Heliosphere in a strong interstellar magnetic field

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Abstract.
We present results of MHD simulations of the global structure of the heliosphere for a wide range of the interstellar magnetic field (ISMF) strengths (2-20 $\mu$G). For a strong interstellar field, the plasma flow in and around the heliosphere as well as the magnetic field draped over the heliopause have a simple structure, reminiscent of (though not identical to) the analytical model by Parker. We show how this structure evolves as the interstellar field strength is reduced down to the values in the observed range (few $\mu$G). We also present an example of using this evolution to understand the present observations of the heliosphere.

1. Introduction
In this paper we investigate the global structure of the heliosphere for the ISMF strengths $B_{\infty}$ range from 2 $\mu$G up to 20 $\mu$G.

First in situ measurements of the ISMF were made by Voyager 1 in 2012 when the spacecraft crossed the heliopause and entered the outer heliosheath region [1]. Since that time the observed ISMF strengths vary from 4 to 6 $\mu$G as shown in Figure 1 [1, 2, 3, 4, 5]. As the spacecraft still traverses the region in which the ISMF is draped around the heliopause, we do not have yet direct information about the field undisturbed by the heliospheric obstacle. Several estimations of the pristine ISMF using global MHD simulations give magnitudes of 2-4 $\mu$G [6, 7, 8, 9, 10]. The latest determination from the IBEX ribbon gives $B_{\infty}=2.93$ $\mu$G [11].

Figure 1. Daily averages of $|B|$ measured by Voyager 1 since 2010 (black line [2]). Two vertical red lines show DOY208 and DOY238 of 2012 (the last one corresponds to the date of the heliopause crossing by Voyager 1).

Why should we therefore consider the hypothetical heliosphere embedded in an unrealistically strongly magnetized (20 $\mu$G) interstellar plasma? Our reasons are as follows.

First is that the interaction of solar (stellar) wind with strong ISMF is of interest in itself as a theoretical problem.
Secondly, the range of the interstellar field strength which we consider (2 to 20 µG) is typical in the galactic disk and bulge [12]. Some of our results may therefore have application for astrospheres, including those of the solar like stars.

Third reason (our main motivation for this paper) is the observation (based on theoretical models [13, 14, 15]) that the large-scale structure of the heliosheath plasma flow and the magnetic field draped over the heliopause become simpler for high $B_\infty$. By following the evolution of these structures with decreasing interstellar field strength one may then gain a better understanding of the heliosphere as actually observed, and explain some observations by Voyager 1 [1] and Interstellar Boundary Explorer (IBEX) [16].

To obtain global time-stationary models of the heliosphere, we use the 3D MHD code, adapted and corrected from [17] and already applied in [14, 15]. Except $B_\infty$, other physical parameters of the local interstellar medium (ISM) as well as the parameters of the solar wind are kept close to the observed values, with the interstellar $B_\infty$ direction towards the IBEX ribbon center [18], and the ISM velocity vector from [19]. The solar magnetic field is not included. The solar wind is either isotropic or two-component (slow/fast). The neutral hydrogen is approximated as a background with a constant flux parallel to the velocity of the undisturbed interstellar medium. To avoid overestimation of the effect of neutral hydrogen on the heliospheric plasma flow, we choose the constant value of the neutral hydrogen density to be $n_H=0.1$ cm$^{-3}$, close to the value observed inside the heliosphere [20], rather than the higher value expected in the interstellar medium. We use a fixed spherical grid with size $n_r \times n_\theta \times n_\phi = 348 \times 90 \times 180$ for most calculations.

The plan of our presentation is as follows. In Section 2 we discuss the analytical model by Parker and our expectations for the structure of the astrosphere of a moving star in a strongly magnetized medium. In Section 3 we concentrate of the two-stream structure of the plasma flow inside the astrosphere. Section 4 deals with the shape of the boundary of the astrosphere in the $(\vec{B}_\infty, \vec{V}_\infty)$ plane. In Section 5 we present our results concerning the structure of the draped magnetic field and their application to Voyager 1 measurements near and beyond the heliopause. Section 6 presents briefly some of our results concerning the production of energetic neutral atoms in the heliosphere. In Section 7 we present our conclusions.

