Pergamon
www.elsevier.nl/locate/asr

Adv. Space Res. Vol. 26, No. 5, pp. 801–806, 2000

0273-1177/00 $20.00 + 0.00
PII: S0273-1177(00)00009-0

INTERPLANETARY MAGNETIC CLOUDS: STATISTICAL PATTERNS AND RADIAL VARIATIONS

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ABSTRACT

Pioneer Venus IMF data have been used to study the correlation between the structure of magnetic clouds in the inner heliosphere and the evolution of solar magnetic fields in the course of the solar cycle. We find that the leading polarity of these magnetic clouds follows the global polarity of the sun's magnetic field. In addition if we interpret the polarity structure of the clouds in terms of twisted magnetic fields, we find that the axes of these twisted ropes must vary greatly over the course of the solar cycle. The helicity of the ropes show no obvious pattern of behavior. Case studies of flux ropes seen at both Earth and the NEAR spacecraft are used to test a new technique for determining the radial variation of flux rope speeds.

INTRODUCTION

Interplanetary coronal mass ejection (ICMEs) are regions of enhanced and twisted magnetic field usually accompanied by lower than usual ion temperatures and often accompanied by bi-directional, streaming electrons. ICMEs with a well-defined rotation of the magnetic field are referred to as magnetic clouds (Burlaga et al., 1981; Gosling 1990). About one-third of ICMEs can be classified in this way. Since ICMEs and magnetic clouds are the interplanetary structure that are most geomagnetically effective (Lindsay et al., 1995) and since southward interplanetary magnetic field (IMF) are much more geomagnetically effective than northward fields, it would be very helpful for geomagnetic predictions if we could predict the polarity of the ICME fields prior to their arrival at 1 AU. It would also be helpful to be able to predict the velocity of the ICME as it passes the Earth as this velocity also helps determine the geomagnetic effectiveness of the ICME.

We have two sets of data that can help us address these questions. The first set is a decade of IMF and solar wind data obtained by the Pioneer Venus orbit at 0.72 AU from 1978 through 1988. The second is data obtained by the WIND and NEAR spacecraft at 1AU that enable the velocity of ICMEs to be monitored over about 0.25 AU in radial distance. The former study complements earlier work on the Helios data by Bothmer and Schwenn (1998). The latter study is a new technique pioneered herein.

CLASSIFICATION OF ICMEs

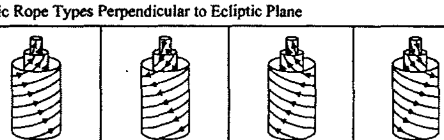
In order to extend the work of Bothmer and Schwenn (1998) we show in Figure 1 a set of eight flux ropes that have varying central field and helicity in two orthogonal directions both perpendicular to the solar wind flow. In this figure we classify each magnetic rope by the sequence of field directions encountered as the rope crosses one of our interplanetary spacecraft. For example, a left-handed ICME such as shown in the top left and right panels with its axis lying in the ecliptic plane would have the sequence of field directions south, east and north (SEN) or north, west, and south (NWS) depending on the polarity of the leading edge of the rope as they moved up out of the page.

If the rope were left-handed with its axis vertical the two possible sequences of the directions of the components perpendicular to the solar wind are ENW and WSE as shown in the two panels on the right bottom. For our simple study described herein, we use the sequence of EW and NS fields to classify each of the magnetic clouds seen by Pioneer Venus at 0.72 AU. Two examples of this classification are shown in Figure 2. In the top panel are shown the three components of the IMF, the field strength and the ion temperature for the period from 2000 on 2/7/89 to 1600 on 2/9/84. The ICME or magnetic cloud is best identified by the period of low ion temperature marked by dashed lines. Initially the field is northward. In the middle of the event it is westward and at the end of the event it is southward. Referring back to Figure 1 we see that an NWS structure lies with its axis in the ecliptic plane and is left-handed. Because the rope has two major periods of north-south fields, one northward and one southward, we call this a bipolar cloud. In the bottom panel is shown the same information for the period 1200 on 7/3/80. In this event initially the field is eastward, then it is southward and then westward. Referring to Figure 1 again we see that an ESW structure is best approximated by a right-handed rope standing vertically perpendicular to the ecliptic plane. Because such a rope has a mainly unipolar magnetic field in the north-south direction we refer to such a structure as a unipolar cloud.

