The local interstellar magnetic field direction from direction-finding measurements of heliospheric 2-3 kHz radio emissions

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Abstract. Direction-finding measurements of heliospheric 2-3 kHz radio emissions with the Voyager 1 and 2 spacecraft have shown that the source of the emissions is distributed along a line in the sky that passes near the nose of the heliosphere. It is now accepted that the radio emissions are generated near the heliopause by the interaction of an outward propagating interplanetary shock that originates from the sun during periods of intense solar activity. In this paper we suggest that the source is localized to regions where the interstellar magnetic field is nearly perpendicular to the shock normal, i.e., $\mathbf{B}\cdot\mathbf{n} = 0$. For a spherical shock and the expected draping of the interstellar magnetic field over the heliopause this condition allows us to determine the projected direction of the local interstellar magnetic field as viewed from the sun looking toward the nose of the heliosphere. In this view the magnetic field (or its negative) is aligned at an angle of $44^\circ \pm 5^\circ$ from the north ecliptic pole as measured clockwise looking toward the nose. By comparing the direction-finding measurements with computer simulations of the magnetic field draping it may also be possible to obtain information on the inclination angle of the magnetic field relative to the sun-nose line.

INTRODUCTION

For over twenty years the plasma wave instruments on the Voyager 1 and 2 spacecraft have been detecting radio emissions from the outer heliosphere at frequencies from about 2 to 3 kHz [1–3]. It is now known that these radio emissions are generated when a strong interplanetary shock originating from the sun interacts with the heliopause [2, 4]. Recently, radio direction-finding measurements from Voyagers 1 and 2 have been used to determine the positions near the heliopause at which the radio emissions are generated [5]. A plot showing the ecliptic longitude and latitude of all of the radio emissions for which direction-finding measurements have been made is shown in Figure 1. As can be seen the sources lie along a line in the sky that passes near the nose of the heliosphere at an angle that is roughly parallel to the galactic plane. Based on the fact that the galactic magnetic field is oriented nearly parallel to the galactic plane, Kurth and Gurnett [5] initially suggested that the local interstellar magnetic field lies near the galactic plane. However, no physical basis was given to support this conclusion and, as they point out, there was no certainty that the magnetic field immediately upstream of the heliosphere would bare any simple relationship to the large-scale galactic magnetic field. In this paper we present a physical principle that allows us to relate the Voyager direction-finding measurements to the direction of the local interstellar magnetic field. The principle is that the magnetic field in the source region must be nearly perpendicular

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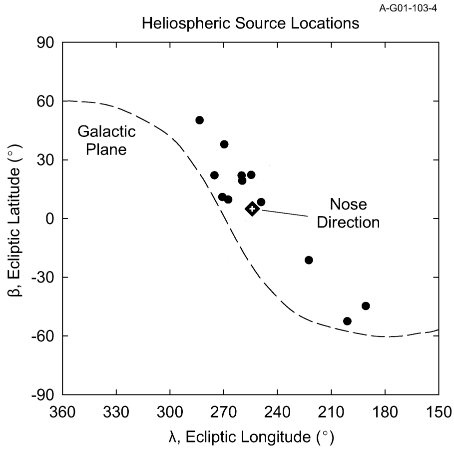

FIGURE 1. The source locations of heliospheric 2-3 kHz radio emissions obtained from direction-finding measurements by Kurth and Gurnett [5]. Note that the radio emissions tend to occur along a line that passes near the nose of the heliosphere. The nose is located at an ecliptic latitude and longitude of $\beta = 5°$ and $\lambda = 254°$ [6].

to the shock normal (**B**·**n** = 0). As we will show, the **B**·**n** = 0 condition has the implication that the local interstellar magnetic field projected onto a plane perpendicular to the line from the sun to the nose is at an angle of about 90° to the galactic plane, i.e., perpendicular to the direction initially suggested by Kurth and Gurnett [5].

PHYSICAL BASIS FOR THE B·n = 0 CONDITION

It has been known for many years that interplanetary shocks generate radio emissions at the electron plasma frequency, f_p = 8980 $\sqrt{N_e}$ Hz, where N_e is the electron density in cm^{-3}, and its harmonic $2f_p$. These radio emissions are called type II solar radio bursts [7]. The widely accepted source of these radio emissions is a beam of electrons accelerated by the shock that escapes into the upstream region along the interplanetary magnetic field lines. The generation of radio emissions by this beam is a two-step process. The electron beam first excites electron plasma oscillations, also called Langmuir waves, via a process known as a beam-plasma instability [8]. Nonlinear effects then cause the plasma oscillations to decay into electromagnetic radiation at f_p and $2f_p$. This process is illustrated in Figure 2. An important factor that controls the energy of the electron beam, and thereby the intensity of the radiation, is the angle, θ, between the shock normal, **n**, and the magnetic field, **B**. Studies of the solar wind interaction with the Earth's bow shock [9] show that time-of-flight considerations cause the beam energy to increase rapidly as the angle θ approaches 90°. Large beam velocities, well above the electron thermal speed, are required for the beam-plasma instability to occur. This condition, namely that **B**·**n** = 0, is called the tangent field condition. Since the relative orientations of the upstream magnetic field and the shock normal typically vary with

