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A magnetic cloud as a distended flux rope occlusion in the heliospheric current sheet

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Abstract. A magnetic cloud was detected both near Earth by IMP 6-8 and 30° of longitude away from Earth by Pioneer 11 at 4.8 AU. The nearly identical magnetic signatures at the two spacecraft imply that its radial dimension increased little between them. The magnetic field within the cloud rotated from toward to away polarity, marking sector boundary passage at both locations. Interpreted in terms of a flux rope, its axis was highly inclined to the ecliptic plane, implying that its cylindrical cross section in the ecliptic plane was distended by at least 30° of longitude, forming an extensive occlusion in the heliospheric current sheet. A similar magnetic signature was observed at the same sector boundary by Pioneer 10 at 6.1 AU, at a longitude between Earth and Pioneer 11. Its radial dimension, however, was diminished by a factor of 3. We suggest that it was the same cloud, compressed by a second, oncoming transient that was observed behind the cloud at 1 AU.

1. Introduction

Coronal mass ejections (CMEs), observed with coronagraphs in white light, are rounded bubbles of solar material that leave the Sun [e.g., *Hundhausen*, 1993]. Their shapes in the solar wind, however, are not well known. *Newkirk et al.* [1981] addressed the issue with a two-dimensional model that tracked the ecliptic plane cross sections of round magnetic bubbles released into a solar wind with a longitudinally confined stream of high-speed flow. Since no magnetic forces were assumed, the bubbles became kinematically distorted as they moved out into the heliosphere. Those released far from the high-speed stream retained their radial heights and longitudinal angular widths so that their initially round cross sections became longitudinally distended. Those released near the stream underwent additional distortions. Early observational papers adopted the simple distended shapes for their schematic drawings [e.g., *Gosling et al.*, 1987; *Cane*, 1988], consistent with a two-dimensional view of CMEs as plasmoids completely detached from the Sun.

Three-dimensional views of CMEs in the solar wind arose with the realization that magnetic clouds, which are cold plasma structures with strong, smoothly rotating magnetic fields [*Burlaga*, 1991], form a subset of CMEs [*Gosling*, 1990]. Clouds give magnetic signatures consistent with flux rope topology [*Goldstein*, 1983; *Suess*, 1988; *Burlaga*, 1988]. Global sketches of these ropes generally show cylindrical forms with round cross sections and with axes (core fields) lying in [*Suess*, 1988; *Burlaga et al.*, 1990; *Lepping et al.*, 1990] or slightly inclined to [*Cane et al.*, 1994] the ecliptic plane. They look like adaptations of the longitudinal distentions of *Newkirk et al.* [1981], where the distended form becomes the lengthwise cross section of the rope, containing the rope axis, and connection to the Sun in the ecliptic plane is suggested via the rope ends. Although this may be the most common orientation for flux rope fits to clouds [*Bothmer and* Schwenn, 1996], ropes with axes highly inclined to the ecliptic are not uncommon [*Lepping et al.*, 1990]. On the basis of a case study of data from a single spacecraft, *Crooker et al.* [1990] depicted a highly inclined flux rope connected to the Sun, with a cross section they assumed was distended. The configuration is a natural extension of the *Newkirk et al.* [1981] model into the third dimension, since the ecliptic cross section of a highly inclined flux rope looks like a detached plasmoid. This paper gives multispacecraft evidence of cross sectional distention for a case with a similar magnetic cloud signature.

Another aspect of CMEs that is not well known is their relation to the heliospheric current sheet (HCS). On the Sun, CMEs usually arise from the bright streamer belt [*Hundhausen*, 1993], which forms the base of the HCS. *Gosling and McComas* [1987] depicted a CME in the solar wind pushing aside the HCS, implying that in the corona the CME arose on one side of the HCS. But since CMEs commonly form in the helmet fields of the streamer belt and the HCS extends from the peak of the helmet streamers rather than from the base of the corona to either side, more likely CMEs become occlusions in the HCS as helmet fields reconnect beneath them to form a flux rope. This paper supports that view.

The data used for this study come from the most well-ordered interval in the history of solar wind observations, the year 1974, when two giant streams recurred on 10 successive solar rotations. The IMP spacecraft orbiting Earth and the closely aligned Pioneer 10 and 11 spacecraft at ~4-6 AU provided a rich data set for studying various properties of these streams [e.g., *Siscoe and Intriligator*, 1993]. This study uses data from a single region of interstream flow which contains a well-defined field rotation. Section 2 presents and analyzes these data, and section 3 interprets the data in terms of a flux rope with a distended cross section.

