Space Sci Rev (2007) 130: 377–387
DOI 10.1007/s11214-007-9203-5

Filtration of Interstellar Atoms through the Heliospheric Interface

V.V. Izmodenov

Received: 22 January 2007 / Accepted: 28 March 2007 /
Published online: 6 June 2007

Abstract Interstellar atoms penetrate deep into the heliosphere after passing through the heliospheric interface—the region of the interaction of the solar wind with the interstellar medium. The heliospheric interface serves as a filter for the interstellar atoms of hydrogen and oxygen, and, to a lesser extent, nitrogen, due to their coupling with interstellar and heliospheric plasmas by charge exchange and electron impact ionization. The filtration has great importance for the determination of local interstellar abundances of these elements, which becomes now possible due to measurements of interstellar pickup by Ulysses and ACE, and anomalous cosmic rays by Voyagers, Ulysses, ACE, SAMPEX and Wind. The filtration of the different elements depends on the level of their coupling with the plasma in the interaction region. The recent studies of the filtration of the interstellar atoms in the heliospheric interface region is reviewed in this paper. The dependence of the filtration on the local interstellar proton and H atom number densities is discussed and the roles of the charge exchange and electron impact ionization on the filtration are evaluated. The influence of electron temperature in the inner heliosheath on the filtration process is discussed as well. Using the filtration coefficients obtained from the modeling and SWICS/Ulysses pickup ion measurements, the local interstellar abundances of the considered elements are determined.

Keywords ISM: atoms · Interplanetary medium · Solar wind · Circumstellar matter

V.V. Izmodenov (✉)
Department of Mechanics and Mathematics, Lomonosov Moscow State University, Moscow, Russia
e-mail: izmod@iki.rssi.ru

V.V. Izmodenov
Space Research Institute (IKI), Russian Academy of Sciences, Moscow, Russia

V.V. Izmodenov
Institute for Problems in Mechanics, Russian Academy of Sciences, Moscow, Russia

1 Introduction

The chemical composition of the Local Interstellar Cloud (LIC) surrounding the Sun has great importance for understanding the composition of the local interstellar matter. At the present time the local interstellar parameters and composition can only be explored with remote and indirect measurements. There are two types of diagnostics of the LIC: 1) spectroscopic observations of stellar absorptions (e.g. Linsky et al. 1995; Lallement 1996) that provide data averaged over long distances; 2) measurements of pickup ions and anomalous cosmic rays (ACRs) inside the heliosphere at one or several AU (Geiss et al. 1994; Gloeckler and Geiss 2004; Cummings et al. 2002a) that allows the determination of the local interstellar composition in the vicinity of the Sun. The pickup ions originate from the interstellar atoms penetrating into the heliosphere through the heliospheric interface, which is formed by the interaction of the solar wind (SW) with the charged component of the interstellar medium. The parameters of the interstellar atom flow are significantly disturbed in the interface due to effective coupling with protons by charge exchange. In particular, charge exchange results in the filtration of the interstellar atoms in the heliospheric interface before they enter the heliosphere. The filtration means that only a fraction of the interstellar atoms penetrate into the heliosphere. The filtration can be different for different chemical elements since it depends on the level of their coupling with the charged particles. Therefore, to study composition of the interstellar medium surrounding the Sun from pickup ion data obtained inside the heliosphere one needs to take into account the effects of the heliospheric interface.

This paper gives a brief overview on the structure and modeling of the heliospheric interface and on the problem of the interstellar atom filtration in the interface region.

2 The Heliospheric Interface

The heliospheric interface is formed by the interaction of the solar wind with the partly ionized interstellar medium. The interface has a complex structure (Fig. 1) with two shock waves—the interstellar bow shock (BS) and the heliospheric termination shock (TS), and the heliopause that is the contact discontinuity separating the solar wind from interstellar plasma. The SW/LIC interaction has a truly multi-component nature. The interplanetary and interstellar magnetic fields, interstellar atoms of hydrogen, galactic and anomalous cosmic rays (GCRs and ACRs), and pickup ions play important roles in the formation of the heliospheric interface (e.g. Izmodenov and Kallenbach 2007). To reconstruct the structure and the physical processes at the interface using remote observations a theoretical model should be employed.

The development of a theoretical model of the heliospheric interface requires the correct approach for each of the interstellar and solar wind components. Interstellar and solar wind protons and electrons can be described as fluids. However, the mean free path of interstellar H atoms is comparable with the size of the heliospheric interface. This requires a kinetic description for the interstellar H atom flow in the interaction region. For the pickup ion and cosmic ray components the kinetic approach is required as well.

