Interstellar atoms in the heliospheric interface

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In order to enter the heliosphere the interstellar atoms pass through the heliospheric interface - the region of the solar wind and interstellar plasma interaction. In the interface, the interstellar hydrogen atoms strongly interact with the LISM plasma component by charge exchange. This interaction results in the modification of both plasma and interstellar atom flows. Thus, the atoms penetrate into the heliosphere disturbed. This opens a possibility to use interstellar atoms and their derivatives - pickup ions and anomalous cosmic rays - for remote diagnostics of the heliospheric interface plasma structure. However, the interpretations of remote experiments are critical to accurate theoretical models.

In this paper advanced self-consistent models of the heliospheric interface are reviewed. Evolution of the atom velocity distribution in the heliospheric interface is discussed with the emphasis on interpretation of present and future space experiments.

1. Introduction

At the present time there is no doubt that local interstellar medium (LISM) is partly ionized plasma. Interstellar plasma component interacts with the solar wind (SW) plasma and forms the heliospheric interface (Figure 1). The heliospheric interface is a complex structure, where the solar wind and interstellar plasma, interplanetary and interstellar magnetic fields, interstellar atoms, galactic and anomalous cosmic rays (GCRs and ACRs) and pickup ions play prominent roles. In this paper I will review physical processes connected with interstellar atoms.

Interstellar atoms of hydrogen are the most abundant component in the circumsolar local interstellar medium. These atoms penetrate deep into the heliosphere and interact with interstellar and solar wind plasma protons by charge exchange. This interaction influences the structure of the heliospheric plasma interface significantly. Being disturbed in the interface, interstellar H atoms and their derivatives such as pickups and ACRs can serve as remote diagnostics of the heliospheric interface. To make constructive conclusions from space experiments one must use an adequate theoretical model. The main difficulty in the modelling of the heliospheric interface is a kinetic character of the interstellar H

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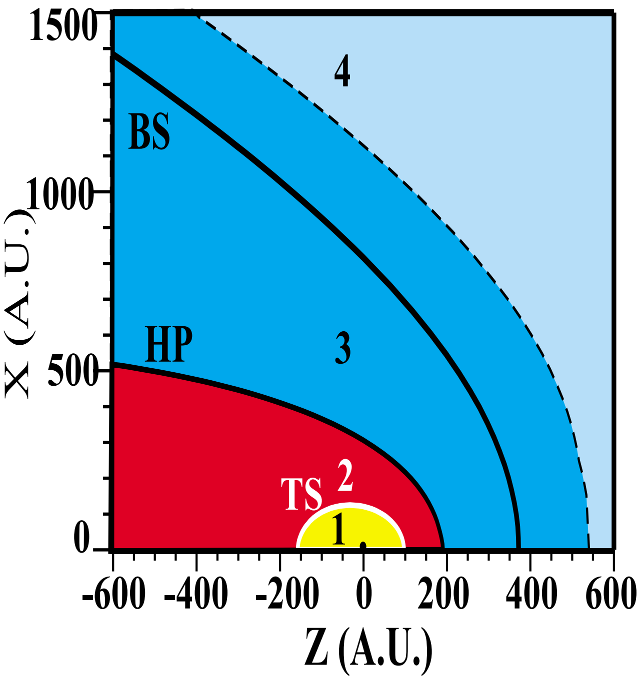

Figure 1. Structure of the heliospheric interface. The termination shock (TS), the heliopause (HP), the bow shock (BS) separates the heliospheric interface in four regions. Region 1 is the supersonic solar wind. Region 2 is the heliosheath with compressed solar wind plasma. Region 3 is the region of disturbed interstellar medium. The region is extended upstream BS (see, section 3). Region 4 is undisturbed interstellar medium.

atom flow in the heliospheric interface. Since the effects of elastic H-H, H-p collisions are negligibly small as compared with charge exchange, the latter process determines the character of the H atom flow in the interface (see, e.g., [10] and section 3 of this paper).