Magnetic Rope Types Lying in Ecliptic Plane

Magnetic Cloud Type	SEN	SWN	NES	NWS
Leading Field	South (-Bz)	South (-Bz)	North (+Bz)	North (+Bz)
Axial Field	East (+By)	West (-By)	East (+By)	West (-By)
Trailing Field	North (+Bz)	North (+Bz)	South (-Bz)	South (-Bz)
Helicity	LH	RH	RH	LH

Magnetic Rope Types Perpendicular to Ecliptic Plane



Magnetic Cloud Type	WNE	ESW	ENW	WSE
Leading Field	West (-By)	East (+By)	East (+By)	West (-By)
Axial Field	North (+Bz)	South (-Bz)	North (+Bz)	South (-Bz)
Trailing Field	East (+By)	West (-By)	West (-By)	East (+By)
Helicity	RH	RH	LH	LH

Figure 1. Classification scheme for magnetic flux ropes convected over interplanetary spacecraft. The letters N, S, E, and W indicate the polarities of the north-south and east-west components of the ropes. By characterizing the leading, middle and trailing component polarities the handedness, predominant orientation and the axial field direction can be characterized.

STATISTICAL BEHAVIOR OF ICME POLARITY

The classification scheme described above leads immediately to two important results regarding the behavior of ICMEs. The first result was foreseen in the study of Bothmer and Schwenn (1998) and confirmed in the studies of Bothmer and Rust (1997) and Mulligan et al. (1998). Figure 3 illustrates this result by displaying a plot of the number of north to south bipolar signatures and the number of south to north bipolar signatures as a function of time. Clearly south to north transitions were most numerous before the solar maximum of cycle 22 and north to south transitions afterwards. This behavior is in step with the reversal of the polar magnetic field of the sun and with the leading polarity of the magnetic clouds being determined by that polarity.

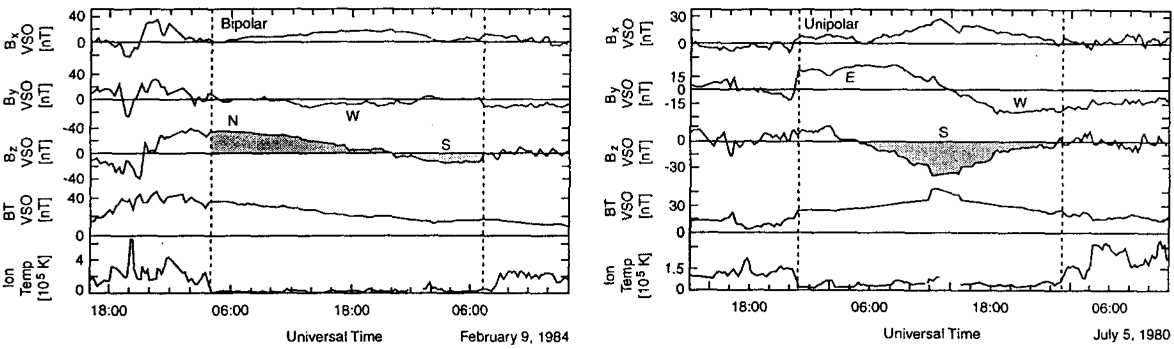


Figure 2. The magnetic time series in Venus solar orbital coordinates and the ion temperature for two ICMEs seen by Pioneer Venus. The dotted vertical lines delineate the ICME and the letters denote the component polarities used to classify the events.

The second result is shown in Figure 4 that plots both the number of bipolar and unipolar ropes over the solar cycle. If we use the interpretation of such structures given in Figure 1 then such structures represent ropes lying in the ecliptic plane and perpendicular to the ecliptic plane respectively. Figure 4 implies that there is a variation in the dominant orientation of flux rope axes over the solar cycle so that near solar maximum the axes are more perpendicular to the ecliptic plane and at solar minimum more parallel to it. This behavior is similar to that of the neutral line deduced from source surface models of the coronal magnetic field (Mulligan et al., 1998).

DECELERATION OF ICMEs AT 1AU

Being able to predict the orientation and leading polarity of ICMEs is important in predicting their geoeffectiveness but so too is predicting their speed at arrival. This enables both the timing of the event and the severity of the event to be better predicted. The advent of continuous data in the solar wind at 1 AU and the installation of a magnetometer on the NEAR mission has allowed the magnetic structure of ICMEs to be probed over a series of baselines (Mulligan et al., 1999). Herein we report on a new aspect of that study that allows the velocity of ICMEs to be monitored prior to their arrival at Earth. We use the consistency of 4 independent measures of the ICME velocity at 4 different distances from the sun to establish the accuracy of our procedure.

