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An Axisymmetric Magnetohydrodynamic Model for the Interaction of the Solar Wind with the Local Interstellar Medium

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Abstract—We numerically analyze a magnetohydrodynamic, steady-state model for the interaction of a spherically symmetric solar wind with a three-component local interstellar medium (LISM), which is composed of plasma, hydrogen atoms, and a magnetic field. The magnetic field is assumed to be parallel to the velocity in the LISM. In this case, the model is axisymmetric. We study the effects of magnetic field on the plasma-flow geometry and on the distribution of hydrogen-atom parameters. In particular, we show that the presence of hydrogen atoms does not affect the qualitative change in the shape of the bow shock, the heliopause, and the solar-wind shock with increasing strength of the interstellar magnetic field. The presence of a magnetic field in the LISM can strongly affect the parameters of the energetic hydrogen atoms originated in the solar wind, although its effect on the "hydrogen wall" observed with the GHRS instrument onboard the HST spacecraft (Linsky and Wood 1996) is marginal. © *2000 MAIK "Nauka/Interperiodica".*

Key words: *Solar system, heliosphere, heliopause, shock waves, interstellar medium, solar wind, interstellar magnetic field, hydrogen atoms*

1. INTRODUCTION

At present, the kinetic gas-dynamical model proposed by Baranov *et al.* (1991) and developed by Baranov and Malama (1993, 1995, 1996) is widely used in studying the interaction of the solar wind (SW) with the local interstellar medium (LISM). In this model, the interaction between the SW and LISM plasma components was considered on the basis of Euler's equations with the "source terms" describing the effect of hydrogen atoms in terms of their ionization via charge exchange with protons, photoionization, and electron impact ionization followed by the "capture" of newly formed protons by plasma. Since the mean free path of hydrogen atoms for these processes is comparable to the scale size of the problem, for example, to the size of the heliopause separating the LISM plasma from the SW plasma, it is improper to describe the motion of hydrogen atoms in terms of the equations of continuum mechanics. Therefore, to determine the "source terms," Baranov and Malama (1993) calculated the trajectories of hydrogen atoms by the Monte Carlo method with the trajectory "splitting" proposed by Malama (1991) and used the method of global iterations proposed by Baranov *et al.* (1991) to solve the self-consistent problem. A proper allowance for the LISM hydrogen atoms in the model is of particular importance, because one of the most efficient experimental methods for studying interstellar gas parameters is currently the method based on an analysis of scattered and absorbed radiation in the $L\alpha$ hydrogen line.

The model was further improved by taking into account the effects of new physical phenomena found experimentally. Thus, for example, Myasnikov *et al.* (2000a, 2000b) considered a self-consistent model of the SW–LISM interaction that allowed for Galactic cosmic rays. However, an adequate magnetohydrodynamic (MHD) model that allows for the interstellar and interplanetary magnetic fields has not yet been constructed, although numerous attempts have been made to construct such a model. For example, Linde *et al.* (1998) calculated a three-dimensional MHD model but took into account the resonant charge exchange by using an improper hydrodynamic model for hydrogen atoms proposed by Baranov *et al.* (1981) and severely criticized by Baranov and Malama (1993). Myasnikov and Barsky (1997) and Barsky (1999) considered the kinematic approximation, in which gas-dynamical model parameters are used to calculate the magnetic field, but MHD effects in the gas-dynamical flow are disregarded. There are also many papers devoted to axi-

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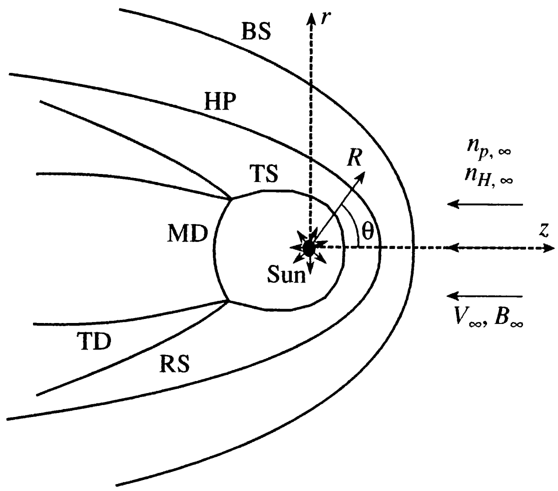

