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Solar cycle evolution of the structure of magnetic clouds in the inner heliosphere

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Abstract.
Nearly ten years of continuous magnetic field observations by the Pioneer Venus spacecraft allows us to study the correlation between the structure of magnetic clouds in the inner heliosphere and the phase of the solar cycle. Fifty-six magnetic clouds have been identified in the PVO data at .7AU during 1979-1988. As this period spans nearly two solar maxima and one solar minimum we can study the evolution of the structure of these magnetic clouds through varying solar activity and under various orientations of the coronal streamer belt. Until shortly after the 1979 solar maximum the majority of clouds had an initially southward magnetic field which turned northward as the cloud was traversed, while in the period leading up to the 1988 solar maximum the majority had a northward field that turned southward. In the declining phase of solar activity magnetic clouds continued to occur, but only a minority can be classified as having south-to-north and north-to-south rotations. The majority of these clouds occurred with the field remaining entirely north or south relative to the solar equator. These results confirm observations using Helios and ISEE data indicating that the structure of magnetic clouds varies in response to changes in the magnetic structure of the source region. By interpreting these observations to imply that the leading magnetic field in magnetic clouds is controlled by the polarity of the sun's global field and that the inclination of the coronal streamer belt controls the axis of symmetry of the clouds, we can predict preferred magnetic cloud structure and orientation during varying phases of the solar cycle. The helicity of the observations does not seem to be ordered by the solar cycle.

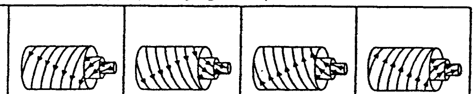
Introduction

Magnetic clouds in the interplanetary medium are regions of enhanced magnetic fields, where direction rotates slowly and within which solar wind proton temperature is unusually low [*Burlaga et al.*, 1981]. Magnetic clouds are a subset of the interplanetary manifestations of coronal mass ejections [*Gosling*, 1990] comprising about one-third of CMEs. Despite extensive studies of the association of magnetic cloud occurrence and photospheric phenomena such as disappearing filaments [*Behannon et al.*, 1989; *Marubashi*, 1986] the connection between magnetic clouds and processes at their source region is poorly understood. If we could predict the polarity structure of magnetic clouds we could in turn improve our predictions of their effects on the Earth's magnetosphere. In this paper we show how this may be done.

While at first the magnetic field rotations in these clouds appear almost random, *Zhang and Burlaga* [1988] and *Bothmer and Schwenn* [1998] showed that during the period 1974-1982 there was a preference for the magnetic field to rotate from south to north as the magnetic cloud was traversed. At the end of this period *Bothmer and Rust* [1997] observed that the majority of magnetic clouds had the opposite sense of this rotation. The orientation of the magnetic field in the leading half of these clouds was the same as the overall dipolar magnetic field of the sun. In solar cycle 20 just after solar maximum in 1969, the north pole of the sun assumed a positive polarity which lasted until just after the maximum of solar cycle 21 in 1980. The association between the orientation of the dipolar field of the sun and that of the leading half of magnetic clouds is important because it links the structure of magnetic clouds to the global magnetic field of the sun. Thus, when the global field of the sun reversed in 1980, according to *Bothmer and Rust* [1997] it should have caused the leading polarity in magnetic clouds to reverse as well. Ample data with which to check this reversal are available in the records obtained by the Pioneer Venus spacecraft and in the study detailed below we undertake such a comparison.

In a study of Helios observations *Bothmer and Schwenn* [1998] interpreted their magnetic clouds in terms of the magnetic flux rope model used to interpret interplanetary magnetic clouds [*Goldstein*, 1983]. They interpreted their structures as belonging to one of four categories corresponding to the leading and trailing north-south magnetic field polarities and the east-west magnetic field in the center of the rope.

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

Figure 1. Four orientations of ecliptically oriented flux rope model and its magnetic signatures. Note N=north, S=south, E=east, W=west [after *Bothmer and Rust* [1997]].

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Magnetic Rope Types Perpendicular to Ecliptic Plane

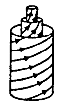
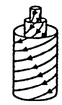
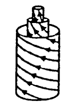
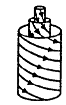
Magnetic Cloud Type	 WNE	 ESW	 ENW	 WSE
Leading Field	West (-By)	East (+By)	East (+By)	West (-By)
Axial Field	North (+Bz)	South (-Bz)	North (+Bz)	South (-Bz)
Trailing Field	East (+By)	West (-By)	West (-By)	East (+By)
Helicity	RH	RH	LH	LH

Figure 2. Four flux rope model orientations highly inclined with respect to the ecliptic plane. Note N=north, S=south, E=east,W=west [after *Zhao and Hoeksema* [1996]].

