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Letter to the Editor

Direction of the interstellar H atom inflow in the heliosphere: Role of the interstellar magnetic field

V. Izmodenov[1,3], D. Alexashov[2,3], and A. Myasnikov[2]

[1] Lomonosov Moscow State University, Department of Mechanics and Mathematics & Institute of Mechanics, Moscow, 119899, Russia
e-mail: izmod@ipmnet.ru
[2] Institute for Problems in Mechanics, Russian Academy of Sciences
[3] Space Research Institute (IKI) Russian Academy of Sciences, Moscow, Russia

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Abstract. Recently Lallement et al. (2005, Science, 307, 1447) reported that the direction of the flow of interstellar neutral hydrogen in the heliosphere is deflected by $\sim 4°$ from the direction of the pristine local interstellar gas flow. The most probable physical phenomenon responsible for such a deviation is the interstellar magnetic field inclined to the direction of the interstellar gas flow. In this case the flow of the interstellar charged component is asymmetric and distorted in the region of the solar wind interaction with the local interstellar medium, which is called the heliospheric interface. The interstellar H atoms pass through the heliospheric interface and interact with the plasma component by charge exchange. Some imprints of the asymmetry of the heliospheric plasma interface should be seen in the distribution of the interstellar H atom component. In this letter we explore this scenario quantitatively and demonstrate that our new self-consistent 3D kinetic-MHD model of the solar wind interaction with the magnetized interstellar plasma is able to produce the measured deviation in the case of a rather strong interstellar magnetic field of $\sim 2.5\,\mu$G inclined by $\sim 45°$ to the direction of interstellar flow.

Key words. Sun: solar wind – interplanetary medium – ISM: atoms

1. Introduction

The heliospheric interface is formed due to the interaction of the solar wind and interstellar plasmas. The qualitative pattern of the heliospheric interface is shown in Fig. 1. The heliospheric interface consists of the termination shock (TS) decelerating the supersonic solar wind to subsonic, the heliopause (HP) – the contact discontinuity separating the interstellar and solar wind plasmas, and possibly a bow shock (BS). The local interstellar cloud (LIC) surrounding the Sun is partially ionized. In contrast to the interstellar plasma component, which is deflected around the heliopause, the interstellar atoms penetrate deep into the heliosphere, where they and their derivatives, such as pickup ions and anomalous cosmic rays (ACRs) can be observed. The properties of the interstellar H atoms within the heliosphere can be inferred from the analysis of backscattered solar Lyman-alpha radiation measurements. In particular, absorption cell measurements by SOHO/SWAN (Bertaux et al. 1995) allow to measure the Doppler shifts of the backscattered (by interstellar H atoms) solar Lyman-alpha glow, and, therefore, to obtain information on the velocity vector of the interstellar H atom flow in the heliosphere. Recently Lallement et al. (2005) reported that the flow of interstellar neutral hydrogen deviates by $\sim 4°$ from the direction of the unperturbed interstellar flow.

The most probable explanation for such a deviation is connected with the presence of the interstellar magnetic field inclined to the direction of the interstellar wind. The magnetic field distorts the heliospheric plasma interface making it asymmetric. Imprints of this asymmetry should be pronounced in the distribution of interstellar H atoms, because the interstellar H atom and proton components are coupled by charge exchange. The process of charge exchange is essentially effective in the outer heliosheath region between the HP and BS. As the result of the charge exchange the *secondary interstellar H atom population* is created in the region, and the heliosphere is filled by the mixture of the primary (i.e. original) and secondary populations of the interstellar H atoms.