The first self-consistent stationary axisymmetric model of the interaction of the two-component (plasma and H atoms) LIC with the solar wind (B&M model, hereinafter) had been developed by Baranov and Malama (1993). The main physical process considered in the model is the resonance charge exchange processes of the H atoms with protons although the processes of photoionization and ionization of H-atoms by electron impact can be important in some regions of the heliosphere (for example, in the inner heliosheath or in the

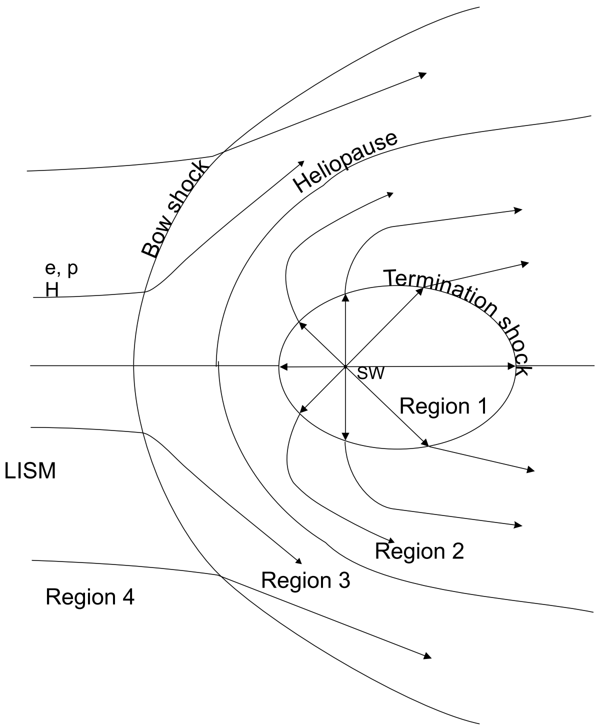

Fig. 1 Qualitative picture of the SW interaction with the LIC. The *heliopause* (HP) is a contact (or tangential) discontinuity, which separates the solar wind plasma and the interstellar plasma component. The *termination shock* (TS) is formed due to the deceleration of the supersonic solar wind. The *bow shock* (BS) may also exist if the interstellar plasma flow is supersonic. Four regions are distinguished: the supersonic solar wind (region 1); the solar wind flow between the TS and the HP (region 2 or the *inner heliosheath*); the disturbed interstellar plasma component flow (region 3 or the *outer heliosheath*); the undisturbed interstellar gas flow (region 4)

supersonic solar wind). The significant effect of the resonance charge exchange is connected with the large cross section of such collisions which is a function of the relative velocity of colliding particles. Izmodenov et al. (2000) have shown that the elastic H–H and H–proton collisions are negligible in the considered problem. The main results of the B&M model can be briefly summarized as follows:

1. Interstellar atoms strongly influence the heliospheric interface structure. The heliospheric interface is much closer to the Sun in the case when H atoms are taken into account in the model, as compared to a pure gas dynamical case. The distance to the TS in the upwind direction is on the order of 90–100 AU depending on the outer and inner boundary conditions.

The termination shock becomes more spherical in the presence of H atoms and the flow in the region between HP and TS becomes entirely subsonic. The complicated shock structure in the tail (see, e.g. Izmodenov and Alexashov 2003) disappears in the presence of H atoms.

2. 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 by 15–30%, strongly heated by a factor of 5–8, and loaded by the pickup proton component (approximately 20–50%).

The interstellar plasma flow is disturbed upstream of the bow shock (region 4 in Fig. 1) by charge exchange of the interstellar protons with secondary H atoms originating in the solar wind. This leads to heating (40–70%) and deceleration (15–30%) of the interstellar plasma before it reaches the bow shock. The Mach number decreases upstream of the BS and for a certain range of interstellar parameters ($n_{\mathrm{H,LIC}} \gg n_{\mathrm{p,LIC}}$) the bow shock may disappear.

The supersonic solar wind flow (region 1 in Fig. 1) is disturbed due to charge exchange with the interstellar neutrals penetrating into the heliosphere.