Fig. 1. The general pattern of flow produced by SW interaction with the LiSM. Here, r and z are the cylindrical coordinates; R is the heliocentric distance; θ is the polar angle; BS and TS are the bow and terminal shocks, respectively; HP is the heliophase; TD is the tangential discontinuity; RS is the reflected shock; and MD is the Mach disk.

symmetric (see, e.g., Fujimoto and Matsuda 1991; Baranov and Zaitsev 1995; Myasnikov 1997; Pogorelov and Semenov 1997) and three-dimensional (Pogorelov and Matsuda 1998) numerical MHD models ignoring the presence of hydrogen atoms in the LISM. Since the effect of LISM hydrogen atoms is significant, such papers are of purely theoretical interest and cannot form a basis for interpreting experimental results. Studying the effect of interstellar magnetic field on the penetration of hydrogen atoms from the LISM into the SW seems to be of crucial importance in interpreting measurements of hydrogen-atom parameters from spacecraft such as Ulysses, HST, SOHO, etc. (Izmodenov *et al.* 1999; Kirola *et al.* 1998; Lallement 1996; Gruntman 1993 and 1997). In particular, such an interpretation makes it possible to determine indirectly the plasma flow geometry, which seems of particular importance in view of the fact that its in-situ plasma measurements from the Voyager spacecraft are problematic in the near future, since, according to estimates, this spacecraft can leave the supersonic SW region only in several years.

The effect of interstellar magnetic field on the model is difficult to study theoretically primarily because its magnitude and direction in the LISM are virtually unknown. They can vary widely in models. Here, we present the first MHD model of the SW–LISM interaction, in which the interstellar magnetic field is taken into account within the framework of MHD equations with "source terms," and in which the trajectories of hydrogen atoms are calculated by the Monte Carlo method, as was done by Baranov *et al.* (1991) and Baranov and Malama (1993, 1995, 1996). For simplicity, we consider an axisymmetric model, in which the magnetic vector is assumed to be parallel to the interstellar-plasma velocity vector, and the SW is assumed to be spherically symmetric.

2. STATEMENT OF THE PROBLEM AND THE METHOD OF SOLUTION

Let us consider the interaction of a spherically symmetric solar wind with a uniform, translational flow of interstellar medium composed of plasma (electrons and protons), neutral hydrogen atoms, and magnetic field with the magnetic vector **B** parallel to the bulk velocity vector **v**. For a supersonic incoming flow, the emerging axisymmetric current is characterized by three surfaces of strong discontinuity (Fig. 1): a tangential discontinuity or heliopause (HP) separating the SW plasma from the LISM plasma, a bow shock (BS) through which the supersonic flow of interstellar plasma around the heliopause passes; and a terminal shock (TS) through which the SW decelerates. The plasma flow is assumed to be described in terms of steady-state MHD equations, which take the following form in cylindrical coordinates:

$$\frac{\partial \mathbf{D}}{\partial z} + \frac{\partial \mathbf{G}}{\partial r} = \mathbf{H} + \mathbf{Q}, \tag{1}$$

where

$$\mathbf{D} = \begin{bmatrix} \rho v_z \\ p + \rho v_z^2 + \dfrac{B_r^2 - B_z^2}{8\pi} \\ \rho v_z v_r - \dfrac{B_r B_z}{4\pi} \\ v_z\left(E + p + \dfrac{B^2}{8\pi}\right) - \dfrac{B_z}{4\pi}\mathbf{v}\cdot\mathbf{B} \\ 0 \\ v_z B_r - v_r B_z \end{bmatrix},$$

$$\mathbf{G} = \begin{bmatrix} \rho v_r \\ \rho v_z v_r - \dfrac{B_r B_z}{4\pi} \\ p + \rho v_r^2 + \dfrac{B_z^2 - B_r^2}{8\pi} \\ v_r\left(E + p + \dfrac{B^2}{8\pi}\right) - \dfrac{B_r}{4\pi}\mathbf{v}\cdot\mathbf{B} \\ v_r B_z - v_z B_r \\ 0 \end{bmatrix},$$