2. Star in a strong interstellar magnetic field

A simple analytical model of a stellar wind confined by the ISMF was proposed by Parker [13]. This model is applicable to the case of a star at rest relative to strongly magnetized ISM, with the magnetic field pressure much higher than the pressure of the interstellar plasma. The model atmosphere, from which the ISMF is excluded, consists of a central cavity connected with two outflow tunnels, parallel and anti-parallel to the interstellar field direction. After passing the (spherical) termination shock, the stellar wind plasma flows down these tunnels, forming two oppositely directed streams. The ISMF draped over the astropause has a simple form, described by an analytical formula [13].

Figure 2 shows the solution obtained from our simulations [15] for the case of the ISMF strength of 20 µG with the star at rest relative to the undisturbed medium, which includes also a neutral hydrogen component. The result is similar to the Parker model. Two streams (parallel and anti-parallel to the ISMF direction) as well as the tube-like shape of the heliopause are well visible. Note that the termination shock is not deformed by the magnetic field but approximately spherical, also in agreement with Parker model.

What happens when the star is moving through a strongly magnetized medium? There is no simple analytical model able to answer this question and we have to rely on qualitative arguments and numerical simulations.

The following qualitative argument suggests the form of the solution. The motion of the astrosphere through the magnetized medium induces the interstellar plasma flow, directed partly
Figure 2. Flow lines of the solar plasma for the MHD solution corresponding to the hypothetical heliosphere with the Sun at rest \( V_\infty = 0 \) relative to the ISM with plasma density \( n_{IS} = 0.04 \) cm\(^{-3} \), neutral hydrogen density \( n_H = 0.1 \) cm\(^{-3} \) and very strong ISMF \( (B_\infty = 20 \) µG). The solar wind is spherically symmetric with the speed \( V_{SW} = 750 \) km/s and the proton density at 1 AU \( n_{SW,1AU} = 4.2 \) cm\(^{-3} \). The solution is similar to the Parker model. The heliopause and the termination shock are shown by thick lines.

Figure 3. Schematic view of induced interstellar plasma flow in vicinity of an astrosphere when the star is moving through the strongly magnetized ISM. The induced ISM plasma flow moves partly along the magnetic field lines (denoted by B). The motion of the star (a thick arrow shows its direction) affects also the flow inside the astrosphere (see next Figure).

along the magnetic field lines, parallel and anti-parallel to the ISMF (see Figure 3). Combination of the motion along the magnetic field lines with the motion of the star would slightly deflect the flow, as seen in the rest frame of the star, from the magnetic field (and anti-field) direction. Apart from this deflection, the leading part of the boundary between the outer and the inner plasma would then be similar to the (slightly bent) tube-like structure of the Parker model. The flow inside the astrosphere would adjust to the boundary, suggesting that at least a part of the inner flow would also form two streams.

Our MHD simulation for strong ISMF (10-20 µG) is consistent with this simple picture (Figure 4, left panel). We conclude that the two-stream structure of the flow inside the astrosphere, obtained in the case of a star at rest, may survive to some extent also for a moving star.

Figure 4 also shows the effect of asymmetric pressure of the ISMF, which causes the atmosphere expansion in the \( (\vec{B}_\infty, \vec{V}_\infty) \) plane (upper panels) and contraction in the perpendicular direction (bottom panels). This effect is well known from many numerical simulations.

The boundary surface of the atmosphere (the astropause) in the Parker model has the topology of a tube, open on two sides. One could imagine a similar structure for the astropause.
Figure 4. Plasma flow lines in the \((x,y)\equiv(\vec{B}_\infty, \vec{V}_\infty)\) plane (top panels) and the shape of the heliopause and the termination shock in the \((x,z)\) plane (bottom panels) obtained from MHD simulations for \(B_\infty=20\ \mu G\) (left panels) and \(B_\infty=5\ \mu G\) (right panels), assuming \(V_\infty=23.2 \text{ kms}^{-1}\), \(n_\infty=0.06 \text{ cm}^{-3}\), \(n_H=0.1 \text{ cm}^{-3}\), and a spherically symmetric solar wind with \(V_{SW}=750 \text{ kms}^{-1}\), \(n_{SW,1AU}=4.2 \text{ cm}^{-3}\). The dashed lines in the bottom panels show the results obtained in a simulation using a coarse grid \((95 \times 50 \times 100)\).

