AXISYMMETRIC SELF-CONSISTENT MODEL OF THE SOLAR WIND INTERACTION WITH THE LISM: BASIC RESULTS AND POSSIBLE WAYS OF DEVELOPMENT

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Abstract. We analyze the main results of the axisymmetric self-consistent model of the solar wind (SW) and supersonic local interstellar medium (LISM) interaction proposed by Baranov and Malama (1993, hereafter BM93, 1995) for an interstellar flow assumed to be composed of protons, electrons and hydrogen atoms. Here, in addition to the resonant charge exchange we also take into account the photoionization and the ionization by electron impact. The characteristics of the plasma in the interface region and inside the heliosphere depend strongly on the ionization degree of the LISM. The distribution function of the H atoms which penetrate the solar system from the LISM is non-Maxwellian, which implies that a pure hydrodynamic description of their motion is not appropriate. The H atom number density is a non-monotonic function of the heliocentric distance and the existence of a "hydrogen wall" in the vicinity of the heliopause is important for the interpretation of solar Lyman-alpha scattering experiments.

The influence of the interface plasma structure on the interstellar oxygen penetration into the solar system is also illustrated. Possible ways of development of the model are analyzed.

1. Introduction

The model of the solar wind interaction with the supersonic flow of the local interstellar medium (LISM) was first suggested by Baranov et al. [1970]. They proceeded from the concept of the Sun's motion relative to the nearest stars (consequently, relative to the interstellar gas at rest) with a velocity of $V_\infty \cong 20$km/s. This velocity is supersonic for a temperature $T_\infty \cong 10^4$K. The first model was constructed in a Newtonian approximation of a thin layer (hypersonic flows) under the assumption that the LISM is a fully ionized gas (two-shock model). The model by Baranov et al. [1970] has become especially interesting after the beginning of the 1970s, when experiments on scattered solar radiation in 1216 and 584Åwavelengths and their interpretation [Bertaux and Blamont, 1971; Thomas and Krassa, 1971; Blum and Fahr, 1970; Fahr, 1974; Weller and Meier, 1974] proved that H and He atoms of the LISM move with supersonic velocity $V_\infty \cong 20 - 25$km/s relative to the Sun. However, the direction of this motion did not coincide with the direction of the solar motion with respect to the nearest stars (apex direction). After the experimental discovery of the penetration of H and He atoms into the solar system it became impossible to construct the model of the solar wind interaction with the LISM on the basis of hydrodynamic equations, because the mean free path of neutral atoms is comparable with the characteristic length of the system, for example, with the size of the heliosphere (the hydrodynamic approximation can be correct for the solar wind interaction with the ionized hydrogen of the LISM only).

At present there is no doubt, that the LISM contains a partially ionized gas. Therefore, it is necessary to develop a correct model of the solar wind interaction

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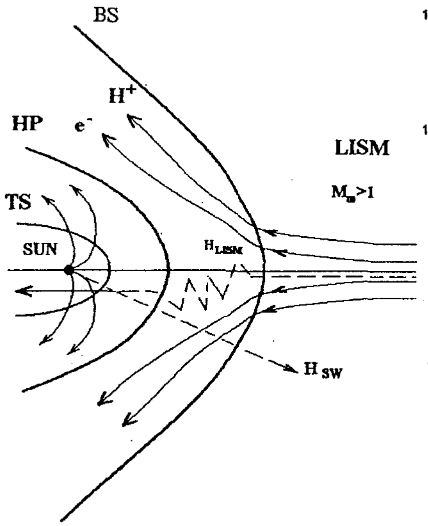


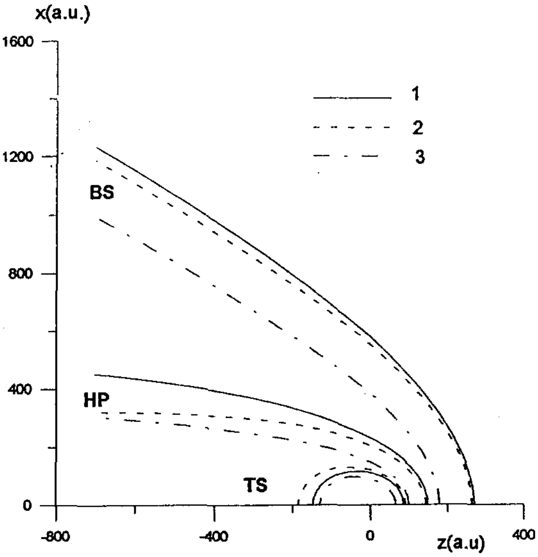


Figure 1. left: Qualitative picture of the solar wind interaction with the supersonic LISM: BS is the bow shock, HP is the heliopause, TS is the termination shock; H_{LISM} are H atoms of the LISM's origin, H_{SW} are energetic H atoms of solar wind origin.
Figure 2. right: Geometrical pattern of the interface for $n_{e\infty} = 0.1 \mathrm{cm}^{-3}$, $n_{H\infty} = 0.2 \mathrm{cm}^{-3}$ (curves 1) and for $n_{e\infty} = 0.2 \mathrm{cm}^{-3}$, $n_{\mathrm{H}\infty} = 0.3 \mathrm{cm}^{-3}$ (curves 3). The curves 2 correspond to the same conditions as for the curves 1, but when neglecting H atoms ionization due to electron impact.

with the LISM taking into account the mutual influence of plasma (electrons and protons) and neutral (H atoms) components of the flow (helium atoms are negligible in the problem considered because their cosmic abundance is much less than that of H atoms).

