Two sides of the heliopause

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Interaction of the solar wind with the interstellar medium leads to the formation of the heliosphere and termination shock. This article addresses three aspects of the plasma and magnetic field on two sides of the heliopause: (1) The interstellar magnetic field surrounding the heliopause. In the limit of very low plasma $\beta$-ratio an analytical solution is obtained for the 3D interstellar magnetic field by means of a line dipole method. The undisturbed magnetic field in the upstream is allowed to have an arbitrary inclination angle. The solution describes the heliosphere as having a blunt-nosed geometry on the upwind side and approaching a cylindrical geometry on the downwind side. The distortion of the magnetic field can penetrate very deep into the interstellar space. (2) Interaction of the interstellar neutral hydrogen with the global solar wind. The ionization process leads to removal of interstellar neutral hydrogen in the heliosphere: on the upwind side, 90% of hydrogen depletion occurs inside 60 AU, the hydrogen density changes rapidly inside 10 AU. A hydrogen cavity forms inside ~4 AU; the cavity extends on the downwind side to form a long cavity wake. Outside the cavity and cavity wake, pickup protons are produced, they cause deceleration and heating of the solar wind. The wind speed and temperature also increase steadily with heliolatitude caused by the latitudinal increase in wind speed at the inner boundary. (3) The global geometry of the termination shock. The termination shock has been treated as having a closed geometry in previous heliosphere models. This study presents a new perspective that the global termination shock may have a bow-shaped open geometry. The termination shock forms on the upwind side because the forward motion of the supersonic solar wind is blocked at the blunt-nosed heliopause. However, the heliopause likely to be open on the downwind side; the motion of the supersonic solar wind is unobstructed for shock formation. Thus, the global termination shock likely has an open geometry. On the upwind side the shock flares out and weakens from the nose to its flanks. Eventually, the shock asymptotically reduces to a Mach wave. The supersonic solar wind remains shock free in the heliotail.

solar wind, interstellar medium, magnetic fields, plasmas, magnetohydrodynamics (MHD)


The interaction of the solar wind with the interstellar medium leads to the formation of the heliosphere and termination shock. The heliopause is the outer boundary of the heliosphere. While the plasma and magnetic field of solar origin are confined inside the heliosphere, the interstellar magnetic field and plasma flow are confined and substantially distorted on the upwind side of the heliopause. The magnetic field lines and the plasma flow are tangential to the heliopause on both sides at the boundary. This article covers three topics related to plasma and magnetic field on two sides of the heliopause.

The first topic is a study on the distortion of the magnetic field surrounding the heliopause in the limit of very low plasma $\beta$-ratio. The strength and direction of the undisturbed interstellar magnetic field at great distances upstream of the heliopause are poorly known. If the interstellar magnetic field is weak, then the flow speed of the interstellar medium can be greater than the magnetosonic speed. In this case, a bow shock could form on the interstellar side of the heliopause and the distortion of the interstellar magnetic
field would be confined in a relatively narrow region between the bow shock and the heliopause. However, if the interstellar magnetic field is strong, then the flow speed of the interstellar medium can be less than the magnetosonic speed and no bow shock should form upstream of the heliopause. In this case, the plasma $\beta$-ratio is small and the distortion of the interstellar medium penetrates deep into the interstellar space. We obtain analytical solutions to represent the magnetic field vector on the interstellar side of the heliopause in the limit of very low plasma $\beta$-ratio. The solution describes the heliosphere as having a blunt-nosed geometry on the upwind side and it asymptotically approaching a cylindrical geometry on the downwind side so that the tail region provides an open exit for continuous outflow of the solar wind.

The second topic is a study on the interstellar neutral hydrogen that freely penetrates through the heliopause to enter the heliosphere. Interstellar hydrogen may become ionized in the heliosphere by photoionization or by charge exchange process to produce pickup proton. Thus, in the heliosphere, the solar wind plasma is composed of pickup protons, protons of solar origin, and electrons. We use MHD equations to describe the dynamics of the solar wind plasma and use fluid equations to describe the dynamics of the interstellar neutral hydrogen; the two equation systems are coupled by the ionization terms. Simultaneous numerical solutions of the two equation systems are obtained. The ionization process causes the removal of interstellar hydrogen in the heliosphere. On the upwind side, 90% of hydrogen depletion occurs inside 60 AU; the hydrogen density changes rapidly inside 10 AU. The hydrogen density diminishes sharply inside ~4 AU to form a hydrogen cavity; the cavity extends on the downwind side to form a long cavity wake. Outside the hydrogen cavity and cavity wake, pickup protons have significant effects on the solar wind speed and temperature.

