PHYSICS AND GASDYNAMICS OF THE HELIOSPHERIC INTERFACE

VLADISLAV V. IZMODENOV
Lomonosov Moscow State University, Faculty of Mechanics and Mathematics, Department of Aeromechanics and Gas Dynamics, Vorob'evy Gory, Moscow 119899, Russia; E-mail: izmod@ipmnet.ru

Abstract. During 30 years, a big theoretical effort to understand the physical processes in the heliospheric interface has followed the pioneer papers by Parker (1961) and Baranov *et al.* (1971). The heliospheric interface is a shell formed by the solar wind interaction with the ionized component of the circumsolar local interstellar medium (LISM). For fully ionized supersonic interstellar plasma two-shocks (the termination shock and the bow shock) and a contact discontinuity (the heliopause) are formed in the solar wind/LISM interaction. However, LISM consists of at least of three components additional to plasma: H-atoms, galactic cosmic rays and magnetic field. The interstellar atoms that penetrate into the solar wind, are ionized there and form pickup ions. A part of the pickup ions is accelerated to high energies of anomalous cosmic rays (ACRs). ACRs may modify the plasma flow upstream the termination shock and in the heliosheath. In this short review I summarize current understanding of the physical and gasdynamical processes in the heliospheric interface, outline unresolved problems and future perspectives.

1. Introduction

Our star – the Sun – is moving through the local interstellar cloud (LIC) (Lallement, 1996). The solar wind is the fully ionized mainly hydrogen plasma that blows from the Sun. The heliospheric interface is a region where the solar wind interacts with the LIC. This interaction is a complex phenomenon where the solar wind and interstellar plasmas, interstellar neutral gas, magnetic field, and energetic particles play important role. The solar wind/LIC interaction scenario and structure of the heliospheric interface depend on the solar wind and LIC properties. The solar wind is supersonic at the Earth orbit. In spite of significant progress during the last years (Lallement, 1996, 1999; Frisch, 1995, 1997, 2000) our knowledge of the local properties of the interstellar medium is still poor and indirect. This opens a possibility to construct different scenarios of the heliospheric interface.

Parker (1961) originally suggested two heliospheric interface scenarios. In the first model, Parker considered the solar wind interaction with the *subsonic interstellar wind*. In this case the interstellar thermal pressure is larger than the interstellar dynamic and magnetic field pressures. Hydrodynamic approach was used to describe the interacting flows. In this approach the interacting flows must be separated by a tangential discontinuity, the heliopause. For the Mach number of the interstellar wind $M_{LIC} \ll 1$, the interstellar flow can be considered as in-

Astrophysics and Space Science **274:** 55–69, 2000.

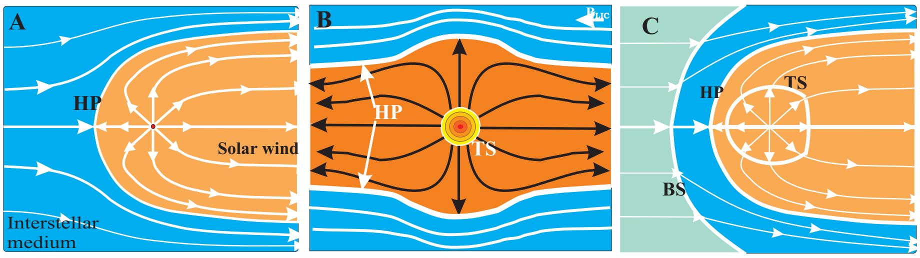

Figure 1. Sketches of three different heliospheric interface scenarios. A. Parker's model of the solar wind interaction with the subsonic interstellar wind. Since in the model $R_{HP} \gg R_{TS}$ the termination shock is not shown; B. Parker's model of the solar wind interaction with the interstellar magnetic field; C. Baranov's model of the two-shock heliospheric interface.

compressible. The supersonic solar wind must go through a shock (the termination shock or TS) before contacting the subsonic interstellar medium at the heliopause. To get analytical solution Parker assumed the entire solar wind flow to be irrotational, then each flow streamline comes to the same stagnation pressure at infinity (see also, Baranov and Krasnobaev, 1977). In the heliosheath – the region of the shocked solar wind between the termination shock and the heliopause – the flow has also been considered as incompressible. Under these assumptions it is possible to find the streamlines of the flow and shape of the heliopause (Figure 1A). The termination shock is not shown on Figure 1A, because $R_{HP} \gg R_{TS}$ in the model. R_{HP}, R_{TS} are the heliocentric distances to the heliopause and termination shock respectively.

