THE TRUE DIMENSIONS OF INTERPLANETARY CORONAL MASS EJECTIONS

C. T. Russell and T. Mulligan

*Department of Earth and Space Sciences and Institute of Geophysics and Planetary Physics
University of California Los Angeles*

ABSTRACT

The majority of observations of Interplanetary Coronal Mass Ejections (ICMEs) are made with a single spacecraft and their properties inferred from a fit to a cylindrically symmetric model. This process produces a single dimension for a magnetic cloud, its radial thickness. If the radius of curvature of an ICME were equal to its half thickness, the shock front driven by the ICME would be at a distance of only about 0.15 times the ICME thickness according to the gas dynamic model, while the observed median thickness is closer to 0.4. The agreement with theory can be improved if the obstacle has two radii of curvature, one corresponding to the rope cross-section and one corresponding to the curvature of the rope axis. This picture is in accord with the popular paradigm of an ICME as a twisted flux rope rooted in the sun. Nevertheless this correction is insufficient to bring full agreement, suggesting ICMEs have yet a third scale size, a cross-flow diameter that may be of the order of four times their radial thickness. This inference is in accord with both indirect evidence in the form of the distribution of impact parameters derived from the cylindrical cross-section model and with direct evidence from the fit of multi-point observations with oval cross-section ropes.   © 2002 COSPAR. Published by Elsevier Science Ltd. All rights reserved.

INTRODUCTION

Interplanetary Coronal Mass Ejections (ICMEs) are the interplanetary manifestations of coronal mass ejections. Often, but less than half the time, ICMEs can be represented by a magnetic cloud with an enhanced field strength and a depressed ion temperature [Burlaga et al., 1981]. While fast CMEs produce fast ICMEs and slow CMEs produce slow ICMEs, both approach the ambient solar wind velocity as they move outward [Lindsay et al., 1999]. Magnetic clouds can often be fit quite well with a model that assumes that the cloud is cylindrically symmetric and force-free [Lepping et al., 1990]. This does not, however, mean that such clouds are either force-free or cylindrically symmetric because the fitting process does not produce unique answers. Thus it is important to look for clues, possibly outside the magnetic fitting process, to determine what are the true dimensions of an ICME. We examine herein three pieces of evidence: the standoff distance of the bow shock in front of the ICME; the impact parameter of ropes fitted with cylindrical models; and the orientation of the normals to shocks in front of ICMEs. We use the 44 magnetic clouds found in the Pioneer Venus data from 1979-1988 and fit with a non-force-free model by *Mulligan et al.* [2001].