Atoms newly created by charge exchange have local plasma properties. Since plasma properties are different in four regions shown in figure 1, there are four populations of interstellar atoms in the heliospheric interface. Population 1 is the atoms created in the supersonic solar wind. Population 2 is the atoms created in the heliosheath. Population 3 is the atoms created in the region of disturbed interstellar plasma (region 3 in Figure 1). Population 4 is the original interstellar atoms. The strength of H atom-proton coupling can be estimated through the calculation of mean free paths of H atoms in plasma. Generally, the mean free path of s-particle in t-gas can be calculated by the formulae: $L = \frac{w_s^2}{\delta M_{st}/\delta t}$. Here, w_s is the individual velocity of s-particle, $\delta M_{st}/\delta t$ is individual s-particle momentum transfer rate in t-gas, which is a function of local plasma parameters.

Table 1 shows the mean free paths of H atoms with respect of charge exchange with protons. The mean free paths are calculated for typical atoms of different populations at different regions of the interface in the upwind direction. For every population of H atoms there is at least one region in the interface where Knudsen number $Kn = \frac{MeanFreePath}{CharacteristicLength} \approx 0.5 - 1.0$. Therefore, kinetic Boltzmann approach must be used to describe interstellar atoms in the heliospheric interface.

Table 1
Meanfree paths of H-atoms in the heliospheric interface with respect to charge exchange with protons, in AU

Population	At TS	At HP	Between HP and BS	LISM
4 (primary interstellar)	150	100	110	870
3 (secondary interstellar)	66	40	58	190
2 (atoms originated in the heliosheath	830	200	110	200
1 (neutralized solar wind)	16000	510	240	490

2. Heliospheric Interface Model

Baranov et al. [1] and Baranov and Malama [2] considered a two-dimensional (2-D) axisymmetric model of the SW/LISM interaction. The interstellar and solar wind plasma components were treated as fluids. To describe the flow of interstellar atoms the Boltzmann equation was solved:

$$\mathbf{w}_{\mathrm{H}} \cdot \frac{\partial f_{\mathrm{H}}(\mathbf{r},\mathbf{w}_{\mathrm{H}})}{\partial \mathbf{r}} + \frac{\mathbf{F}}{m_{\mathrm{H}}} \cdot \frac{\partial f_{\mathrm{H}}(\mathbf{r},\mathbf{w}_{\mathrm{H}})}{\partial \mathbf{w}_{\mathrm{H}}} = -f_{\mathrm{H}}(\mathbf{r},\mathbf{w}_{\mathrm{H}}) \int |\mathbf{w}_{\mathrm{H}} - \mathbf{w}_p| \sigma_{ex}^{\mathrm{HP}} f_p(\mathbf{r},\mathbf{w}_p) d\mathbf{w}_p \tag{1}$$

$$+ f_p(\mathbf{r},\mathbf{w}_{\mathrm{H}}) \int |\mathbf{w}_{\mathrm{H}}^* - \mathbf{w}_{\mathrm{H}}| \sigma_{ex}^{\mathrm{HP}} f_{\mathrm{H}}(\mathbf{r},\mathbf{w}_{\mathrm{H}}^*) d\mathbf{w}_{\mathrm{H}}^* - (\beta_i + \beta_{\mathrm{impact}}) f_{\mathrm{H}}(\mathbf{r},\mathbf{w}_{\mathrm{H}}).$$

Here $f_{\mathrm{H}}(\mathbf{r},\mathbf{w}_{\mathrm{H}})$ is the distribution function of H atoms; $f_p(\mathbf{r},\mathbf{w}_p)$ is the local distribution function of protons, assumed to be Maxwellian; $\mathbf{w}_p$ and $\mathbf{w}_{\mathrm{H}}$ are the individual proton and H atom velocities, respectively; $\sigma_{ex}^{\mathrm{HP}}$ is the charge exchange cross section of a H atom with a proton; β_i is the photoionization rate; m_{H} is the atomic mass; β_{impact} is the electron impact ionization rate; and $\mathbf{F}$ is the sum of the solar gravitational force and the solar radiation pressure force.