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2. Data Analysis

Figure 1 shows IMP 6-8 data during passage of a magnetic cloud first identified by *Klein and Burlaga* [1982]. The plasma variations through the cloud are typical for a fast CME [e.g.,

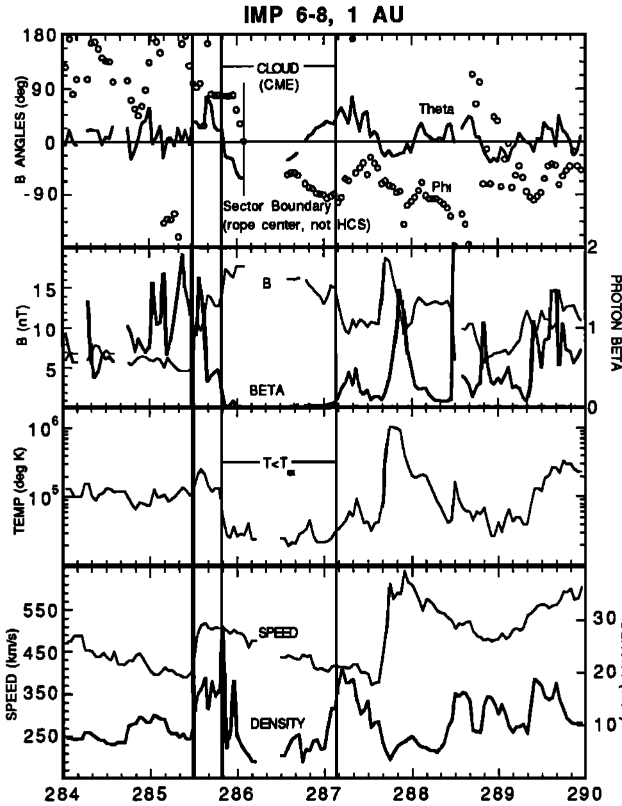

Figure 1. Merged IMP 6-8 hourly averages of data from the National Space Science Data Center for October, 11-17, 1974: magnetic field azimuth and elevation angles phi and theta, in GSE coordinates, where phi has been rotated about the z axis by 180° to approximate the SH coordinates used in Figure 2 and Figure 4; magnetic field magnitude B and proton beta; temperature T; speed; and density. A magnetic cloud coincides with the interval where T is less than T_{ex}, the expected temperature for normal solar wind expansion [*Richardson and Cane*, 1995]. The cloud carries the polarity change in phi that marks the sector boundary crossing.

Gosling, 1990]. The leading shock, identified by *Borrini et al.* [1982], causes the sharp rise in speed, proton temperature T, density, and magnetic field magnitude B on day 285 at 1300 UT. The speed then declines monotonically, a common CME pattern, indicating cloud expansion [*Klein and Burlaga*, 1982]. The magnetic cloud boundaries marked on day 285 at 2000 and day 287 at 0300 are those determined by *Richardson and Cane* [1995] on the basis of the depression in T relative to T_{ex}, the expected temperature for normal solar wind expansion, proportional to speed. These are also the boundaries of depressed plasma beta (ratio of gas pressure (electron pressure missing) to magnetic pressure), another cloud indicator, plotted in the second panel. The boundaries differ somewhat from those first identified by *Klein and Burlaga* [1982] (day 285 at 1200 and day 286 at 2200), who noted the difficulty of determining cloud boundaries from magnetic field data alone. On the basis of the mid-cloud speed of 450 km/s, we calculate a radial extent of 0.34 AU.

In the first panel of Figure 1, the azimuthal field angle phi, measured from the direction pointing away from the Sun, shows that the field changed from toward to away polarity in the middle of the cloud. This was the major polarity change marking sector boundary passage. Hence this case is an example of a magnetic cloud, not a current sheet, forming the sector boundary. The elevation angle theta, measured from the ecliptic plane, makes its largest negative excursion to -64° when the polarity changes. The data gap after this point precludes knowing the full extent of the negative excursion, but we can infer that the cloud is a flux rope with an axis considerably inclined to the ecliptic plane by the presence of the maximum theta excursion in the middle rather than at the edges of the cloud [cf. *Lepping et al.*, 1990]. Minimum variance analysis through the cloud yields a nearly radial direction, with components (0.90, 0.14, -0.41) in geocentric solar ecliptic (GSE) coordinates, consistent with the findings of *Klein and Burlaga* [1982]. The direction of intermediate variance, with components (0.43, -0.48, 0.77), gives an estimate of the orientation of the inferred flux rope's axis: It lies in a plane roughly parallel to the Parker spiral, inclined to the ecliptic by ~60°.

Following the cloud in Figure 1, the rise in speed and T accompanied by a decrease in density on day 287 near 1600 is characteristic of a stream interface [e.g., *Burlaga*, 1974]. On the other hand, *Richardson and Cane* [1995] identified the feature as a transient, based on intervals of $T < T_{ex}$, bidirectional ion flows, and a helium abundance enhancement. Minimum variance analysis across the changes in the nonradial flow components (not shown) at the leading edge of the feature yields GSE surface normal components of (-0.15, 0.76, -0.63), with a flow component of ≈100 km/s in that direction. If the feature was a transient, these results indicate that it expanded southward and azimuthally over the spacecraft, opposite to the sense of corotation. If it was an interface corotating past the spacecraft, the deflections would have been flows away from its pressure ridge, the minimum vari-