Labeling these structures by their leading, center, and trailing polarities relative to "solar ecliptic" coordinates they obtained the four categories shown in Figure 1, namely: SEN, SWN, NES, and NWS where "N" is "North", "S" is "South", "E" is "East", and "W" is "West" and where two of these variations represent right-handed ropes and the other two represent left-handed ropes. No preference for either helicity was found. In the present study we will also characterize magnetic clouds according to this scheme. However, we find we cannot force all magnetic clouds into these categories and add four more categories that can be visualized as flux ropes with axes oriented perpendicular to the ecliptic plane as shown in Figure 2. Using a similar convention these categories are: WNE, ESW, ENW, and WSE with the first two categories having right-hand helicity while the last two having left-hand helicity. It is the purpose of our paper to show how the magnetic structure of magnetic clouds evolves across the change in polarity of the sun using this extended categorization.

Observations and Classifications

For our purpose we used ten minute averaged plasma and magnetic field data from the fluxgate magnetometer and plasma analyzer instruments aboard the Pioneer Venus Orbiter (PVO) spacecraft. The complete data set spans August 1978 through July 1988. Consistent with *Bothmer and Rust* [1997] we used criteria established by *Burlaga* [1991] as a guideline in selecting magnetic clouds for this study. The criteria are: the magnetic field vector must rotate through a large angle on the time scale of a day; the magnitude of the field must be enhanced throughout the interval in question; the proton temperature must be lower than the ambient. Since such magnetic field rotations are readily identifiable in the magnetic field displayed in the VSO (Venus Solar Orbital) coordinate system (which only differs about three degrees from the solar heliographic coordinate system) we found it unnecessary to rotate the data into heliographic coordinates to make the qualitative Bz measurements for this study.

Figure 3 shows two examples of typical magnetic clouds in the PVO data set which meet the above criteria. The large magnetic rotation and cold proton signature are characteristic of magnetic clouds. In all our search yielded fifty-six acceptable clouds for January 1979 through July 1988 at .7 AU which can be classified under one of the eight flux rope categories we mentioned earlier. Within this classification scheme each rope schematic differs only in the direction of the field at the rope's outer boundary and along its axis. In Figure 1 the ropes lie with their axes in the ecliptic plane while those in Figure 2 lie with their axes perpendicular to the ecliptic plane. The resulting sequence of magnetic field directions seen by spacecraft for each rope type is shown on the right side of the corresponding figure. Note that the highly inclined ropes exhibit a unipolar signature in the Bz component whereas the more ecliptically aligned ropes exhibit a bipolar signature in Bz.

Returning to Figure 3 we now categorize these clouds using our classification scheme. Looking at the magnetic field components in Figure 3a we see that Bz rotates from north to south through the time interval indicated while By remains negative near the center of the interval. Referring back to Figure 1 we can identify this "bipolar Bz" cloud as having a "NWS" signature. We also identify it as having left-handed helicity. Categorizing the "unipolar Bz" cloud in Figure 3b, we find it has an "ESW" signature (see Figure 2) as well as right-handed helicity. Applying a similar approach to the fifty-six clouds in our study, we find all eight categories presented in this section are represented during the entire PVO data set.

Solar Cycle Variation

Statistical results of the yearly frequency distribution of the "bipolar Bz" orientations of the fifty-six clouds is shown in Figure 4. The top portion of the figure indicates clouds with a north-to-south (NS) rotation in Bz while the bottom portion shows those with a south-to-north (SN) magnetic signature. The figure shows that the majority of clouds occurring near the maximum of solar cycle 21 (circa 1979) have SN rotations in their magnetic field vectors while clouds occurring near the maximum of the next solar cycle (circa 1988) have predominantly NS signatures. However, a com-

