



The Orientation of the Local Interstellar Magnetic Field

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of progressively more complex hydrocarbon molecules, from benzene to PAHs and ultimately to aerosol particles with ~260-nm radii. The existence of ~40,000-amu aerosols, formed by the growth of complex organic compounds in the upper atmosphere, appears to answer the long-unresolved question of the origin of tholin precursors found at Titan. The chain of molecular growth that we have identified in this study is similar to that first identified in the Miller-Urey experiments (3). We suspect that the ultimate destination of these large organic molecules and aerosols lies in the organic haze layers in Titan's stratosphere (3, 4). However, depending on the dynamic effects of atmospheric and induced corotational electric fields on these particles, they might also escape Titan's atmosphere to become the source of PAHs observed to collect on the surfaces of Saturn's icy moons (34, 35).

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The Orientation of the Local Interstellar Magnetic Field

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The orientation of the local interstellar magnetic field introduces asymmetries in the heliosphere that affect the location of heliospheric radio emissions and the streaming direction of ions from the termination shock of the solar wind. We combined observations of radio emissions and energetic particle streaming with extensive three-dimensional magnetohydrodynamic computer simulations of magnetic field draping over the heliopause to show that the plane of the local interstellar field is ~60° to 90° from the galactic plane. This finding suggests that the field orientation in the Local Interstellar Cloud differs from that of a larger-scale interstellar magnetic field thought to parallel the galactic plane.

The heliosphere created by the supersonic solar wind is compressed by the motion of the Sun relative to the local interstellar medium, producing a comet-like shape with an extended tail. The solar wind abruptly slows, forming a termination shock as it approaches contact with the interstellar medium at the heliopause. Beyond the heliopause, the interstellar wind contains mainly hydrogen and helium, both as neutral

atoms and as ions that carry the frozen-in interstellar magnetic field.

Recent Voyager observations of ions streaming from the termination shock (1, 2) have led to the suggestion that north-south and east-west asymmetries of the heliosphere are induced by the interstellar magnetic field (3). However, the inferred field direction from the model of (3) was parallel to the hydrogen deflection plane (HDP)

rather than the galactic plane (GAL). On the basis of the polarization of light from nearby stars, Frisch (4, 5) suggested that the galactic magnetic field is parallel to the GAL. However, the direction of the galactic magnetic field is deduced from measurements averaged over a much larger distance (light-years). A direction parallel to the HDP was suggested by Lallement *et al.* (6) for the local interstellar field, on the basis of solar Lyman- α radiation that is resonantly backscattered by interstellar hydrogen atoms. The HDP is tilted from the ecliptic plane by 60° and differs from the GAL by 60°. We used Voyager 1 and 2 observations in conjunction with a magnetohydrodynamic model to discriminate between these two planes and to constrain the orientation of the local interstellar magnetic field.

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In the past 20 years, Voyager 1 (V1) and 2 (V2) have been detecting radio emissions in the outer heliosphere at frequencies from 2 to 3 kHz (7–9). The radio emissions were detected each solar cycle: first in 1983–1984 during solar cycle 21 (7), second in 1992–1994 during solar cycle 22 (8), and most recently during solar cycle 23 (9). The currently accepted scenario is that the radio emissions are generated when a strong interplanetary shock produced by a period of intense solar activity reaches the vicinity of the heliopause and moves into the interstellar plasma beyond (9, 10). Radio direction-finding measurements from V1 and V2 have been used to determine the positions near the heliopause at which the radio emissions are generated (11) (Fig. 1). The sources lie along a line that passes near the nose of the heliosphere that roughly parallels the GAL. The GAL is 120° from the ecliptic plane (12). Because the galactic magnetic field is oriented nearly parallel to the GAL, Kurth and Gurnett (11) suggested that the local inter-

stellar magnetic field (in the local neighborhood of the Sun) was also parallel to the GAL.

However, Gurnett *et al.* (13) recently pointed out that at Earth’s bow shock and interplanetary shocks, the radio emission occurs where the magnetic field lines are tangential to the shock surface, and they suggested that heliospheric radio emissions occur where the local interstellar magnetic field is tangential to the surface of the shock that excites the plasma (or $\mathbf{B} \cdot \mathbf{n} = 0$, where \mathbf{B} is the magnetic field and \mathbf{n} is the shock normal). They concluded that the condition $\mathbf{B} \cdot \mathbf{n} = 0$, combined with the source location observed by the two Voyager spacecraft, implies that the local interstellar magnetic field is perpendicular to the GAL. This direction differs from the earlier suggestion (9) and is within 16° of the HDP.