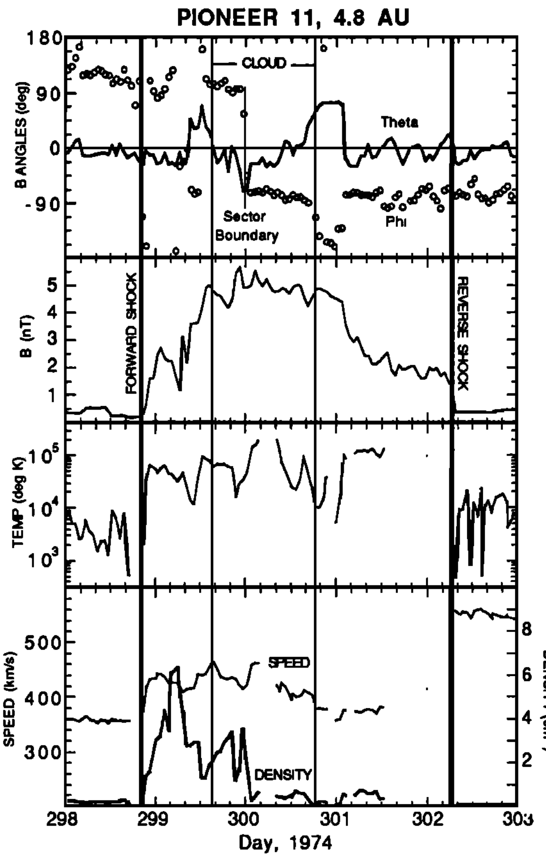

Figure 2. Pioneer 11 hourly averages of the same parameters (in SH coordinates) across the same sector boundary as in Figure 1, observed at 4.8 AU on October 25-30, 1974.

ance normal probably would lie in the plane of the interface, and the component of flow in that direction would not be particularly meaningful. In this paper we assume the feature was a transient. The interface option is discussed further by *Crooker and Intriligator* [1996].

Figure 2 shows data from Pioneer 11 across the same sector boundary at 4.8 AU. Given the nearly radial orientation of the minimum variance direction at 1 AU, the time delay should be consistent with primarily radial advection at the cloud speed rather than with the combined effects of radial advection and corotation. This proves to be the case. The polarity changes at the two spacecraft are separated by 13.9 days, implying an advection speed of 470 km/s under the assumption of constant speed. This is precisely the speed at the polarity change at 1 AU. At 4.8 AU, it is slightly less, consistent with a slightly shortened time delay owing to a minor corotation contribution.

What is striking about Figure 2 is the first panel. It is remarkably similar to the first panel in Figure 1: the magnetic variations in and around the cloud are nearly identical. A negative excursion in theta occurs exactly where phi changes from toward to away polarity. Minimum variance analysis through the cloud yields essentially the same nearly radial direction, with components (0.96, 0.19, 0.21) in solar heliographic (SH) coordinates. The magnetic field magnitude in the second panel also shows the same strong signal in the cloud as in Figure 1.

To further demonstrate the similarity of the magnetic variations at the two spacecraft, Figure 3 shows a plot of phi against theta for the two data sets, including points from either side of the cloud where theta makes large positive excursions. The points from Pioneer 11 nearly overlie those from IMP 6-8. Together, they outline a nearly complete sine wave passing through 360°. The well-separated eigenvalues of (1.5, 45, 150) for IMP 6-8 and (0.09, 3.3, 16.4) for Pioneer 11 indicate an almost planar field rotation. The points from the cloud proper at IMP 6-8, determined by $T < T_{ex}$, are distinguished from those outside by a different symbol. The cloud points cover 180° of the rotation, as expected for a flux rope. The magnetic structure outside the cloud that completes the 360° rotation is not understood at this time, but a similar case has been reported by *Fainberg et al.* [1995] in Ulysses data.

Under the assumption that Pioneer 11 and the IMP spacecraft observed the same cloud, its longitudinal span between the two observation points is calculated as follows. When Pioneer 11

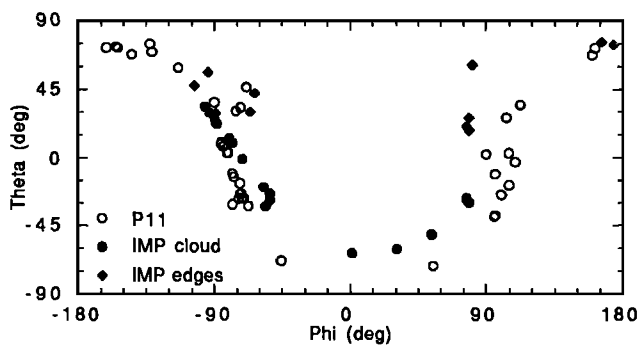

Figure 3. Scatterplot of magnetic field azimuth phi against elevation theta for IMP 6-8 (solid symbols) and Pioneer 11 (open circles) covering the intervals of magnetic cloud passage, including the bordering excursions to large positive theta. The magnetic structures appear to be nearly identical at the two spacecraft.