To estimate quantitatively how strong the imprints of the plasma asymmetry are in the H atom distributions we employ a 3D kinetic-continuum model of the interface. This model is an advancement of kinetic-continuum models developed by the Moscow group, following the approach by Baranov & Malama (1993). The main advantage of these models is the rigorous kinetic description of the interstellar H atom component, which is required because the mean free path of the interstellar H atoms is comparable with the characteristic size of the interface. Advanced recent continuum-kinetic models take into account additional physical effects, such as solar cycle

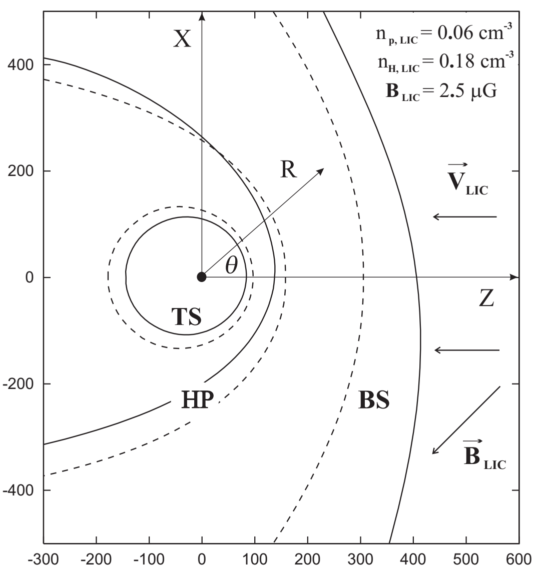

Fig. 1. The structure of the heliospheric interface. TS is the termination shock, HP is the heliopause and BS is the bow shock. Solid curves correspond to the model, when the interstellar magnetic field is taken into account, dashed curves correspond the model with vanishing magnetic field.

variations of the solar wind (Izmodenov et al. 2005), interstellar ionized helium and solar wind alpha particles (Izmodenov et al. 2003b), galactic cosmic rays (Myasnikov et al. 2000), and anomalous cosmic rays (Alexashov et al. 2004b). In addition, the Baranov-Malama model was extended far into the tail direction by Izmodenov & Alexashov (2003a), Alexashov et al. (2004a). For recent reviews on developments made by the Moscow group see Izmodenov (2004). However, the role of the interstellar magnetic field was not explored in these previously developed models.

Numerical 2D MHD modeling of the heliospheric plasma interface was performed by Fujimoto & Matsuda (1991), Baranov & Zaitsev (1995), Myasnikov (1997). It was shown that the interstellar magnetic field (ISMF) could change the structure of the interaction region as well as locations and shapes of the termination shock and heliopause. Inclined magnetic field, when the angle between the direction of ISMF and the direction of the interstellar flow is between 0° and 90°, distorts the heliospheric interface making it essentially three-dimensional (Ratkiewicz et al. 1998, 2000; Linde et al. 1998; Pogorelov & Matsuda 1998, 2000; Tanaka & Washimi 1999; Opher et al. 2004; Pogorelov 2004). To evaluate how these plasma distortions in the heliospheric interface are pronounced in the distribution of H atoms inside the heliosphere proper 3D self-consistent modeling is required. Up to date mutual effects of the interstellar H atoms and the interstellar magnetic field were considered only in the case, when the direction of IMF coincides with the direction of the interstellar flow (Alexashov et al. 2004b; Florinski et al. 2004). Interstellar H atoms are treated kinetically in the first paper, while Florinski et al. (2004) employ multi-fluid approach. The essential differences between kinetic and multi-fluid approaches are discussed in detail by Alexashov & Izmodenov (2005).

We present results of a new 3D kinetic-MHD model of the heliospheric interface, which allows quantitative study of combined effects of the tilted ISMF and interstellar H atoms. In this Letter we focus our study on the direction of the resulting interstellar H flow vector in the heliosphere and compare our model predictions with the recently reported results obtained from SOHO/SWAN solar Lyman-alpha backscattering observations. The comparison of model and data allow to constrain the direction and magnitude of the interstellar magnetic field.