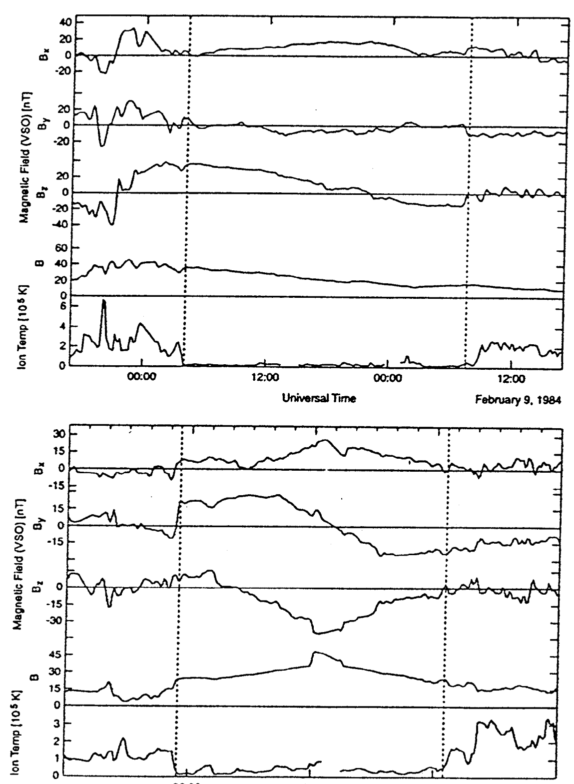


Figure 3. Two typical magnetic clouds in Pioneer Venus Orbiter (PVO) data used in this study.

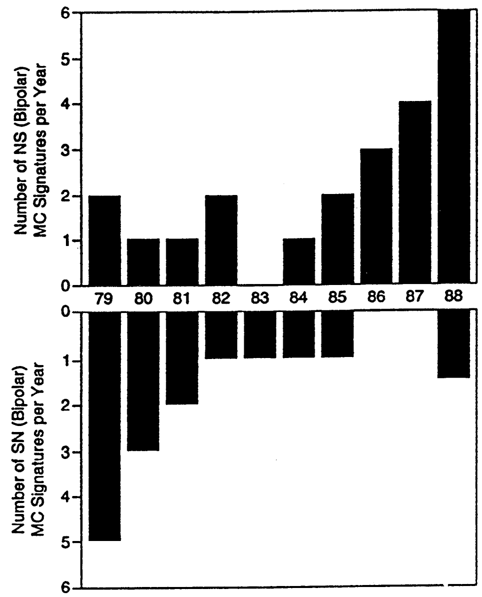


Figure 4. Yearly frequency distribution of magnetic clouds with NS and SN rotations over the solar cycle. As the PVO mission ended in August 1988, statistics for the last column have been extrapolated through December 1988.

parison of the distribution of magnetic helicity of the "bipolar Bz" clouds in Figure 4 shows fifty nine percent are right-handed (SWN, NWS) while forty one percent are left-handed (SEN, NES), indicating little or no preference for right-handed over left-handed flux rope formation. This suggests the change from predominantly SN to NS rotations in Bz during the declining phase of solar cycle 21 is indicative of a change in polarity of the global magnetic field of the sun verifing the *Bothmer and Schwenn* [1998] conjecture that the leading polarity of a cloud reverses across solar maximum.

By combining statistics for both the "bipolar Bz" and "unipolar Bz" clouds as Figure 5, we can go further than the Helios study and compare the occurrence rate of near ecliptic and highly inclined ropes. The top and bottom panels show the yearly distribution of "bipolar Bz" and "unipolar Bz" cloud signatures respectively. The figure indicates that highly inclined cloud orientations are characteristic of the period when the neutral line and streamer belt are also highly inclined just after solar maximum [*Behannon et al.*, 1989]. The low inclination structures are found from near solar minimum to solar maximum when the streamer belt is more equatorial. Note the comparison of magnetic helicity of the "unipolar Bz" clouds in Figure 5, shows forty one percent are right-handed (WNE, ESW) while fifty nine percent are left-handed (WSE, ENW). Thus as is the case with low inclination clouds, high inclination clouds show little or no preferred magnetic helicity. Unlike low inclination clouds, however, highly inclined clouds show no evidence of a preferred leading polarity which reverses when the solar polar field reverses. The orientation of the leading field for these clouds appears equally distributed over the four "unipolar Bz" rope types throughout the study.

The observed patterns of behavior of the magnetic clouds can be understood in terms of the picture where the clouds originate in the coronal helmet streamer belt *Crooker et al.* [1993]. To illustrate this Figure 6 shows Carrington Rotation plots of coronal field lines derived from potential field source surface models [*Hoeksema et al.*, 1986] extending out to at least 2 solar radii (Rs). The streamer belt neutral line is a large black trace superposed on each of the 2.5 Rs source surfaces to show which arcades form the helmet streamer belt. If one assumes magnetic clouds are derived from these structures, it is reasonable to consider the neutral line orientation as defining the orientation of the axis of symmetry of the clouds as first described by *Zhao and Hoeksema* [1996]. One observes for the period dominated by the highly inclined structures that the neutral line and streamer belt are in many places tilted at large angles to the solar equator. This can be seen in the first two panels of Figure 6. In contrast, when the clouds are dominated by the "bipolar Bz" structures, the neutral line is either almost equatorial or simply and gently tilted (as in the last two panels of Figure 6) so that the overarching arcades maintain the solar dipole orientation. Thus the global magnetic field of the sun controls the leading and trailing polarities of the clouds and the orientation of the streamer belt controls the clouds' relative orientation.