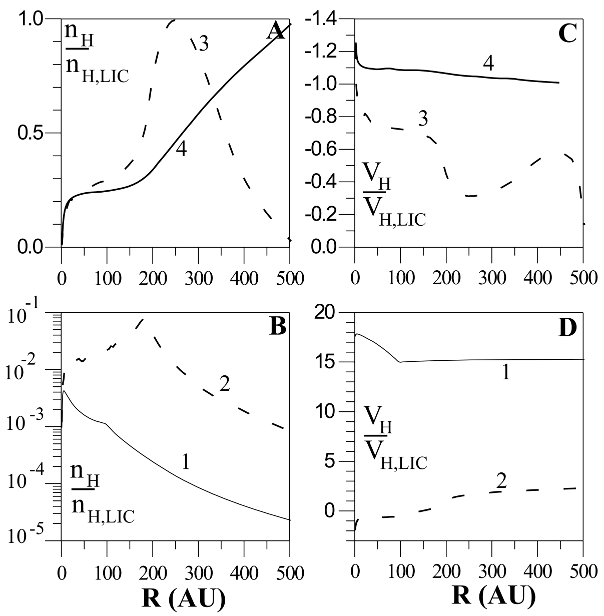

Fig. 2 Number densities and velocities of 4 atom populations as functions of heliocentric distance in the upwind direction. *1* designates atoms created in the supersonic solar wind, *2* atoms created in the heliosheath, *3* atoms created in the disturbed interstellar plasma, and *4* original (or primary)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

3. Interstellar neutrals also modify the plasma structure in the heliosheath. In a pure gasdynamic case (without neutrals) the density and temperature of the postshock plasma are nearly constant. However, the charge exchange process leads to a large increase in the plasma number density and decrease in its temperature. 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 (Baranov and Malama 1996). The influence of interstellar atoms on the heliosheath plasma flow is important, in particular, for the interpretation of kHz-radio emissions detected by Voyager and for possible future imaging of the heliosphere using the energetic neutral atom (ENA) fluxes.

Charge exchange significantly alters the interstellar atom flow. Atoms newly created by charge exchange have the velocity of their ion counterparts in charge exchange collisions. Therefore, the velocity distribution of these new atoms depends on the local plasma properties in the place of their origin. It is convenient to distinguish four different populations of atoms, depending on the region in the heliospheric interface where the atoms were formed. Population 1 are the atoms created in the supersonic solar wind up to the TS (region 1 in Fig. 1), population 2 are the atoms created in the inner heliosheath (region 2 in Fig. 1), and population 3 are the atoms created in the outer heliosheath (region 3 in Fig. 1). The atoms of population 3 are often called the secondary interstellar atom component. We will call the original (or primary) interstellar atoms as population 4. The number densities and mean velocities of these populations are shown in Fig. 2 as functions of the heliocentric distance. The distribution function of H atoms, $f_{\mathrm{H}}(\mathbf{r}, \mathbf{w}_{\mathrm{H}})$, can be represented as a sum of the distribution functions of these populations: $f_{\mathrm{H}} = f_{\mathrm{H},1} + f_{\mathrm{H},2} + f_{\mathrm{H},3} + f_{\mathrm{H},4}$. The Monte Carlo method allows us to calculate these four distribution functions which were presented by Izmodenov (2001) and Izmodenov et al. (2001) at 12 selected points in the heliospheric interface.

Original (or primary) interstellar atoms (population 4) are significantly filtered (i.e. their number density is reduced) before reaching the termination shock (Fig. 2A). The outer heliosheath is the main "filter" for these atoms. Since slow atoms have a small mean free path

Table 1 Results of parametric calculations in the frame of Baranov and Malama (1993) model with $n_{H,LIC} = 0.2\ cm^{-3}$

$n_{p,LIC}\ cm^{-3}$	Primary	Secondary	Total			
	$n_{H4,TS}\ cm^{-3}$	$n_{H3,TS}\ cm^{-3}$	$n_{H,TS}\ cm^{-3}$	$F_{H,TS}$	$V_{H,TS}$ km/s	$T_{H,TS}$ K
0.3			0.07	0.35	17.0	14000
0.2	0.0045	0.075	0.08	0.40	18.0	13500
0.1	0.02	0.07	0.09	0.45	20.0	12500
0.07	0.03	0.065	0.095	0.475	21.0	12000
0.04	0.055	0.05	0.105	0.525	22.5	10500

(due to both larger charge exchange cross section and smaller velocities) in comparison to the fast atoms, they undergo larger losses. This kinetic effect, called *selection*, results in ∼10% increase in the primary atom mean velocity towards the termination shock (Fig. 2C).

