3 does not have a leading shock but that is not a factor in its selection as a group 2 ICME; however its rather constant central pressure indicates that the spacecraft passed through the ICME well away from any twisted flux rope. To interpret these three classifications we use Fig. 5.

In Fig. 5 we have inserted a fluxrope as the obstacle to the flow in Spreiter *et al.*'s (1966) gas dynamic simulation of the flow passing a blunt object. The contours show the density which we will take as a rough proxy for the pressure. Depending on where the spacecraft passes through the ICME relative to the

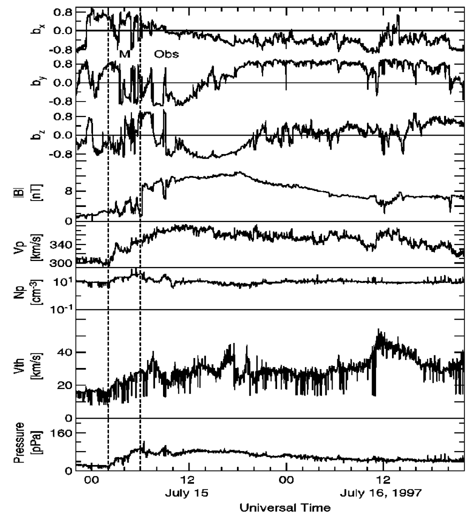


Figure 3. Group 2 ICME. Comments in caption of Figure 2 apply.

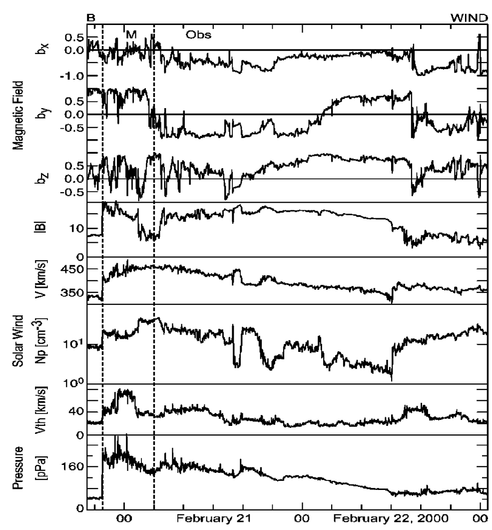


Figure 4. Group 3 ICME. Comments in caption of Figure 2 apply.

center of the flux rope, there are three groups of P_{tpp} profiles of ICMEs. For Group 1 ICMEs, the spacecraft penetrates the central fluxrope where magnetic curvature forces (twist in the rope) contribute to enhancing the magnetic field strength and our simple pressure balance calculation is insufficient to describe the forces. Group 2 ICMEs, having a rapid rise (if there is a shock) with a pressure plateau and a much later return to earlier lower pressure (Fig. 3), are interpreted as occurring further from the nose of the obstacle. Perhaps the outer parts of the obstacle are penetrated. When the spacecraft just passes through the shock well to one side of the ICME interaction without entering the magnetic obstacle, we get a pressure profile with a rapid rise followed by a decay over hours or over days (Fig. 4). These ICMEs are classified as Group 3 ICMEs in our study, and the individual features of the magnetic cloud, such as the stronger than ambient and rotating magnetic field, may not be recognizable. The rotating field in Fig. 4 may have led to an ICME classification independently of other characteristics but the pressure profile shows that this must be a high impact parameter encounter, far from the central obstacle that is responsible for the deflection.

3. VARIATION OF THE PROPERTIES OF ICMES DURING 1995-2003

From an examination of the behavior of the total perpendicular pressure P_{tpp} and the solar wind speed variation, we have classified 148 ICME events from 1995-2003 WIND solar wind data. The annual average ICME event number is about 16. We denote P_{max} as the peak of P_{tpp} and ΔV as the change in the solar wind speed during each event. Fig. 6 shows the probability distribution of P_{max} and ΔV respectively. The P_{max} distribution is quite broad, centered on 141 pPa, varying from 42 pPa up to 2500 pPa. And the ΔV profile has a low most probable value and a long tail, varying from 33 km/s up to 603 km/s.