$$\mathbf{H} = -\frac{1}{r}\begin{bmatrix} \rho v_r \\ \rho v_r v_z - \frac{B_r B_z}{4\pi} \\ \rho v_r^2 - \frac{B_r^2}{4\pi} \\ v_r\left(E + p + \frac{B^2}{8\pi}\right) - \frac{B_r}{4\pi}\mathbf{v}\cdot\mathbf{B} \\ v_r B_z - v_z B_r \\ 0 \end{bmatrix}, \quad \mathbf{Q} = \begin{bmatrix} Q_1 \\ Q_{2,z} \\ Q_{2,r} \\ Q_3 \\ 0 \\ 0 \end{bmatrix},$$

$$\mathbf{v} = (v_z, v_r), \quad \mathbf{B} = (B_z, B_r), \quad v = |\mathbf{v}|,$$

$$B = |\mathbf{B}| \text{ and } E = p/(\gamma - 1) + \rho v^2/2 + B^2/8\pi.$$

Here, ρ, $\mathbf{v}$, and p are the mass density, mean velocity, and pressure of the plasma, respectively; γ is the ratio of specific heat capacities; E is the internal energy; and $\mathbf{B}$ is the magnetic vector. The functions Q_1, $\mathbf{Q}_2$, and Q_3 on the right-hand sides of the equations of continuity, motion, and energy, respectively, represent the "source terms," which are related to the main process of resonant charge exchange between hydrogen atoms and protons (we also take into account the photoionization of hydrogen atoms and their electron impact ionization). Since these functions depend both on the plasma parameters and on the parameters of hydrogen atoms, it is necessary to add equations describing the motion of the neutral component. As was pointed out above, the neutral component cannot be described in terms of the continuum equations. Therefore, for the system of equations to be closed, the Boltzmann equation for the distribution function f_H of hydrogen atoms must be added [as was shown by Baranov *et al.* (1998), this function differs markedly from the local Maxwell function]:

$$\mathbf{w}_H\frac{\partial f_H(\mathbf{r}, \mathbf{w}_H)}{\partial \mathbf{r}} + \frac{\mathbf{F}}{m_H}\frac{\partial f_H(\mathbf{r}, \mathbf{w}_H)}{\partial \mathbf{w}_H}$$
$$= -f_H(\mathbf{r}, \mathbf{w}_H)\int|\mathbf{w}_H - \mathbf{w}_p|\sigma_{ex}^{HP} f_p(\mathbf{r}, \mathbf{w}_p)d\mathbf{w}_p$$
$$+ f_p(\mathbf{r}, \mathbf{w}_p)\int|\mathbf{w}_H^* - \mathbf{w}_p|\sigma_{ex}^{HP} \qquad (2)$$
$$\times f_H(\mathbf{r}, \mathbf{w}_H^*)d\mathbf{w}_H^* - \beta f_H(\mathbf{r}, \mathbf{w}_H),$$

where $\mathbf{w}_H$ and $\mathbf{w}_p$ are the hydrogen-atom and proton velocities, respectively; $\mathbf{r}$ is the particle radius vector; f_p is the proton distribution function (assumed to be the local Maxwell one); $\mathbf{F}$ is the sum of the forces of solar attraction and radiative repulsion; σ_{ex}^{HP} is the cross section for charge exchange between hydrogen atoms and protons; β is the sum of the rates of photoionization β_i and electron impact ionization β_{im}; and m_H is the hydrogen atomic mass.

The "source terms" can be written as

$$Q_1 = \beta n_H \quad \left(n_H = \int f_H d\mathbf{w}_H\right),$$

$$\mathbf{Q}_2 = n_H\int\beta\mathbf{w}_H f_H d\mathbf{w}_H$$
$$+ n_H\iint\sigma_{ex}^{HP}|\mathbf{w}_H - \mathbf{w}_p| f_H f_p d\mathbf{w}_H d\mathbf{w}_p, \qquad (3)$$

$$Q_3 = n_H\int\beta\frac{w_H^2}{2}f_H d\mathbf{w}_H$$
$$+ n_H\iint\sigma_{ex}^{HP}\frac{w_H^2 - w_p^2}{2}f_H f_p d\mathbf{w}_H d\mathbf{w}_p.$$

In order to solve the system of equations (1)–(3), it is necessary to specify boundary conditions for the plasma velocity V, its temperature (or the Mach number M), and proton (electron) number density n_p in the Earth's orbit and in the incoming undisturbed LISM flow. As the boundary conditions for f_H in the undisturbed LISM, we take the Maxwell distribution with a given density $n_{H,\infty}$ and with the temperature and velocity equal to the plasma ones.