Figure 5 shows the geometry and speed calculations for the first event on December 10 to 12, 1997 when the Earth and NEAR were almost radially aligned and separated by 0.18 AU. The first speed we record is that of the shock driven by the ICME as it passes the Earth. Although calculation of the shock normal proves ineffective in this event due to the large time variation of the IMF upstream and downstream of the shock, plasma velocity across the shock in the radial direction. Therefore we deduce this speed using conservation of mass through the shock from

$$v_{sh} = \left[\frac{\rho_u v_u - \rho_d v_d}{\rho_d - \rho_u} \right] \bullet \hat{n} \tag{1}$$

where subscripts indicate the upstream and downstream densities and velocities. We assume that, like the bow shock in front of the Earth, the shock is standing relative to the leading edge of the obstacle. Thus, the speed of the shock represents the speed of the ICME at some distance closer to the sun. We judge that distance by the time at which the leading edge of the ICME arrives and the known velocity of the shock and the plasma at the leading edge. The latter velocity also is our measure of the ICME speed at 1 AU. The NEAR magnetic measurements allow us to calculate two more speeds, one of the average speed of the shock as it moves from Earth to NEAR. This speed corresponds to the average distance from Earth to NEAR minus the standoff distance from the shock to the ICME. The second speed is also an average, derived from the time needed for the ICME to go from Earth to NEAR and is attained halfway between Earth and NEAR if the deceleration is constant.

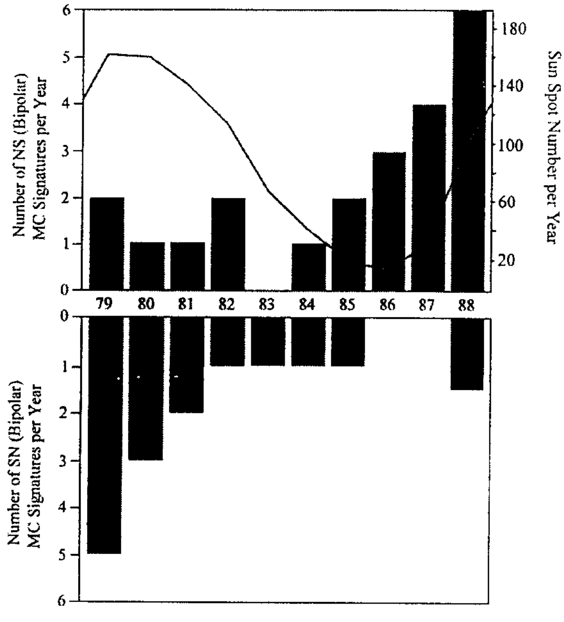


Figure 3. Yearly frequency distribution of magnetic clouds with NS and SN polarities as the solar polar magnetic field reverses. The line in the top panel indicates the yearly sunspot number.

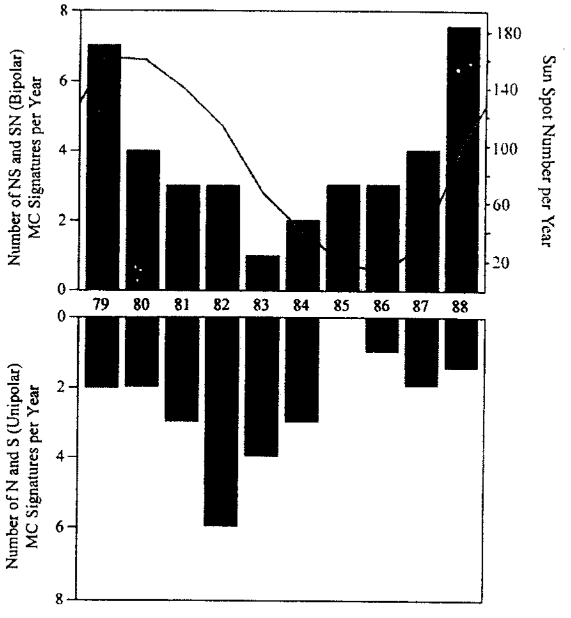
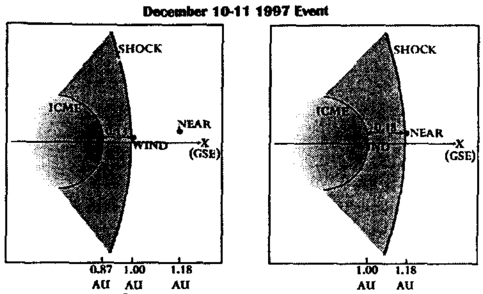


Figure 4. Yearly frequency distribution of magnetic clouds with bipolar and unipolar Bz signatures over the last half of solar cycle 21 and the beginning of solar cycle 22. As in the previous figure the top panel indicates sunspot number.

The four speed estimates and their locations are shown in the bottom panel of Figure 5. The speed drops rapidly from over 400 km/s near 0.87 AU to almost 300 km/s at 1.10 AU. We note that the shock may be moving slightly more rapidly than the ICME because of the varying radius of curvature of the ICME. The distance at which the shock should stand does depend on this radius of curvature. It increases slightly with distance because the scale size of the ICME increases with heliocentric distance and because we expect that the magnetic pressure in the ICME is leading to expansion of the ICME with time.