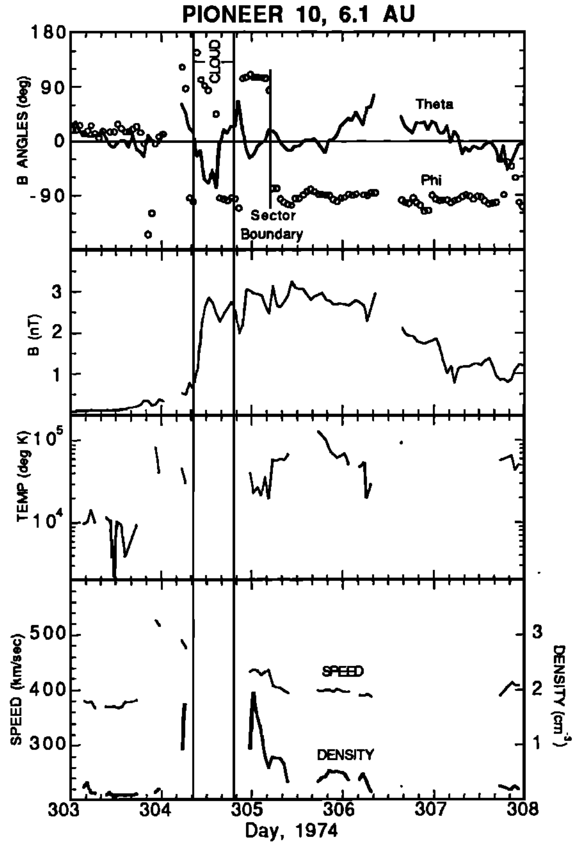

Figure 4. Pioneer 10 hourly averages of the same parameters across the same sector boundary as in Figure 2, observed at 6.1 AU on October 30 to November 4, 1974.

encountered the cloud, Earth was at a longitude 44° ahead of Pioneer 11 (in the direction of orbital motion). During the 14-day interval between cloud encounter at the two locations, Earth traveled 14° of longitude around the Sun. Since the cloud traveled as a nearly radially symmetric shell, the longitudinal span between observation points is the difference 44° - 14° = 30°. The cloud's radial extent at Pioneer 11 was 0.27 AU, slightly less than at 1 AU. Thus the longitudinal length is at least 8 times larger than the radial width.

In contrast to the magnetic variations in Figure 1 and Figure 2, the temperature profiles, in the fourth panels, are decidedly different. Figure 2 shows no depression. Thus, by strict definition, the structure at Pioneer 11 should not be called a cloud [*Burlaga*, 1991]. Here we relax the definition, since the similarity of the magnetic variations at the same sector boundary in the two figures argues in favor of their being the same structure. The difference in temperature patterns is discussed in section 3.2. Since the cloud boundaries cannot be determined on the basis of a T depression in Figure 2, as was done for Figure 1, they are simply mapped from Figure 1 according to their positions in the theta variation.

Another difference between Figure 1 and Figure 2 is the shock pattern. The two shocks at Pioneer 11 in Figure 2 look like the typical forward and reverse shocks that bound corotating interaction regions at distances beyond 2 AU. There is no evidence for a separate shock associated with the magnetic cloud, as in Figure 1. The transient shock at 1 AU in some way may have merged with or evolved into the corotating shock at Pioneer 11 [e.g., *Heinemann and Siscoe*, 1974]. Alternatively, if the cloud was still expanding radially, it may have generated both the forward and reverse shocks itself, as observed in the Ulysses data [*Gosling et al.*, 1994].

Figure 4 shows data from Pioneer 10 across the same sector boundary at 6.1 AU. The time delay from Pioneer 11 converts to a constant radial advection speed of 484 km/s, slightly higher than the ~440 km/s observed at Pioneer 11. Pioneer 10 was located at a longitude between Earth and Pioneer 11. The longitudinal span between the Pioneer 10 and Earth observation points was 19°. As in Figure 1 and Figure 2, the top panel shows the signature of a magnetic cloud with surrounding positive theta excursions, and minimum variance through the cloud yields the same nearly radial direction, with SH components (0.95, 0.16, 0.25). But there are also significant differences compared to Figure 1 and Figure 2: The cloud is shorter by a factor of 3, and the polarity change in the middle does not mark the final crossing into the away sector. At first these differences led us to believe that the cloud at Pioneer 10 could not be the same one observed at Earth and at Pioneer 11, but closer study of the plasma data admitted this possibility.

The available Pioneer 10 plasma data in the lower two panels of Figure 4 are intermittent, making shock signatures difficult to identify. Nevertheless, unlike the Pioneer 11 data, these data indicate major speed and temperature rises preceding the major density and field magnitude rises associated with the cloud. It is possible that these plasma signatures arose from impact with what we have interpreted as the second transient in the IMP data. In this case, the cloud at Pioneer 10 could have been the same as the one at Pioneer 11 and IMP, with the differences in magnetic signatures also resulting from the impact. This argument is presented in section 3.2.