The plasma and neutral components interact mainly by charge exchange. However, photoionization, electron impact ionization, solar gravitation, and radiation pressure are also taken into account in equation (1). The interaction of the plasma and neutral components leads to the mutual exchange of mass, momentum and energy. The effect of this interaction can be represented by adding source terms $\boldsymbol{Q} = \{q_1, q_{2,z}, q_{2,r}, q_3, 0\}^T$ to the right-hand side of the plasma equations. The terms $q_1, \boldsymbol{q}_2 = \{q_{2,z}, q_{2,r}\}$, q_3 describe the mass, momentum, and energy sources in the thermal plasma component due to interaction with neutrals. These source terms can be expressed through the integrals of the atom distribution function f_{H}:

$$q_1 = n_{\mathrm{H}} \cdot (\beta_i + \beta_{impact}), n_{\mathrm{H}} = \int f_{\mathrm{H}}(\mathbf{w}_{\mathrm{H}}) d\mathbf{w}_{\mathrm{H}},$$

$$\boldsymbol{q}_2 = \int (\beta_i + \beta_{impact}) \mathbf{w}_{\mathrm{H}} f_{\mathrm{H}}(\mathbf{w}_{\mathrm{H}}) d\mathbf{w}_{\mathrm{H}} + \int\int \beta_{ex}(\mathbf{w}_{\mathrm{H}} - \mathbf{w}_p) f_{\mathrm{H}}(\mathbf{w}_{\mathrm{H}}) f_p(\mathbf{w}_p) d\mathbf{w}_{\mathrm{H}} d\mathbf{w}_p,$$

$$q_3 = \int (\beta_i + \beta_{impact}) \frac{\mathbf{w}_{\mathrm{H}}^2}{2} f_{\mathrm{H}}(\mathbf{w}_{\mathrm{H}}) d\mathbf{w}_{\mathrm{H}} + \int \int \beta_{ex} \frac{1}{2} (\mathbf{w}_{\mathrm{H}}^2 - \mathbf{w}_p^2) f_{\mathrm{H}}(\mathbf{w}_{\mathrm{H}}) f_p(\mathbf{w}_p) d\mathbf{w}_{\mathrm{H}} d\mathbf{w}_p.$$

Here $\beta_{ex} = \int u \sigma_{ex}^{HP}(u) f_p(\mathbf{w}_p) d\mathbf{w}_p$ is the charge exchange rate, and u is the relative atom-proton velocity.

Supersonic boundary conditions are used for the unperturbed interstellar plasma and for the solar wind plasma at the Earth's orbit. The velocity distribution of interstellar atoms is assumed to be Maxwellian in unperturbed interstellar medium.

3. On the effect of H-H, H-p elastic collisions

Recently Williams et al. [3] have suggested that a population of hot hydrogen atoms is created in the heliosphere through elastic H-H collisions between atoms of population 1 and interstellar atoms of populations 3 and 4. *Izmodenov et al.* [5] examined the approach used by Williams and argued that two assumptions used by Williams et al. result in significant overestimation of the H-H collision effect.

1. Williams et al. [3] applied the momentum transfer cross-section calculated by Dalgarno [4] for quantum mechanically indistinguishable particles in H-H collisions. Treating the colliding particles as quantum mechanically indistinguishable or classically distinguishable could lead to significant differences in the meaning and values of the cross-sections. Dalgarno's approximation is appropriate for a quantum particle ensemble when velocities of distinct particles are correlated with each other. However Williams et al. applied this *like-particles* H-H collision momentum transfer cross-section to the description of the collisions between different populations of H atoms that are classically distinguishable. Classical statistics should be used under such conditions. Izmodenov et al. [5] calculated the momentum transfer cross-section for H-H collisions in the 0.01-1000 eV energy range treating colliding particles as classically distinguishable. Figure 2A compares the calculated momentum transfer, Dalgarno, and charge exchange cross sections as functions of relative velocity of the colliding particles. It is seen that the cross-section calculated in [5] is significantly smaller than the Dalgarno cross-section when $V > 10$ km/s.