2. Model

In this work we present results of our new 3D kinetic-continuum model of the solar wind interaction with a two-component (plasma component and interstellar H atoms) interstellar medium. The kinetic equation of the interstellar H atom component was solved self-consistently together with the ideal MHD equations for the charged component. The charged and neutral components interact mainly by charge exchange. Photoionization and electron impact ionization are also taken into account in the model. For simplicity, we assume here that solar gravitation is equal to the solar radiation pressure, i.e. $\mu = F_{\rm rad}/F_{\rm gravit} = 1$. The influence of the interstellar H atoms was taken into account on the right-hand sides of the MHD equations. Details on the governing equations and expressions for the source terms can be found, for example, in Izmodenov (2004).

The boundary conditions for the charged component are determined by the solar wind parameters at the Earth's orbit and by parameters in the undisturbed LIC. At the Earth's orbit it is assumed $n_{\rm p,E} = n_{\rm e,E} = 7.39$ cm^{-3}, $V_{\rm E} = 432$ km s^{-1}, $T_{\rm E} = 51\,109$ K. The velocity and temperature of the pristine interstellar medium were recently determined from the consolidation of all available experimental data (Möbius et al. 2004; Witte 2004; Gloeckler 2004; Lallement 2004a,b). We adopt in this paper $V_{\rm LIC} = 26.4$ km s^{-1} and $T_{\rm LIC} = 6527$ K. In order to get a noticeable effect on the direction of the H atom flow we assume a rather strong ISMF, $B_{\rm LIC} = 2.5$ μG, which corresponds to an Alfvénic Mach number $M_{\rm A} = 1.18$, and fast magnetosonic Mach number is 1.01. The angle between the direction of the interstellar magnetic field and the direction of the interstellar flow is assumed to be 45°. For the local interstellar H atom and proton/electron number densities we assume $n_{\rm H,LIC} = 0.18$ cm^{-3} and $n_{\rm p,LIC} = 0.06$ cm^{-3}, respectively. The velocity distribution of interstellar atoms is assumed to be Maxwellian in the unperturbed LIC. For the plasma component at the outer boundary in the tail we used soft outflow boundary conditions. For the details of the computations in the tail direction see Izmodenov & Alexashov (2003a), Alexashov et al. (2004a).

3. Results

Figure 1 presents the shapes of the termination shock (TS), heliopause (HP), and the bow shock (BS) in the plane xz plane along with their heliocentric distances. The xz plane is determined by the Sun-LIC relative velocity and the interstellar magnetic field vectors. The direction of the z axis is chosen to be opposite to the interstellar gas velocity vector. The direction of the ISMF vector constitutes −135° relative to the z axis. For the purpose of comparison Fig. 1 presents the TS, HP and BS for the case of vanishing ISMF (dashed curves). It is seen that the interstellar magnetic field pressure pushes the heliopause and the termination shock towards the Sun as compared with a model without magnetic field. In the upwind direction the TS and HP are closer to the Sun by ∼10 AU and ∼20 AU, respectively. The maximum and minimum of the magnetic field pressure occur in the directions of $\theta = -45°$ and $\theta = 45°$, respectively. (The definition of θ is given in Fig. 1, and an interval $-180° < \theta < 180°$ is adopted here.) The difference in magnetic pressure creates a strong asymmetry of the heliopause with respect of the z axis. The distances to the heliopause are ∼144 AU and ∼164 AU, for $\theta = -45°$ and $\theta = 45°$, respectively. For comparison, the distance to the HP is ∼180 AU in the case of a vanishing magnetic field. The asymmetry is weaker, but still pronounced, for the TS. The distances to the TS are 87 AU for $\theta = -45°$ and 95 AU for $\theta = 45°$, respectively.

The asymmetry of the bow shock (Fig. 1) is connected with both the asymmetry of the heliopause, which serves as an obstacle for the interstellar plasma flow, and different propagation of MHD waves along and perpendicular to the interstellar magnetic field. As a result of the discussed asymmetry, the distance between the HP and BS is larger in the upper half of the zx-plane, where θ is positive, as compared with the negative half of the plane. In fact, the interstellar plasma is more compressed for the positive values of θ and less compressed for its negative values (see also Fig. 2A). The maximum of the plasma pileup region is shifted towards the upper half of the plane in Fig. 2A. It is important to note that due to the rather strong magnetic field and the massloading of interstellar plasma by charge exchange with secondary interstellar atoms the BS becomes very weak and tends to turn into the characteristic.