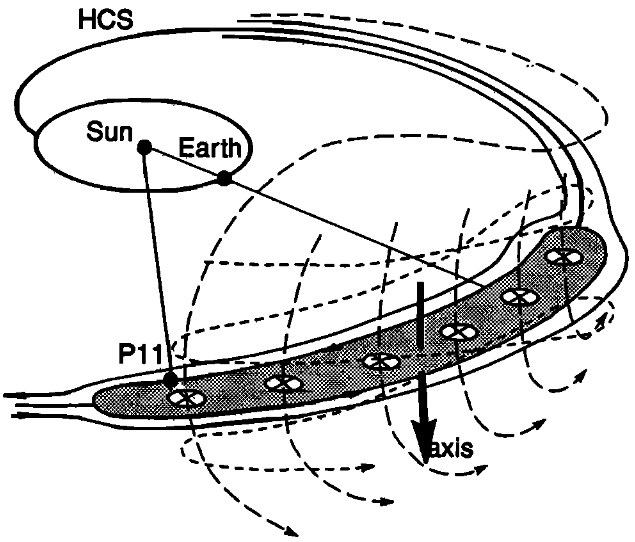

Figure 5. Schematic drawing of a magnetic cloud as a distended flux rope with a highly inclined axis forming an occlusion in the heliospheric current sheet (HCS). The solid lines lie in the ecliptic plane and the dashed lines rise out of it. The curved lines with long dashes indicate core fields on a highly inclined sector boundary surface that pierce the shaded cross section at right angles. These field lines may connect back to the Sun along the Parker spiral above and below the ecliptic plane to form the feet of the flux rope loop.

3. Cloud Geometry

3.1. IMP and Pioneer 11

Figure 5 schematically illustrates a possible global geometry and magnetic topology of the observed magnetic cloud at the radial distance of Pioneer 11, under the assumptions that it was the same cloud observed at the IMP spacecraft and that it had the form of a flux rope. The solid curves lie in the ecliptic plane, and the dashed curves rise out of that plane. The shaded area is the ecliptic cross section of the rope, substantially distended from the round shape normally assumed in models [e.g., *Burlaga*, 1988; *Lepping et al.*, 1990; *Osherovich et al.*, 1995]. The longitudinal span of the cross section exceeds the 30° separation between the Pioneer 11 and Earth observation points. The solid magnetic field lines on either side of the shaded area point in opposite directions, indicating that the rope carries the sector boundary. Outside the rope the sector boundary is shown as a single curve marking the intersection of a highly inclined HCS with the ecliptic plane. The encircled crosses in the shaded area and the curves with long dashes running through them represent the southward magnetic field at the core of the rope, which determines the direction of the rope axis, marked by the heavy arrow. The curve with the short dashes represents one of the helical field lines spiraling around the core. If both the core and helical field lines connect back to the Sun, forming closed loops, then they would follow the plane of the sector boundary back to the Sun, as suggested for the leading core field line.

The Figure 5 view is consistent with the sizes of CMEs observed near the Sun, which have average angular widths of 45° [*Hundhausen*, 1993]. Average angular widths as large as 100° have been deduced from relationships between interplanetary CMEs with shocks and their inferred solar sources [*Richardson and Cane*, 1993]. *Kahler* [1994] pointed out that if CMEs maintain their roughly round shapes as well as their angular widths, their signatures at 1 AU would last for several days, much longer than observed. This is unlikely, however, since it implies major dynamic expansion. The distended rather than round shape in Figure 5 and the data upon which it is based are consistent with a combination of dynamic and kinematic expansion.

As mentioned in the introduction, purely kinematic expansion has been modeled in two dimensions by *Newkirk et al.* [1981] for detached plasmoids in the ecliptic plane. A kinematically expanding plasmoid with a round cross section near the Sun maintains both its angular and radial widths as it moves outward. Consequently, the plasmoid becomes highly distended, with its radial dimension much shorter than its longitudinal dimension. In terms of Figure 5, the two-dimensional plasmoid of *Newkirk et al.* [1981] becomes the shaded cross section of our three-dimensional flux rope. In this kinematic view, the distended flux rope in essence becomes a thick current sheet across which the magnetic field rotates, giving an angular magnetic field variation nearly independent of where the structure is encountered, as observed at IMP and Pioneer 11.

On the other hand, the large radial dimension of the cloud and the speed gradient within it in Figure 1 demand some degree of radial expansion at least between the Sun and 1 AU [cf. *Klein and Burlaga*, 1982]. *Suess* [1988] argued that the observed radial expansion could be purely kinematic, as for a force-free rope, if strong magnetic forces prevented distention and maintained a round cross section. Since our two-point measurement has established distention for this case, we conclude that the radial expansion that must have occurred between the Sun and 1 AU was dynamic and not purely kinematic. Some dynamic distention also may have occurred close to the Sun owing to MHD forces from propagation of the rope through the ambient solar wind [*Cargill* *et al.*, 1995]. Beyond 1 AU, while kinematic distention continued, the cloud's unchanged radial dimension between IMP and Pioneer 11 suggests that dynamic expansion had ceased. On the other hand, the speed gradient at Pioneer 11 suggests continued expansion, implying nonuniformity in longitude.

