# A magnetic cloud at Pioneers 10 and 11: Relation to heliospheric current sheet, stream interface, and energetic ions

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# A magnetic cloud at Pioneers 10 and 11: Relation to heliospheric current sheet, stream interface, and energetic ions

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**Abstract.** A magnetic cloud detected at 1 AU by Earth-orbiting spacecraft, at 4.8 AU by Pioneer 11, and at 6.1 AU by Pioneer 10 is interpreted in terms of a flux rope with a steeply inclined axis and a highly-distended, cylindrical cross-section. A possible double-rope interpretation is also considered. The field rotation within the cloud carried the polarity change marking sector boundary passage; the cloud thus formed an extensive occlusion in the heliospheric current sheet. Within the cloud at Pioneer 11 and following it at Pioneer 10 are stream interface signatures bounding energetic particle fluxes, a pattern documented earlier adjacent to sector boundaries without clouds. This finding raises a number of interesting questions about the relationship between transient and steady state features.

## 1. Introduction

The main results reported at the conference have been submitted for publication elsewhere [*Crooker and Intriligator*, 1995] and are reviewed in Section 2. Sections 3 and 4 describe two areas of ongoing research stimulated by these results.

## 2. Magnetic cloud as single flux rope

*Crooker and Intriligator* [1995] identified a magnetic cloud at ~ 5-6 AU in data from Pioneers 10 and 11 at the same sector boundary where a cloud had been identified earlier at 1 AU by *Klein and Burlaga* [1982]. The remarkable similarity between the magnetic signatures at all three locations, illustrated in Figure 1, led Crooker and Intriligator to conclude that the same cloud intercepted all three spacecraft. Its smaller size at Pioneer 10 was ascribed to compression by a second fea-ture observed behind the cloud at 1 AU that began with a sharp rise in speed about a half day behind the cloud's trailing edge. (The only evidence of this feature in the top panel of Figure 1 is the large phi excursion at the end of the plot about a day after the rise in speed.) Interpreted as a transient, the second feature expanded in the anticorotation direction, presumably overtaking only Pioneer 10, at a longitude between Earth and Pioneer 11.

Figure 2 illustrates the cloud geometry in terms of a single flux rope, prior to impact by the second transient. Since the axis is nearly vertical with respect to the ecliptic plane, the 30° separation between the 1 AU and Pioneer 11 observation points implies that the cylindrical cross-section (shaded) was highly distended. Other multipoint measurements of magnetic clouds have covered wider longitude spans [e.g., *Burlaga et al.*, 1981]; but the axes of these clouds lay close to the ecliptic plane so that no distention of their cross-sections was necessary to account for the observations. The elongated shape in Figure 2 looks like the kinematically distended, detached plasmoids created by *Newkirk et al.* [1981] in their two-dimensional model, and Figure 2 is a natural extension of their model to the third dimension.

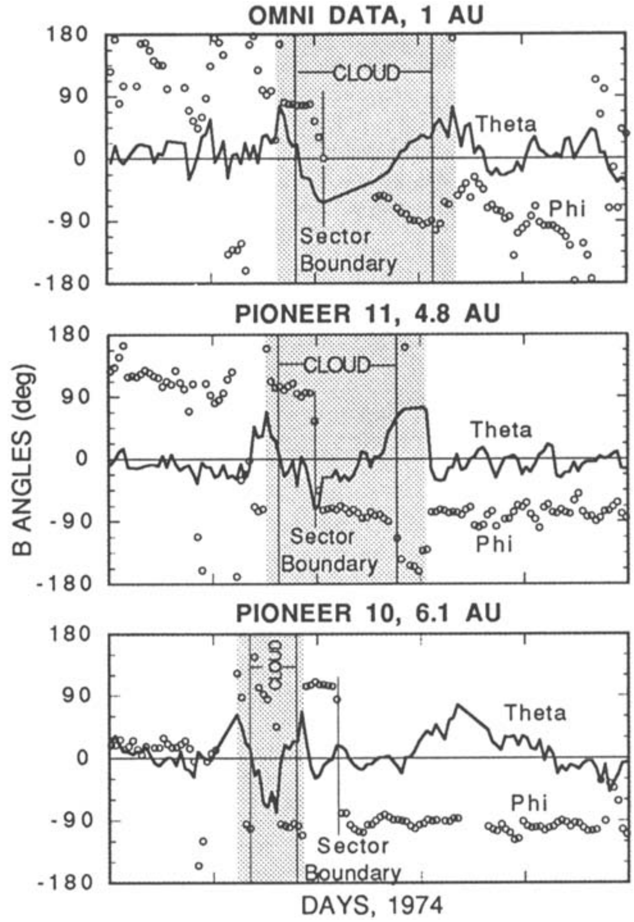


**Figure 1.** Hourly averages of magnetic field azimuth and elevation angles phi and theta across the same sector boundary at three locations on 11-16 October, 25-30 October, and 30 October - 4 November, 1974, respectively. OMNI data, in the top panel, are from multiple Earth-orbiting spacecraft at 1 AU, merged at the National Space Science Data Center. The angles are plotted in RTN coordinates, except for the OMNI data, where phi in GSE coordinates has been rotated about the z axis by 180° to approximate RTN coordinates [*Crooker and Intriligator*, 1995]. The vertical lines bracket a magnetic cloud fitting a single flux rope structure, and the shaded intervals extend to a double structure.