of a moving star, with the stellar plasma evacuated along the two tunnels rather than the single astrotail. Apart from the special case of the magnetic field parallel to the star motion, to our knowledge this possibility is not supported by numerical simulations. In particular, our results shown in Figure 4 indicate the presence of a single tail flattened by the magnetic field. The tube-like topology of the heliopause was, however, proposed in a different context [21, 22].

As shown in the bottom panel of Figure 4, our results for the thickness of the distant tail (although not for the shape of the heliosphere in the \((\vec{B}_\infty, \vec{V}_\infty)\) plane) are sensitive to the choice of the grid. The full solution for the tail structure requires a separate study.

3. Two-stream structure of plasma flow
Figure 4 (top panels) shows plasma flow streamlines in the \((\vec{B}_\infty, \vec{V}_\infty)\) plane for the case of the ISM moving relative to the Sun at the velocity \(V_\infty=23.2 \text{ kms}^{-1}\). For the 20 \(\mu G\) case, the two-stream structure can be distinguished as two ”bunches” of approximately straight streamlines near the forward boundary of the heliopause (which separates the interstellar and solar plasmas). Compared to Figure 2, the streams are deflected from the directions parallel and anti-parallel to ISMF.

After \(~300-500\) AU of approximately straight flow, the streams can be seen to commence turning tailward. This is caused by charge-exchange interaction between the plasma flow and the background neutral hydrogen. In the absence of this interaction, the two straight streams structure would be more extensive and prominent even for the 5 \(\mu G\) case.

Looking for a quantitative characterization of the two-stream structure, we examined different
Figure 5. Directional distribution of the plasma speed at a distance of 200 AU from the Sun, obtained from MHD simulations for $B_\infty=10 \, \mu G$. The all-sky Mollweide projection is centered on the anti-apex direction of the ISM flow (white dot). Also shown are the interstellar magnetic field and anti-field directions (white dots denoted by RC and $-B_\infty$, respectively), and the heliopause shape at the sphere shown here (white oval).

Figure 6. Directional distribution of the plasma speed at a distance of 315 AU from the Sun, obtained from MHD simulations for $B_\infty=5 \, \mu G$. See Figure 5 caption for other descriptions.

Figure 7. Directional distribution of the plasma speed at a distance of 302 AU from the Sun, obtained from MHD simulations for $B_\infty=2 \, \mu G$. See Figure 5 caption for other descriptions.

possibilities. Figures 5, 6, and 7 show the calculated distributions of the plasma speed over the Sun-centered spheres of the radii 200 ($B_\infty=10 \, \mu G$), 315 ($B_\infty=5 \, \mu G$) and 302 AU ($B_\infty=2 \, \mu G$). The heliopause is shown by the white ovals, with the enclosed region corresponding to the inside of the heliosphere. For strong ISMF (10 $\mu G$) the two streams appear as two separate high speed regions near the directions parallel and anti-parallel to the undisturbed ISMF. For 5 $\mu G$ at 315 AU there is one high speed region, near the anti-field direction. However, two streams would be present at 200 AU (not shown). In the case of 2 $\mu G$, the speed distribution is approximately symmetric with respect to the center of the heliotail, which we interpret as the absence of the magnetic field-related stream structure.

Another way to illustrate the two-stream structure is to consider the energy flux distribution. Figure 8 shows the distribution of the radial component of the plasma energy flux in the $(\mathbf{B}_\infty, \mathbf{V}_\infty)$ plane at the heliocentric distance 200 AU (20 $\mu G$) and 300 AU (5 $\mu G$), plotted as a function of the angle counted from the ISM inflow direction. Again we can see two maxima near the field and anti-field direction appearing for the strong magnetic field 20 $\mu G$ and only one surviving for the 5 $\mu G$ case at 300 AU.