SHOCK STANDOFF DISTANCE

The standoff distance of a shock in front of an obstacle depends on the shape of the obstacle and the Mach number of the flow relative to the obstacle. The pioneering work of *Spreiter et al.* [1966] used a gas dynamic approach and a shape that approximated that of the Earth's magnetosphere. They also adopted the assumption that the Mach number was much greater than unity, an assumption that is not always correct at Earth and is even less so at an ICME. To address this latter concern *Farris and Russell* [1994] adopted a slightly different functional form for the downstream density compression that had the same asymptotic value at high Mach number for the density but that also gave reasonable compression at low Mach numbers. In particular, the new functional form allowed the shock to move to infinity when the Mach number approached unity as it must do physically.
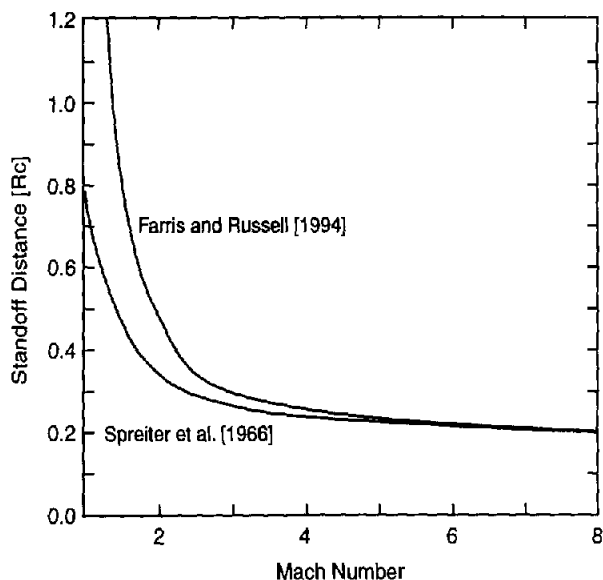
Fig. 1. Standoff distance of a shock from a cylindrically symmetric obstacle with its axis of symmetric along the flow expressed in terms of the radius of curvature for the models of Spreiter et al., [1966] and Farris and Russell [1999].
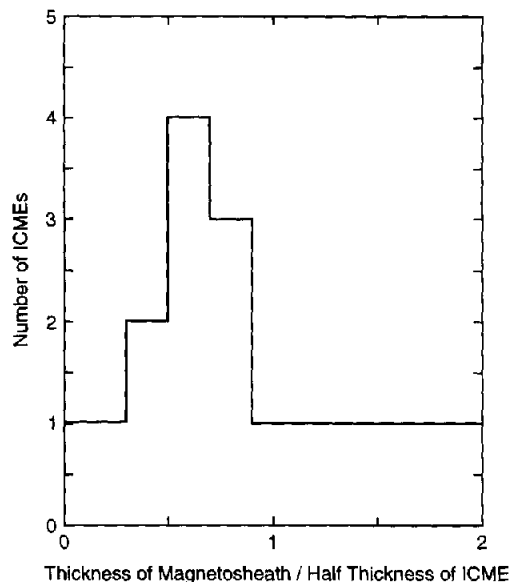
Fig. 2. Histogram of number of ICME with differing magnetosheath thickness in bins of 0.2 ICME half thicknesses. If the ICMEs were cylindrically symmetric the half thickness would be the radius of curvature.

The original gas dynamic study by *Spreiter et al.* [1966] was performed for the terrestrial magnetosphere with the Earth at its center and all distances measured from the center of the Earth. However, the solar wind does not know where the center of the Earth is or the center of an ICME. What really controls the standoff distance is the shape of the obstacle that we can characterize by its radius of curvature at the subsolar point. We replot the relationship between standoff distance and radius of curvature in Figure 1 for both the original high Mach number approximation of *Spreiter et al.* [1966] and the approximation hypothesized to be appropriate at low Mach numbers [*Farris and Russell,* 1994]. Unless the typical Mach number of ICMEs relative to the ambient solar wind is below 1.5 we expect the standoff distance of the bow shock to be a small fraction of the cloud radius.

Figure 2 shows the number of PVO magnetic clouds whose leading shocks have standoff distances of various amounts. The median standoff distance normalized by half the thickness of the magnetic cloud is 0.8, far greater than the value of about 0.22 we would obtain for Earth where the Mach number is about 5. Here we have normalized by the half thickness of the ICME, about 0.1 AU in this data set. The median Mach number for these shocks is 2.5 [*Lindsay,* 1996] for which the standoff distance should be 0.33 times the radius of curvature of the obstacle. Thus the observed shock standoff distance is much greater than could be produced by a spherical obstacle where radius is equal to half of the observed cloud thickness. This standoff distance would require a spherical obstacle of radius about 0.25 AU, not the 0.1 AU observed half thickness of these ropes [*Mulligan et al.,* 2001]. Perhaps the answer is that the cloud has two different radii of curvature, one small corresponding to the radial thickness and one appropriate to the bend in the axial field.

Figure 3 shows our current paradigm of a magnetic cloud. It is a twisted flux rope with a circular cross-section and a large arching axial field looping back to the sun in a perhaps dipolar loop. The structure provides two radii of curvature but are they the sizes needed to explain the discrepancy? Furthermore, how can we deduce the standoff distance when there are two radii of curvatures? The answer to this dilemma was provided by *Stahara et al.* [1989] who showed that, if an obstacle has two radii of curvatures, then the standoff distance is governed by the geometric mean of the two radii of curvature.