The Figure 5 view is consistent with models of CME flux rope formation in helmet streamers [*Crooker et al.*, 1990, 1993; *Gosling*, 1990]. In a simplified view of solar topology, the magnetic fields of helmet streamers arch over the heliomagnetic equator in an arcade that encircles the Sun and forms the base of the coronal streamer belt. Magnetic fields on either side of the arcade have opposite polarity. They meet at the apex and extend out into space separated by the HCS. A CME flux rope formed within a limited section of the arcade by reconnection of helmet fields will have its axis aligned with the heliomagnetic equator, which is often highly inclined to the heliographic equator [*Shodhan et al.*, 1994]. Under the rope, the reconnecting fields will have reestablished the helmet arcade with the HCS extending upward from its apex to the rope. The rope thus becomes an occlusion in the HCS, where the field rotation within the rope carries the polarity change that marks the sector boundary. If the portion of the heliomagnetic equator that lies under the CME is highly inclined to the ecliptic plane, subsequent outward motion and distention will result in the Figure 5 view, where the occlusion can be considered as a thickened HCS with rotational structure.

The flux rope in Figure 5 stands in sharp contrast to the familiar view offered by *Burlaga et al.* [1990], *Lepping et al.* [1990], and *Burlaga* [1991], based primarily on a cloud observed by multiple spacecraft in January 1978 [*Burlaga et al.*, 1981]. The rope axis fit to that cloud lay in the ecliptic plane, orthogonal to the rope axis in Figure 5, and the rope's cross section was assumed to be round. Rope axes of the 18 magnetic clouds modeled by *Lepping et al*, [1990] had inclinations evenly distributed between 0° and 90° with respect to the ecliptic plane, suggesting that high inclinations, as in Figure 5, are at least as common as low inclinations. On the other hand, in a study of 46 clouds, *Bothmer and Schwenn* [1996] found low inclinations more common.

3.2. IMP, Pioneer 11, and Pioneer 10

The Figure 5 view does not take into account the Pioneer 10 data in Figure 4. As described in section 2, Pioneer 10 passed through the same sector boundary as IMP and Pioneer 11 at a longitude between them and observed a cloud with the same magnetic field variations but with a substantially decreased width. The sector boundary carried by this cloud was followed by a second sector boundary. Under the assumption that all three spacecraft intercepted the same cloud, Figure 6 shows how the ecliptic cross section of the rope in Figure 5 can be modified to accommodate these variations. A second transient is shown impacting and compressing the cloud at solar longitudes east of Pioneer 11, forming a compound transient [cf. *Burlaga et al.*, 1987]. This view is consistent with the transient interpretation of the feature following the cloud in Figure 1, in which the transient expanded over the IMP and Pioneer 10 spacecraft from the anticorotation direction.

Flux ropes emanating from the same section of the streamer belt and subsequently distending and compounding seem to be a natural way to account for the common occurrence of multiple sector boundary crossings. The variations of phi and theta through the possible second transient at IMP, in the top panel of Figure 1, are not nearly as regular as through the identified

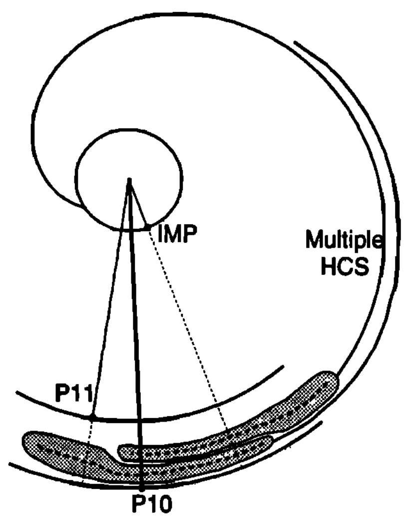

Figure 6. Positions of Earth and Pioneers 10 and 11 in the ecliptic plane at the time when each observed the same sector boundary with the magnetic cloud. The schematic cross section of the cloud at the heliocentric distance of Pioneer 11 is compressed at longitudes ahead of the spacecraft by a second transient emanating from the same sector boundary.

cloud, but they show some degree of helicity and a brief change in polarity, suggesting a basic flux rope structure. At Pioneer 10, presumably that same polarity change became the final sector boundary crossing. Without knowledge of its history, this crossing would probably be identified as the HCS. In Figure 6, the curves leading from the two transients along the Parker spiral back to the Sun indicate a double HCS, possibly emanating from a double helmet streamer [*Crooker et al.*, 1993]. The two transients form occlusions in these HCSs. The heavy dashed lines within them indicate that they carry field polarity changes marking the sector boundary crossings.