Figure 2A presents also the streamlines of the plasma component. The stagnation point is located in the upper half of the zx plane. The stagnation point is shifted by ∼10° away from the z axis. It is important to note that the velocity vector of the plasma passing through the region of maximum plasma density has a noticeable V_x component. The secondary interstellar atoms, which originate in the region between the BS and the HP, should have the properties of the plasma of this region. Figure 2B presents the number density of this secondary interstellar atom component. The maximum density appears in the region between the TS and HP. This is so-called hydrogen wall, which was predicted by Baranov et al. (1991) and confirmed later by Linsky & Wood (1996). It is seen in the figure that the maximum of the hydrogen wall is also slightly shifted to the upper half of the XZ plane and reflects the behavior of the plasma distributions. "The streamlines" of the H atom component are also shown in Fig. 2B. "The streamlines" were plotted based on the mean velocity field distribution of the interstellar H atoms, which was calculated in a Monte-Carlo scheme as the integral $\boldsymbol{V}_{\mathrm{H}} = \int \boldsymbol{w} f_{\mathrm{H}}(\boldsymbol{r},\boldsymbol{w})\mathrm{d}\boldsymbol{w}$, where $f_{\mathrm{H}}(\boldsymbol{r},\boldsymbol{w})$ is the velocity distribution function of the H atom component. The velocity vector $\boldsymbol{V}_{\mathrm{H}}$ determines the direction of the H atom flow on average. It is seen from the figure that in the heliosphere the velocity vector $\boldsymbol{V}_{\mathrm{H}}$ has a noticeable V_x component even very close to the Sun. Therefore, the effect observed by Lallement et al. (2005) is clearly reproduced by our numerical results. To quantify the effect we plot the angle α_{H}, which determines the direction of the H atom flow: $\alpha_{\mathrm{H}} = \mathrm{acrtg}\,(V_{x,\mathrm{H}}/V_{z,\mathrm{H}})$. Figure 3 shows α_{H} for the primary (right plot) and secondary (left plot) populations of the interstellar H atoms. α_{H} is presented as function of the heliocentric distance for three different lines of sight, which correspond to the angles $\theta = 0°, 45°, -45°$. It is seen that for the upwind direction ($\theta = 0°$) $\alpha_{\mathrm{H}} \sim -5°$ for the secondary interstellar H atom population and $\alpha_{\mathrm{H}} \sim -1°$ for the primary interstellar H atoms. The small erratic variations on the curves are due to statistical uncertainties in our Monte-Carlo calculations. Dashed curves in Fig. 3 correspond to lines of sight of $\theta = 45°$ and $-45°$. It is seen that the curves are nearly symmetric around $\alpha_{\mathrm{H}} = -5°$ for the secondary H atom component and $\alpha_{\mathrm{H}} = -1°$ for the primary interstellar component. For the purposes of comparison Fig. 3 also shows α_{H} toward $\theta = 45°$