In the second model, Parker assumed the interstellar magnetic field (IMF) pressure to be much larger than static and dynamic pressures of the interstellar gas. Since the magnetic field influences the solar wind plasma flow differently in parallel and perpendicular directions, spherical symmetry of the solar wind is disturbed. The solar wind plasma pushes out the interstellar magnetic field and creates a cavity along the direction of the interstellar magnetic field (Figure 1B). The boundary of the cavity, the heliopause, is determined by the balance of the interstellar magnetic field and solar wind static pressures.

Baranov *et al.* (1971) introduced the solar wind interaction with *the supersonic interstellar wind*. The bow shock is formed in the interstellar plasma flow in addition to the termination shock and the heliopause. The bow shock decelerates the interstellar wind before contacting the solar wind at the heliopause (Figure 1C). This model is conventionally called the two-shock model. The shape of the heliopause has been calculated by Baranov *et al.* (1971) under assumption of $M_{LIC} \gg 1$. Later, using the method of the thin boundary layer, Baranov *et al.* (1976) calculated the structure of the postshock interstellar flow. Baranov *et al.* (1979) calculated the structure of the flow between the two shocks numerically.

In 1960s, it was realized (e.g. Patterson *et al.*, 1963; Fahr, 1968; Blum and Fahr, 1970) that the interstellar wind could be measured as interstellar atoms penetrating deeply into the heliosphere. The interstellar atoms of hydrogen have been detected by measurements of the solar backscatterred Ly α radiation (Bertaux and Blamont, 1971; Thomas and Krassa, 1971). Later, Ly-α absorption cell measurements (e.g. Bertaux *et al.*, 1985) and the direct measurements of the interstellar helium (Witte *et al.*, 1996) proved that the interstellar wind is supersonic. Thus, the Baranov-type model should be used for description of the heliospheric interface.

The original two-shock model did not taken into account the influence of interstellar hydrogen atoms that are probably the most dominant component of LIC. The mean-free path of H atoms is comparable with the characteristic size of the heliospheric interface. These neutrals can penetrate deep into the heliosphere. Interstellar atoms and their derivatives as pickup ions, energetic neurals atoms (ENAs) and anomalous cosmic ras (ACRs) are measured on spacecraft and are major sources of information on the interstellar medium and physical processes in the heliospheric interface (e.g. Gloeckler and Geiss, 1998; Jokipii and McDonald, 1995; Jokipii, 1997, 1999; Lee, 1997; Stone and Cummings, 1999; Kallenbach *et al.*, 2000; Isenberg, 1999; Fahr, 2000; Chalov, 2000).

In this paper, I review current understanding of the physical and gasdynamical processes in the heliospheric interface, discuss unsolved problems and future perspectives.

2. Heliospheric Interface Plasma Structure: Influence of Interstellar Neutrals

The two-shock heliospheric interface is formed in the interaction of the supersonic solar wind with the supersonic interstellar plasma flow. Interstellar H atoms interacts with plasma protons by charge exhange. The charge-exchange process leads to exchange of momentum and energy between the plasma and neutral components. It results in a perturbation of the interstellar H atom flow in the heliospheric interface and, in turn, the disturbance of the heliospheric interface plasma structure by the interstellar atoms. Thus, the theoretical models of the heliospheric interface must take into account the plasma and neutral components self-consistently.

The main difficulty in theoretical modelling of the heliospheric interface is that the interstellar H atoms must be described kinetically, because their mean free path is comparable with the size of the heliospheric interface. (The mean free path of the interstellar atoms with respect to charge exchange in LISM is about 100 AU. See for details, Izmodenov *et al.*, this issue.) The velocity distribution of interstellar neutrals that passed through the heliospheric interface deviated from maxwellian.

2.1. Baranov-Malama model

The first self-consistent model of the two-component (plasma and H atoms) LIC interaction with the solar wind was developed by Baranov and Malama (1993).