If the median standoff distance is 0.8 obstacle minor radii and the standoff distance we expect if both the minor and major radii were the same is 0.33 radii, then the major radii must be about 7 times the minor radii for a minor radius of 0.1 AU. This value, 0.7 AU, is far too large since the radius of curvature of a circular field line reaching Venus from the Sun would only be 0.35 AU. The radius of curvature of a dipole field line would be even less, about 0.25 AU. As shown above if the major radius were 0.25 AU then the minor axis would have to be 0.25 AU
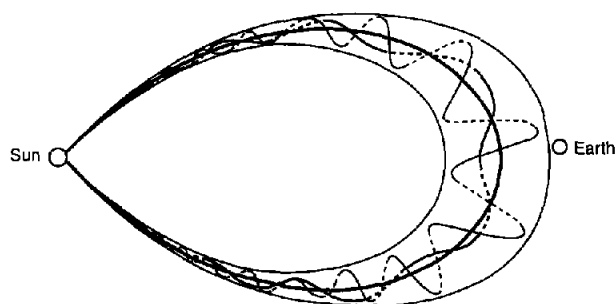
Fig. 3. Standard paradigm of a magnetic cloud, a twisted magnetic flux tube extending back to the sun. The axial field may be in the ecliptic plane or be at high inclinations to the ecliptic plane or any angle in between.
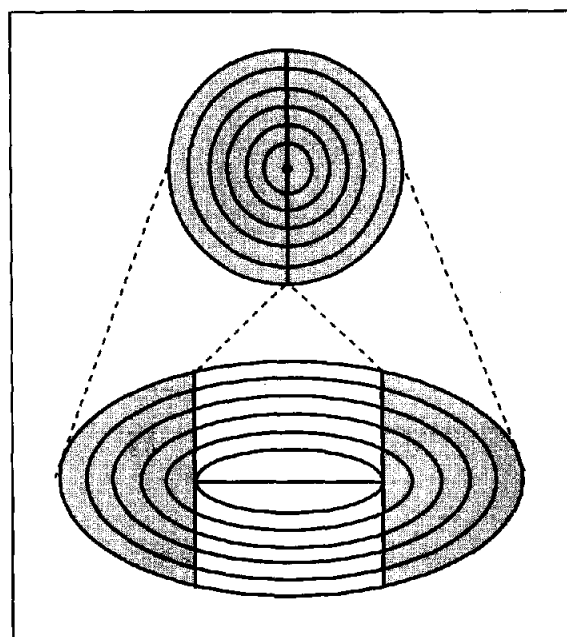
Fig. 4. While inversions of magnetic cloud structure usually use a cylindrical cross section our magnetosheath thicknesses suggest that the cross section must be oval. Since the central region of the oval rope would be most similar to the very center of the circular rope, inversions assuming circular cylindrical symmetry produce an over abundance impact parameters close to zero.

also and the cloud would therefore have to be significantly stretched in the direction perpendicular to both the flow and the axis of the rope. In this model the minor radius of the obstacle is no longer equal to the thickness of the rope. The minor and major radii of curvature are provided by the azimuthal extent of the rope (perpendicular to the solar wind flow and the rope axis) and the major axis is provided by the curvature of the axial field of the rope. At 0.7 AU these two quantities appear to be nearly equal and about 2.5 times larger than the half thickness of the ICME. This implies that the paradigm shown in Figure 3 needs to be refined so that the rope is not circular in cross section but quite oval. This hypothesis solves our standoff problems but is this in accord with other data?