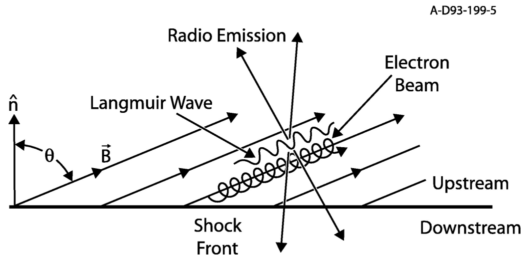

FIGURE 2. The mechanism by which radio emissions are generated upstream of an interplanetary shock. Due to time-of-flight considerations electrons accelerated at the shock escape as a beam along magnetic field lines upstream of the shock. These electrons excite electron plasma oscillations via a beam-plasma instability. Nonlinear interactions then cause the electron plasma oscillations to decay into electromagnetic radiation at f_p and $2f_p$. The energy of the electron beam and the intensity of the radio emission is strongly dependent on the angle θ between the magnetic field and the shock normal, and is the largest near $\theta = 90°$, i.e., when **B**·**n** = 0.

spatial position there is usually only a very restricted region along the shock front where the magnetic field is tangent to the plane of the shock. Electron beam acceleration in this region then leads to the generation of radio emission at f_p and $2f_p$. Radio emissions of this type are commonly observed at the Earth's bow shock. There is also evidence that Type II solar radio bursts originate from small localized regions where the interplanetary magnetic field is perpendicular to the shock normal [10]. Thus, a good case can be made that radio emissions produced by electron beams accelerated by interplanetary shocks originate from regions where the magnetic field is nearly perpendicular to the shock normal, i.e., when **B**·**n** = 0.

It is now believed that the heliospheric 2-3 kHz radio emission is generated by the same two-step beam-plasma mechanism as interplanetary shocks. For an overview of the various radio emission mechanisms that have been considered, see Cairns and Gurnett [11]. One question that sometimes arises is why the radio emission intensifies when the interplanetary shock reaches the heliopause, since radio emissions are not normally detected by Voyagers 1 and 2 as an interplanetary shock propagates past the spacecraft. That some important change might occur in the emission process at the heliopause is not in itself surprising, since very large changes in the plasma temperature and density occur at this boundary. However, the detailed mechanism involved has been elusive. A promising explanation has recently been offered by Cairns and Zank [12], who attribute the intensification to the presence of electrostatic lower-hybrid waves driven by charge exchange with neutral hydrogen in the dense plasma near the heliopause. The presence of these waves heats the interstellar electrons, thereby greatly increasing the beam intensity by providing "seed" particles for the shock acceleration mechanism.

Due to the flow of the interstellar plasma around the heliosphere, the magnetic field geometry in the region immediately beyond the heliopause is controlled by the draping of the interstellar magnetic field over the heliopause. As we will show, if the interstellar magnetic field is reasonably uniform and if the interplanetary shock is approximately spherical, then the **B**·**n** = 0 condition leads to a well-defined band across the sky where the radio emission should be observed, in agreement with the observations. The potential

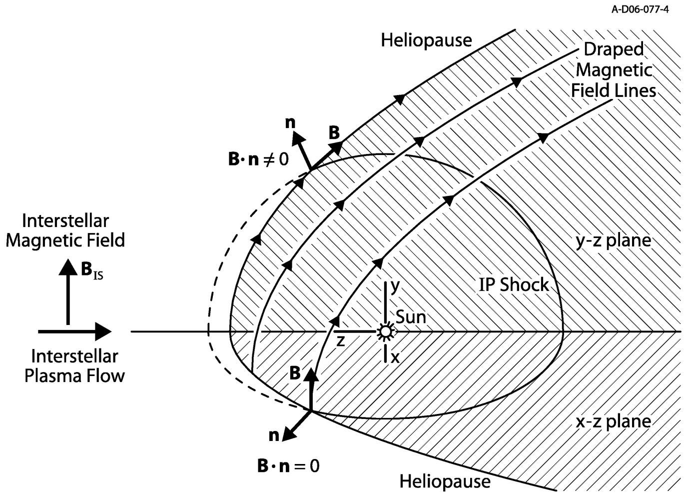

FIGURE 3. A simple model showing the interaction of an interplanetary (IP) shock with the heliopause. The interstellar plasma flow causes the interstellar magnetic field to be draped over the heliopause as shown. Radio emissions generated near the heliopause by the shock are expected to be primarily generated in the region where **B**·**n** = 0, which is located in the x-z plane and is perpendicular to the direction of the upstream interstellar magnetic field.

importance of such a magnetic constraint is made more apparent if one consider what would happen if there were no such constraint. If there were no such constraint, radio emissions would be generated along an annular ring in the sky where the shock front is in contact with the heliopause, the size of which becomes very large as the shock continues to propagate outward from the sun. When averaged over many events one would then expect a large disk-shaped source region extending to large angles from the nose of the heliosphere. That a well-defined linear band of radio emission is observed instead provides strong evidence that some other process plays a crucial role in controlling the geometry of the radio emission source [5]. We propose that the process involves the interstellar magnetic field via the **B**·**n** = 0 condition. No attempt is made in this paper to explain the fine structure of the radio emission spectrum, such as the rising tones that are frequently observed. These features are most likely due to the finite thickness of the heliopause and to yet unresolved structures within or beyond the heliopause boundary.