The secondary interstellar atoms (population 3) are created in the disturbed interstellar medium by charge exchange of primary interstellar neutrals with protons decelerated in the vicinity of the heliopause. The secondary interstellar atoms collectively make up the *hydrogen wall*, a density increase at the heliopause. The *hydrogen wall* has been predicted by Baranov et al. (1991) and detected in the direction of αCen on the Hubble Space Telescope by Linsky and Wood (1996). At the termination shock, the number density of secondary neutrals is comparable to the number density of the primary interstellar atoms (Fig. 2A, dashed curve). The relative abundances of secondary and primary atoms entering the heliosphere vary with the degree of interstellar ionization (see Table 1). The bulk velocity of population 3 is about −18 to −19 km/s. (The "–" sign means that the population approaches the Sun.)

Another population (population 2) of the heliospheric hydrogen atoms consists of the atoms created in the inner heliosheath by charge exchange with hot and compressed solar wind and pickup protons. The number density of this population is an order of magnitude smaller than the number densities of the primary and secondary interstellar atoms. Therefore, this population has a minor importance for the filtration problem. Inside the termination shock the atoms propagate freely. These atoms may serve as a rich source of information on the plasma properties at the place of their birth, i.e. at the inner heliosheath. There are plans to measure this population of atoms on future missions, including the Small Explorer called Interstellar Boundary Explorer (IBEX) that was selected by NASA and is scheduled for launch in June 2008.

During the last several years a large effort in the multi-component modeling of the heliospheric interface has been done by several groups (e.g. Zank 1999; Baranov and Izmodenov 2006). In particular, our Moscow group has developed models of the heliospheric interface, which follow the kinetic-continuum approach of the B&M-model and take into account effects of the solar cycle (Izmodenov et al. 2005a), interstellar helium ions and solar wind alpha particles (Izmodenov et al. 2003), the interstellar magnetic field (Izmodenov et al. 2005b), and galactic and anomalous cosmic rays (Myasnikov et al. 2000; Alexashov et al. 2004). Recently, Malama et al. (2006) presented a new model that retains the main advantage of our previous models, which is a rigorous kinetic description of the interstellar H atom component. In addition, the model considers pickup protons as a separate kinetic component. The next section briefly discuss factors affecting the filtration of interstellar H atoms in the interface.

3 Filtration of Interstellar Hydrogen

Newly created in the outer heliosheath (between the HP and BS), secondary interstellar atoms have the velocities of the protons that are their companions in charge exchange. The proton component is decelerated and heated at the BS and continues to be decelerated and heated toward the heliopause. Therefore, the bulk velocity of the secondary interstellar atoms is smaller and the effective kinetic temperature is higher as compared with those of the primary interstellar atoms. Because of this, more H atoms have individual velocities not directed toward the Sun, and less atoms penetrate through the heliopause into the heliosphere.

Let us introduce *filtration* (or, more correctly, *penetration*) factor as the ratio of the H atom number density at the TS in the upwind direction to the interstellar number density:

$$F_{\mathrm{H,TS}} = n_{\mathrm{H}}(TS)/n_{\mathrm{H}}(LIC) = [n_{\mathrm{pop.4,H}}(TS) + n_{\mathrm{pop.3,H}}(TS)]/n_{\mathrm{H}}(LIC).$$

In this section we explore how different physical effects influence the penetration factor for H. Izmodenov et al. (1999) in the frame of the B&M model studied the effects of interstellar proton number density on the structure of the heliospheric interface. Table 1 presents relevant results of the study. The filtration factor varies from 0.35 for $n_{\mathrm{p,LIC}} = 0.3$ cm^{-3} to 0.525 cm^{-3} for $n_{\mathrm{p,LIC}} = 0.04$ cm^{-3}. At present low values of $n_{\mathrm{p,LIC}}$ are more favorable because of at least three observational facts: a) Voyager 1 crossed the TS at 94 AU in December 2004 implying a rather small interstellar pressure that is not consistent with a high proton number density, b) the number density of H atoms at TS of 0.1 ± 0.05 cm^{-3} derived from analysis of Ulysses and ACE pickup ion data (Gloeckler and Geiss 2004) that corresponds to $n_{\mathrm{p,LIC}}$ of 0.04–0.07 cm^{-3}; similar values of $n_{\mathrm{H,TS}} \approx 0.09$ cm^{-3} were derived from the analysis of the distant solar wind deceleration measured by Voyager 2 (e.g., Richardson et al. 2007); c) analysis of backscattered solar Lyman-alpha spectra showing line-of-sight velocities that correspond to $V_{\mathrm{H,TS}} = 22$–23 km/s (Quémerais et al. 2006). More recent and detailed parametric analysis of the filtration of interstellar hydrogen was done in Izmodenov et al. (2004) for the range of $n_{\mathrm{p,LIC}} = 0.032$–$0.07$ cm^{-3} and $n_{\mathrm{H,LIC}} = 0.16$–$0.20$ cm^{-3}. The study was done in the frame of the Izmodenov et al. (2003) model that differs from Baranov–Malama model by taking into account effects of interstellar helium ions and solar wind alpha particles. Results of the study are summarized in Table 2. The filtration factor does not change significantly for the considered range of parameters and it is equal to $F_{\mathrm{H,LIC}} = 0.54 \pm 0.04$.