IMPLICATIONS FROM THE DISTRIBUTION OF IMPACT PARAMETERS

We recall that to date almost every inversion of a magnetic cloud's structure has assumed that it has a cylindrical cross section but we have shown above that this is probably incorrect. How would this flattening affect the fits obtained by the cylindrical symmetry assumption. Figure 4 shows us qualitatively what happens. The lower panel shows an oval rope and the upper panel is the cylindrical rope that is being forced to fit to it. The central region of the oval rope of course looks like the central region of the circular rope and the edges of both are similar as well. If we encountered the oval rope randomly, we would more often encounter rope structure that mapped into the central region of the circular rope than near the edges. Thus if we examined the distribution of impact parameters (the distance of the spacecraft from the central axis of the rope at closest approach) we would find a clustering of impact parameters near zero. If the cylindrical model were correct, we would find impact parameters that were evenly spread from 0 to 1. Figure 5 shows the distribution of impact parameters for the Pioneer Venus study together with a similar distribution of impact parameters found by Lepping and Berdichevsky [2000]. Clearly there is a preponderance of impact parameters near zero. Lepping and Berdichevsky [2000] attributed the asymmetry in the distribution to a selection effect, that it is easier to identify a rope if one passes through the center of it. Also they felt that they were passing through the center of ropes more often because the Earth orbits the sun near its equator. This latter hypothesis might be true only if the axes of ropes were predominantly at low inclinations, but many ropes have axes that are quite north-south in orientation.
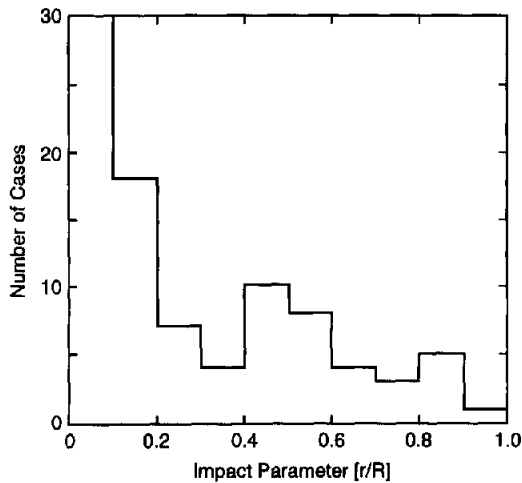
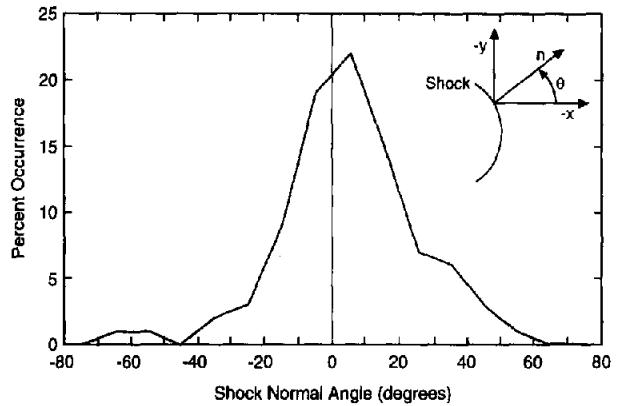Fig. 5. Histogram of impact parameters for the sum of IMP 8,   Fig. 6. Shock normals for ICME-driven shocks at Pioneer
Wind and Pioneer Venus flux ropes.   Venus.

SHOCK NORMAL ORIENTATIONS

At 0.7 AU the majority of interplanetary shocks are associated with ICMEs [*Lindsay et al.*, 1994]. If ICMEs had circular cross sections, the shock fronts would be curved around them much as the bow shock curves around the Earth's magnetosphere. However, just as there are few large impact parameters, there is little evidence for shock normals that are clearly near the edge of the ICME region. Figure 6 shows the distribution of shock normals seen by the PVO spacecraft at 0.7 AU [*Lindsay*, 1996]. Forty-three percent of shocks have these normals within $10°$ of the ICME - Sun line. Two-thirds are within $20°$. This implies that the obstacle has a very wide front surface with a large radius of curvature, much as our shock standoff results implied.

MULTIPOINT OBSERVATIONS

Several spacecraft have observed ICMEs at different locations nearly simultaneously. In some instances these have been separated by distances that were greater than the radial ICME thickness. One particularly useful suite of observations was the inbound trajectory of the NEAR spacecraft to Earth for a gravitational assist on its way to the asteroid, 433 Eros. If the circular symmetry assumption were correct, these well separated simultaneous observations would imply that an ICME had multiple flux rope structure [*Mulligan et al.*, 1999] but examination of the magnetic field structure of these "separate" flux elements reveals many similarities that suggest that they are the same rope, not separate. The flattened structures with oval cross sections that our above studies imply resolve this paradox as well.

Recently an inversion routine that relaxes the cylindrically symmetric assumption has been developed [*Mulligan and Russell*, 2001] and applied to a simultaneous ICME crossing by PVO and ISEE-3 in August 1978. A very good fit was obtained for a structure whose azimuthal extension was 4 times its thickness. This inversion is not unique. Two separate cylindrical ropes are also consistent with the observations but the flattened flux rope paradigm provides the simplest explanation for similar contemporaneous ropes over such a wide azimuthal extent and it is consistent with our inferences from standoff distances, shock normals and impact parameters.