In solving the formulated gas-kinetic problem, we used the method of global iterations proposed by Baranov *et al.* (1991) and implemented by Baranov and Malama (1993, 1995, 1996). In the first iteration, the distributions of MHD parameters in the interaction region are calculated by the relaxation method by solving unsteady-state analogs of Eqs. (1) with zero source terms (3). Since the applied numerical technique (Myasnikov 1997) makes it possible to roughly distinguish the main MHD discontinuities obtained during the first iteration, the flow parameters can be directly used to solve Eq. (2) by the Monte Carlo method with trajectory splitting (Malama 1991). The calculated source terms (3) are used to solve Eqs. (1) in the next iteration. The iteration process terminates when the distributions of the plasma, hydrogen-atom, and magnetic-field parameters cease to depend markedly on the iteration number.

3. RESULTS OF CALCULATIONS AND THEIR ANALYSIS

In order to solve the stated problem, we fix the density of interstellar hydrogen atoms, 0.2 cm^{-3} (Gloekler *et al.* 1997), and take the parameters of the undisturbed SW and LISM plasma to be

$$V_E = 450 \text{ km/s}, \quad n_{p,E} = \rho_E/m_H = 7 \text{ cm}^{-3},$$
$$M_E = V_E/\sqrt{2kT_E/m_H} = 10,$$
$$V_\infty = 25 \text{ km/s}, \quad n_{p,\infty} = \rho_\infty/m_H = 0.07 \text{ cm}^{-3},$$
$$M_\infty = V_\infty/\sqrt{2kT_\infty/m_H} = 2.$$

Here, the subscripts E and ∞ refer to the Earth's orbit and the undisturbed LISM, respectively; T is the temperature, and k is the Boltzmann constant. We also fixed the adiabatic index $\gamma = 5/3$ and the ratio of the forces of radiation pressure and solar gravitation $\mu = 0.75$. The effect of the interstellar magnetic field was taken into account by varying the Alfvén Mach number $M_{A,\infty} = V_\infty\sqrt{4\pi\rho_\infty}/B_\infty$ over the range $\infty \le M_{A,\infty} \le 0.9$.

3.1. *Effects of Magnetic Field on the Flow Geometry*

Figure 2 shows the positions of the shocks (BS and TS) and the tangential discontinuity (HP) at various Alfvén Mach numbers in the undisturbed LISM. It is easy to see that the bow shock straightens out with decreasing Alfvén Mach number (increasing magnetic-field strength in the LISM). It approaches the Sun near the symmetry axis, but recedes from it on the flanks. By contrast, the nose of the heliopause recedes from the Sun due to the tension of magnetic field lines, while the heliopause in its wings approaches the Sun under magnetic pressure [the effect of heliopause stretching was obtained by Baranov and Krasnobaev (1971) in the Newtonian approximation of a thin layer]. The pattern of change in the bow shock and in the heliopause causes the region of the most effective "filtration" of interstellar hydrogen atoms (the region between BS and HP), where the primary hydrogen atoms are lost most intensely due to their charge exchange with interstellar protons, to decrease along the symmetry axis approximately by 50 AU, i.e., by almost 30% (see Fig. 2), as the magnetic field increases from zero to $B_\infty = 3.5 \times 10^{-6}$ G ($M_{A,\infty} = 0.9$).