Another characterization of the stream structure can be provided by the distribution of the plasma mass flux across the sphere surrounding the Sun at the chosen distance. The plasma
mass flux is, however, dominated by the region outside the heliopause.

The above results were obtained for the symmetric solar wind case. The two-stream structure of the heliospheric flow is present also when the two-component solar wind is considered. For our simulations of this case see [15].

4. Shape of the heliopause: Alfvén wings

For strong $B_{\infty}$ (20 $\mu$G and, if $n_H$ is small, even for 5 $\mu$G) we find that the forward part of the heliopause in the ($\vec{B}_\infty, \vec{V}_\infty$) plane has the form of straight "wings". This is reminiscent of the Alfvén wings [23, 24], which appear when a conducting body (like a satellite or a planetary magnetosphere) is moving through a magnetized plasma (Figure 9). The angle $\alpha$ between the Alfvén "wings" and the x axis (the $V_\infty$ direction) is given by:

$$\tan \alpha = \frac{\tan \gamma}{1 \pm V_\infty/V_A \cos \gamma},$$

where $\gamma$ is the angle between the interstellar magnetic field and the x axis, and $V_A$ is the Alfvén speed in the interstellar medium.

The Alfvén wings shape of the heliopause in the ($\vec{B}_\infty, \vec{V}_\infty$) plane was derived in a simplified model [25] using the Newtonian approximation [26]. The heliosphere of this form was also recently proposed by [27].
5. Draped interstellar magnetic field structure
We found it convenient to present our discussion in terms of the magnetic field lines projected on a celestial sphere (sky projections for short).

Figure 12 (left panel) shows a set of magnetic field lines passing through selected points just
above the heliopause (the change from black to red occurs at these points). Their sky projections are shown in the right panel. The lines result from our MHD simulation for the ISMF direction towards the IBEX ribbon center (RC, [18]), and the field magnitude $B_\infty = 3 \mu G$.

Away from the heliopause, the field lines must finally become parallel to the undisturbed field direction. Their sky projections must therefore approach the point corresponding to the $\vec{B}_\infty$ direction (here: RC) (Figure 12, right panel).

In the analytical Parker model [13], the magnetic field lines in this projection have the form of great circles crossing at the points corresponding to the directions parallel and antiparallel to the undisturbed magnetic field. From our calculations we found [14] that, for a strong interstellar field (20 $\mu G$), the magnetic field draped around the moving heliosphere still has a simple structure similar to the Parker model. The weaker the field, the more the sky projections of its lines differ from great circles, especially in vicinity of the undisturbed field direction (Figure 12, right panel).

5.1. Direction of the ISMF observed by Voyager 1 just beyond the heliopause

Our analysis of evolution of the magnetic field draped over the heliopause for the decreasing interstellar field magnitude helped us in our attempt [14] to understand the observations by Voyager 1 just beyond the heliopause.

Voyager 1 crossed the heliopause and entered the interstellar medium in August, 2012 [1]. Observed before the crossing, the interplanetary magnetic field direction was close to the expected Parker spiral (i.e. lying in the spacecraft’s heliographic parallel plane). Unexpectedly, there was no significant (in fact: $\sim 20^\circ$) change in the field direction during crossing of the boundary [1].

In [14] we proposed a simple explanation of this fact. We noticed a special coincidence between the directions of Voyager 1 trajectory and of the undisturbed ISMF (assumed to be given by the IBEX ribbon center). They share approximately the same heliolatitude ($\sim 35^\circ.5$) and are not far separated in longitude (see Figure 12, right panel).
In a sky projection, the Parker spiral of solar magnetic field just ahead of the heliopause approximately follows the heliographic parallel. The projection of the interstellar magnetic field line, observed by Voyager 1 just beyond the heliopause, should connect Voyager 1 trajectory direction with the direction of the undisturbed interstellar field [14].

