Voyager 1 Observations of the Interstellar Magnetic Field and the Transition from the Heliosheath

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Abstract. Voyager 1 (V1) has been observing interstellar magnetic fields (ISMF) for more than one year, from 2012/209 to at least 2013.6. From 2013.0 to 2013.6 the difference between the azimuthal angle of the ISMF and the Parker spiral angle at the latitude 34.6° of V1 was (22 ± 3)° and the corresponding difference of the elevation angle was (0 ± 8)°. During 2012 the deviation from the Parker spiral angle was somewhat smaller. The interstellar magnetic field has a West to East polarity, opposite to the direction of planetary motions. The magnitude of the ISMF varied smoothly in the range 0.38 nT to 0.59 nT with an average strength 0.49 nT. The strongest interstellar fields were observed behind a shock at 2012/297 that was preceded by 2.2 KHz plasma oscillations, which implies an interstellar electron density n_e = 0.05/cm^3. The ISMF was observed after V1 crossed a current sheet CS0 having the structure of a tangential discontinuity. The inclination of this current sheet is consistent with an interstellar magnetic field draped on a blunt heliopause. Two other current sheets (sector boundaries) were observed earlier in the heliosheath at 2012/167 and 2011/276 with high inclinations (99 ±10)° and (89 ± 10)°, respectively. The transition from heliosheath to interstellar magnetic fields is related to a two-step increase in the cosmic ray intensity observed by V1 from 2012.30 to 2012.65. The first step-increase began near the end of an unusual away-polarity sector, and it reached a plateau when V1 moved in to a toward-polarity sector that ended at CS0. The second step-increase began slowly after V1 crossed CS0, and it ended abruptly at 2012/237.728.

Introduction

Voyager 1 (V1) encountered a boundary across which the flux of low-energy termination shock particles (TSPs) and anomalous cosmic rays (ACRs) accelerated in the heliosphere dropped to very low values compared to heliosheath values. The spacecraft crossed this “particle boundary” five times, first on 2012/210.6 and last on 2012/237.7 [1]. Initially, it was widely thought that the particle boundary might be the heliopause, which separates the heliosheath from the interstellar medium; although an alternative explanation had been suggested by McComas and Schwadron [2]. It is expected that the magnetic field direction should be different in the interstellar medium than in the heliosheath, since heliosheath magnetic fields are produced by the rotation of the sun, whereas interstellar magnetic fields have a very different origin. However, Burlaga et al. [3] found that the magnetic field direction did not change significantly across the particle boundaries. Since small differences in the B can be measured accurately (± 2°), it was concluded that the particle boundaries were not multiple crossings of the heliopause.

The purpose of this paper is a) to study the nature and structure of the heliosheath magnetic fields before and after the last polarity boundary CS0 observed by V1 during 2012/208-209, b) discuss the structure of this boundary, c) show how this boundary relates to the heliopause, and d), describe the nature and properties of B beyond CS0, including the observation of a shock or pressure wave. We use V1 magnetic field observations [4] to study B within CS0, prior to CS0 and after V1 crossed CS0.

2. Heliosheath and interstellar magnetic fields

Voyager 1 observations from 2012.5 to 2013.6 are shown in figure 1. Prior to crossing a current sheet CS0, V1 was observing heliosheath magnetic fields directed along the Parker spiral direction [5, 6] pointing toward the...
sun ($\lambda_p = 90^\circ$). In this paper, we use an RTN coordinate system whose origin is at the spacecraft. Immediately after crossing the current sheet, V1 observed magnetic fields significantly different from the Parker spiral field direction pointing away from the sun ($\lambda_p = 270^\circ$). The difference between $\lambda$ and $\lambda_p$ increased following the crossing of CS0, reaching a plateau after $\approx 2013.2$ when $<\lambda> - \lambda_p = 22^\circ \pm 3^\circ$ and $<\delta> - \delta_p = 23^\circ \pm 8^\circ$. The sustained difference between the observed magnetic field direction and the Parker spiral magnetic field direction and absence of sectors following the crossing of CS0 at $\approx 2012.5691$ ($\approx 2012/209.3$) $\approx$ July, 27, 2012 and continuing to 2013.6, as shown in figure 1, strongly suggests that V1 was observing interstellar magnetic fields throughout the interval. The direction of this interstellar magnetic field is close to the $\sim T$ direction, pointing from west to east when looking from Voyager to the sun.

The small difference between the interstellar magnetic field direction and the heliosheath magnetic field direction observed by V1 was initially surprising. However, a re-examination of the results of Pogorelov et al. [7], plotting angles instead of components of $\mathbf{B}$, showed that they actually predicted that the angle between the draped interstellar magnetic field in the heliosheath fields should be $\delta \approx 25^\circ$ and $\lambda \approx 290^\circ$ ($<\lambda> - \lambda_p) \approx 20^\circ$, consistent with the observations shown in figure 1, within the uncertainties of the observations. The simulations of Borovikov and Pogorelov [8] based on exact fitting of the HP do not support the idea of Opher and Drake [9] that the ISMF vector becomes nearly parallel to the solar equatorial plane regardless of its direction in the unperturbed LISM.