The interstellar magnetic field is frozen into interstellar plasma that is deflected around the heliopause, causing the field to drape over the heliopause. As a result, the region where $\mathbf{B} \cdot \mathbf{n} = 0$ will depend on the shape of the heliopause,

which is distorted by pressure of the local interstellar magnetic field. For intensities around a few microgauss, the ambient interstellar magnetic pressure is comparable to the gas pressure, with the magnetic pressure increasing in those regions where the interstellar flow decreases as it approaches the heliopause. We investigated how the proposed location of the radio sources (where $\mathbf{B} \cdot \mathbf{n} = 0$ on the surface of the heliopause) varies with the orientation and strength of the local interstellar magnetic field.

We considered several directions of the interstellar magnetic field—the HDP, the GAL, and the plane perpendicular to the radio source plane (13) (PPG)—with different inclination angles α (the angle between the interstellar magnetic field and interstellar wind velocity). In the model coordinate system, where β is the angle between the interstellar magnetic field and the solar equator, the HDP corresponds to $\beta = 60^\circ$, the GAL to $\beta = 120^\circ$, and the PPG to $\beta = 44^\circ$ (12). Assuming a spherical interplanetary shock,

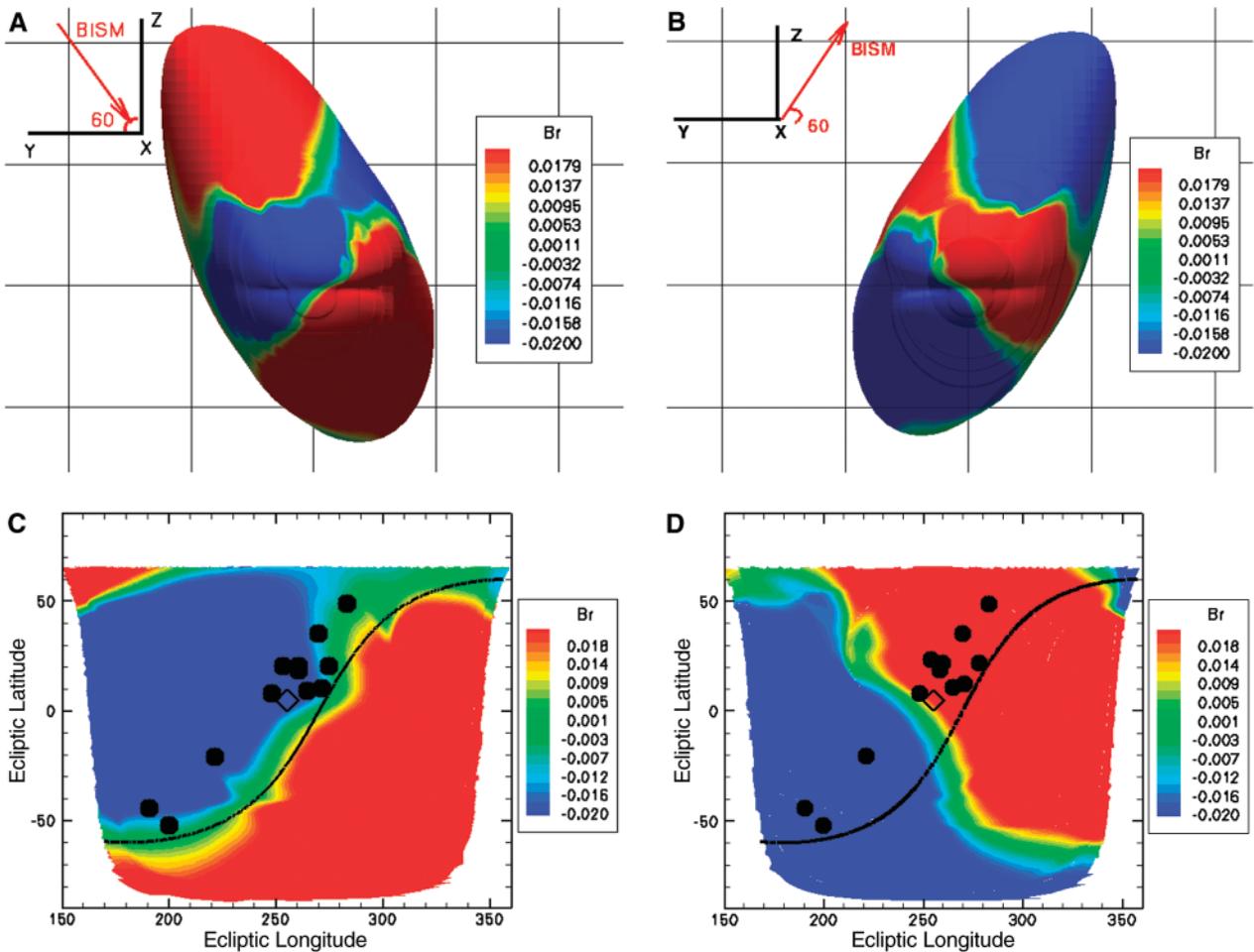


Fig. 1. (A and B) Radio source location as a function of the interstellar magnetic field (B_{ISM}) direction in (A) the HDP plane and (B) the GAL plane (with $\alpha = 45^\circ$). The surface of the heliopause is shown from upwind with respect to the interstellar wind. The isocontours show the strength of the radial component of the interstellar magnetic field, B_r , on the heliopause. The green band is the location of the radio sources (at $B_r = 0$). The red arrows show the direction of B_{ISM} . (C and D) Same as (A) and (B)