Figure 13 illustrates schematically (left panel) and basing on our simulation for \( B_\infty = 3 \mu \text{G} \) (right panel) such projections for two cases: strong ISMF (solid red line) and weak ISMF (dashed red line). V1 and RC denote the projections of Voyager 1 trajectory and the direction of \( B_\infty \) (IBEX ribbon center) which share the same heliographic latitude. The solid red line is the arc of great circle which corresponds to sky projection of the magnetic field line in the analytical Parker model. The angle (denoted by \( \phi \)) between the projections and the heliographic parallel (which is approximately the projection of the solar magnetic field line) for the case of strong field is small, but may be bigger for the weaker field. However, our simulations (Figure 13, right panel) give the value of this angle which is small enough [14] to be consistent with Voyager 1 observations.

Figure 13. Sky projection of magnetic field lines which cross the Voyager 1 trajectory just beyond the heliopause, and approach RC far from the heliopause (left panel: schematic view, right panel: our simulation results). Solid red line (arc of a great circle) corresponds to the analytical Parker model for a strong ISMF, dashed red line to a weak field case. The (dashed red / solid black) line shown in the right panel is obtained from the same simulation as in Figure 12 (\( B_\infty \) of 3 \( \mu \text{G} \)).

Figure 14. Geometrical construction showing the segments of the magnetic field lines draped over the inner (IN) the outer (OUT) side of the surface element of the heliopause (HP), and their sky projections (the top of the figure). The angle between the field lines is not equal to the angle between their sky projections, but the difference is small provided that the surface element of the heliopause over which the field lines are draped is approximately perpendicular to the heliocentric radial direction.

Note that the angle between the sky projected vectors is not the same as the angle between the vectors draped on both sides of the heliopause (Figure 14). However, the difference will be
small it the surface element of the heliopause is not far from perpendicular to the heliocentric radial direction. This condition was met by our MHD simulation.

5.2. Evolution of magnetic field direction beyond the heliopause along Voyager 1 trajectory

Figure 15. Celestial sphere in orthogonal projection and solar ecliptic coordinates. Shown are the magnetic field directions observed by Voyager 1 just beyond the heliopause (blue dot [1]) and then daily averages up to 2016.0 [2] (black curve inside a circle of $\sim 9^\circ$ radius). The evolution of magnetic field direction from the heliopause to $\sim 5000$ AU distance from the Sun at Voyager 1 direction, obtained from our MHD simulations for $B_\infty = 3 \mu G$, and projected on the celestial sphere is shown by red dots.

The interstellar magnetic field directions observed by Voyager 1 up to 2016 [2, 5] are shown in Figure 15 (black curve inside the circle). The observed field was disturbed by several shocks of solar origin [5]. The draped ISMF directions obtained from our simulations for $B_\infty$ from 2.7 to 3 $\mu G$ ([14], Table 1), but not for stronger field, fall inside this region.

Our simulations permit us to follow the variation of the magnetic field direction at Voyager 1 with the increasing distance from the Sun (Figure 15, red dotted curve). The curve links the region of observed field directions with the undisturbed field (RC). The shape and position of the curve depends on the parameters assumed in the simulation, in particular on $B_\infty$ (in Figure 15, 3 $\mu G$).

6. Simulated ENA flux distribution originated in the inner heliosheath

A detailed discussion of production of the energetic neutral atoms (ENA) in the heliosphere for a wide range of ISMF strengths was presented in [15]. In the present work we limit ourselves to a brief presentation of our recent results based on a new model (Zank et al. [28]) of the termination shock energetic ion spectrum.

We calculate the heliospheric ENA flux assuming that the ENA derive from the energetic ions accelerated at the termination shock and transported from there to the ENA production site by plasma convection (spatial diffusion is unimportant for the ions in the IBEX energy range). ENA flux from a given line-of-sight (LOS) is then determined by the energetic ion spectrum at those points of the termination shock which are linked to the line of sight by plasma streamlines (Figure 17).

The main factors which shape the directional dependence of the ENA flux are: (1) the energetic ion flux intensity in the relevant region at the termination shock, (2) the length of the line-of-sight interval within the heliosphere and (3) the transport effects on the energetic ion
distribution, mainly the neutralization loss due to charge-exchange with the background neutral hydrogen.