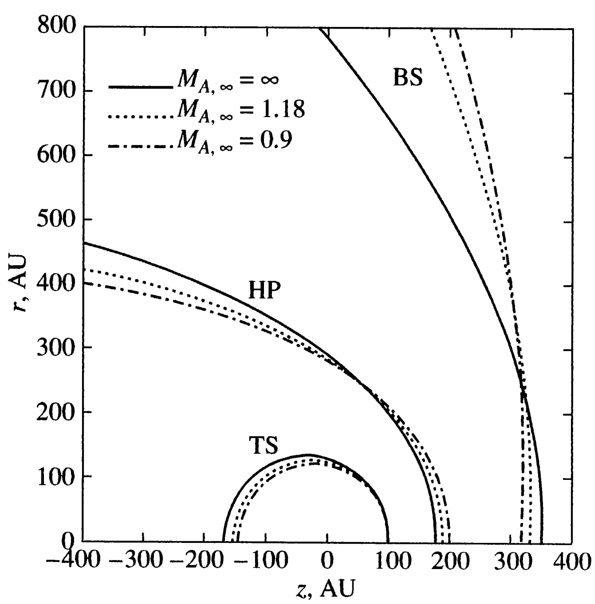

Fig. 2. Positions of the bow shock, the heliopause, and the terminal shock for various Alfvén–Mach numbers.

The fact that the heliopause approaches the Sun on the flanks, in turn, results in a decrease in the detachment of the terminal shock at $\theta = \pi$. Since the detachment of the terminal shock at $\theta = 0$ is independent of the magnetic-field strength (in the absence of hydrogen atoms, this fact can be easily obtained analytically by using the Bernoulli integral and relationships at the shocks), the terminal shock tends to become spherical in shape with increasing magnetic field. Thus, the pattern of change in the flow geometry with increasing magnetic field at $n_{H,\infty} \neq 0$ qualitatively agrees with the results of Baranov and Zaitsev (1995) and Myasnikov (1997).

Studies of the effects of magnetic field on the structure of the region of interaction between the SW and the LISM indicate that, in the absence of physical effects related to hydrogen atoms, an increase in the magnetic field results in the destruction of the complex flow structure in the tail region associated with the formation of a Mach disk (MD) and a triple point or a point of intersection of the Mach disk, the tangential discontinuity (TD), and the reflected shock (RS) (see Fig. 1). Resonant charge exchange produces the same effect, as was shown by Baranov and Malama (1993). Thus, the effects of both neutral hydrogen atoms and the interstellar magnetic field lead to the flow in the region between the terminal shock and the heliopause being subsonic in all calculations.

The reduction in the influence of magnetic field on the structure of the region of interaction between the SW and the LISM plasma with increasing $n_{H,\infty}$ is an important but predictable effect (Myasnikov and Barsky 1997). In particular, at $n_{H,\infty} = 0.2$ cm^{-3} and $M_{A,\infty} = 0.9$, there is a bow shock in the flow whose detachment on the symmetry axis differs only slightly from the case with $n_{H,\infty} = 0.2$ cm^{-3} and $M_{A,\infty} = \infty$ (Fig. 2). At the same time, the calculations performed at $n_{H,\infty} = 0$ and $M_{A,\infty} = 0.9$ (Myasnikov 1997) indicate that the solution falls within the ellipticity region of Eqs. (1), which results in the disappearance of the bow shock. Baranov and Zaitsev (1995) predicted the possibility of such an effect.

3.2. *Effects of Magnetic Field on the Characteristics of Hydrogen Atoms*

Resonant charge exchange of interstellar hydrogen atoms gives rise several kinds of hydrogen atoms with different characteristics, depending on the region of their production. The high-energy hydrogen atoms produced by charge exchange of SW protons before and after their passage through the terminal shock belong to kinds 1 and 2, respectively. Clearly, kind-1 hydrogen atoms must have a high mean radial velocity comparable to the supersonic SW velocity, while kind-2 hydrogen atoms must have a high thermal velocity deter-