but converted to ecliptic coordinates for B_{ISM} in (C) the PPG (with $\alpha = 30^\circ$) and (D) the GAL (with $\alpha = 45^\circ$). The direction of the nose of the heliosphere (diamond) and the GAL (black line) are indicated for reference. The radio sources detected by V1 and V2 are shown as solid circles. Note that the colors are inverted from (C) to (D) because the interstellar magnetic direction was inverted from (A) to (B) (see red vectors in the insets).

the tangential field condition for the radio sources translates to $B_r = 0$, where B_r is the radial component of the interstellar magnetic field. For each modeled direction of the interstellar magnetic field, we compared the expected location of the radio sources ($B_r = 0$ at the heliopause) with the observed location of the radio sources detected by V1 and V2.

The model used here is the same as used by (3) [see (12)]. The interstellar magnetic field (B_{ISM}) magnitude is taken to be $B_{\text{ISM}} = 1.8 \mu\text{G}$ [with the y component of B_{ISM} ($B_{\text{ISM},y}$) < 0]. The coordinate system has the interstellar velocity direction in the $+x$ direction and the z axis as the solar rotation axis of the Sun, with y completing the right-handed coordinate system. In this

coordinate system, V1 is at 29.1° latitude and 213.4° longitude and V2 is at -31.2° latitude and 178.4° longitude, which ignores the 7.25° tilt of the solar equator with respect to the ecliptic plane.

Figure 1 indicates that the heliopause is strongly influenced by the interstellar magnetic field direction; the heliopause is asymmetric both north-south and east-west and has a plane of symmetry approximately parallel to the plane of the local interstellar magnetic field. As a result, the heliopause surfaces for HDP and GAL field orientations are almost mirror images of each other.

With B_{ISM} parallel to the GAL (with $\alpha = 45^\circ$, Fig. 1D), the region where $B_r = 0$ is almost perpendicular to the GAL, which is inconsistent with the radio observations. With B_{ISM} in the PPG with $\alpha = 30^\circ$ (Fig. 1C) produces the best agreement with the Voyager radio observations, as suggested by Gumett *et al.* (13). The HDP orientation differs from that of PPG by only 16° and is also in general agreement, as suggested by the similarity of the regions with $B_r = 0$ in Fig. 1A (HDP) and Fig. 1C (PPG). The offset of $\sim 15^\circ$ between the observations and the region with $B_r = 0$ for the model in best agreement (Fig. 1C) indicates that the accuracy of the model is not adequate to distinguish between the PPG and HDP field orientations.

We also investigated the effects of changing the interstellar wind direction to 5° above the ecliptic plane [in the solar ecliptic coordinate system, the interstellar wind direction is 255° (longitude) and 5° (latitude)] and changing the intensity of B_{ISM} from $1.8 \mu\text{G}$ to $2.5 \mu\text{G}$. For both cases, the change in the predicted location of radio sources was minor (12). As α increases from 15° to 60° , the $B_r = 0$ band moves counterclockwise, with the best agreement for $\alpha = 30^\circ$ to 45° (12).

The second set of observational data that we used to constrain the orientation of the local interstellar magnetic field was the streaming ions from the termination shock. V1 crossed the termination shock at 94 AU in December 2004 and is now beyond 100 AU in the heliosheath (1, 2, 14). V2 is already detecting signs of the upcoming termination shock (2, 15) and is expected to cross the termination shock within the next 1 to 2 years. In mid-2002, V1 began observing enhanced intensities of ions streaming from the shock (16, 17). The beams of energetic termination shock particles (TSPs) were streaming outward along the solar spiral magnetic field. The strong upstream TSP beams were observed much of the time until V1 crossed the shock at 94 AU. The streaming along the magnetic field upstream of the shock source was expected to be inward along the spiral field if the termination shock were spherical. However, the observed flow was outward along the field, requiring a shock source located inward along the spiral field several AU closer to the Sun than is V1. With a nonspherical shock, V1 could be connected to the termination shock along magnetic field lines that crossed the termination shock and crossed back to the supersonic solar wind. This led to the suggestion that the upstream