DISCUSSION AND CONCLUSIONS

We have examined multiple lines of evidence that our present simple paradigm of a cylindrically symmetric flux rope is incorrect. The standoff location of the shock front is consistent with an obstacle moving though the solar wind whose dimensions are much bigger than implied by its observed thickness. In fact we have argued that the major and minor axes of the rope must both be large. We have examined the impact parameters obtained by fitting the ropes and found that they are best explained by oval not circular cross sections. We have looked at the distribution of shock normals and concluded that they too are consistent with a structure with a rather large radius of curvature. Finally, while there are few examples of multipoint encounters with ICMEs, these too provide evidence for a flattened flux rope. The one multipoint encounter that has been modeled can be fit with a rope four
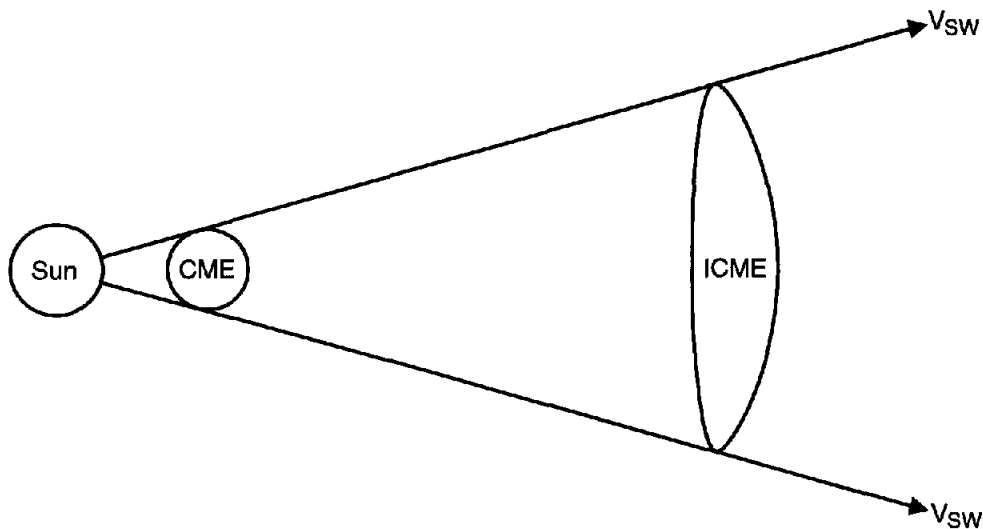
Fig. 7. Schematic of the radial and azimuthal expansion of an ICME in the plane perpendicular to the axial field of the rope. Near the Sun the CME has a circular cross section but the spreading of the solar wind flow lines stretches the ICME.

times as wide as it is thick. Other ropes that have not yet been modeled show clear resemblance across distances much greater than the rope thickness again indicating that they may be the same magnetic structure.

Why is the flux rope flattened? Figure 7 shows the solar wind flow and ICME expansion in the plane perpendicular to the rope axis and illustrates why the rope flattens. The solar wind expands radially from the sun and beyond some distance remains at a nearly constant velocity. However, streamlines are moving apart as they move away from the sun. Plasma on those streamlines will tend to move radially and thus separate but the twisted magnetic field in any magnetic flux ropes will pull the plasma toward the rope axis acting to keep the ICME together. Near the sun these magnetic forces may well be strong enough to keep the rope together, but at some distance the plasma inertial forces will overcome the magnetic forces and the flux tube will be stretched azimuthally.

In short, the cylindrically symmetric flux rope paradigm needs to be modified for ICMEs at and beyond the orbit of Venus. The ropes are significantly oval in cross section and may be as much as four times as wide as they are thick. This hypothesis is consistent with many otherwise puzzling aspects of the behavior of the ICME magnetosheath thickness, shock normal orientations, impact parameter distributions, and multipoint measurements. Occam's razor states that the simplest hypothesis is to be preferred and this flattening is a very simple addition to our present paradigm of a magnetic cloud. We recommend that a non-cylindrical model be used whenever well separated measurements are available and that conclusions drawn from fits with the cylindrically symmetric model such as their flux content, be viewed with appropriate caution.

ACKNOWLEDGMENTS

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