The magnitude of $\mathbf{B}$ shown in Figure 1a is stronger than the magnetic fields observed in the heliosheath prior to the crossing of CS0 by V1, except in the region labelled T in figure 1a. In this region, Burlaga et al., [3] showed that, there were 5 boundaries at which the strength of $\mathbf{B}$, changed abruptly in association with changes in the energetic particles and cosmic rays [1]. Some people suggested that V1 crossed the heliopause moving from the heliosheath to the LISM three times before it remained in the LISM after August 25. However, Burlaga et al. [3] showed that the magnetic field direction did not change significantly ($< 2^\circ$) across any of these boundaries, and argued that V1 was not crossing the heliopause at these times, because one does not expect the interstellar magnetic field (ISMF) to have the same direction as the heliosheath magnetic field.

The ISMF has been observed continually since V1 crossed CS0, and the five boundaries observed previously separated interstellar magnetic flux tubes that alternately contained heliosheath plasma and the plasma of the LISM as shown by Burlaga and Ness [10]. It is possible that some of the ISMF magnetic field
lines and region T reconnected to interstellar magnetic field lines beyond the location of V1, allowing heliosheath plasma and energetic particles to move to the position of V1. Magnetic reconnection has been suggested by Swisdak et al. [11] and Strumik et al. [12]. Alternatively, configurations analogous to flux transfer events in the earth’s heliosheath might be responsible for the structure and region T [13].

The magnetic field strength following region T, from 2012.5691 to at least 2013.6, is stronger than the magnetic fields observed in the heliosheath, varying from 0.38 nT to 0.59 nT, with an average \(<B> = 0.49 \text{ nT}\). The fluctuations of 48 s averages of B during each hour were extremely small, at the limit of measurement (0.005 nT). Thus, the extended observations of the magnetic fields following the passage of CS0 clearly indicate that V1 is in the new region, with properties expected from magnetic fields of interstellar origin.

Gurnett et al. [14] showed that Voyager 1 (V1) observed electron plasma oscillations from 2013/99 to 2013/142 at a frequency of 2.6 kHz, corresponding to a very high electron density of 0.8 cm\(^{-3}\), during the intervals indicated by the horizontal line to the right in figure 1a. They also noted an earlier electron plasma oscillations event at 2.2 kHz in October-November, 2012 shown by the horizontal line to the left in figure 1a. Since such densities are characteristic of interstellar plasma and are at least 50 times larger than expected for heliosheath plasma, Gurnett et al. concluded that V1 was immersed in the interstellar plasma. Gurnett et al. [14] suggested that the increase in density from 0.05 cm\(^{-3}\) to 0.08 cm\(^{-3}\), from the time of the first burst of electron plasma oscillations to the second, is an indication of a density ramp like that inferred by Gurnett et al. [15] from remote observations of radio waves by V1, which were assumed to be radio waves generated by a shock in interstellar plasma just beyond the heliopause.

Figure 1 shows that B varies little before and after each of these two electron plasma oscillation events, apart from a slowly monotonically increasing trend with time. Thus, it appears that V1 was immersed in interstellar magnetic fields from the time that it crossed CS0, on day 219, 2012 to at least 2013.6.

3. CS0 and heliopause

![Figure 2. Minimum variance analysis of CS0. (a) The normalized component B\(_i\) in the intermediate variance direction versus B\(_{max}\) in the maximum variance direction. (b) the normalized component B\(_{min}\) in the minimum variance direction versus time in days.](image)

In this section we consider the structure of B in the current sheet CS0 and its possible relationship to the heliopause. The direction of B rotated within CS0 during the interval from approximately day 207.2271 - 209.7087, 2012. We examine the structure of this rotation using the minimum variance method. A well-defined minimum variance direction was found in the direction \(\mathbf{n} = (-0.91, 0.05, 0.415)\) in the RTN coordinate system whose origin is at V1. The elevation angle \(\delta = 23.9^\circ\) and the azimuthal angle \(\lambda = 177.1^\circ\). The normalized components of B in the intermediate variance direction versus the components of B in the maximum variance direction, respectively, are plotted in figure 2(a), where one sees that B rotates through a large angle in the plane...
normal to \( \mathbf{n} \). A geometrical construction shows that this minimum variance plane is inclined by an angle \( \theta = 100.6^\circ \) with respect to the solar equatorial plane. The magnitude of the component of \( \mathbf{B} \) in the minimum variance direction \( B_{\text{min}} \) is shown in figure 2(b) as a function of time in doy. If CS0 were the current sheet associated with a tangential discontinuity, the average of \( B_{\text{min}} \) would be 0. The observed value of \( \langle B_{\text{min}} \rangle = 0.095 \text{ nT} \) with a standard deviation of 0.057 nT. Thus, the observations of CS0 are consistent with the tangential discontinuity, but one cannot exclude very small nonzero component.