ASSOCIATED ICME FEATURES

Calculated Shock Speed [km/s]	405
Apparent ShockSpeed [km/s]	395
WIND Plasma ICME Speed [km/s]	359
Apparent ICME Speed [km/s]	306

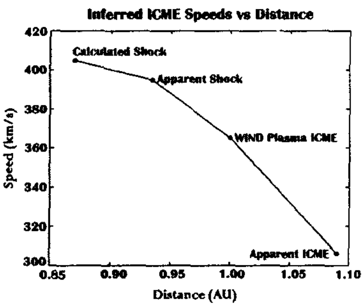
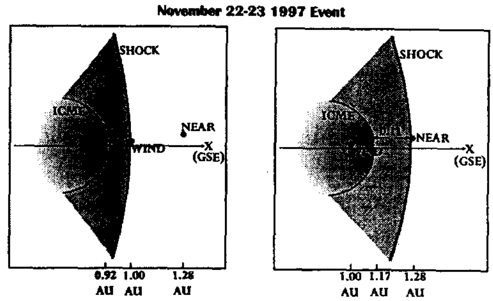


Figure 5. Estimated ICME speeds for the events of December 10-12, 1997 when WIND and NEAR were nearly radially aligned. The top panel shows the geometry of the event at two times. The bottom panel show the speeds versus radial distance.



ASSOCIATED ICME FEATURES

Calculated Shock Speed [km/s]	495
Apparent ShockSpeed [km/s]	440
WIND Plasma ICME Speed [km/s]	458
Apparent ICME Speed [km/s]	377

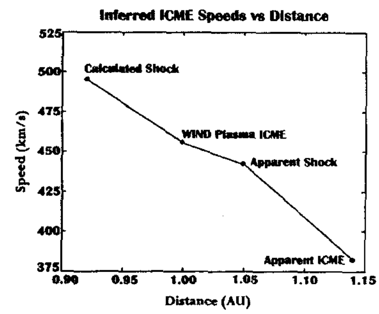


Figure 6. Estimated ICME speeds for the events of November 23-25, 1997 when WIND and NEAR were nearly radially aligned. See caption of Figure 5 and the text for further details.

A second event is illustrated in Figure 6. Here NEAR is 0.28 AU further from the Earth and separated in azimuth by 5°. In this case the calculated mixed mode shock normal is less than 13° from the radial direction. So again we can measure the speed at four locations using the same methods. This time because of the greater distance of NEAR the relative ordering of the locations of the measurements is different but the result is the same. The ICME appears to decelerate about 120 km/sec over a distance of 0.25 AU.

SUMMARY AND CONCLUSIONS

Magnetic clouds seen at Pioneer Venus at 0.72 AU have been classified according to the sequence of magnetic polarities seen in the north-south and east-west directions. These sequences can be interpreted in terms of magnetic ropes with right-handed and left-handed polarity, with varying polarities of their axial fields and as predominantly in the ecliptic plane or standing with their axes predominantly perpendicular to the ecliptic plane. Over the course of the 22-year solar cycle the leading magnetic polarity of ropes lying in the ecliptic plane follows that of the polar magnetic field of the sun. This observation shows that ICMEs are a global phenomenon linked to the large scale solar field and are not just small features. Further this observation can be used to improve our predictions of the geoeffectiveness of ICMEs. The orientation of the axes, i.e. the number of ropes that appear to have mainly vertical axes versus the number that appear to have mainly horizontal axes varies in concert with the sunspot number over an 11-year cycle. This would be expected if the orientation of the neutral line on the solar source surface determined the orientation of the axes of these ropes.

Finally, we have introduced a new technique for monitoring the velocity of ICMEs. This technique uses the shock velocity determined from the compression of the plasma and the observed velocity to judge the velocity of the ICME closer to the sun. Used by itself it can be employed to predict the velocity of the ICME plasma when it reaches the Earth thus improving our estimates of storm size used with measurements of the speed of the ICME plasma, this technique allows single spacecraft monitoring of ICME acceleration and deceleration. Used with multiple spacecraft, it can be employed to monitor the acceleration and deceleration of ICMEs over radial and longitudinal baselines. In this paper we have used two spacecraft measurements to validate the shock velocity method. While it is possible to improve the technique to make it even more accurate, the present first order method provides a good estimate of the deceleration of CMEs as they cross Earth's orbit.

ACKNOWLEDGMENTS

This work was supported by the National Aeronautics and Space Administration through research grant 730607 administered by the Johns Hopkins University's Applied Physics Laboratory and by a grant from the IGPP, Los Alamos National Laboratory.

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