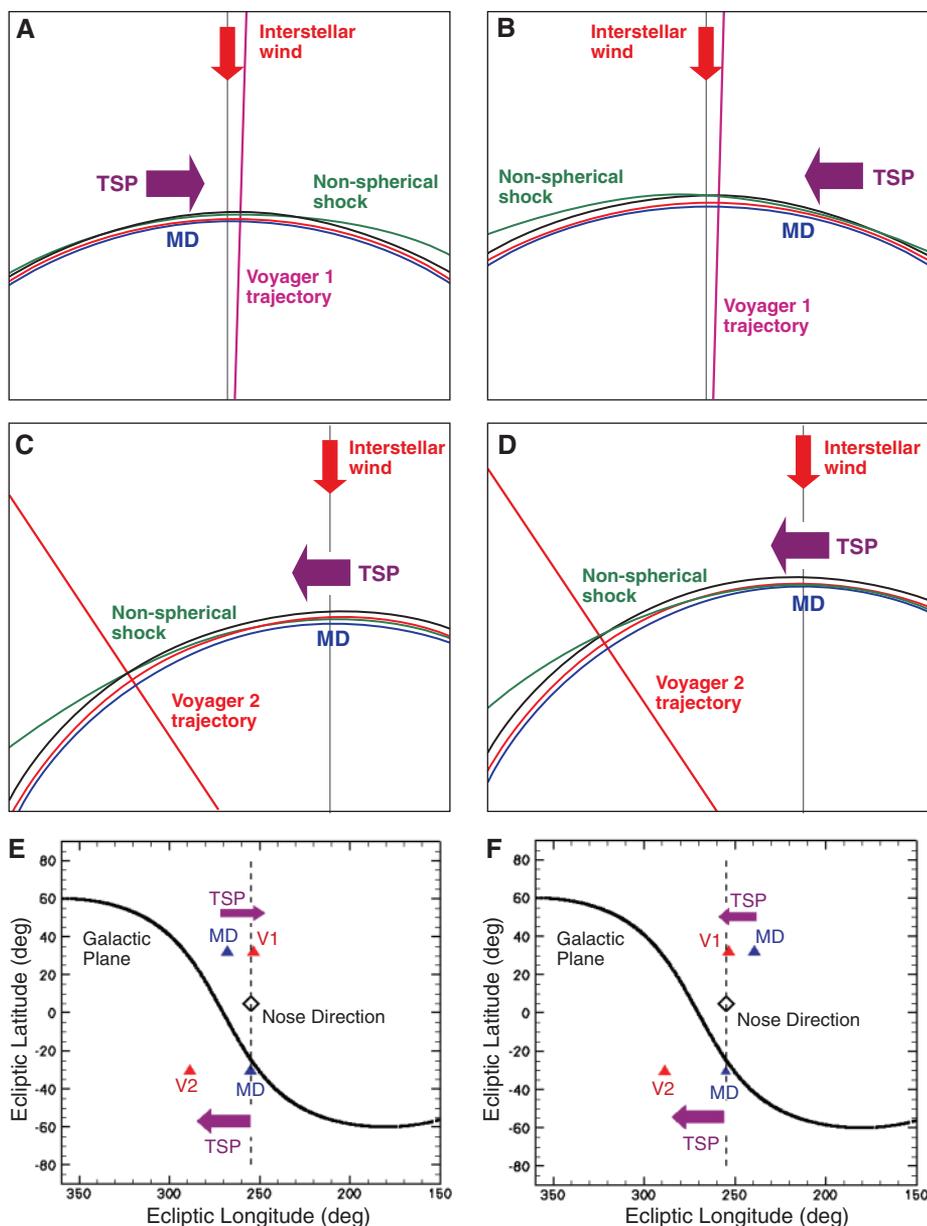


Fig. 2. (A and B) Streaming of TSPs from the MD point to V1 for the interstellar magnetic field in (A) the HDP (with $\alpha = 45^\circ$) and (B) the GAL (with $\alpha = 45^\circ$). The interplanetary magnetic field is carried radially outward by the solar wind, forming a spiral on a conical surface. The conical surfaces coinciding with the V1 trajectory are shown. V1 is first connected to the shock along the spiral magnetic field lines that contact the shock at the MD point. The solar magnetic field lines that intersect V1 are colored as follows: black, the 0 AU field line intersecting the shock where V1 crosses the shock; red and blue, magnetic field lines 2.0 AU and 3.0 AU upwind, respectively, from the 0 AU line; green, the nonspherical termination shock. The magenta arrow indicates the streaming direction of the TSPs from the shock along the field line to V1. (C and D) Similar plots for V2, showing field lines 3.0 AU (red) and 5.0 AU (blue) upwind of the 0 AU line. Note that in both views the solar magnetic field spirals clockwise with increasing distance outward. (E and F) Summary of the streaming of TSPs from the MD point back to V1 and V2. The nose direction (diamond) and the GAL are indicated.