For the ion spectrum at the termination shock we use the model of Zank et al. [28], based on the ideas of Zank et al. [29] and Lee [30] (in our previous work [15] we have used a simpler trial model). Figure 16 shows a comparison of the energetic proton spectrum which we derived using the model of Zank et al. [28] for the case of the termination shock crossing by Voyager 2, with the result of hybrid simulation by Giacalone and Decker [31]. The latter was shown to approximately match the termination shock particle spectra measured by Voyagers [32].

For the "comet-like" heliosphere expected for the case of weak interstellar magnetic field, the large length of LOS occurs for the heliotail direction (Figure 17). However, this LOS is fed by the energetic ions coming from the rear parts of the termination shock, where the energetic ion flux intensity is relatively low, due to low pick-up ion density. In result, the ENA flux from the heliotail direction can be lower than from the ISM apex region. For higher energy (above $\sim 50$ keV), the flux from the tail direction may become higher than from the apex because of lower neutralization losses.

For the "two-stream", strong interstellar magnetic field heliosphere, large LOS length occur also for the parts of the heliosphere corresponding to the streams. These are fed by the energetic ions from the forward and flank parts of the termination shock. The pick-up ion density in these regions can be high, and therefore one may expect a high value of the ENA flux from the two stream directions. Our results (Figures 18, 19) confirm this conclusion.

We wish to stress the difference between the stream directions (corresponding to large LOS length and high ENA flux) and the heliotail direction (large LOS length but low ENA flux). By the above argument, the models of the heliosphere similar to the Parker model would correspond to the ENA intensity map with two peaks (and not two low flux regions) near the stream (tunnel).
Figure 18. Directional distribution of the 4.3 keV ENA flux for the model heliosphere with spherically symmetric solar wind in the 20 µG interstellar field directed towards the IBEX ribbon center. The Mollweide projection is centered at the heliotail (ISM anti-apex) direction.

Figure 19. As Figure 18, but for the case of 5 µG interstellar field.

Figure 20. As Figure 18, but for the case of 3 µG interstellar field.

Figure 21. As Figure 20, but for the ENA with energy 2.7 keV and the asymmetric (fast/slow) solar wind.

directions. This observation may be relevant in view of some authors referring to Parker-like models of the heliosphere in connection with ENA observations [33, 34].

Figures 20, 21 show the ENA flux distributions calculated for the case of ISMF strength of 3 µG, which can be compared with IBEX observations. The solar wind is assumed to be either spherically symmetric (Figure 20) or two-component, with the fast wind restricted to within ±36° from the solar equator (Figure 21), respectively. For asymmetric solar wind, the ENA distribution near the heliotail corresponds to the ”split-tail” structure, with two low ENA flux lobes flanking the heliotail direction. This ”split-tail” effect was already obtained in [15], using a different termination shock spectrum. A similar structure was recently derived by [35].

Figure 21 shows some similarity to the ENA distribution observed by IBEX [36]. Some of the differences can be attributed to our assumption of constant neutral hydrogen background.

7. Conclusions
We constructed a range of time-stationary MHD models of the heliosphere for different ISMF strengths, from 2 to 20 µG. The ISMF direction (the IBEX ribbon center) and the parameters of the solar wind and the ISM were assumed to be close to the observed values.

Comparing the models for different ISMF, we were able to follow the evolution of the global structure of the heliosphere, with the ISMF decreasing from unrealistically high to observed
values. In particular, we found that the two-stream structure of the heliospheric plasma flow may survive down to $\sim 5 \mu$G ISMF.

As an example of application of this evolution to understand the actual heliosphere, we review our suggested explanation [14] of the observations by Voyager 1, indicating an unexpectedly small change in direction of the magnetic field during crossing of the heliopause.

We also used our models to obtain the directional distribution of the heliospheric ENA in the IBEX energy range. Basing on our results for high $B_{\infty}$, we point out that a heliosphere open at two ends would correspond to two areas of high ENA flux coming from the directions of the tunnels, rather than two low flux areas. Differently from our previous work [15], our ENA calculations presented here use the new model of the termination shock spectrum proposed by Zank [28]. The "split tail" effect, which we found in [15] for another termination shock spectrum, is still present when we use the model of Zank.

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