Wallis [1975] was the first who showed that plasma and neutral components can influence each other by resonance charge exchange processes. This mutual influence has two aspects: first, the plasma interface between two shocks (the solar wind termination shock TS and the interstellar bow shock BS) in the model of Baranov et al. [1970, 1979] becomes a kind of filter for H atoms penetrating from the LISM to the solar system and, second, the resonance charge exchange processes can change the plasma interface structure and its distance from the Sun. However, it was difficult to obtain quantitative results, because the electron (proton) number density of the LISM ($n_{e\infty} \cong n_{p\infty}$) is a parameter which is measured very poorly. In particular, the observed magnitude of this parameter could range from $0.003 cm^{-3}$, deduced from LISM observations of the ionization state of magnesium [Frisch et al.,1990], up to about $0.1 cm^{-3}$ according to ionization calculations by integrated celestial UV radiation [Reynolds, 1990]. There is no clear observational upper limit to the local magnitude of $n_{p\infty}$. For example, an interpretation neutral magnesium absorption detected by Goddard High-Resolution Spectrograph (GHRS) on board of the Hubble Space Telescope (HST) in terms of an extremely small Local Interstellar Cloud (LIC), could give rise to a very large proton number density $n_{p\infty} = 0.3 cm^{-3}$ [Lallement et al., 1992, 1994], if the LIC temperature is as small as measured toward Capella and for the neutrals in the solar system.

The first papers [Baranov et al., 1979; Baranov and Ruderman, 1979; Ripken and Fahr, 1983; Fahr and Ripken, 1984] did not take into account the influence of the resonance charge exchange on the motion of the plasma component, although they showed that the effect of the filter can be important.

Baranov et al. [1981] were the first who have constructed a self-consistent model taking into account the mutual influence of plasma and neutral components via the processes of the resonance charge exchange to estimate the influence of the LISM's H atoms on the plasma structure of the heliosphere. However, this model had a number of defects (see, for instance, the review by Baranov [1990] and BM93): (1) the motion of the LISM's H atoms was described by hydrodynamical equations, although the mean free path of H atoms and the characteristic length scale of the problem are comparable; (2) the temperature T_H and velocity V_H of H atoms were assumed constants and the change of H atom number density n_H was determined by the continuity equation taking into account the charge exchange loss term only; (3) plasma momentum and energy sources, which are due to resonance charge exchange processes, were used in the hydrodynamical equations in the Maxwellian approximation for the H atom distribution function [Holzer, 1972]. To correct these defects, we decided to use the Monte Carlo method, suggested by Malama [1991], for simulation of the H atom trajectories. This simulation gives us an opportunity to calculate "source" terms of the momentum and energy equations for the plasma component on the basis of the kinetic description of the H-atoms. An iterative method was proposed by Baranov et al. [1991] to solve the problem of the solar wind interaction with the two-component (plasma and H atoms) interstellar gas. A complete numerical solution of the self-consistent axisymmetric problem was obtained by BM93 (below self-consistent two-shock model or, abbreviated, SCTS model).

2. The SCTS model. Mathematical formulation of the problem.

Let us consider the problem of the solar wind interaction with the supersonic flow of the LISM consisting of neutral (H atoms) and plasma (electrons and protons) components. The qualitative structure of the flow formed is given in Figure 1 under the assumption that the interaction between the solar wind and the plasma component of the LISM can be described by hydrodynamical equations. Here the BS is formed in the LISM's plasma due to deceleration of the plasma component. The HP (contact or tangential discontinuity) separates the LISM plasma component, compressed by the BS, and the solar wind, compressed by the TS. Neutral atoms (including H atoms) can penetrate the surface HP into the solar wind, because their mean free path is comparable with the characteristic length of the problem (for example, with the HP heliocentric distance). In so doing, there are two kinds of H atoms: H atoms of the LISM's origin (H_{LISM}) and energetic H atoms of the solar wind origin (H_{SW}) formed due to the charge exchange with solar wind protons. In the following we will distinguish with primary H_{LISM} from secondary H_{LISM} (born following charge exchange processes) and the solar wind H atoms (H_{SW}), which were born in the supersonic solar wind, from thise born in the subsonic region (in the region between TS and HP).