2. Williams et al. [3] used a Bhatnagar-Gross-Krook (BGK)-like approximation for the Boltzman's equation collision term. This approximation is based upon on an assumption of a complete randomization of particle velocities in the collisions, without making a distinction between 'strong' and 'weak' collisions. If one calculates momentum transfer term for different H-atom populations using the BGK-like approximation, one would obtain the values that 1-2 order of magnitude larger than for our approximation. For calculations with the Dalgarno's cross section, the overestimation introduced by the BGK-like approximation is much smaller, but still significant. This effect can be explained by different functional dependencies of the cross sections and by the BGK-like collision term.

Izmodenov et al. [5] concluded that the influence of elastic H-H, H-p collisions is negligible in the heliospheric interface since the dynamic influence of charge exchange is stronger by several orders of magnitude.

4. Basic results of the model: H atoms

Since the elastic H-H, H-p collisions are not important dynamically, Baranov-Malama model [2] describes the main physical processes correctly. In this section main results of

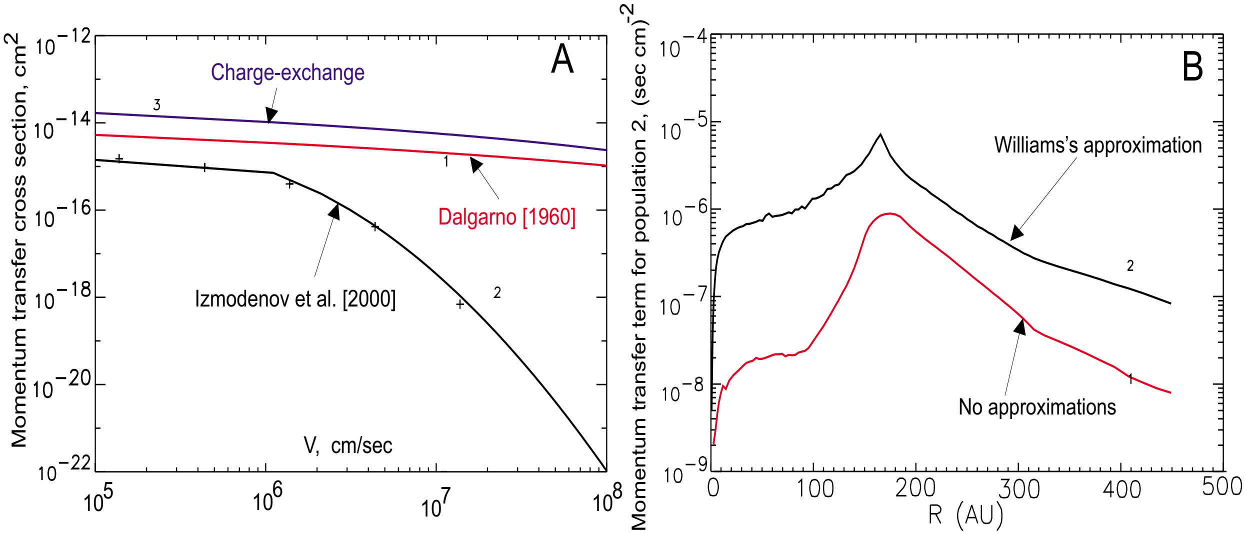

Figure 2. A. Momentum transfer cross section (in cm^2) as functions of relative velocity (in cm sec^{-1}; B. Comparison of momentum transfer of population 2 due to elastic collisions with other H atom populations (in (cm sec)$^{-2}$) in the upwind direction.

the model are briefly reviewed. Detailed results of the model reported in Baranov and Malama ([2], [6], [7]), Baranov et al. [8], Izmodenov et al. [9], Izmodenov [10].