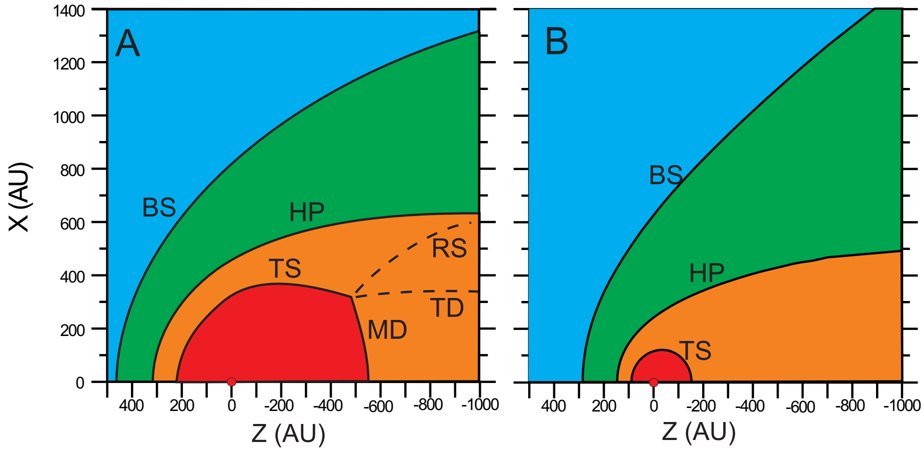

Figure 2. Effect of the interstellar neutrals on the size and structure of the interface. (a) The heliospheric interface pattern in the case of fully ionized local interstellar cloud (LIC), (b) the case of partly ionized LIC. BS is the bow shock. HP is the heliopause. TS is the termination shock. MD is the Mach disk. TD is the tangential discontinuity and RS is the reflected shock.

The interstellar wind is assumed to be uniform parallel flow in the model. The solar wind is assumed to be spherically symmetric at the Earth's orbit. Under these assumptions, the heliospheric interface has axisymmetric structure.

Plasma and neutral components interact mainly by charge exchange. However, the photoionization, the solar gravitation and solar radiation pressure, which are especially important in the vicinity of the Sun, are also taken into account.

Kinetic and hydrodynamic approaches were used for the neutral and plasma components, respectively. The kinetic equation for neutrals is solved together with the Euler equations for plasma. The influence of the interstellar neutrals is taken into account in the right hand sides of the Euler equations (e.g. Baranov and Malama, 1996) that contain integrals of the H atom distribution function $f_H(\vec{V}_H)$ and can be calculated directly by the Monte-Carlo method (Malama, 1991). The set of kinetic and Euler equations is solved by iteractive procedure, suggested by Baranov *et al.* (1991). Supersonic boundary conditions were 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 the unperturbed LIC.

2.2. Basic Results of Baranov-Malama model

2.2.1. *Plasma*

Interstellar atoms strongly influence the heliospheric interface structure. In the presence of interstellar neutrals, the heliospheric interface is much closer to the Sun than in a pure gasdynamical case (Figure 2). The termination shock becomes more spherical. The Mach disk and the complicated shock structure in the tail disappear.