The region between BS and TS we will call the interface. It is interesting to note here that the plasma outside of the interface (pre-shock regions of BS and

TS) is disturbed due to processes of resonance charge exchange and the "pickup" of "new" protons. The solar wind disturbance is mainly caused by H atoms of the LISM (H_{LISM}) whereas the disturbance of the LISM plasma is mainly a result of the interaction with the energetic H atoms of the solar wind (H_{SW}) penetrating the LISM [Gruntman, 1982; Gruntman et al., 1990]. These effects were also taken into account in the model by Baranov and Malama [1993, 1995].

Hydrodynamic equations for the plasma component must take into account the momentum and energy changes due to processes of resonance charge exchange ("source" terms). For a stationary problem, the equations of mass, momentum and energy conservation for ideal gas (without viscosity and thermal conductivity) have the following form (one-fluid approximation for plasma component)

$$\begin{gathered}\nabla \cdot \rho \mathbf{V} = 0,\\ (\mathbf{V} \cdot \nabla)\mathbf{V} + (1/\rho)\nabla p = \mathbf{F}_1[f_H(\mathbf{r}, \mathbf{w}_H), \rho, \mathbf{V}, p],\\ \nabla \cdot [\rho \mathbf{V}(\varepsilon + p/\rho + V^2/2)] = F_2[f_H(\mathbf{r}, \mathbf{w}_H), \rho, \mathbf{V}, p],\\ p = (\gamma - 1)\rho\varepsilon,\end{gathered} \tag{1}$$

where p, ρ, $\mathbf{V}$ and ε are pressure, mass density, bulk velocity and internal energy of the plasma component, respectively; γ is the ratio of specific heats; $\mathbf{F}_1$ and F_2 are the functionals, describing the change of momentum and energy of the plasma component due to collisions between H atoms and protons which characterize the resonance charge exchange ("source" terms); and $f_{\mathrm{H}}(\mathbf{r}, \mathbf{w}_{\mathrm{H}})$ is the H atom distribution function depending on position-vector $\mathbf{r}$ and the individual velocity $\mathbf{w}_{\mathrm{H}}$ of H atoms.

The trajectories of H atoms were calculated by the complicated Monte Carlo scheme with "splitting" of the trajectories [Malama, 1991] in the field of the plasma gasdynamic parameters. Such an approach allows the calculation of $\mathbf{F}_1$ and F_2 in equations (1) within the framework of a kinetic description of H atoms (multiple charge exchange are also taken into account by the Monte Carlo method). The use of this method is identical (Malama, 1991) to the numerical solution of the Boltzmann equation for f_{H}

$$\begin{aligned}&\mathbf{w}_{\mathrm{H}} \cdot \partial f_{\mathrm{H}}(\mathbf{r}, \mathbf{w}_{\mathrm{H}})/\partial \mathbf{r} + [(\mathbf{F}_r + \mathbf{F}_g)/m_{\mathrm{H}}] \cdot \partial f_{\mathrm{H}}(\mathbf{r}, \mathbf{w}_{\mathrm{H}})/\partial \mathbf{w}_{\mathrm{H}} =\\ &= f_p(\mathbf{r}, \mathbf{w}_{\mathrm{H}}) \int \mid \mathbf{w}'_{\mathrm{H}} - \mathbf{w}_{\mathrm{H}} \mid \sigma f_{\mathrm{H}}(\mathbf{r}, \mathbf{w}'_{\mathrm{H}}) d\mathbf{w}'_{\mathrm{H}}\\ &- f_{\mathrm{H}}(\mathbf{r}, \mathbf{w}_{\mathrm{H}}) \int \mid \mathbf{w}_{\mathrm{H}} - \mathbf{w}_p \mid \sigma f_p(\mathbf{r}, \mathbf{w}_p) d\mathbf{w}_p\end{aligned} \tag{2}$$

In equation (2) f_p is the local Maxwellian distribution function of protons with gasdynamic values $\rho(\mathbf{r}), \mathbf{v}(\mathbf{r})$ and $T(\mathbf{r})$ from equations (1), $\mathbf{w}_p$ is the individual velocity of a proton, $\mathbf{F}_g$ and $\mathbf{F}_r$ are the solar gravitational force and the force of radiation pressure, respectively, and σ is the cross section of the resonance charge exchange, which is determined by the formula $\sigma = (A_1 - A_2 \ln u)^2 \mathrm{cm}^{-2}$, where u is the speed of the proton relative to the H atom (in cm/s), $A_1 = 1.64 \cdot 10^{-7}$, $A_2 = 6.95 \cdot 10^{-9}$ [Maher and Tinsley, 1977].