One of the main and the most spectacular results of the model is prediction of the hydrogen wall, a density increase at the heliopause (figure 3A). The hydrogen wall is made up by secondary interstellar atoms of population 3. The hydrogen wall was predicted by Baranov et al. [1]. Linsky and Wood [11] were first to demonstrate that observed by HST Ly-α spectra toward Sirius can not be understood without taking into account the absorption produced by heliospheric hydrogen wall. Figure 3C shows the heliospheric absorption toward α-Cen calculated on the basis of Baranov-Malama model. There is still a missing absorption on the blue side. This is probably absorption produced by heated neutral gas around the target star (”astrosphere”), as suggested first by Wood and Linsky. Interpretation of stellar spectra can provide us constraints on both the heliospheric interface and astrospheres. The first attempt to constrain the interface with to help of stellar spectra was done by Gayley et al. [12]. Later, Izmodenov et al. [13] interpreted Ly-α spectra toward star Sirius-A (Figure 3D) on the basis of the heliospheric interface model. It has been shown that in this direction (41^o from downwind) two populations (populations 3 and 2) of neutral H atoms produce a non-negligible absorption. Figure 3B shows number density of population 2 toward Sirius direction. Despite small number density this population produces non-negligible absorptions due to high temperature. During this COSPAR Colloqium Wood, Muller and Zank reported the study of Ly-α spectra toward six nearby stars observed by HST. Comparing their model calculations with data the authors concluded that their model predict too much absorption in sidewind and downwind directions. More theoretical work has to be done to understand these discrepancies between theory and observations.