The third topic is concerned with the geometry of the termination shock. The global termination shock has been treated as having a closed geometry in all previous calculations of the heliosphere model. In this study, we explore the possibility that the termination shock may have an open geometry instead of a closed one. We argue that the forward motion of the supersonic solar wind is blocked at the blunt-nosed heliopause for the formation of termination shock on the upwind side. However, the motion of supersonic solar wind is unobstructed on the downwind side of the heliosphere. Thus, the global termination shock likely has a bow-shaped open geometry.

1 Interstellar magnetic field in the limit of small $\beta$-ratio

1.1 Interstellar medium surrounding the heliopause

The interstellar medium is a partially ionized gas between the stars. Hydrogen atoms are the principal neutral component of interstellar medium. Interstellar medium approaches the Sun at a speed $V = 20–25$ km s$^{-1}$, the interstellar medium temperature $T = 6000–10000$ K, the interstellar proton number density $N = 0.035–0.125$ cm$^{-3}$. The direction of the interstellar magnetic field is not known; the strength of the interstellar magnetic field $B = 2–5$ $\mu$G. Higher field strength of about 6 or 7 $\mu$G have been predicted based on a model studying the formation of the Local Cloud [1].

There are two parameters that strongly determine the interaction between the interstellar medium and the heliosphere; they are the plasma $\beta$-ratio and the magnetosonic Mach number. The former is the ratio of the energy density of the plasma to that of the magnetic field; the latter is the ratio between the bulk speed to the magnetosonic speed $C_p = (c^2 + \alpha^2)^{1/2}$, where $c$ is the gasdynamic sound speed and $\alpha$ is the Alfven speed. Table 1 shows the range of possible value of the plasma $\beta$-ratio and magnetosonic speed of the interstellar medium as functions of the field magnitude.

The interstellar magnetic field and plasma flow are substantially distorted due to the presence of the heliosphere. If the interstellar field is weak, the plasma $\beta$-ratio becomes less than 1 and the flow speed becomes less than the magnetosonic speed, and a bow shock may exist on the upstream side of the heliopause. MHD models have been used to show that, in this case the distortion of the interstellar magnetic field is confined in a relatively narrow region between the bow shock and the heliopause [2–6].

However, if the interstellar field is strong, the plasma $\beta$-ratio becomes less than 1 and the flow speed becomes less than the magnetosonic speed, no bow shock should occur upstream of the heliopause. In this case, the distortion of the magnetic field due to the presence of the heliopause penetrates deep into the interstellar space. In the limit of very low plasma $\beta$-ratio, we introduce a line dipole method to study the distortion of the interstellar magnetic field resulting from the solar wind interstellar interaction [7]. We obtain analytical solutions from which we can study 3D magnetic fields on the interstellar side of the heliopause.

1.2 Dipole solution

In the limit of very low plasma $\beta$-ratio, we use the method of dipole solution to study the distortion of the interstellar

<table>
<thead>
<tr>
<th>$B$ ($\mu$G)</th>
<th>$\beta$-ratio $C_p$</th>
<th>Magnetosonic speed (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.36–2.17</td>
<td>17.8–28.6</td>
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<tr>
<td>3</td>
<td>0.16–0.96</td>
<td>22.5–38.7</td>
</tr>
<tr>
<td>4</td>
<td>0.09–0.54</td>
<td>27.8–49.5</td>
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<tr>
<td>5</td>
<td>0.06–0.35</td>
<td>33.4–60.6</td>
</tr>
<tr>
<td>6</td>
<td>0.04–0.24</td>
<td>39.2–71.9</td>
</tr>
<tr>
<td>7</td>
<td>0.03–0.18</td>
<td>45.1–83.3</td>
</tr>
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