Table 1. ICME Statistics

Year	ICME #	% with Shock	<Pmax> (δPmax)	< ΔV > (δΔV)
1995	9	44.4	110.83 (48.83)	80.00 (30.16)
1996	6	50.0	119.44 (111.31)	73.33 (40.97)
1997	19	57.9	169.89 (100.11)	108.53 (47.60)
1998	18	83.3	304.67 (274.63)	167.22 (97.51)
1999	16	72.2	245.06 (182.05)	215.50 (154.25)
2000	31	93.5	333.58 (389.72)	149.16 (75.52)
2001	20	95.0	485.25 (629.55)	206.13 (85.32)
2002	21	100.0	336.05 (248.46)	176.67 (100.18)
2003	8	87.5	271.25 (281.94)	238.33 (117.58)
All	148	82.4	294.91 (345.81)	164.63 (101.93)

Table 1 lists the number of ICME events, the percentage of events with shocks, the average P_{max} as well as its standard deviation, and the average ΔV as well as its standard deviation. In contrast to SIRs, the occurrence rate of ICMEs varies greatly over the solar cycle, with a maximum value, 31, in 2000, at solar maximum. And in 2000, there are 9 group 1 events among the total 31 ICME events, indicating that in about 29% of ICMEs WIND passed through the flux rope. This percentage is consistent with the conventional wisdom that about 1/3 ICMEs are Magnetic Clouds. Due to data gaps and noise, and sometimes the passage of WIND through the magnetosphere, we may miss some events. As expected, on average about 82% of ICMEs occur with shocks. In addition, the ΔV averaged over the 148

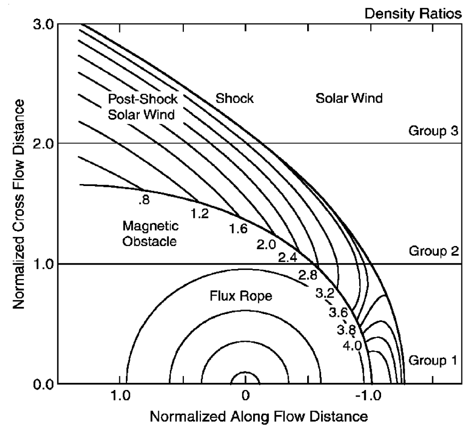
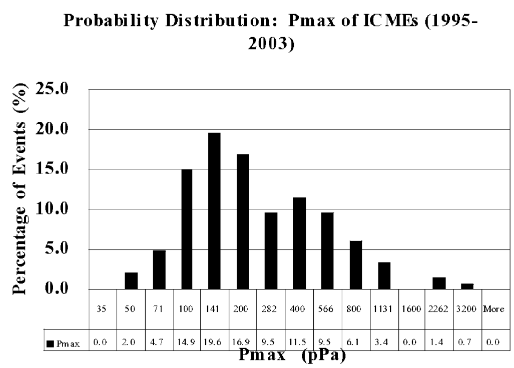
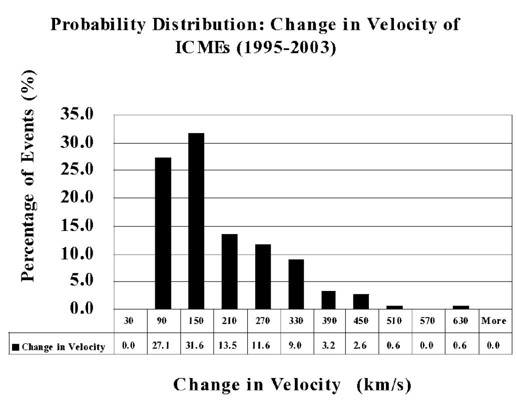


Figure 5. Interpretive sketch of ICME encounters using Spreiter et al. (1996) gasdynamic simulation results. Group 1 events encounter the magnetic rope. Group 2 events encounter the ICME near the obstacle. Group 3 events catch the shock away from the obstacle.