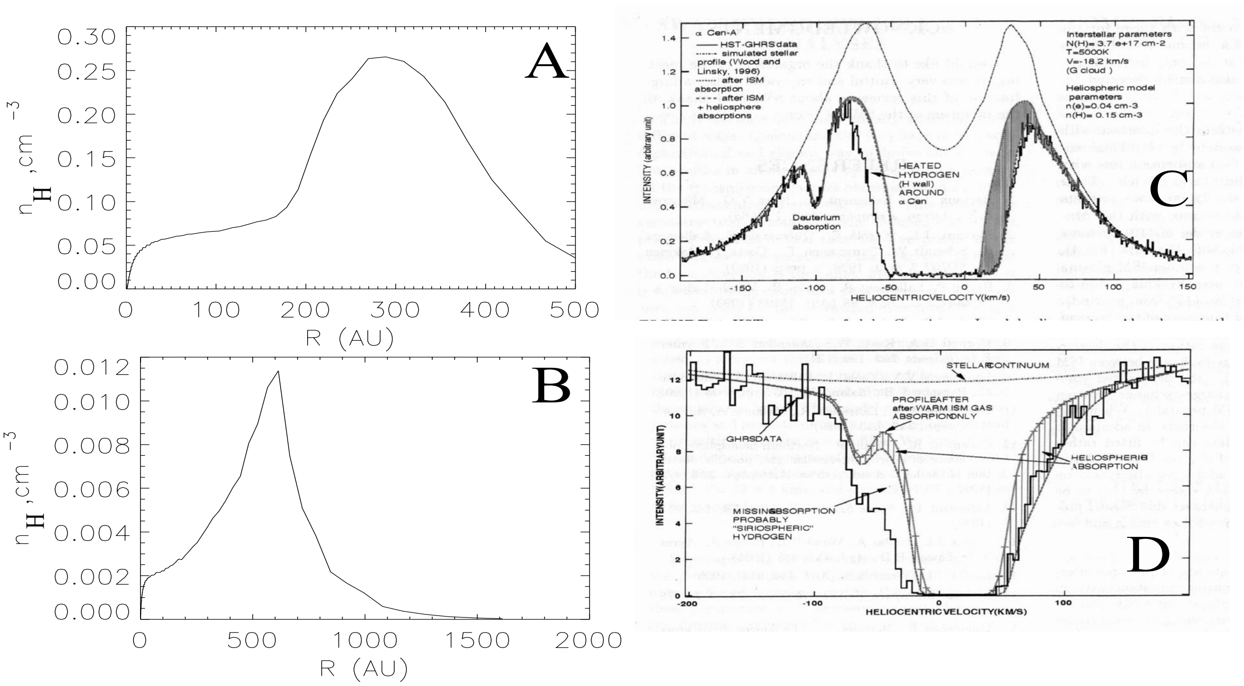

Figure 3. A. The hydrogen wall is an increase of number density of population 3 at the heliopause. The distribution is shown for direction toward αCen. B.The distribution of population 2 toward Sirius. C. HST spectrum of α Cen-A near Ly-α line center. Also shown is simulated stellar profile prior to interstellar absorption, the same profile after interstellar absorption and the expected profile after the cloud plus the calculated heliospheric H absorption. A missing absorption on the blue side is probably "astrospheric". D. HST spectrum of Sirius-A near Ly-α line center. Simulated profiles are similar of profiles on plot C.

5. Basic results of the model: influence on plasma flows

Interstellar atoms strongly influence the heliospheric interface structure. In the presence of interstellar neutrals, the heliospheric interface is much closer to the Sun than it would be in a pure gas dynamical case (see, e.g., figure 2 in Izmodenov, 2000 [10]). The termination shock becomes more spherical. The Mach disk and the complicated shock structure in the tail disappear. Interstellar neutral atoms also affect the flow of supersonic interstellar plasma upstream of the bow shock, the flow of the supersonic solar wind upstream of the termination shock, and plasma structure in the heliosheath.

The flow of the supersonic solar wind upstream of the termination shock is disturbed by charge exchange with the interstellar neutrals. The new created by charge exchange ions are picked up by the solar wind magnetic field. The Baranov-Malama model assumes immediate assimilation of pickup ions into the solar wind plasma. The effect of charge exchange on the solar wind is significant. By the time the solar wind flow reaches the termination shock it is decelerated (15-30 %), strongly heated (in 5-8 times) and mass loaded (20-50 %) by the pickup ion component.

The interstellar plasma flow is disturbed upstream of the bow shock by charge exchange with the secondary atoms originated in the solar wind and compressed interstellar plasma. Charge exchange results in the heating (40-70 %) and deceleration (15-30 %) of the interstellar plasma before it reaches the bow shock. The Mach number decreases and for a certain set of interstellar parameters ($n_{H,LISM} >> n_{p,LISM}$) the bow shock may disappear.

The plasma structure in the heliosheath is also modified by the interstellar neutrals. In a pure gasdynamic case (without neutrals) the density and temperature of the post-shock plasma is nearly constant. However, the charge exchange process leads to a strong increase of the plasma number density and decrease of its temperature. *Baranov and Malama* (1996) [7] pointed out that the electron impact ionization process may influence the heliosheath plasma flow by increasing the gradient of the plasma density from the termination shock to the heliopause. The effects of interstellar atom influence on the heliosheath plasma flow may be important, in particular, for the interpretations of (1) kHz radio emission detected by Voyager (see, [15], [16]) and (2) possible future heliospheric imaging in energetic neutral atom (ENA) fluxes [17].