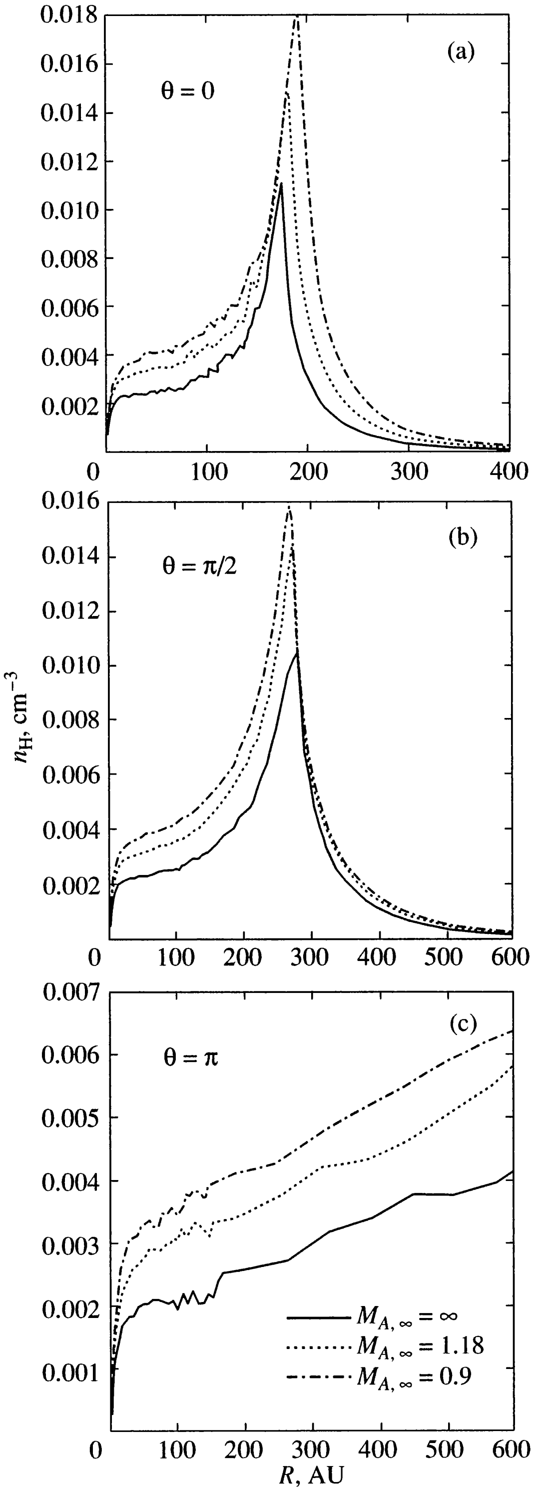

Fig. 3. The density distribution of energetic hydrogen atoms produced behind the terminal shock (kind 2) for $\theta = 0$, $\pi/2$, and π (a, b, c, respectively).

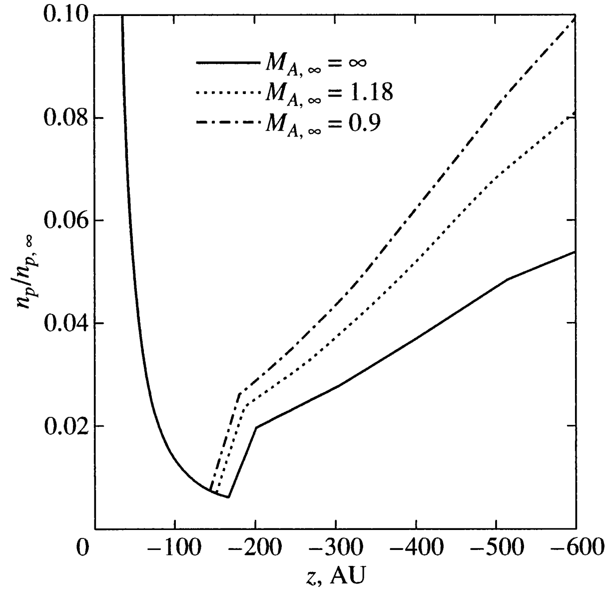

Fig. 4. The proton density distribution for $\theta = \pi$ at various Alfvén–Mach numbers.

mined by the SW proton temperature behind the terminal shock. The secondary hydrogen atoms produced by charge exchange of LISM atoms with inherent protons belong to kind 3, while the primary LISM atoms that underwent no charge exchange belong to kind-4. Kind-3 and 4 atoms have the LISM particle energy and are detected at a wavelength of 1216 Å in absorption lines from the nearest stars (Linsky and Wood 1996) and by analyzing scattered solar radiation (Bertaux and Blamont 1971; Thomas and Krassa 1971; Kirola *et al.* 1998; Lallement 1996). As for the hydrogen atoms with the SW particle energy (kinds 1 and 2), their flows can be measured from a distance of 1 AU by direct methods based on the technique proposed by Gruntman (1993, 1997).