From the analysis of the results of more recent advanced models of the interface mentioned at the end of previous section one can conclude that the considered effects do not change the filtration factor significantly despite their high importance for other aspects of heliospheric physics. Indeed, Myasnikov et al. (2000) and Alexashov et al. (2004) have shown that GCRs and ACRs do not change the filtration factor noticeably. The Malama et al. (2006) model that advances the B&M model by employing a multi-component treatment for heliospheric plasma gives slightly larger filtration factor as compared with the B&M model. In fact in the multi-component model the electron temperature in the heliosheath is smaller as compared to B&M model. The effect of filtration in the inner heliosheath (the region between the TS and HP) due to electron impact ionization is shown in Fig. 5c of Malama et al. (2006) paper. The value of $F_{\mathrm{H,LIC}}$ is smaller by less than 10% for the multi-component model as compared to B&M model.

Effects of the 11-year solar cycle variations of the solar wind parameters on the structure of the heliospheric interface were studied in Izmodenov et al. (2005b). In particular, it was

Table 2 Results of parametric calculations

#	$n_{\mathrm{H,LIC}}$ cm^{-3}	$n_{\mathrm{p,LIC}}$ cm^{-3}	$R(TS)$ AU	$F_{\mathrm{H,TS}}$[a]	$F_{O,TS}$	$F_{N,TS}$
1	0.16	0.032	109	0.58	0.72 (0.84)	0.80 (0.90)[b]
2	0.16	0.05	102	0.55	0.70 (0.83)	0.80 (0.90)
3	0.16	0.06	99	0.54	0.70 (0.82)	0.80 (0.90)
4	0.16	0.07	96	0.53	0.69 (0.81)	0.80 (0.90)
5	0.18	0.032	101	0.57	0.69 (0.82)	0.77 (0.90)
6	0.18	0.05	96	0.54	0.68 (0.81)	0.79 (0.89)
7	0.18	0.06	93	0.53	0.68 (0.81)	0.79 (0.89)
8	0.18	0.07	88	0.52	0.66 (0.80)	0.79 (0.89)
9	0.20	0.032	94	0.55	0.68 (0.82)	0.76 (0.89)
10	0.20	0.04	93	0.54	0.67 (0.81)	0.77 (0.89)
11	0.20	0.05	90	0.53	0.67 (0.79)	0.78 (0.89)
12	0.20	0.06	88	0.52	0.67 (0.80)	0.78 (0.89)
13	0.20	0.07	86	0.51	0.67 (0.79)	0.78 (0.88)

[a] $F_{\mathrm{A,TS}} = n_{\mathrm{A,TS}}/n_{\mathrm{A,LIC}}$ (A = H, O, N) are the filtration factors of interstellar H, O, N atoms, respectively

[b] In parentheses we present filtration factors calculated under an assumption of reduced (by factor of 3) the electron temperature in the inner heliosheath between the TS and BS (Izmodenov et al. 2004)

shown that the number densities of the primary and secondary interstellar H atoms vary within 10% in the outer heliosphere, while closer to the Sun the variations increase.

Izmodenov et al. (2005a), Izmodenov and Alexashov (2006), Opher et al. (2006), Pogorelov et al. (2006) have studied the influence of the interstellar magnetic field on the structure of the interface assuming that the interstellar magnetic field (ISMF) is inclined with respect to the direction of the interstellar flow. In this case the SW/LIC interaction region becomes asymmetric and the flow pattern becomes essentially three-dimensional. Since interstellar H atoms are coupled to the charged component by charge exchange the flow of the interstellar atoms becomes asymmetric too, as observed in the backscattered solar Lyman-alpha radiation spectra measured by SOHO/SWAN (Lallement 2005).