6. Interpretations of spacecraft experiments on the basis of the Baranov-Malama model

The Sun/LISM relative velocity and the LISM temperature are now well constrained. Using the new SWICS pickup ion results and an interstellar HI/HeI ratio of 13 ± 1 (the average value of the ratio toward the nearby white dwarfs), *Gloeckler et al.* (1997) [18] concluded that $n_{LISM}(HI) = 0.2 \pm 0.03$ cm $^{-3}$. However there are no direct ways to measure the circumsolar interstellar electron (or proton) density. Therefore, there is a need for indirect observations (inside the heliosphere) which can bring stringent constraints on the interstellar plasma density and on the shape and size of the interface. Such constraints can been done on the basis of theoretical models of the interface. *Izmodenov et al.* [9] used the Baranov-Malama model to study the sensitivity of the various types of indirect diagnostics of local interstellar plasma density. The diagnostics are the degree of filtration, the temperature and the velocity of the interstellar H atoms in the outer heliosphere (at the termination shock), the distances to the termination shock, the heliopause, and the bow shock, and the plasma frequencies in the LISM, at the bow shock and in the maximum compression region around the heliopause which constitutes the "barrier" for radio waves formed in the interstellar medium. *Izmodenov at al.* [9] searched also for a number density of interstellar protons compatible with SWICS/Ulysses pickup ion and Voyager, HST, SOHO observations of backscattered solar Ly α and kHz radiations observed on Voyager. Table 2 presents estimates of $n_{p,LISM}$ obtained from different types of observations using the Baranov-Malama model. Izmodenov et al. [9] concluded that it is difficult to reconcile these estimates without some modification to the model. Two mutually exclusive solutions have been suggested: (1) It is possible to reconcile the pick-up ions and Ly α measurements with the radio emission time delays if a small additional interstellar (magnetic or low energy cosmic ray) pressure is added to the main plasma pressure. In this case, $n_{\mathrm{p,LISM}} = 0.07\,\mathrm{cm}^{-3}$ and $n_{\mathrm{H,LISM}} = 0.23\,\mathrm{cm}^{-3}$ is the favored pair of interstellar densities. However, in this case, the low frequency cutoff at 1.8 kHz doesn't correspond to the interstellar plasma density, and one has to search for another explanation. (2) The low frequency cutoff at 1.8 kHz constrains to the interstellar plasma density, i.e., $n_{\mathrm{p,LISM}} = 0.04$ cm^{-3}. In this case, the bulk velocity deduced from the Ly α spectral measurement is underestimated by about 30-50% (the deceleration is by 3 km s^{-1} instead of 5-6 km s^{-1}). Model limitations (e.g. stationary hot model to derive the bulk velocity) or the influence of a strong solar Ly α radiation pressure may play a role. In this case, there would be a need for a significant additional interstellar (magnetic or cosmic ray) pressure as compared with case (1).

Table 2
Intervals of Possible Interstellar Proton Number Densities

Type of Heliospheric Interface Diagnostics	Range of Interstellar Proton Number Density
SWICS/Ulysses pick-up ion 0.09 cm^{-3} $< n_{\mathrm{H,TS}} <$ 0.14 cm^{-3} *Gloeckler et al.*, [1997]	0.02 cm^{-3} $< n_{\mathrm{p,LISM}} <$ 0.1 cm^{-3}
Ly- α, intensity 0.11 cm^{-3} $< n_{H,TS} <$ 0.17 cm^{-3} *Quémerais et al.*, [1994]	$n_{\mathrm{p,LISM}} < 0.04$ cm^{-3} or $n_{\mathrm{p,LISM}} < 0.07$ cm^{-3} (for $n_{\mathrm{H,LISM}} = 0.23$ cm^{-3})
Ly-α, Doppler shift 18 km s^{-1} $< V_{H,TS} <$ 21 km s^{-1} *Bertaux et al.* [1985], *Lallement et al.* , [1996], *Clarke et al.* [1998]	0.07 cm^{-3} $< n_{\mathrm{p,LISM}} <$ 0.2 cm^{-3}
Voyager kHz emission (events) 110 AU $< R_{\mathrm{AU}} <$ 160 AU *Gurnett and Kurth* [1996]	0.08 cm^{-3} $< n_{\mathrm{p,LISM}} <$ 0.22 cm^{-3}
Voyager kHz emission (cutoff) 1.8 kHz *Gurnett et al.* [1993], *Grzedzielski and Lallement* [1996]	$n_{\mathrm{p,LISM}} = 0.04$ cm^{-3}

7. Next Frontiers

Several important physical effects are not taken into account in the model. These effects may be: 1) interstellar and heliospheric magnetic fields; 2) heliolatititudional and solar cycle variations of the solar wind; 3) galactic and anomalous cosmic rays; 4) essentially multi-fluid character of the solar wind, when the solar wind protons, pickup protons and electrons must be considered as different fluids.