ICMEs is 165±8 km/s, where the uncertainty is the

Figure 6. Probability distribution of Pmax and ΔV of ICMEs (WIND 1995-2003).

Table 2. ICME Rate Comparison

Year	ICME #	C+R ICMEs #	C+R MCs #	Lepping MCs #
1995	9	NA	NA	8
1996	6	4	4	4
1997	19	22	18	17
1998	18	38	21	11
1999	18	28	11	4
2000	33	53	26	14
2001	24	47	26	10
2002	21	22	12	10
2003	11	NA	NA	4
All	159	214	118	82

probable error of the mean. The annual average P_{max} varies greatly from year to year. During the 9 years, the largest average P_{max} occurs in 2001, with a value 485±141 pPa. The P_{max} averaged over the 148 events is 295±28 pPa, while the large uncertainty is associated with the large variability of P_{max}.

In Table 2, we list the number of our identified ICMEs including 11 events from ACE spacecraft when WIND data is unavailable and compare them with ICMEs identified by Cane and Richardson (without and with magnetic clouds, MCs) (Cane *et al.*, 2003) as well as MCs identified by Lepping for the 9 years. We can see that we identify 55 fewer events than Cane and Richardson (We note that 1995 and 2003 results are not available (NA) in their study). We also note some events classified as ICMEs by the two other research groups are considered in our study as parts of Stream Interaction Regions (SIRs). The leading and trailing parts of SIRs often contain regions of low temperature, and there are rotations of magnetic fields at the sector boundary that often occurs ahead of the SIRs, easily causing the mis-classification if care is not taken. Moreover, there are about 28 hybrid events consisting of both SIRs and ICMEs during the 9 years. Fig. 7 shows an example of a fast stream overtaking an ICME.

4. CONCLUSIONS

Total perpendicular pressure P_{tpp} has a simple temporal variation, smooth except for shocks, while the temporal variations of its individual components are not simple. Depending on the position of the spacecraft passing through the ICME, we can classify the P_{tpp} of ICMEs into three groups. Corresponding to Group 1, 2 and 3 ICMEs, the profile of P_{tpp} is with central pressure maxima, or a sharp rise following by a steady plateau or a gradual decay. From 1995-2003 in the solar wind data from WIND, we find 148 ICMEs, and that 82.4% of these ICMEs occur with leading shocks. In contrast to the behavior of stream interactions, the occurrence rate of ICMEs varies greatly over the 9 years, indicating it is strongly correlated with solar activity. The peak pressure P_{max} has a broad distribution, centered on 141 pPa. The average value over the 148 events is 295±28 pPa. We note that our technique depends on the assumption that all ICMEs have pressure enhancements. It is possible that some ICMEs

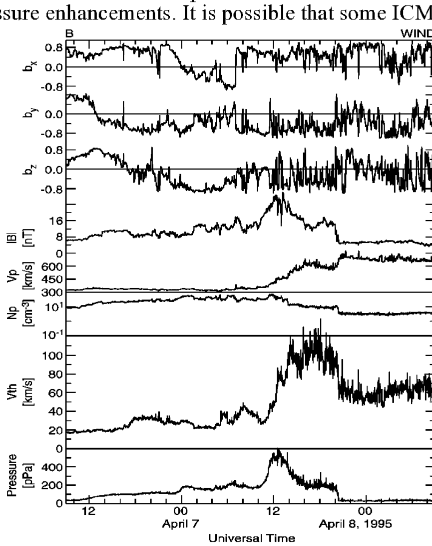


Figure 7. Fast stream overtaking ICME. Comments of Figure 2 caption apply.

have come to pressure equilibrium with the surrounding solar wind plasma. If that is true they may be weak and of lesser geoeffectiveness.

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