Since the magnetic polarity change that marked the sector boundary at 1 AU and Pioneer 11 was carried by the cloud rather than a current sheet, the cloud formed an occlusion in the helio-spheric current sheet (HCS), in the sense that it obstructed the current flow in sheet form. This configuration is consistent with rope formation in helmet streamers at the base of the coronal streamer belt [e.g., *Crooker et al.*, 1993]. Pioneer 10 also observed a polarity change within the cloud, but two additional

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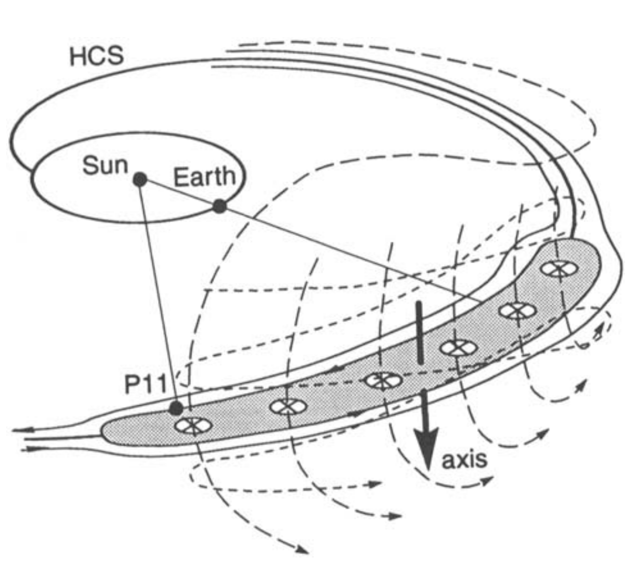


**Figure 2.** Schematic drawing of a magnetic cloud as a distended flux rope with a vertical axis forming an occlusion in the heliospheric current sheet (HCS). The solid lines lie in the ecliptic plane and the dashed lines rise out of it. The curved lines with long dashes indicate core fields on a highly 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 [*Crooker and Intriligator*, 1995].

changes followed (Figure 1). These presumably were brought by the second transient, suggesting how compound transients may create multiple polarity changes at sector boundaries.

## 3. Double flux rope structure

The vertical lines marking the cloud boundaries at 1 AU in the top panel of Figure 1 were based on the temperature profile [*Richardson and Cane*, 1995], and these boundaries were mapped to the theta profiles in the Pioneer data. Between the boundaries the magnetic field rotates ~ 180° through mostly negative theta, consistent with the topology of a single flux rope with its axis pointing in the negative theta direction, as drawn in Figure 2. The shaded regions extend beyond these boundaries and cover a ~ 360° rotation, beginning and ending with large, positive theta. This larger pattern is preserved remarkably well from one panel to the next. A similar pattern has been reported by *Fainberg et al.* [1995] in Ulysses data. These authors treated the region of additional rotation as a sheath surrounding a flux rope, since the bidirectional electron heat flux indicative of a closed structure was confined to the central 180° rotation region. On the other hand, in a study underway, a comparison of bidirectional heat flux intervals in ISEE 3 data listed by *Gosling et al.* [1987] and magnetic field rotation intervals listed as magnetic clouds by *Zhang and Burlaga* [1988] revealed that the former extend beyond the cloud boundaries to cover ~ 360° field rotation in at least 7 of 14 cases. This finding implies that the shaded regions in Figure 1 may cover a complete magnetic cloud structure consisting of nested or double flux ropes. Whether such structures can form on the sun or in interplanetary space, by CME-induced reconnection [*McComas et al.*, 1995], for example, is an open question. Recent documentation of the magnetic topology of the suspected solar source of magnetic clouds--helmet streamer arcade loops and their underlying filaments--show patterns of opposing fields consistent with nested- or double-rope development on the sun [*Martin and McAllister*, 1995].

## 4. Stream interface and energetic ions

*Intriligator and Siscoe* [1994] noted that stream interfaces at the Pioneer spacecraft usually occur at or slightly after sector boundary (HCS) passage and that the interfaces bound the corotating energetic ion population associated with the trailing reverse shock. Surprisingly, these presumably steady state features on open solar wind field lines appear within the cloud occlusion at Pioneer 11, which is assumed to be a transient feature on closed field lines (connected to the sun at both ends).