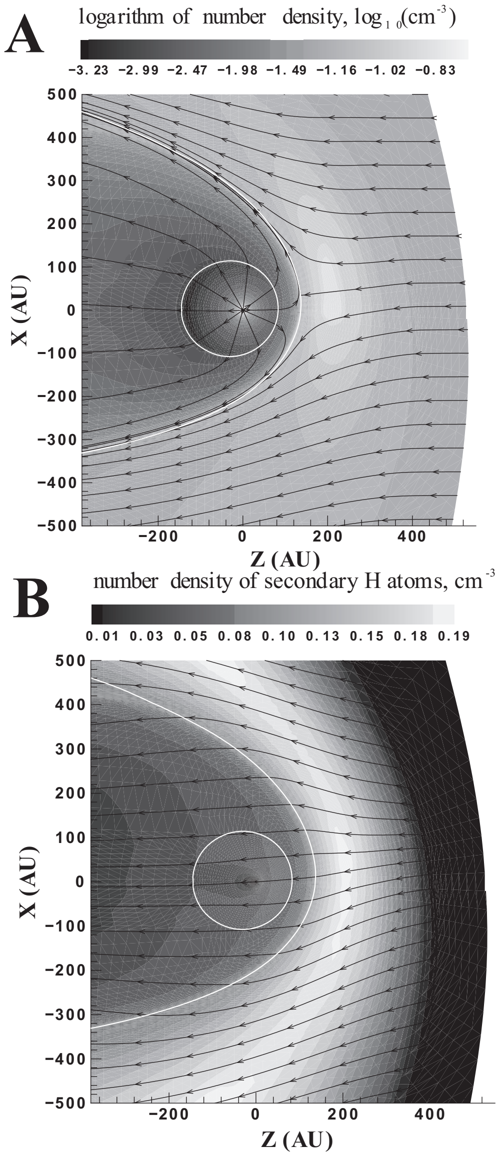

Fig. 2. Isolines of the number density and streamlines of the plasma component **A)** and secondary H atom population **B)**. The asymmetry of the plasma pileup region due to the ISMF is clearly seen.

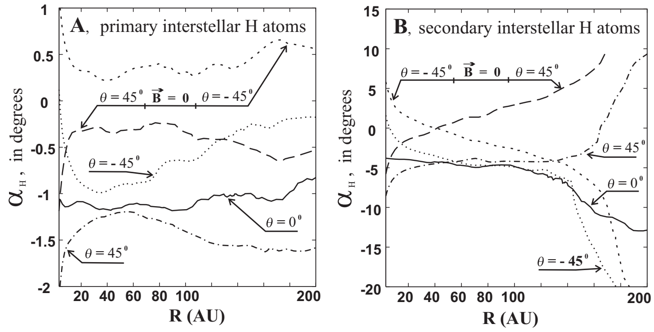

Fig. 3. The angle $\alpha_H = \arctan(V_{X,H}/V_{Z,H})$ as a function of the heliocentric distance for the primary **A)** and secondary **B)** interstellar H atoms. α_H is shown for different line of sights and for the models with and without interstellar magnetic field.

and $-45°$ lines of sight for the axysimmetric model, when the ISMF vanishes. It is seen that the curves are symmetric around $\alpha_H = 0$ in this case. Therefore, we conclude that for the ISMF under consideration the direction of the secondary H atom flow is $\alpha_H = -5°$ and that of the primary H atom population is $\alpha_H = -1°$. The direction of the combined H flow in the heliosphere is the averaged sum of the two populations, which is ~3.5–4°. This number is in very good agreement with the results obtained by Lallement et al. (2005) from the analysis of backscattered solar Lyman-alpha radiation.

4. Conclusions

Our new 3D continuum-kinetic self-consistent model of the heliospheric interface, which takes into account effects of both the interstellar magnetic field and the interstellar H atom component have shown that there is a ~4° difference in the direction of the interstellar H atom flow in the heliosphere as compared with the direction of the undisturbed interstellar flow. This result, which is in agreement with observational evidence reported by Lallement et al. (2005), was obtained in the case of a moderately strong interstellar magnetic field of $B_{LIC} = 2.5\ \mu$G with a direction of 45° relative to the interstellar flow vector. The results presented here demonstrate that the direction of the interstellar H atom flow in the heliosphere determined from SOHO/SWAN experiment can serve as unique diagnostics of the interstellar magnetic field amplitude and direction. A parametric study is needed in order to establish the magnetic field direction and amplitude more accurately.