Discussion and Conclusions

Throughout this study we find evidence indicating a correlation between the structure of magnetic clouds in the inner heliosphere and the phase of the solar cycle. When examining near ecliptic "bipolar Bz" clouds, we find in the majority of these clouds the leading polarity reverses when the solar polar field reverses. They also occur more frequently relative to the "unipolar Bz" clouds during solar extrema. In contrast, the highly inclined "unipolar Bz" clouds do not show a leading polarity reversal when the solar polar field reverses and they have different solar cycle dependencies than the "bipolar Bz" clouds. This is expected if the orientation of the magnetic clouds is controlled by the orientation of the streamer belt. The maximum dipolar inclination of the streamer belt neutral line, which occurs from just after solar maximum to near solar minimum [*Behan-*

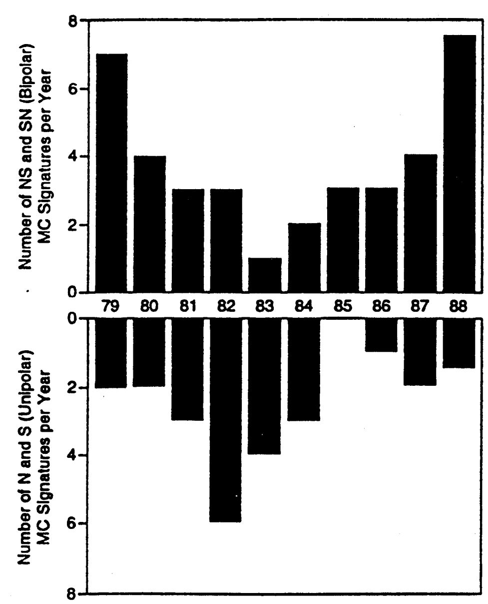


Figure 5. Top: Yearly frequency distribution of magnetic clouds with bipolar signature in Bz over the solar cycle. Bottom: Same distribution but for clouds with unipolar Bz. Statistics for the last column have been extrapolated through December 1988.

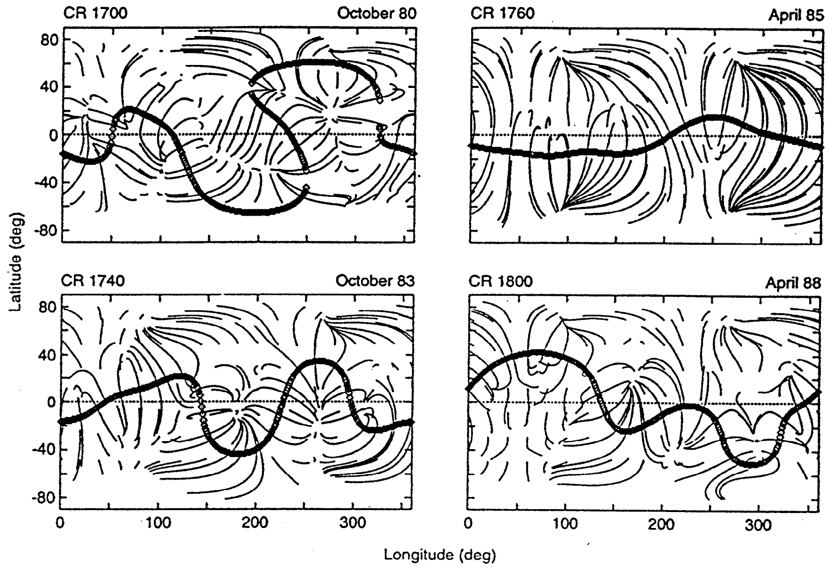


Figure 6. Carrington Rotation plots of coronal field lines reaching out to at least 2 Solar Radii (Rs). Field lines have been calculated from Hoeksema's coefficients for potential field models based on Wilcox Solar Observatory synoptic charts of the photospheric field. Large black traces indicate streamer belt neutral line.

non et al., 1989], produces the high number the "unipolar Bz" cloud signatures evident in the observations. One visualizes this preferred "unipolar Bz" cloud production in terms of flux rope formation in the highly inclined regions of the streamer belt during the declining phase of the solar cycle. This result is consistent with the association of transients with the streamer belt found by *Crooker and McAllister* [1997] among others. Finally, the structures of magnetic clouds at .7 AU show no sign of preferential magnetic helicity which is consistent with *Rust* [1994], *Martin and McAllister* [1997], and *Bothmer and Rust* [1997]. The rope-like structures may result from reconnection in sheared helmet streamer arcades [*Gosling*, 1990] as the helmet streamer belt configuration evolves through the solar cycle.

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