If the distribution function f_{H} is known, then the "source" terms $\mathbf{F}_1$ and F_2 in (1) can be calculated exactly according to the Monte Carlo procedures of Malama [1991]. We have in this case

$$\begin{aligned}&\mathbf{F}_1 = 1/n \int d\mathbf{w} \int d\mathbf{w}_p \sigma \mid \mathbf{w}_{\mathrm{H}} - \mathbf{w}_p \mid (\mathbf{w}_{\mathrm{H}} - \mathbf{w}_p) f_{\mathrm{H}}(\mathbf{r}, \mathbf{w}_{\mathrm{H}}) f_p(\mathbf{r}, \mathbf{w}_p),\\ &F_2 = m \int d\mathbf{w} \int d\mathbf{w}_p \sigma \mid \mathbf{w}_{\mathrm{H}} - \mathbf{w}_p \mid (w_{\mathrm{H}}^2/2 - w_p^2/2) f_{\mathrm{H}}(\mathbf{r}, \mathbf{w}_{\mathrm{H}}) f_p(\mathbf{r}, \mathbf{w}_p),\\ &n_{\mathrm{H}} = \int d\mathbf{w}_{\mathrm{H}} f_{\mathrm{H}}(\mathbf{r}, \mathbf{w}_{\mathrm{H}}), \qquad n_p = \int d\mathbf{w}_p f_p(\mathbf{r}, \mathbf{w}_p).\end{aligned} \tag{3}$$

To solve the system of equations (1) - (3) the following boundary conditions for the plasma component were used: the Rankine-Hugoniot relations on the shock waves BS and TS (see Figure 1); the condition of equality of pressures and the no-flow condition (a vanishing normal component of the plasma velocity) through the contact discontinuity (HP); the symmetry conditions (the axisymmetric problem was solved by BM93); the velocities, electron (proton) number densities and Mach numbers are given in the undisturbed LISM (index "∞") and at Earth orbit (index "E"); and the non-reflecting conditions on the right boundary of the computation region. To calculate H atom trajectories and the "source" terms (3) the distribution function $f_{\rm H}$ was assumed to be Maxwellian in the undisturbed LISM (at infinity) with the temperature T_∞, number density $n_{\rm H\infty}$ and velocity V_∞. In so doing, the motion of H atoms is determined by the solar gravitational force $\mathbf{F}_g$, the force of solar radiation pressure $\mathbf{F}_r$, and the resonance charge exchange. Photoionization of H atoms is also taken into account near the Sun (we have now calculated our model taking also into account the H atom ionization due to electron impact in the region between HP and TS).

An iterative method for the solution of the problem, suggested by Baranov et al.[1991] and completed by Baranov and Malama [1993, 1995] consists of several steps. First the trajectories of H atoms are calculated by the Monte Carlo method in the field of plasma parameters obtained without "source" terms for fully ionized H (see, for instance, the zero iteration made by Baranov et al.[1991]). Then the momentum and energy "sources" $\mathbf{F}_1$ and F_2 in (1) are calculated in this step of the iteration using equations (3). In the first iteration, the hydrodynamical equations (1) with these "sources" are solved using the gasdynamic boundary conditions as formulated above. Then, the new distribution of plasma parameters is used for the next Monte Carlo iteration for H atoms. The gasdynamic problem is solved again with the new "source" terms of this iteration (the second iteration) and so on. This process of iterations is continued until the results of two subsequent iterations practically coincide. To solve the gasdynamic part of the problem numerically BM93 have used the discontinuity-fitting "second order" technique, which is based on the scheme of Godunov's method [Godunov et al.,1976; Falle, 1991]. We have also used the time stabilization method to solve the stationary problem, i.e. we solved the non-stationary version of equations (1).

3. Basic results of the SCTS model and their connection with experimental data.

3.1. GEOMETRICAL PATTERN OF THE INTERFACE

One of the main results of the axisymmetric model, described in Sec.2, is the geometrical pattern of the interface as a function of the H fractional ionization of the LISM. Figure 2 shows the BS, TS and HP shapes and heliocentric distances in the xOz plane for different magnitudes of electron (proton) and H atom number densities in the LISM. Here the Oz axis coincides with axis of symmetry and is antiparallel to the vector of the LISM's velocity V_∞ (the Sun is in the center of the coordinate system). The Ox axis is normal to the Oz axis.

The results presented in Figure 2 take into account the H atom ionization due to electron impact and photoionization and not just the resonance charge exchange

(Baranov and Malama, [1993,1995]). It should be noted here that the effect of ionization due to electron impact can be important in the region between TS and HP (the effect of H atom photoionization can be significant only near the Sun). For comparison the geometrical pattern of the flow without the processes of H atom ionization due to electron impact and photoionization is drawn in Figure 2 by the dashed lines (case 2). All results were obtained for the following values of the specified parameters

$$n_{pE} = 7\text{cm}^{-3}, \qquad V_E = 450\text{km/s}, \qquad M_E = 10$$
$$V_\infty = 26\text{km/s}, \qquad T_\infty = 6700\text{K} \qquad (M_\infty = 1.914), \tag{4}$$
$$\mu = F_r/F_g = 0.80,$$

where n_p, V_E and M are the proton number density, the solar wind radial velocity at the Earth's orbit and the Mach number, respectively. The values of the LISM parameters in (4) were chosen based on the observations of the Local Interstellar Cloud (LIC) by Lallement and Bertin [1992] and Lallement et al. [1994].