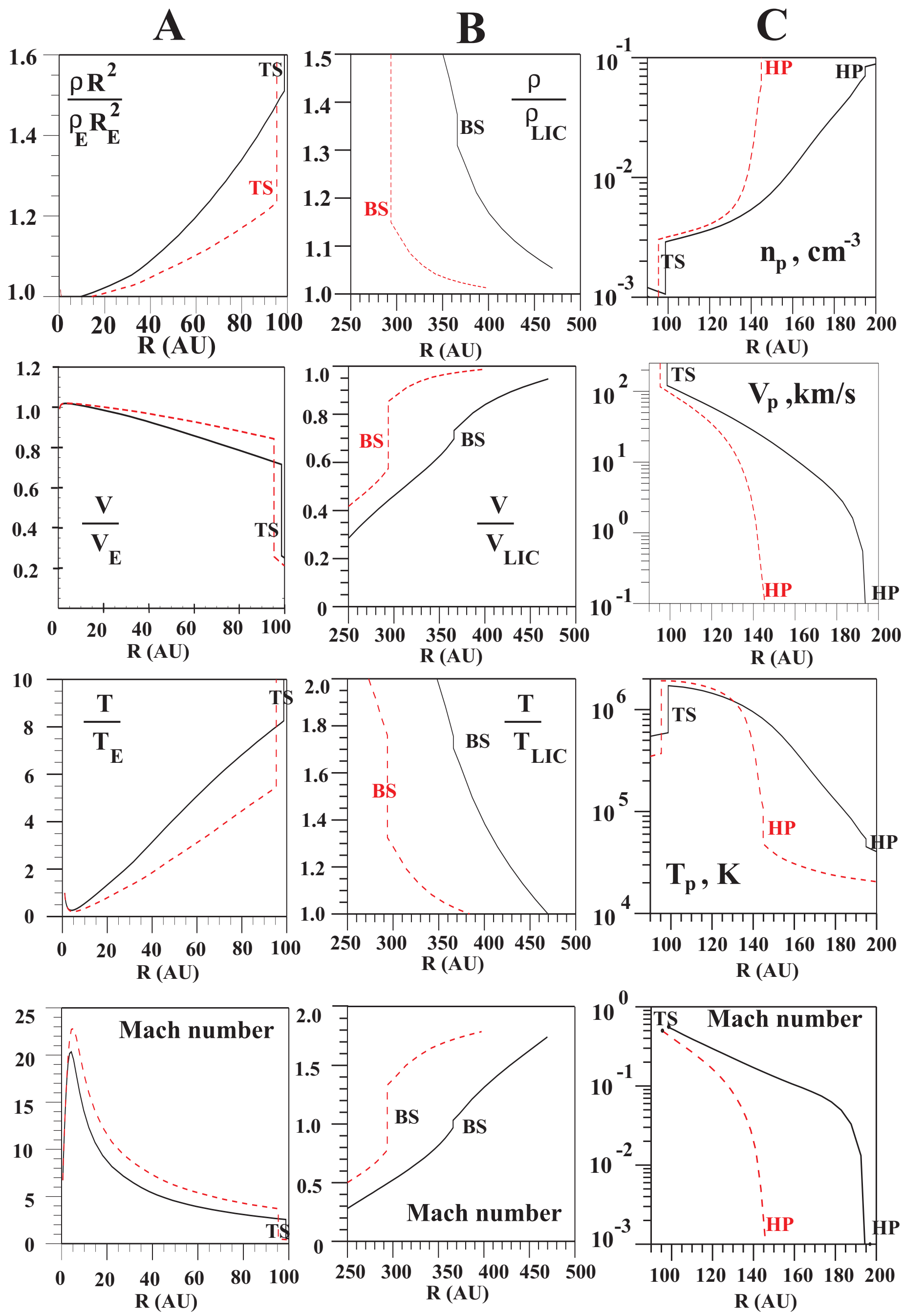

Figure 3. Plasma density, velocity, temperature and Mach number (A) upstream the termination shock, (B) upstream the bow shock, and (C) in the heliosheath. The distributions are shown for the upwind direction. Solid curves correspond to $n_{H,LIC}$=0.2 cm^{-3}, $n_{p,LIC}$=0.04 cm^{-3}. Dashed curves correspond to $n_{H,LIC}$=0.14 cm^{-3}, $n_{p,LIC} = 0.10$ cm^{-3}. $V_{LIC} = 25.6$ km s^{-1}, $T_{LIC} = 7000$ K.

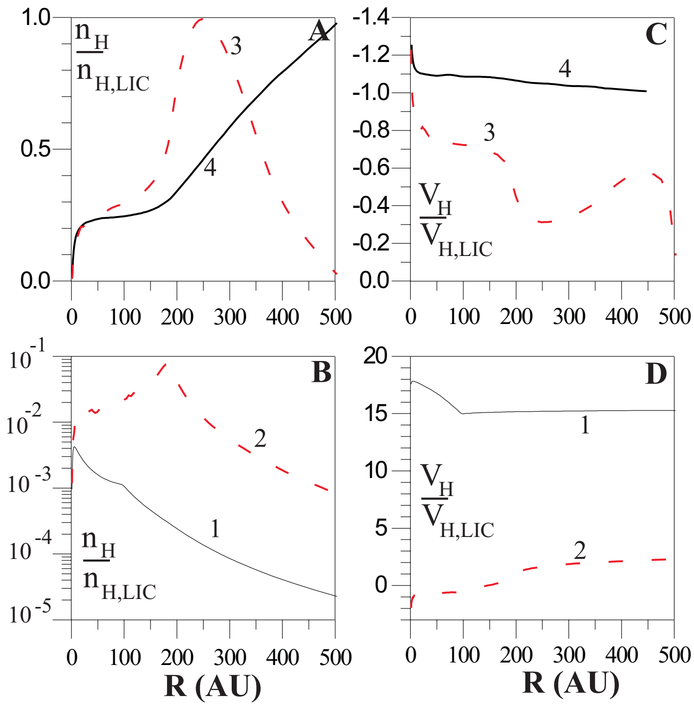

Figure 4. Number densities and velocities of 4 atom populations as functions of heliocentric distance in the upwind direction. 1 – designates atoms created in the supersonic solar wind, 2 – atoms created in the heliosheath, 3 – atoms created in the disturbed interstellar plasma, 4 – original (or primary) interstellar atoms. Number densities are normalized to $n_{H,LIC}$, velocities are normalized to V_{LIC}. It is assumed that $n_{H,LIC} = 0.2$ cm^{-3}, $n_{p,LIC} = 0.04$ cm^{-3}.