![Diagram of the heliosphere]

**Figure 3.** Schematic of the heliopause interacting with interstellar plasma flow. The tangent to the heliopause at the position of V1 is qualitatively consistent with the orientation of CS0.

Figure 3 shows a schematic of the heliosphere. The solar wind velocity is directed radially away from the sun and moves toward the termination shock, where it is diverted tailward and moves through the heliosheath.

4. Interstellar shock or pressure wave

Figure 4 shows that a large smooth jump in \( B \) on 2012/333 followed the interval containing electron plasma oscillations from 2012 day 297 to 2012 day 332, which was analysed by Burlaga et al. [16]. This jump resembles a shock with \( B_2/B_1 = 1.4 \). The jump in \( B \) was associated with a small but significant change in \( \lambda \). From the change in the magnetic field direction one can calculate that the normal to the surface corresponding to the jump in \( B \) is directed 27° above the radial direction in the meridional plane. Knowing direction of \( B \) prior to the jump, we calculate that the angle between the ambient magnetic field and the shock normal is 85°, indicating a quasi-perpendicular shock. Knowing the density of the upstream medium from the plasma wave oscillations, one can calculate the density behind the shock, since the shock is quasi-perpendicular with \( N_2/N_1 = B_2/B_1 = 1.4 \). Assuming an interstellar temperature of 20,000° K just beyond the heliopause as suggested by Zank et al. [17] the upstream Alfvén speed is \( V_{A1} = 38 \text{ km/s} \) and the sound speed is \( V_{S1} = 17 \text{ km/s} \), which gives a magnetoacoustic speed of 40 km/s. Thus, the shock was moving at greater than 40 km/s, consistent with the shock speed beyond the heliopause calculated by Washimi et al. [18]. The ratio \( (V_{AS}/V_s)^2 = 5 \).
By analogy with shocks observed at 1 AU (where pickup protons, and neutral particles do not affect the dynamics) this shock in interstellar plasma appears to be a sub-critical, laminar, quasi-perpendicular, shock. However, the shock seems to be much thicker than those observed at 1 AU. Further theoretical studies are needed to understand the nature of such shocks or pressure waves in the interstellar plasma and magnetic field.

5. Transition from the heliosheath to the LISM

We have presented evidence for a distinct boundary CS0 after which interstellar magnetic fields were observed, which has the orientation expected for the heliopause. However, observations of the heliosheath plasma on interstellar magnetic field lines in region T in figure 1 indicate that the transition from the heliosheath to the interstellar plasma is not simply an isolated tangential discontinuity. Figure 5 above, from Burlaga & Ness [10], shows that the transition occurs over a broader region, beginning prior to the crossing of SB1 by V1. This transition is most evident in the 2-step increase in the counting rate of cosmic rays >70 MeV/nuc [19] shown in figure 5 (d). The first step, beginning on ≈2012.30 within an away sector in which B points toward the sun.
along the Parker field direction, and it ends at the boundary of that sector, SB-1. This step-increase is followed by a brief plateau in the cosmic ray counting rate when V1 observed a short sector in which B points toward the sun. The second step-increase in the cosmic ray counting rate begins at the time V1 crosses CS0 and it ends when V1 crosses region T and remains in the interstellar magnetic field until 2013.6.

The two-step profile of the cosmic ray counting rate has not yet been explained. Although it has been proposed that magnetic bubbles may exist in the region observed prior to the crossing of CS0 [11, 12], there is no clear evidence for a series of nested magnetic bubbles. However, Burlaga and Ness [10] show that the sector boundaries, SB-2 and SB-1 are nearly parallel to CS0, and the away polarity sector within these boundaries has an unusual jump in \( \delta \) extending from near 0° to nearly 90°, declining to 0° prior to the onset of the first step-increase in the cosmic ray counting rate. The magnetic field strength varies within the sector between SB-1 and SB-2, and there are large dips in B at the sector boundaries, as well as at the jump in \( \delta \) between the boundaries. Such decreases in B are often observed at sector boundaries, but they are occasionally observed at structures called D-sheets by Burlaga and Ness [20] which could be associated with magnetic reconnection. The structure of the region observed prior to and following the passage of CS0 shown in figure 5 is not understood.

There are many theories of various types of instabilities that might occur on the heliopause [21]. A large-scale instability [8, 22] driven by a charge exchange instability [23, 24, 25] can explain why V1 observed interstellar plasma, even though theories predict that the heliopause of a stationary heliosphere should be well beyond the position of V1.

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