In a series of recent measurements from ground and space [Lallement and Bertin, 1992] the interstellar absorption lines due to the LIC were identified through reconstruction of its velocity vector by Doppler triangulation. It was proved that the solar system is embedded in the LIC moving relative to the Sun with the velocity $V_\infty = 25.7 \pm 0.5$km/s and temperature $T_\infty = 7000$K (supersonic flow with $M_\infty \cong 2$). The derived velocity V_∞ coincides with the vector by Lyman-alpha glow observations [Bertaux et al., 1985]. The motion of the LIC relative to the Sun with the same velocity vector was recently confirmed by the results of the Neutral Gas Experiment [Witte et al., 1993] on board the Ulysses spacecraft, which measured in situ the velocity distribution of the interstellar helium (the effect of the "filter" at the interface is negligible for He atoms).

From Figure 2 we see that in framework of the SCTS model (see Sec.2) the TS and HP positions in the upwind direction range from 65 up to 85 A.U and from 100 up to 148 A.U., respectively, for the range of parameters chosen (a different range of LISM parameters was used by Baranov and Malama [1993, 1995]). The position of the TS in the downwind direction ranges from 130 up to 150 A.U. Therefore, we estimate that the Voyager spacecraft moving in the upwind direction could cross the TS in the near future. The flow in the region between TS and HP is subsonic; and the Mach disc, reflected shock and tangential discontinuity are absent if the resonance charge exchange processes are taken into account. It should be stressed that the use of the discontinuity-fitting technique by BM93 provides the possibility to calculate exactly the TS, HP and BS locations and shapes , and at the same time to satisfy both the Rankine-Hugoniot relations at BS and TS, and the boundary conditions at the HP.

3.2. Predicted parameters of the plasma component in the distant solar wind and interface region

Plasma parameters and interplanetary magnetic field of the distant solar wind are measured by direct experiments on board the Voyager 1/2 and Pioneer 10/11 spacecraft. These experiments have shown that the average magnetic field as a function of the distance from the Sun follows Parker's model of the spiral structure (see, for example, Parker, [1963]). In this case the interplanetary magnetic field is negligible for considering the gas dynamics of the supersonic solar wind since $M_A \gg 1$, where M_A is the Alfven Mach number. However, the influence of H atoms penetrating from the LISM into the solar system, on the plasma parameters of the distant solar wind may be strong enough to be observed by spacecraft. This effect increases with decreasing LISM proton number density (at constant H number density in the LISM). The reason is that the role of the plasma "filter" between the BS and the HP decreases with decreasing LISM's H fractional ionization (Baranov and Malama, [1995]).

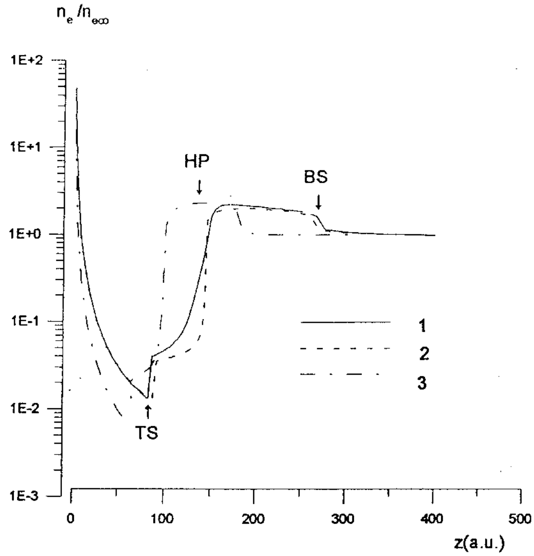
The following effects in the distant supersonic solar wind due to the process of resonance charge exchange were predicted by the SCTS model: the decrease of the solar wind velocity; the deviation of the proton number density from the law $1/r^2$, where r is the distance from the Sun; and the increase of the plasma temperature. It is interesting to note that there is experimental evidence of such effects obtained by Voyager and Pioneer (see, Richardson et al., [1995]). For example, the deceleration of the solar wind velocity as 30km/s (about 8% of the average velocity 440km/s) was estimated from experiments on Voyager 2 and IMP 8.