Izmodenov and Alexashov (2006) performed a parametric study by varying the angle α between the direction of the interstellar flow and interstellar magnetic field from 0 to 90 degrees. Despite the fact that interstellar magnetic field significant disturbs the heliospheric interface and interstellar H flow, the filtration factor was in the range of 0.555−0.574 for all considered angle values of angle α that is very close to the results of the B&M model.

Finally, we conclude that despite that the effects of the ionization level of the LIC, the interstellar magnetic field, the solar cycle and others significantly influence the structure of the heliospheric interface and plasma and H atom distributions within the heliosphere, the filtration factor of interstellar hydrogen varies insignificantly for all considered models. It remains in the range from 0.5 to 0.6.

4 Heavier Elements

The theoretical study of the penetration of interstellar heavier elements into the heliosphere was done in a large number of papers (Fahr 1991; Rucinski et al. 1993; Fahr et al. 1995; Kausch and Fahr 1997; Mueller and Zank 2003; Cummings et al. 2002a, 2002b; Izmodenov et al. 1997, 1999, 2003). The papers studied different aspects of the penetration of He, C, N, O through the interface. We will focus on the most recent results.

Firstly, the charge exchange cross section of the helium with protons is so small that the mean free path of the helium atoms is larger than the size of the heliospheric interface. Therefore, the helium atoms penetrate the heliospheric interface unperturbed. This fact was used in order to measure the local interstellar temperature and velocity (Witte et al. 1996; Witte 2004; Möbius et al. 2004). The filtration coefficient for helium $F_{\mathrm{He,TS}} \sim 1$. Cummings et al. (2002b) found that electron impact ionization from the HP to the TS resulted in a factor of about 0.9.

Izmodenov et al. (2004) used the advanced heliospheric interface model by Izmodenov et al. (2003) to perform a comparative study of the penetration through this interface of three interstellar elements—hydrogen, oxygen and nitrogen. Similar to hydrogen, the interstellar atoms of oxygen have large charge exchange cross sections and, therefore, the filtered in the heliospheric interface.

For O atoms both the direct $\mathrm{O} + \mathrm{p} \rightarrow \mathrm{O}^+ + \mathrm{H}$ and the reverse $\mathrm{O}^+ + \mathrm{H} \rightarrow \mathrm{O} + \mathrm{H}^+$ charge exchange processes should be taken into account. It was estimated by Cummings et al. (2002a, 2002b) that the charge exchange of nitrogen with protons may result only in $\sim$1% of filtration, and, therefore, it can be neglected. Electron impact ionization is important for interstellar oxygen (Izmodenov et al. 1999) and hydrogen, while it is almost negligible for filtration of H atoms.

Voronov's formula was employed for electron impact rate coefficients for O and N (Voronov 1997). For charge exchange cross sections for oxygen, the formula given by Stancil et al. (1999) was used. The number density of oxygen ions in the undisturbed LIC is determined by the ionization balance condition $n(\mathrm{OII})/n(\mathrm{HII}) = 8/9 \cdot n(\mathrm{OI})/n(\mathrm{HI})$. This condition is very close to the condition that can be derived from model 17 of Slavin and Frisch (2002). To calculate the number density of oxygen ions the continuity equation for this component (Izmodenov et al. 1999) was solved.

Izmodenov et al. (2004) performed parametric studies by varying the interstellar proton, $n_{\mathrm{p,LIC}}$, and atomic hydrogen, $n_{\mathrm{H,LIC}}$, number densities in the ranges of 0.032–0.07 cm^{-3} and 0.16–0.2 cm^{-3}, respectively. The calculations were performed for 13 models with $n_{\mathrm{p,LIC}}$ and $n_{\mathrm{H,LIC}}$ listed in Table 2.

Figure 3 shows typical distributions of interstellar atomic number densities in the heliospheric interface region in the upwind direction (i.e. opposite to the Sun–LIC relative velocity vector). Qualitatively, such distributions take place for all models. Analogous to the hydrogen wall, the oxygen wall is formed due to the charge exchange process $\mathrm{O}^+ + \mathrm{H} \rightarrow \mathrm{O} + \mathrm{H}^+$.