The supersonic plasma flows upstream the bow and termination shocks are disturbed. The supersonic solar wind 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 solar wind protons and pickup ions are treated as one fluid called the solar wind. The number density, velocity, temperature, and Mach number of the solar wind are shown in Figure 3a. 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 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 ($n_{H,LIC} \gg n_{p,LIC}$)

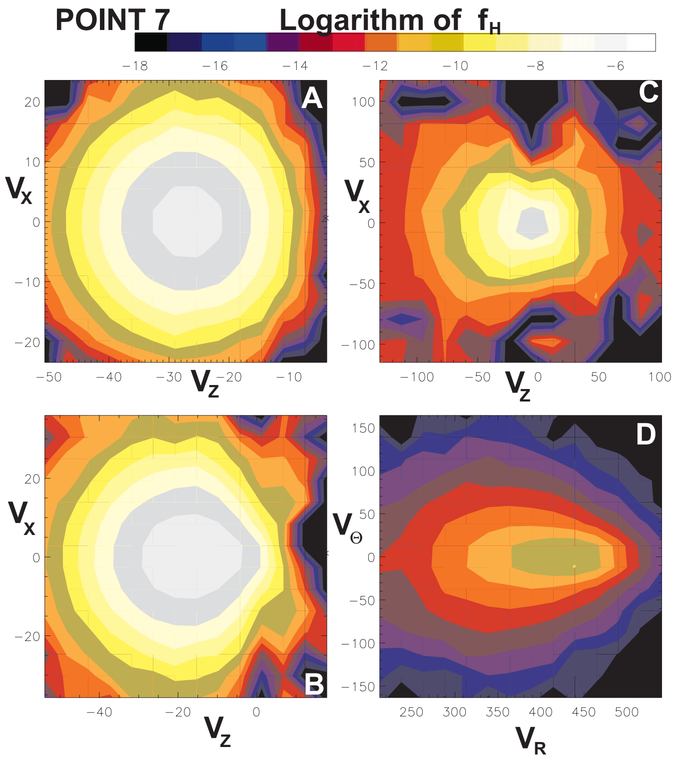

Figure 5. Velocity distributions of four atom populations at the termination shock in the upwind direction. (A) primary interstellar atoms, (B) secondary interstellar atoms, (C) atoms created in the heliosheath, (D) atoms created in the supersonic solar wind. V_z is the projection of velocity on the axis parallel to the LIC velocity vector. Negative values of V_z mean approaching to the Sun. V_x is the radial component of the projection of velocity vector on the perpendicular plane. V_z, V_x are in cm sec^{-1}. It is assumed that $n_{H,LIC} = 0.2$ cm^{-3}, $n_{p,LIC} = 0.04$ cm^{-3}.

the bow shock may disappear. Solid curves on Figure 3B correspond to the small ionization degree of LIC ($n_p/(n_p+n_H) = 1/6$). The bow shock almost disappears.

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 postshock plasma is nearly constant. However, the charge exchange process leads to a strong increase of the plasma number density and decrease of its temperature (Figure 3C). Baranov and Malama (1996) 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 Gurnett and Kurth, 1996; Treumann *et al.*, 1998) and (2) possible future heliospheric imaging in energetic neutral atom (ENA) fluxes (Gruntman *et al.*, 2000).

2.2.2. *Atoms*

Charge exchange significantly disturbs the interstellar atom flow. Newly created (by charge exchange) atoms have velocities of their ion partners in charge exchange collisions. Therefore, the velocity distribution of these new atoms depends on the local plasma properties. It is convenient to distinguish four different populations of atoms depending on the place of their origin in the heliospheric interface. Population 1 is the atoms created in the supersonic solar wind. Population 2 is the atoms originated in the heliosheath. Population 3 is the atoms created in the disturbed interstellar wind. We will call original (or primary) interstellar atoms – population 4. The number densities and mean velocities of these populations are shown on Figure 4 as function of the heliocentric distance. The velocity distribution function of interstellar atoms $f_H(\vec{w}_H, \vec{r})$ can be represented as a sum of the distribution functions of these populations: $f_H = f_{H,1} + f_{H,2} + f_{H,3} + f_{H,4}$. The Monte Carlo method allows us to calculate these four distribution functions. Izmodenov *et al.* (1999b) presented the velocity distributions of the interstellar atoms in the twelve selected points in the heliospheric interface. For example the velocity distributions at the termination shock in upwind direction are shown in Figure 5.

Original (or primary) interstellar atoms are significant filtered (i.e. their number density is reduced) before reaching the termination shock (Figure 4A). Since slow atoms have smaller mean free path as compared with fast atoms, they undergo more charge exchange. This kinetic effect, called ‘selection’, results in a deviation of the interstellar distribution function from Maxwellian (Figure 5A). The selection also results in $\sim$10 % increase of the primary atom mean velocity to the termination shock (Figure 4C).