Our calculations indicate that the density distribution of kind-1 hydrogen atoms is virtually unchanged at all polar angles $0 \le \theta \le \pi$ and over the entire assumed range of $M_{A,\infty}$. In particular, for $M_{A,\infty} = \infty$, these results closely agree with those obtained by Baranov *et al.* (1998). The magnetic field has the strongest effect on the density distribution of kind-2 hydrogen atoms presented in Fig. 3 for $\theta = 0$ (in the "leeward" direction), $\theta = \pi/2$ (perpendicular to the leeward direction), and $\theta = \pi$ (in the tail region). The physical causes of an almost a factor of 1.5 rise in the density of kind-2 hydrogen atoms as the interstellar magnetic field increases from zero to 3.5×10^{-6} G differ in different regions. In the leeward direction, the rise can be caused by an increase in the thickness of the region between HP and TS responsible for the production of kind-2 hydrogen atoms. In the tail region, the increase in the number of kind-2 hydrogen atoms is facilitated by an increase in the number of thermalized SW protons behind the terminal shock with growing magnetic field as it approaches the Sun (see Figs. 2 and 4).

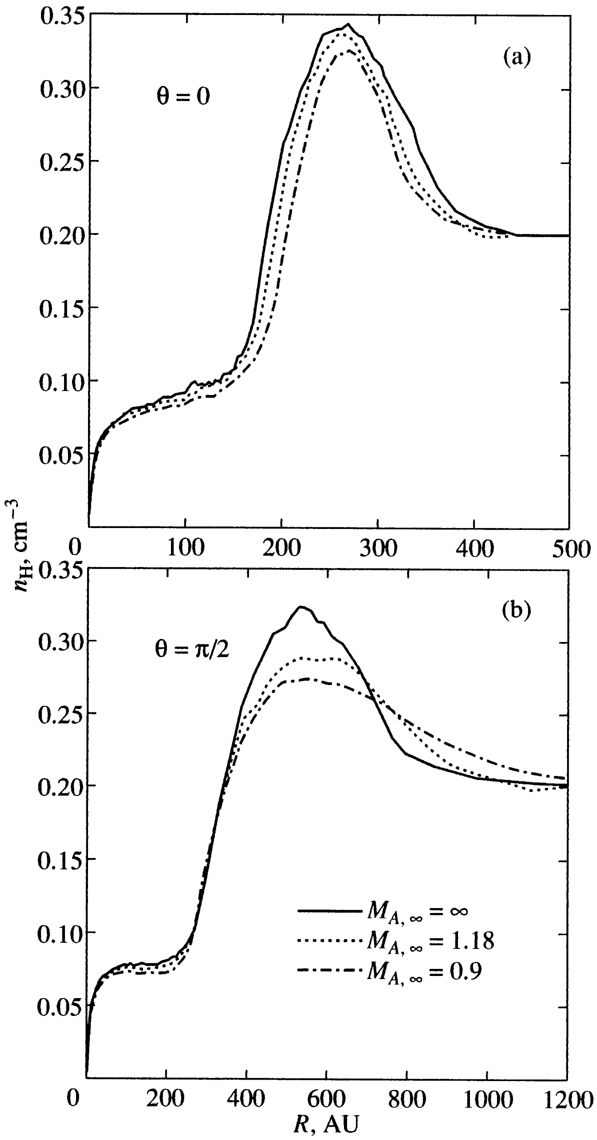

Fig. 5. The density distribution of hydrogen atoms produced in the LiSM (kind 3) at $\theta = 0$ (a) and $\theta = \pi/2$ (b) for various Alfvén–Mach numbers.

The effect of an increase in the number of kind-2 hydrogen atoms with growing interstellar magnetic field can be useful in their direct detection, because the efficiency of the method proposed by Gruntman (1993, 1997) is determined by the sensitivity of the instruments measuring the fluxes of these particles.