During the last years a big theoretical effort of several groups has been focused on understanding the influence of these (and other) effects on the heliospheric interface. For a recent review of of the theoretical models of the heliospheric interface see *Zank* (1999) [19].

In spite of many interesting and important physical effects studied, many models don't take into account the interstellar neutrals or take them into account in oversimplified approximations. Since the H atoms are probably the most dominant component of LISM, one must be very careful when applying these models in the interpretations of the heliospheric interface observations. The use of inadequate theoretical models can result in incorrect interpretations of spacecraft experiments. This, in turn, may results in wrong conclusions on the interstellar parameters.

From our point of view, the future theoretical models of the heliospheric interface must preserve the main advantage of the Baranov-Malama model - the kinetic description of nterstellar atoms - and introduce the new effects one by one. An example of a such study has been done in [21], [20]. These authors considered the effect of the galactic cosmic rays (GCRs) on the heliospheric interface structure. Firstly, the influence of GCRs on the heliospheric interface plasma structure has been studied in the absence of the interstellar neutrals ([21], [20]). Then the interstellar atoms have been added to the model. The results were compared with the results of Baranov-Malama model. In spite of the significant influence of the GCRs on the heliospheric plasma structure in the two component (plasma+ GCRs) model, most of the effects reduce or disappear in case of the three-component model. The influence of GCRs on the plasma flow pattern is negligible as compared to the influence of H atoms everywhere in the heliospheric interface, except near the bow shock, the structure of which can be strongly modified by GCRs. Another example of such study were presented by Vladimir Baranov during this COSPAR Colloquim. He and his co-workers made self-consistent study of the interstellar magnetic field (IMF). It has been shown that in the presence of interstellar atoms the effect of IMF signicantly reduces.

Similar studies are needed to account for other physical effects that that have been found to influence the structure of the heliospheric interface in the models without neutrals. Such studies can bring new constraints on the local interstellar parameters and on the structure of the heliospheric interace.

Significant progress can be reached if such new theoretical models will be tested by the old and new measurements. One of the promising methods of the heliospheric interface diagnostics is interpretation of absorption spectra measured toward nearby stars. It was briefly discussed in section 4. Another possible heliospheric interface diagnostics is the study of the interstellar minor elements as O, N, Ne, C. The interest in minor species is now growing due to the recent successful detection of pickup and ACR ions, by the Ulysses and Voyager spacecraft, respectively. Oxygen is of particular interest, because it is one of the most perturbed elements due to its large charge exchange cross section with protons. *Izmodenov et al.* [22] [23] compared OI/HI heliospheric and interstellar ratios. The heliospheric interface filtrations of both hydrogen and oxygen have been computed on the basis of the Baranov-Malama model. A rather good agreement has been found between data and theory. More detail study of the interstellar oxygen (and other elements) in the interface and how their density inside the heliosphere sensive to interstellar parameters is required. Such study can give us additional constraints on the heliospheric interface parameters. The interest to interstellar oxygen in the heliospheric interface increases also, because *Gruntman and Fahr* ([24], [25]) proposed a mapping of the heliopause in the oxygen ion O^+ resonance line (83.4 nm).

A very promising and powerful tool to study the solar wind interaction with the surrounding local interstellar medium is global imaging of the heliosphere in the fluxes of energetic neutral atoms (ENA) ([17]). The ENAs that are produced in charge exchange of the heated plasma and background neutral gas can be readily detected at 1 AU. Global ENA images, the angular and energy dependences of ENA fluxes, are dependent on the solar plasma density, temperature, and velocity in the heliosheath. The size and structure of the heliospheric interface region depend on the parameters of the interstellar plasma and gas. Hence the ENA images should also depend on the LISM parameters (*Izmodenov and Gruntman*, this conference).

Finally, we can conclude, that in spite of our general understanding of the physical processes in the heliospheric interface, a major theoretical and experimential effort is needed to obtain the detailed structure of the heliospheric interface and local interstellar parameters.

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