The secondary interstellar atoms are created in the disturbed interstellar medium by charge exchange of primary interstellar neutrals and decelerated (by the bow shock) protons. The secondary interstellar atoms collectively make up the ‘H wall’, a density increase at the heliopause. The ‘H wall’ has been predicted by Baranov *et al.* (1991) and detected toward α Cen (Linsky and Wood, 1996). At the termination shock, the number density of the secondary neutrals is comparable with the number density of the primary interstellar atoms (Figure 4A, dashed curve). The relative abundances of the secondary and primary atoms entering the heliosphere vary with the interstellar ionization degree. Izmodenov *et al.* (1999a) have shown the relative abundance of the secondary interstellar atoms inside the termination shock is larger for larger interstellar proton number density. The bulk velocity of the population 3 is about –18 –19 km s^{-1}. The sign ‘–’ means that the population approaches the Sun. One can see that the velocity distribution of these population is not Maxwellian (Figure 5B). The reason of the abrupt behaviour of the velocity distribution for $V_z > 0$ is that the particles with significant positive V_z velocities can reach the termination shock only from the downwind direction. Izmodenov *et al.* (1999b) calculated the velocity distributions in different direction from upwind. The fine structures of the velocity distribution of the primary and secondary interstellar populations vary with direction. These variations of the velocity distributions reflect the geometrical pattern of the heliospheric interface. The velocity distributions of the interstellar atoms can be a good diagnostic of the global structure of the heliospheric interface.

The third population of the heliospheric neutrals is *the neutrals created in the heliosheath* from hot and compressed solar wind protons. The number density of this population is by the order of magnitude smaller than the number densities of the primary and secondary interstellar atoms. This population has a minor importance for interpretations of Ly α and pickup ion measurements inside the heliosphere. However, some of these atoms may probably be detected by Ly α hydrogen cell experiments due to their large Doppler-shifts. Due to their high energies the particles influence on the plasma distributions in the LIC. Inside the termination shock the atoms propagate freely. Thus, these atoms can be the source of information on the plasma properties in the place of their birth that is the heliosheath (Gruntman *et al.*, 2001).

The last population of the heliospheric atoms are *the atoms created in the supersonic solar wind*. The number density of this atom population has a maximum at ∼5 AU. At this distance, the number density of Population 1 is by the two orders of magnitude smaller that the number density of the interstellar atoms. Outside the termination shock the density decreases faster than $1/r^2$ where r is the heliocentric distance (curve 1, Figure 4B). The mean velocity of population 1 is about 450 km sec^{-1}, that corresponds to the bulk velocity of the supersonic solar wind. The velocity distribution of this population is also not Maxwellian (Figure 5D). The extended ‘tail’ in the distribution function is caused by the solar wind plasma deceleration upstream the termination shock. The ‘supersonic’ atom population results in the plasma heating and deceleration upstream the bow shock. This leads to the decrease of the Mach number ahead of the bow shock.

3. Interpretations of Spacecraft Experiments on the Basis of the Baranov-Malama Model

The Sun/LIC relative velocity and the LIC temperature are now well constrained (Witte *et al.*, 1996; Lallement and Bertin, 1992; Linsky *et al.*, 1993; Lallement *et al.*, 1995). 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) concluded that $n_{LIC}(HI) = 0.2 \pm 0.03$ 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.* (1999a) 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 LIC, 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 *et al.* (1999a) searched also for a number density of interstellar protons compartible with SWICS/Ulysses pickup ion, Voyager, HST, SOHO backscattered solar Ly α and kHz radiations observed on Voyager. Table I presents the ranges of $n_{p,LIC}$ obtained on the basis of the Baranov-Malama model and comparable with different types of observations. From analyses of the ranges it was concluded by Izmodenov *et al.* (1999a) that it is difficult in the frame of the model to reconcile the results obtained from all types of data as they stand now. There is a need for some modifications of the interpretations or the confidence intervals. 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, $n_{\mathrm{p,LIC}} = 0.07$ cm^{-3} and $n_{\mathrm{H,LIC}} = 0.23$ 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., $n_{\mathrm{p,LIC}} = 0.04$ 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).

A need for an additional pressure is in agreement with the conclusions of Gayley *et al.* (1997) derived from the analysis of the H wall absorption toward alpha Centauri. Gayley *et al.* (1997) have compared the observed the H wall absorption toward α Centauri (Linsky and Wood, 1996) with the theoretical absorption determied on the basis of their multi-fluid model of the heliospheric interface. In their model the authors modified the equation of state of the gas to simulate the effect of the interstellar magnetic field (IMF) and concluded that the H wall absorption favors the 'subsonic case'. However, the best model of these authors corresponds to a neutral H density of 0.025 cm^{-3} in the inner heliosphere, at least 4 times smaller than the density derived from the pick-up ions. Also, the precision required to model the differences between the theoretical absorptions, namely small differences of the order of a few kilometers per second at the bottom of the lines, is of the order of the differences between the kinetic and multi-fluid model results for the same parameters in the supersonic case (see Williams *et al.*, 1997, Appendix B; Baranov *et al.*, 1998). Thus, an additional study of the absorption toward α Cen for more realistic densities and models is desired.