Another important result, which is presented in this letter, is that the magnetic field significantly influences the location of the TS. Therefore, the distance of the TS in two different directions, which can be determined in the near future when both Voyager spacecraft cross the shock, will also serve as a crucial tool to establish constraints on the total pressure of the LIC, and the direction of the ISMF. Together with estimations of the interstellar H atom number density at the TS provided by 1) Ulysses/SWICS and ACE/SWICS observations of pickup ions and 2) the deceleration of the distant solar wind measured by Voyager 2 could be sufficient to establish both the magnitude and direction of the interstellar magnetic field as well as the interstellar proton and H atom number densities.

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References

Alexashov, D. B., Izmodenov, V. V., & Grzedzielski, S. 2004a, Adv. Space Res., 34, 109
Alexashov, D. B., Chalov, S. V., Myasnikov, A. V., Izmodenov, V. V., & Kallenbach, R. 2004b, A&A, 420, 729
Alexashov, D. B., & Izmodenov, V. V. 2005, A&A, in press
Baranov, V. B., & Malama, Yu. G. 1993, J. Geophys. Res., 98(A9), 15157
Baranov, V. B., & Zaitsev, N. A. 1995, A&A, 304, 631
Baranov, V. B., Lebedev, M. G., & Malama, Yu. G. 1991, ApJ, 375, 347
Bertaux, J.-L., Kyrola, E., Quemerais, E., et al. 1995, Sol. Phys., 162, 403
Florinski, V., Pogorelov, N. V., Zank, G. P., Wood, B. E., & Cox, D. P. 2004, ApJ, 604, 700
Fujimoto Y., & Matsuda, T. 1991, Preprint No. KUGD91-2, Kobe Univ., Japan
Gloeckler, G., Möbius, E., Geiss, J., et al. 2004, A&A, 426, 845
Izmodenov, V. V. 2004, in The Sun and the Heliosphere as an Integrated System Series: Astrophysics and Space Science Library, ed. G. Poletto, & S. T. Suess, vol. 317, Chap. 2
Izmodenov, V. V., & Alexashov, D. 2003a, Astron. Lett., 29, 58
Izmodenov, V. V., Malama, Yu. G., Gloeckler, G., & Geiss, J. 2003b, ApJ, 594, L59
Izmodenov, V., Malama, Yu. G., & Ruderman, M. S., 2005, A&A, 429, 1069
Lallement, R., Raymond, J. C., Vallerga, J., et al. 2004a, A&A 426, 875
Lallement, R., Raymond, J. C., Bertaux, J.-L., et al. 2004b, A&A, 426, 867
Lallement, R., Qumerais, E., Bertaux, J.-L., et al. 2005, Science, 307, 1447
Linde, T., Gombosi, T., & Roe, P. 1998, J. Geophys. Res., 103, 1889
Linsky, J. L., & Wood, B. E. 1996, ApJ, 463, 254
Möbius, E., Bzowski, M., Chalov, S., et al. 2004, A&A, 426, 897
Myasnikov, A. 1997, Preprint No. 585, Institute for Problems in Mechanics, Russian Academy of Sciences
Myasnikov, A., Alexashov, D., Izmodenov, V., & Chalov, S. 2000, J. Geophys. Res., 105, 5167
Opher, M., Liewer, P. C., Velli, M., et al. 2004, ApJ, 611, 575
Pogorelov, N. V. 2004, AIP Conf. Proc., 719, 39
Pogorelov, N., & Matsuda, T. 1998. J. Geophys. Res., 103, 237
Pogorelov, N., & Matsuda, T. 2000, A&A, 354, 697
Ratkiewicz, R., Barnes, A, Molvik, G. A., et al. 1998, A&A, 335, 363
Ratkiewicz, R., Barnes, A., & Spreiter, J. 2000, J. Geophys. Res., 105, 25021
Tanaka, T., & Washimi, H. 1999, J. Geophys. Res., 104, 12605
Witte, M. 2004, A&A, 426, 835