The nonmonotic behavior of the density of kind-3 hydrogen atoms was first theoretically predicted by Baranov *et al.* (1991). In the literature, this effect was called a *hydrogen wall.* The formation of a hydrogen wall is physically related to the production of secondary hydrogen atoms (kind 3) via charge exchange of primary (kind 4) atoms with almost stagnated protons near the heliopause (that is why the maximum of the hydrogen wall is located in the immediate vicinity of the heliopause). Interpretation of the experimental data on the absorption of $L\alpha$ emission from αCen obtained with the GHRS instrument onboard the HST spacecraft led Linsky and Wood (1996) to conclude that the theoretically predicted hydrogen wall was discovered experimentally. This conclusion was based on the fact that the absorption spectra obtained could be explained only by introducing a hydrogen wall. Therefore, it seems to be important to study the dependence of the position and height of the hydrogen wall on various physical factors, in particular, on the interstellar magnetic field.

We see from Fig. 5 that the interstellar magnetic field parallel to the LISM velocity vector changes the hydrogen-wall parameters only slightly. In particular, the hydrogen-wall height decreases approximately by 10% as the magnetic field changes from zero to 3.5×10^{-6} G; this wall recedes from the Sun together with the heliopause. The decrease in the height of the hydrogen wall is slightly larger in the direction perpendicular to the symmetry axis, as we see from Fig. 5b. The decrease in the hydrogen-wall height near the symmetry axis with increasing magnetic field is clearly attributable to a decrease in the filter thickness in this region. The same effect in the perpendicular direction can be explained by a decrease in the density of LISM protons in the bow-shock wings (oblique shock) compared to the direct shock near the symmetry axis. In both cases, the number of secondary hydrogen atoms responsible for the nonmonotic behavior of the density of hydrogen atoms decreases. In our view, a marginal effect of the magnetic field on the position and height of the hydrogen wall cannot change its interpretation on the basis of analysis of absorption spectra in the $L\alpha$ line (Linsky and Wood 1996). An interpretation of the observed HST absorption spectrum in this line along a line of sight passing through the heliospheric tail (toward Sirius) shows (Izmodenov *et al.* 1999) that the spectrum can be explained by taking into account absorption by kind-2 hydrogen atoms, because there is no hydrogen wall in the tail region.

4. CONCLUSION

(1) We have numerically constructed a steady-state MHD model for the SW interaction with a partially ionized, magnetized LISM for the first time. In this model, we use the kinetic gas-dynamical approach proposed by Baranov and Malama (1993), in which the plasma is described by MHD equations, while the hydrogen-atom parameters are determined by the Monte Carlo method with trajectory splitting proposed by Malama (1991). The magnetic vector is assumed to be parallel to the plasma velocity vector, which makes it possible to consider the problem in terms of axial symmetry.

(2) We have shown that the pattern of change in the flow geometry (the shape of the shocks and tangential discontinuity) with increasing interstellar magnetic

field qualitatively agrees with that calculated by Baranov and Zaitsev (1995) in the absence of neutral atoms and in the range of polar angles $0 \leq \theta \leq \pi/2$. Our calculation of the flow at $0 \leq \theta \leq \pi$ by the numerical method proposed by Myasnikov (1997) indicates that the magnetic field, as well as neutral atoms (Baranov and Malama 1993), destroys the complex flow pattern to form a triple point and a Mach disk. The terminal shock becomes oval, approaching a sphere with increasing magnetic field, while the flow between the heliopause and the terminal shock becomes subsonic.

(3) The magnetic field has a fairly strong effect on the energetic hydrogen atoms produced by charge exchange of LISM hydrogen atoms with thermalized SW protons behind the terminal shock (kind-2). An almost a factor of 1.5 increase in the density of these atoms with increasing magnetic field can relax the requirement on the sensitivity of instruments for their detection (Gruntman 1993, 1997).

(4) A marginal (about 10%) change in the parameters of the hydrogen wall theoretically discovered by Baranov *et al.* (1991) near the heliopause cannot affect the conclusions reached by Linsky and Wood (1996) that this wall was experimentally discovered with the GHRS instrument onboard the HST spacecraft.

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