IMPLICATIONS FOR THE DIRECTION OF THE INTERSTELLAR MAGNETIC FIELD

To investigate the implications of the **B**·**n** = 0 condition for the direction of the interstellar magnetic field consider the simple model shown in Figure 3. In this model a spherical interplanetary shock is shown interacting with the heliopause, which is taken to be a paraboloid of revolution around the direction of the interstellar plasma flow, i.e., the z axis. The magnetic field in the interstellar medium far upstream is assumed to be upward,

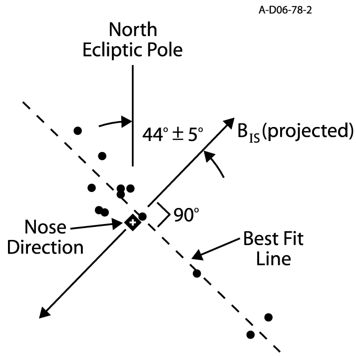

FIGURE 4. The data in Figure 1 re-plotted looking from the sun toward the nose of the heliosphere with the projection of the north ecliptic pole vertical. The dashed line is the best-fit straight line through the measured source locations, and the solid line marked $\mathbf{B}_{IS}$, is the inferred direction of the projection of the local interstellar magnetic field.

in the y direction. Since the heliopause boundary is an impenetrable boundary, the frozen field condition [13] dictates that the magnetic field must be draped over the heliopause in such a way that it is everywhere tangent to the boundary. From simple symmetry conditions one can see that in the y-z plane the magnetic field lines lie in the y-z plane, whereas in the x-z plane the magnetic field lines are perpendicular to the x-z plane. The $\mathbf{B}\cdot\mathbf{n} = 0$ condition is then satisfied at all points in the x-z plane. No other location on the heliopause boundary satisfies this condition. One would then predict that as the shock propagates outward from the sun a continuous band of radio emissions would be observed along a line in the x-z plane.

Comparing the above model to Figure 1, one is immediately drawn to the conclusion that as viewed from the sun the line through the measured source positions is perpendicular to the interstellar magnetic field direction. To take into account the required viewing geometry, in Figure 4 we have re-plotted the direction-finding measurements looking from the sun toward the nose of the heliosphere with the projection of the north ecliptic pole oriented upward. The dashed line shows the best fit straight line through the source directions. To obtain the projected direction of the interstellar magnetic field (or its negative) a solid line is then drawn through the nose perpendicular to the dashed line. This line, marked $\mathbf{B}_{IS}$, is at an angle of $44^\circ \pm 5^\circ$ measured positive clockwise from the north ecliptic pole looking toward the nose of the heliosphere. The only other measurement of the direction of the local interstellar magnetic field that can be compared with this result is from Lallement et al. [14], and is based on the deflection of interstellar hydrogen and helium in the vicinity of the heliopause. They infer that the direction of the magnetic field (or its negative) is at $\beta = -45^\circ \pm 15^\circ$ and $\lambda = 45^\circ \pm 15^\circ$ in ecliptic coordinates. The projection of this direction onto Figure 4 is at an angle of $28^\circ \pm 15^\circ$ measured positive clockwise from the north ecliptic pole. Therefore, the two determinations are very similar, differing by only about 16°, which is well within the quoted error limits.

The above interpretation is for a local interstellar magnetic field that is aligned along the y axis, i.e., at an inclination angle of 90° to the sun-nose line (see Figure 3).

At the present stage of analysis we can say nothing quantitative about the effect of possible deviations of this angle from 90°. Such an analysis requires a full solution of the magnetic field line draping problem for an arbitrary inclination angle. However, we do note that the best fit line in Figure 4 is offset upward and to the right from the nose by about 5°. Analytic analyses and preliminary computer simulations that we have performed suggest that this offset is probably caused by a deviation of the inclination angle from 90°.

CONCLUSION

A new interpretation has been presented of the direction-finding measurements of Kurth and Gurnett [5] based on the assumption that the radio emissions are generated near the heliopause in regions where the interstellar magnetic field is perpendicular to the shock normal. This condition provides a very natural explanation for the fact that the direction-finding measurements of heliospheric 2-3 kHz radio emissions are organized in a straight line across the sky that passes very close to the nose of the heliosphere. The model presented is very simple and is intended to illustrate the basic principle involved. We plan to do further computer modeling to take into account various complexities, such as variations in the inclination angle of the interstellar magnetic field, non-spherical shock geometries, and non-axial distortions in the shape of the heliosphere.

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