TABLE I
Intervals of Possible Interstellar Proton Number Densities

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

4. Discussion and Future Perspectives

Another possible reason of difficulty to reconcile all available indirect observations of the heliospheric interface is that one or 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. Effects of the interstellar and heliospheric magnetic fields, latitudinal and solar cycle variations of the solar wind have been considered. For a recent review of these and many other aspects of the theoretical models of the heliospheric interface see Zank (1999).

In spite of many interesting and important physical effects studied in the papers, these 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 LIC, 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 interstellar atoms – and introduce the new effects one by one. A good example of a such study has been done by Myasnikov *et al.* (2000a,b). 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 (Myasnikov *et al.*, 2000a). 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.

Simular studies are needed for other physical effects that significantly influence the heliospheric plasma structure 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 heliospheric absorption toward different nearby stars. Linsky and Wood (1996) were the first who used the idea of the 'H wall' to interpret absorption along the line-of sight toward α Cen. As discussed in Section 3, Gayley *et al.* (1997) tried to interpret the absorption toward α Cen on the basis of the multi-fluid model of the heliospheric interface. Izmodenov *et al.* (1999d) have shown that the absorption toward another star – Sirius – can also be explained by the heliospheric gas. Simultaneus analysis of absorptions toward different stars on the basis of one theoretical model is desired. If the absorptions are sensitive to the heliospheric interface structure, such analysis can provide additional constraints on the shape and size of the heliospheric interface and show up the model limitations.

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.* (1997, 1999c) 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 (1998, 2000) 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 ENA fluxes (Gruntman, 1997; Gruntman *et al.*, 2000). The ENAs that are produced in charge exchange of the heated plasma and background neutral gas can be readily detected at 1 AU. Global ENAs images, the angular and energy dependences of ENA fluxes, are essentially 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 would also depend on the LISM parameters (Gruntman and Izmodenov, 1999).

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.

Acknowledgements

I thank to V.B. Baranov, S.V. Chalov, J. Geiss, M. Gruntman, H. Fahr, R. Lallement and Yu.G. Malama for fruitful discussions. This work was supported in part by INTAS-CNES grant 97512, ‘The heliosphere in the local interstellar cloud’, the International Space Science Institute (ISSI) in Bern, the Russian Foundation of Basic Research Grants 98-01-00955 and 98-02-16759, and NSF-NATO fellowship DGE-9804533.

References

Baranov, V.B. and Malama, Yu.G.: 1993, *J. Geophys. Res.* **98**, 15157–15163.
Baranov, V.B. and Malama, Yu.G.: 1996, *Space Sci. Rev.* **78**, 305–316.
Baranov, V.B., Krasnobaev, K.V. and Kulikovsky, A.G.: 1971, *Sov. Phys. Dokl.* **15**, 791.
Baranov, V.B., Krasnobaev, K.V. and Ruderman, M.S.: 1976, *Astrophys. Space Sci.* **41**, 481.
Baranov, V.B. and Krasnobaev, K.V.: 1977, *Hydrodynamic theory of a cosmic plasma*, Moscow, Izdatel’stvo Nauka, 336 p. (in Russian)
Baranov, V.B., Lebedev, M.G. and Ruderman, M.S.: 1979, *Astrophys. Space Sci.* **66**, 441–451.