The impact of the possible second transient upon the first may also account for differences in the cloud's plasma signatures at Pioneer 11 (Figure 2) compared to IMP (Figure 1), assuming that impact occurred prior to the Pioneer 11 encounter, consistent with the speed profile at IMP. The Pioneer 11 data lack the temperature depression and smooth speed gradient characteristic of expansion at IMP. The absolute temperature at Pioneer 11 is slightly higher than at IMP, possibly because the temperature east of Pioneer 11 had been raised by compression at impact, with resultant proton heat flux distributing the heat throughout the cloud.

4. Conclusions

From a case study of magnetic cloud signatures observed by the Pioneer 10, Pioneer 11, and IMP spacecraft across the same sector boundary, we deduce the following phenomenological possibilities:

1. Magnetic clouds interpreted as flux ropes with axes inclined to the ecliptic plane can have highly distended cross sections, with length exceeding radial width by at least a factor of 8.

2. Clouds can carry the magnetic field polarity change that marks the sector boundary, consistent with flux rope formation in helmet streamers at the heliomagnetic equator. Thus clouds can form occlusions in the heliospheric current sheet. The preponderance of high-inclination sector boundaries is compatible with highly inclined flux ropes carrying those boundaries.

3. Multiple transients may create multiple polarity changes at sector boundaries. At 1 AU, the cloud appeared to be followed by a second transient that compressed it by the time it reached 6 AU and brought an additional polarity change there.

Point 1 covers the main purpose of the paper, which is to offer a phenomenological model of a magnetic cloud deduced from multipoint observations as a basis for future quantitative modeling efforts. To date, because of mathematical tractability, most flux rope models of clouds have been constrained to have round cross sections [e.g., *Lepping et al.*, 1990; *Osherovich et al.*, 1995]. Spheromak models, with elliptical cross sections, offer more flexibility [*Vandas et al.*, 1993], but how spheromak topology might form at the Sun seems more problematical than flux rope topology. The flux rope results of *Vandas et al.* [1995] come closest to matching our phenomenological model. In a manner similar to *Newkirk et al.* [1981], but using a three-dimensional flux rope in place of a plasmoid, they immersed its initially round cross section in an MHD model of solar wind flow in the ecliptic plane, and distention became apparent as the rope propagated away from the Sun.

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References

Borrini, G., J. T. Gosling, S. J. Bame, and W. C. Feldman, An analysis of shock wave disturbances observed at 1 AU from 1971 through 1978, *J. Geophys. Res.*, *87*, 3065-3073, 1982.

Bothmer, V., and R. Schwenn, The structure and origin of magnetic clouds in the solar wind, *Ann. Geophys.*, in press, 1996.

Burlaga, L. F., Interplanetary stream interfaces, *J. Geophys. Res.*, *79*, 3717-3725, 1974.

Burlaga, L. F., Magnetic clouds and force-free fields with constant alpha, *J. Geophys. Res.*, *93*, 7217-7224, 1988.

Burlaga, L. F., Magnetic clouds, in *Physics of the Inner Heliosphere II*, edited by R. Schwenn and E. Marsch, pp. 1-22, Springer-Verlag, New York, 1991.

Burlaga, L., E. Sittler, F. Mariani, and R. Schwenn, Magnetic loop behind an interplanetary shock: Voyager, Helios, and IMP 8 observations, *J. Geophys. Res.*, *86*, 6673-6684, 1981.

Burlaga, L. F., K. W. Behannon, and L. W. Klein, Compound streams, magnetic clouds, and major geomagnetic storms, *J. Geophys. Res.*, *92*, 5725-5734, 1987.

Burlaga, L. F., R. P. Lepping, and J. Jones, Global configuration of a magnetic cloud, in *Physics of Magnetic Flux Ropes, Geophys. Monogr. Ser.*, vol. 58, edited by C. T. Russell, E. R. Priest, and L. C. Lee, pp. 373-377, AGU, Washington, D. C., 1990.

Cane, H. V., The large-scale structure of flare-associated interplanetary shocks, *J. Geophys. Res.*, *93*, 1-6, 1988.

Cane, H. V., I. G. Richardson, T. T. von Rosenvinge, and G. Wibberenz, Cosmic ray decreases and shock structure: A multi-spacecraft study, *J. Geophys. Res.*, *99*, 21,429-21,441, 1994.

Cargill, P. J., J. Chen, D. S. Spicer, and S. T. Zalesak, Geometry of interplanetary magnetic clouds, *Geophys. Res. Lett.*, *22*, 647-650, 1995.

Crooker, N. U., and D. S. Intriligator, A magnetic cloud at Pioneers 10 and 11: Relation to heliospheric current sheet, stream interface, and energetic ions, in *Solar Wind Eight*, edited by D. Winterhalter, D. McComas, N. Murphy, and J. Phillips, in press, Am. Inst. Phys., College Park, Md., 1996.

Crooker, N. U., J. T. Gosling, E. J. Smith, and C. T. Russell, A bubblelike coronal mass ejection flux rope in the solar wind, in *Physics of Magnetic Flux Ropes, Geophys. Monogr. Ser.*, vol. 58, edited by C. T. Russell, E. R. Priest, and L. C. Lee, pp. 365-371, AGU, Washington, D. C., 1990.