Figure 3 shows the electron number density n_e in upwind direction as a function of distance from the Sun. The key features of these distributions, caused by the effect of the LISM H atoms, are: (1) the deviation from the density law, $1/r^2$, before the TS, connected with the decrease of the solar wind velocity; (2) the strong increase in electron number density from TS to HP (Bernoulli's integral and an adiabatic law are not correct here due to the processes of resonant charge exchange); (3) the "pile-up" region of the LISM electrons near the HP, which are important for interpretation of the kHz radiation detected by Voyager (see, for example, Gurnett et al.[1993]; Gurnett and Kurth [1995]).

3.3. Predicted H atom parameters

The distribution of the H atom number density in the whole region of the flow is presented in Figure 4. As mentioned in Sec.2, we distinguish here two kinds of H_{LISM} (primary and secondary) and two kinds of H_{SW}, which were born due to the charge exchange of solar wind protons in the supersonic (upwind of the TS) and subsonic (between TS and HP) regions. From Figure 4 we see that the effect of the accumulation of H atoms moving from the LISM in the region between BS and HP (peaks of the number density in the vicinity of the HP or the effect of the "hydrogen wall") is connected with the secondary H_{LISM} only since the number density of the primary H_{LISM} decreases smoothly as the Sun is approached. This effect was first obtained by Baranov et al. [1991] numerically for the non-self-consistent problem and confirmed by BM93 with the solution of the self-consistent problem. Quemerais et al. [1993, 1995] used the idea of the "hydrogen wall" to explain the results of Lyman α measurements made by the Ultraviolet Spectrometers on board the Voyager 1 and 2 spacecraft since 1993 (see, also, the paper by Hall et al.[1993], where the validity of the distributions presented in Figure 4 is qualitatively confirmed by measurements of the UV interplanetary glow not only on board of Voyager but on Pioneer as well).

It is interesting to note here that the idea of the "H wall" was also used by Linsky and Wood [1995] for the interpretation of observations of interstellar gas absorption along the line-of-sight toward both components of the α Cen visual binary system $-\alpha$ Cen A (G2V) and α Cen B (K1V) - obtained with the GHRS instrument on board of the HST spacecraft. Linsky and Wood [1995] have shown that their observations cannot be explained by the one-component model of the interstellar gas. To explain the experimental results they suggested the "H wall" in



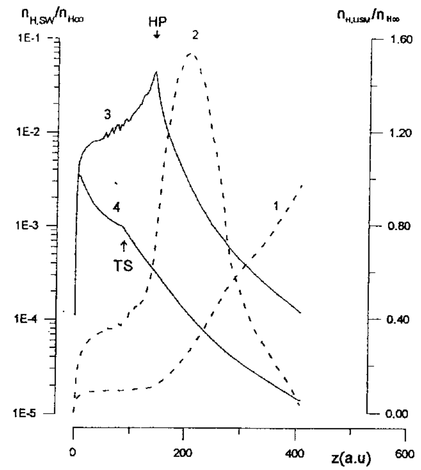


Figure 3. left: Electron number density in the upwind direction as a function of the distance from the Sun for $n_{e\infty} = 0.1\text{cm}^{-3}$, $n_{\text{H}\infty} = 0.2$ (curve 1) and for $n_{e\infty} = 0.2\text{cm}^{-3}$, $n_{\text{H}\infty} = 0.3\text{cm}^{-3}$ (curve 3). Results shown by curve 2 are obtained without taking into account H atom ionization by electron impact and are to be compared with curve 1. *Figure 4. right:* H atom number density in the upwind direction as a function of distance from the Sun for $n_{e\infty} = 0.1\text{cm}^{-3}$, $n_{\text{H}\infty} = 0.2\text{cm}^{-3}$. Dashed lines are for H_{LISM} (curve 1 is for primary H atoms and curve 2 is for secondary H atoms) and solid lines are for H_{SW} (curves 3 and 4 are for H atoms born due to charge exchange in the subsonic and supersonic solar wind, respectively).

the heliosphere as a second component, which contributes significantly to the total H absorption.

Although the effect of H_{LISM} is strong enough to influence the plasma interface structure, the effect of energetic solar wind H atoms (H_{SW}) is also important for the flow considered. This effect, suggested by Gruntman [1982] qualitatively, was first considered by BM93 quantitatively. In particular, the contribution of each H atom component (H_{LISM} and H_{SW}) to the source terms $\mathbf{F}_1$ and F_2 of equations (1) is determined by the following estimates

$$\frac{|\,\mathbf{F}_1\,|_{\text{LISM}}}{|\,\mathbf{F}_1\,|_{\text{SW}}} \simeq \frac{n(\text{H}_{\text{LISM}})V_\infty^2}{n(\text{H}_{SW})V_E^2}, \qquad \frac{|\,F_2\,|_{\text{LISM}}}{|\,F_2\,|_{\text{SW}}} \simeq \frac{n(\text{H}_{LISM})V_\infty^3}{n(\text{H}_{SW})V_E^3}$$

Taking into account these estimates, one can see from Figure 4, where the distribution of the H_{SW} number density is also presented [BM93], that: (1) in the entire LISM region the neutral solar wind H atoms are the main source of heating of the LISM plasma; (2) near the HP we have $|\,\mathbf{F}_1\,|_{\text{LISM}} \cong |\,\mathbf{F}_1\,|_{\text{SW}}$, but $|\,\mathbf{F}_1\,|_{\text{LISM}} > |\,\mathbf{F}_1\,|_{\text{SW}}$ near the BS. Thus, the heating of the LISM plasma by the

H_{SW} atoms leads to the decrease of the Mach number ahead of the BS, which can disappear due to this effect if $n_{H\infty}$ is large enough.