Baranov, V.B., Lebedev, M. and Malama, Yu.: 1991, *Astrophys. J.* **375**, 347.
Baranov, V., Izmodenov, V. and Malama, Yu.: 1998, *J. Geophys. Res.* **103**, 9575.
Bertaux, J.L. and Blamont, J.E.: 1971, *Astron. Astrophys.* **11**, 200.
Bertaux, J.L., Lallement, R., *et al.*: 1985, *Astron. Astrophys.* **150**, 1–20.
Blum, P.W. and Fahr, H.J.: 1970, *Astron. Astrophys.* **4**, 280.
Chalov, S.V.: 2000, this issue.
Clarke, J.T., Lallement, R., *et al.*: 1998, *Astrophys. J.* **499**, 482–488.
Fahr, H.J.: 1968, *Astrophys. Space Sci.* **2**, 496.
Fahr, H.J.: 2000, this issue.
Frisch, P.C.: 1995, *Space Sci. Rev.* **72**, 499–592.
Frisch, P.C.: 1997, in: J.R. Jokipii *et al.* (eds.), *Cosmic Winds and the heliosphere*, Univ. Arizone Press, pp. 733–758.
Gayley, K.G., Zank, G.P., *et al.*: 1997, *Astophys. J.* **487**, 259.
Gloeckler, G. and Geiss, J.: 1998, *Space Sci. Rev.* **86**, 127–159.
Gloeckler, G., Fisk, L. and Geiss, J.: 1997, *Nature* **386**, 374–377.
Gruntman, M.: 1997, *Rev. Space Instr.* **68**, 3617–3656.
Gruntman, M. and Fahr, H.J.: 1998, *Geophys. Res. Lett.* **25**, 1261–1264.
Gruntman, M. and Izmodenov, V.: 1999, *Eos Trans. AGU* **80** (17), Fall Meet. Suppl., F797.
Gruntman, M. and Fahr, H.J.: 2000, *J. Geophys. Res.*, in press.
Gruntman, M., Roelof, E.C., *et al.*: 2001, *J. Geophys. Res.*, submitted.
Grzedzielski, S. and Lallement, R.: 1996, *Space Sci. Rev.* **78**, 247–258.
Gurnett, D.A. and Kurth, W.S.: 1996, *Space Sci. Rev.* **78**, 53–66.
Gurnett, D.A., Kurth, W.S., *et al.*: 1993, *Science* **262**, 199–202.
Isenberg, P.A.: 1999, Proceedings of the Ninth International Solar Wind Conference, *AIP Conf. Proc.* **471**, 189–194.
Izmodenov, V.V., Lallement, R. and Malama, Yu.: 1997, *Astron. Astrophys.* **317**, 193.
Izmodenov, V., Geiss, J., Lallement, R., *et al.*: 1999a, *J. Geophys. Res.* **104**, 4731.
Izmodenov, V., Gruntman, M. and Malama, Yu.: 1999b, *Eos Trans. AGU* **80** (17), Fall Meet. Suppl., F795.
Izmodenov, V.V., Lallement, R. and Geiss, J.: 1999c, *Astron. Astrophys.* **344**, 317–321.
Izmodenov, V., Lallement, R. and Malama, Yu.: 1999d, *Astron. Astrophys.* **342**, L13.
Jokipii, J.R.: 1997, in: J.R. Jokipii *et al.* (eds.), *Cosmic Winds and the heliosphere*, Univ. Arizone Press, pp. 833–856.
Jokipii: 1999, *Conf. Prog. Cosm. Gas Dyn.*, Moscow, Sept. 13–17, Abstracts, 11.
Jokipii, R. and McDonald, F.B.: 1995, *Sci. Am.* **272**, 58.
Kallenbach, R., Geiss, J., Gloeckler, J. and von Steiger, R.: 2000, this issue.
Lallement, R.: 1996, *Space Sci. Rev.* **78**, 361–374.
Lallement: 1999, *Conf. Prog. Cosm. Gas Dyn.*, Moscow, Sept. 13–17, Abstracts, 12.
Lallement, R., and Bertin, P.: 1992, *Astron. Astrophys.* **266**, 479–485.
Lallement, R., Ferlet, R., *et al.*: 1995, *Astron. Astrophys.* **304**, 461.
Lallement, R., Linsky, J.L., *et al.*: 1996, *Space Sci. Rev.* **78**, 299.
Lee, M.A.: 1997, in: J.R. Jokipii *et al.* (eds.), *Cosmic Winds and the heliosphere*, Univ. Arizone Press, pp. 833–856.
Linsky, J. and Wood, B.: 1996, *Astrophys. J.* **463**, 254–270.
Linsky, J.L., Brown, A. and Gayley, K.A.: 1993, *Astrophys. J.* **402**, 694.
Malama, Yu.G.: 1991, *Astrophys. Space Sci.* **176**, 21–46.
Myasnikov, A.V., Izmodenov, V., *et al.*: 2000a, *J. Geophys. Res.*, **105**, 5179–5188.
Myasnikov, A.V., Alexashov, D., *et al.*: 2000b, *J. Geophys. Res.*, **105**, 5167–5178.
Parker, E.N.: 1961, *Astrophys. J.* **134**, 20–27.
Patterson, T., Jonson, F. and Hanson, W.: 1963, *Planet. Space Sci.* **11**, 767–778.
Quémerais, E., Bertaux, J.-L., *et al.*: 1994, *Astron. Astrophys.* **290**, 941–955.

Stone, E.C. and Cummings, A.C.: 1999, Proceedings of the Ninth International Solar Wind Conference, *AIP Conf. Proc.* **471**, 201–204.
Thomas, G.E. and Krassa, R.F.: 1971, *Astron. Astrophys.* **11**, 218.
Treumann, R., Macek, W. and Izmodenov, V.: 1998, *Astron. Astrophys.* **336**, L45.
Williams, L., Hall, D., *et al.*: 1997, *Astrophys. J.* **476**, 366.
Witte, M., Banaszkiewicz, M. and Rosenbauer, H.: 1996, *Space Sci. Rev.* **78**, 289–296.
Zank, G.: 1999, *Space Sci. Rev.* **89**, 413–688.