The top two panels in Figure 3 show Pioneer 11 data from successive crossings of the same sector boundary during solar rotations 1929 and 1931, respectively. The cloud occurred during rotation 1931, in the lower panel, while no obvious cloud signa-

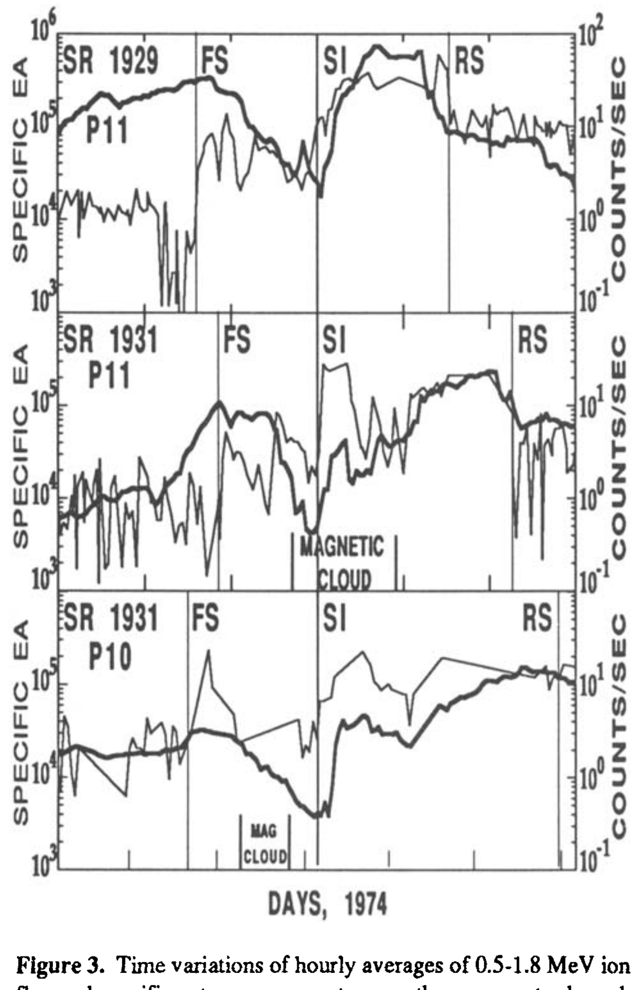


**Figure 3.** Time variations of hourly averages of 0.5-1.8 MeV ion flux and specific entropy argument across the same sector boundary at Pioneer 11 on two different solar rotations, one with (1931) and one without (1929) a magnetic cloud, and at Pioneer 10 on the rotation with a cloud (1931). The data are aligned by stream interface (SI) passage, which nearly coincides with sector boundary passage at this resolution. The SIs are embedded in interaction regions bounded by forward and reverse shocks (FS and RS). All cases show the same characteristic rise in particle flux after SI passage.

ture was apparent during rotation 1929, in the upper panel. The thin traces give the time variation of the specific entropy argument, which varies as $T/n^{1/2}$, where $T$ is temperature and $n$ is number density. The heavy traces give the variation of the 0.5-1.8 Mev ion flux. A rise in entropy marks a stream interface (SI) in each case. The energetic particle flux rose immediately after SI passage in both cases. The Pioneer 10 data in the bottom panel appear to follow the same pattern, within the constraints of the data gaps in the plasma parameters there, with one major difference: The SI occurs near the second (and final) polarity change, located within what we have interpreted as the second transient, rather than at the polarity change within the identified cloud.

In terms of our present understanding of these structures, there appear to be only two interpretations. Either interfaces can be formed within clouds and energetic ions can be created or transported there, or the magnetic field at Pioneer 11 does not form a closed flux rope structure. These interpretations depend upon whether or not the purported second transient observed at 1 AU was instead a stream interface, where a charactieristic density drop and temperature rise accompanied the speed rise. How the data support each possibility is discussed in *Crooker and Intriligator* [1995]. If the feature was an interface, it could then be the same interface observed at Pioneer 11. The density and speed profiles at the two locations are consistent with this interpretation. On the other hand, the magnetic signatures at the two locations would then have to be treated as unrelated, since presumably a stream interface cannot pass through a cloud. The field signatures at Pioneer 10 would also have to be treated as unrelated to those at the other two spacecraft. In view of the striking similarity of the field variations at all three locations, their relation to the same sector boundary, and the resolution of the complications at Pioneer 10 in terms of compression by a transient, we favor the transient rather than SI interpretation of the second feature at 1 AU.

This choice leaves a number of questions unanswered. Why are the entropy and energetic ion signatures within the cloud at Pioneer 11 the same as across sector boundaries without clouds? How can SIs form within clouds? How can energetic ions gain access to presumably closed cloud structures? Why did the SI and ions appear within the cloud at Pioneer 11 but trail the cloud at Pioneer 10? Answers to these questions may become apparent once the basic problem of why SIs serve as energetic ion boundaries is solved [cf. *Intriligator et al.*, 1995; *Intriligator and Siscoe*, 1995]. Perhaps SI formation is related to the evolution and compounding of distending transients, with lateral transport and reconnection playing some role. The ambiguity between SI and transient signatures, as evidenced by the difficulty in interpreting the second feature at 1 AU, supports this possibility. The ions may have been energized upstream by compression associated with the transients [cf. *Richardson*, 1985; *Richardson and Cane*, 1993], since they streamed antisunward at both Pioneer spacecraft for about a day following SI passage. Compression within the distended cloud could account for the ions observed in the cloud at Pioneer 11. Clearly further research is required to test these speculations.

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