The characteristics of the energetic neutral H atom fluxes in the heliosphere (H_{SW}) have never been explored experimentally. Recent developments in experimental technique (see, for example, Gruntman and Morozov [1982], Gruntman et al.[1990], Gruntman [1993]) suggest that these fluxes can be reliably measured. In particular, techniques for viewing the outer heliosphere in energetic neutral atoms from within were suggested by Hsieh and Gruntman [1993].

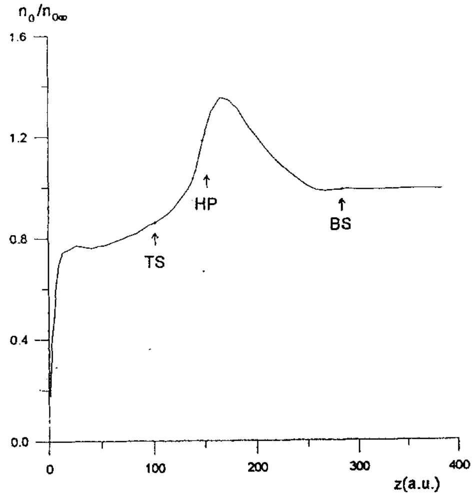
3.4. Oxygen atom penetration from the LISM to the solar system

As we have mentioned above there are no direct ways to measure the LISM electron (or proton) number density. Among the various types of diagnostics are the observations of species which can penetrate deeply in the heliosphere such, as the interstellar neutral atoms. Certain of these neutrals suffer significant modifications during the crossing of the plasma interface region (see Figure 1). Models show that the changes in the abundances and velocity distributions due to the interface filtering do vary strongly from one species to another (for example, He atoms penetrate the solar system through the interface practically without changing). As a result, the relative abundances and the velocity distributions of different species inside the heliosphere can be different from the original interstellar abundances and velocity distributions.

The charge exchange cross-section of O and a proton, as well as H and a proton, is large enough for O and H atoms to suffer significant modifications in the plasma interface. We have already considered above the problem of H atom filtering. The problem of O atom penetration from the LISM to the solar system is also intimately related to the problem of the plasma interface structure. The process of O penetration from the LISM to the solar system was investigated theoretically by Izmodenov et al. [1996], who used a Monte Carlo method for calculations of O atom trajectories with plasma parameters from the SCTS model (Baranov and Malama, [1993, 1995]). An example of these calculations is shown in Figure 5. From Figure 5 we see that the effect of the interface filter is important for O atoms penetrating the solar system from the LISM. Previously this fact was discussed by Fahr and Osterbart [1995], who used the parker's model of the interaction between the incompressible interstellar and solar winds.

4. Possible ways of development of the SCTS model.

The present model does not take into account a number of physical phenomena. It ignores the effects of the interplanetary and interstellar magnetic fields. The Alfven Mach number $M_A \gg 1$ in the supersonic solar wind (ahead of TS) and, therefore, the interplanetary magnetic field is negligible in this region. However, the last inequality is not necessarily fulfilled in the region between TS and HP (especially in the vicinity of the stagnation point) and magnetohydrodynamic effects could be important in this region. At present neither the value nor the direction of the LISM magnetic field is known. That is why Baranov and Zaitsev [1995] began to study the effect of the interstellar magnetic field on heliospheric structure in an axisymmetric