Crooker, N. U., G. L. Siscoe, S. Shodhan, D. F. Webb, J. T. Gosling, and E. J. Smith, Multiple heliospheric current sheets and coronal streamer belt dynamics, *J. Geophys. Res.*, *98*, 9371-9381, 1993.

Fainberg, J., V. A. Osherovich, R. G. Stone, R. J. MacDowall, J. L. Phillips, and A. Balogh, Ulysses observations of a magnetic cloud sheath (abstract), *Eos Trans. AGU*, *76*(17), Spring Meet. Suppl., S232, 1995.

Goldstein, H., On the field configuration in magnetic clouds, in *Solar Wind Five*, edited by M. Neugebauer, *NASA Conf. Publ., CP-2280*, pp. 731-733, 1983.

Gosling, J. T., Coronal mass ejections and magnetic flux ropes in interplanetary space, in *Physics of Magnetic Flux Ropes, Geophys. Monogr. Ser.*, vol. 58, edited by C. T. Russell, E. R. Priest, and L. C. Lee, pp. 330-364, AGU, Washington, D. C., 1990.

Gosling, J. T., and D. J. McComas, Field line draping about fast coronal mass ejecta: A source of strong out-of-the-ecliptic interplanetary magnetic fields, *Geophys. Res. Lett.*, *14*, 355-358, 1987.

Gosling, J. T., M. F. Thomsen, S. J. Bame, and R. D. Zwickl, The eastward deflection of fast coronal mass ejecta in interplanetary space, *J. Geophys. Res.*, *92*, 12,399-12,406, 1987.

Gosling, J. T., S. J. Bame, D. J. McComas, J. L. Phillips, E. E. Scime, V. J. Pizzo, B. E. Goldstein, and A. Balogh, A forward-reverse shock pair in the solar wind driven by over-expansion of a coronal mass ejection: Ulysses observations, *Geophys. Res. Lett.*, *21*, 237-240, 1994.

Heinemann, M. A., and G. L. Siscoe, Shapes of strong shock fronts in an inhomogeneous solar wind, *J. Geophys. Res.*, *79*, 1349-1355, 1974.

Hundhausen, A. J., The sizes and locations of coronal mass ejections: SMM observations from 1980 and 1984-1989, *J. Geophys. Res.*, *98*, 13,177-13,200, 1993.

Kahler, S., Energetic charged particles as probes of the geometry and topology of the interplanetary magnetic field: The detection of coronal mass ejections, in *Proceedings of the Third SOHO Workshop - Solar Dynamic Phenomena and Solar Wind Consequences*, *European Space Agency Spec. Publ., ESA SP-373*, 253-261, 1994.

Klein, L. W., and L. F. Burlaga, Interplanetary magnetic clouds at 1 AU, *J. Geophys. Res.*, *87*, 613-624, 1982.

Lepping, R. P., J. A. Jones, and L. F. Burlaga, Magnetic field structure of interplanetary magnetic clouds, at 1 AU, *J. Geophys. Res.*, *95*, 11,957-11,965, 1990.

Newkirk, G., Jr., A. J. Hundhausen, and V. Pizzo, Solar cycle modulation of galactic cosmic rays: Speculation on the role of coronal transients, *J. Geophys. Res.*, *86*, 5387-5396, 1981.

Osherovich, V. A., C. J. Farrugia, and L. F. Burlaga, Nonlinear evolution of magnetic flux ropes, 2, Finite beta plasma, *J. Geophys. Res.*, *100*, 12,307-12,318, 1995.

Richardson, I. G., and H. V. Cane, Signatures of shock drivers in the solar wind and their dependence on the solar source location, *J. Geophys. Res.*, *98*, 15,295-15,304, 1993.

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*, 23,397-23,412, 1995.

Shodhan, S., N. U. Crooker, G. L. Siscoe, and W. J. Hughes, Heliospheric current sheet inclinations predicted from source surface maps, *J. Geophys. Res.*, *99*, 2531-2536, 1994.

Siscoe, G., and D. Intriligator, Three views of two giant streams: Aligned observations at 1 AU, 4.6 AU, and 5.9 AU, *Geophys. Res. Lett.*, *20*, 2267-2270, 1993.

Suess, S. T., Magnetic clouds and the pinch effect, *J. Geophys. Res.*, *93*, 5437-5445, 1988.

Vandas, M., S. Fischer, P. Pelant, and A. Geranios, Spheroidal models of magnetic clouds and their comparison with spacecraft measurements, *J. Geophys. Res.*, *98*, 11,467-11,475, 1993.

Vandas, M., S. Fischer, M. Dryer, Z. Smith, and T. Detman, Simulation of magnetic cloud propagation in the inner heliosphere in two-dimensions, 1, A loop perpendicular to the ecliptic plane, *J. Geophys. Res.*, *100*, 12,285-12,292, 1995.

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