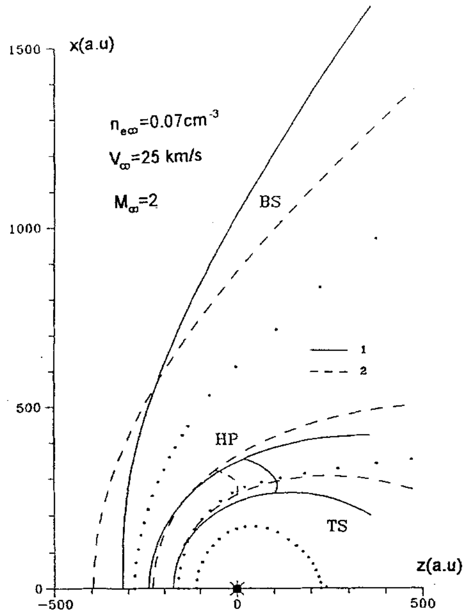


Figure 5. left: Effect of the interface region on oxygen atoms penetrating from the LISM to the solar system. O atoms number density (normalized to the density in the LISM) is presented in the upwind direction for $n_{e\infty} = 0.1\mathrm{cm}^{-3}$, $n_{H\infty} = 0.2\mathrm{cm}^{-3}$ as a function of distance from the Sun (Izmodenov et al.,1996). *Figure 6. right:* Effect of the interstellar magnetic field on the geometrical pattern of the flow (vector of the magnetic field **B** is parallel to the vector of the LISM plasma velocity). Parameter α is equal $B_\infty/V_\infty\rho_\infty^{1/2}$, where ρ_∞ is the LISM mass density. Curves 1 correspond to $\alpha = 2.2$ and curves 2 to $\alpha = 0$ both with $n_{H\infty} = 0$ (Baranov and Zaitsev, 1995); dotted lines correspond to $\alpha = 0$ and $n_{H\infty} = 0.14\mathrm{cm}^{-3}$ (BM93).

approximation (the LISM magnetic field is parallel to the vector of the LISM velocity) and for a one-component (plasma) interstellar gas. A comparison of the effects of the interstellar magnetic field in this case [Baranov and Zaitsev, 1995] and of the H atoms of the LISM [BM93] on the geometrical pattern of the flow is presented in Figure 6 (dashed, solid and dotted lines are used for the non-magnetized and magnetized fully ionized LISM, and for the non-magnetized partially ionized LISM, respectively). We see that the thickness of the region between the HP and BS at the axis of symmetry is reduced by a factor 2.3 and becomes 1.8 times less than when taking into account the resonant charge exchange without magnetic field. On the contrary, the thickness of the region between HP and BS along the line passing through the Sun perpendicular to the z-axis increases by 36%. The thickness of this region affects its transparency to the LISM H atoms penetrating the solar system.

We also did not take into account the effects of galactic and anomalous component cosmic rays (GCR and ACR respectively). We think that these effects do not significantly change the results presented in Sec.3. However, as shown by Chalov and Fahr [1994, 1995], the ACR could decrease the TS strength. A TS of very small strength may not be detected while traversed by a spacecraft.

It should be noted that the BM93 model is a one-fluid model for the plasma component. An attempt to develop a two-fluid model (pick-up and primary

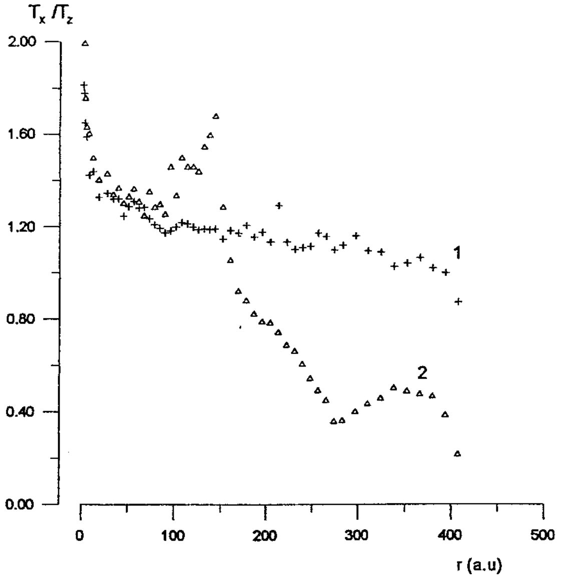


Figure 7. Ratio of H atom apparent temperatures (along the Ox and Oz axes) as a function of distance from the Sun for $n_{e\infty} = 0.1\text{cm}^{-3}$, $n_{H\infty} = 0.2\text{cm}^{-3}$. Crosses (1) and triangles (2) correspond to the primary and secondary H_{LISM} respectively.

solar wind protons) was developed by Whang et al. [1995]. However, the hydrodynamic system of equations used for the H atoms of the LISM is derived from the Boltzmann equation under the assumption of a Maxwellian distribution function (Whang, [1995]). This last assumption is not correct for neutral atoms because their mean free path is comparable with the characteristic length scale of the problem. Figure 7 demonstrates the last statement. "Effective" temperatures along the Ox and Oz axes are different. This means that the distribution function f_H of H atoms is not Maxwellian. Hydrodynamic equations for H atoms of the LISM were also used by Pauls et al. [1995] to describe the interaction of the solar wind with the two-component LISM gas. In so doing, Pauls et al. [1995] did not take into account the multiple charge exchange, energetic solar wind H atoms (H_{SW}), the gravitational force, and the force of radiation pressure (these combined effects were taken into account in the model by BM93). Finally, the present model is axisymmetric and stationary, although experiments on board Ulysses and other spacecraft have shown that the solar wind velocity and electron number density can be functions of solar latitude and solar activity. Therefore, it is necessary to develop three-dimensional and non-stationary models.

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