Atoms that penetrated through the heliopause, can be ionized by hot solar wind electrons in the region between the TS and HP. The filtration in the inner heliosheath due to electron impact is more effective for interstellar N and O atoms as compared with hydrogen. Note that the electron impact ionization rate strongly depends on the electron temperature (Voronov 1997). As it was discussed in the previous section, we use one-fluid description for all plasma components. This approach is appropriate to determine the locations of the shock and the HP and for the plasma velocity, but certainly fails for prediction of the temperatures of the different ionized components. Since the TS is a quasi perpendicular collisionless shock, the electron component of the solar wind is expected to have a lower temperature in the inner heliosheath than one-fluid models predict. To estimate the effect of a change in electron temperature on the filtration factor, Izmodenov et al. (2003) performed calculations with the models where the electron temperature in the inner heliosheath obtained in the frame of the B&M model was arbitrarily divided by a factor of 3.

Fig. 3 Distribution of hydrogen, oxygen, and nitrogen into the upwind direction along the axis of symmetry

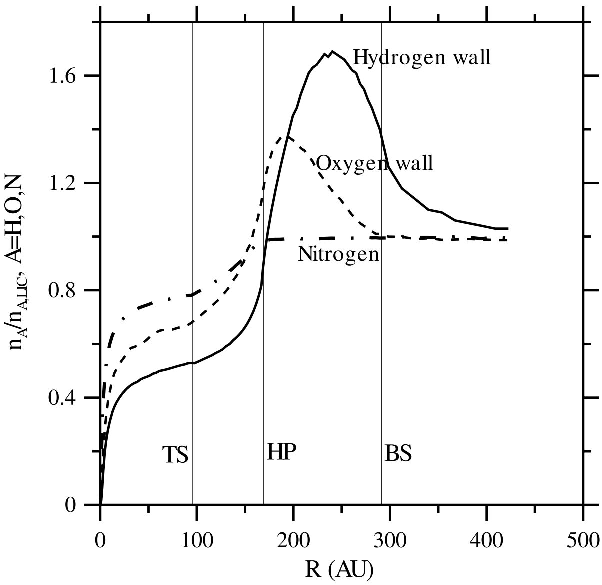

Table 2 summarizes the filtration factors for all 13 models. It shows the location of the TS and the filtration factors, $F_{A,TS}$ (A = H, O, N). The main conclusion, which can be made based on results shown in the table, is that as for hydrogen the filtration factors do not vary significantly with variation of interstellar densities $n_{H,LIC}$ and $n_{p,LIC}$. We find that $68 \pm 3\%$ of interstellar oxygen and $78 \pm 2\%$ of interstellar nitrogen penetrate through the interaction region into the supersonic solar wind. The results of calculations with smaller electron temperature are shown in the table in parenthesis. Small electron temperature leads to stronger penetration of N- and O-atoms into the heliosphere. However, for the two types of models—with and without lowered electron temperature in the heliosheath—the ratio of the nitrogen and oxygen filtration factors changes insignificantly from 1.10 ± 0.02 to 1.15 ± 0.02. Thus, NI/OI in the LIC, if derived from pickup ion data, is not very sensitive to variations in the modeling of the LIC/SW interaction.

Gloeckler and Geiss (2004) derived from Ulysses pickup ion observations that $n_{OI,TS} = (5.3 \pm 0.8) \times 10^{-5}$ cm^{-3} and $n_{NI,TS} = (7.8 \pm 1.5) \times 10^{-6}$ cm^{-3}. Dividing these values by the average of the filtration factors in Table 1, we obtain $n_{OI,LIC} = (7.8 \pm 1.3) \times 10^{-5}$ cm^{-3} and $n_{NI,LIC} = (1.0 \pm 0.2) \times 10^{-5}$ cm^{-3}. Finally, the local interstellar OI/HI and NI/OI ratios are equal $(OI/HI)_{LIC} = (4.3 \pm 0.5) \times 10^{-4}$ and $(NI/OI)_{LIC} = 0.13 \pm 0.01$.

5 Summary and Conclusions

The filtration of the interstellar atoms of H, O, N in the heliospheric interface has been discussed. For hydrogen the filtration was analyzed on the basis of recent advanced multi-component models of the heliospheric interface. It was shown that the filtration coefficient is in the range of 0.5−0.6 for all models. A parametric study by varying local interstellar proton and atom number densities was performed for hydrogen, oxygen, and nitrogen by Izmodenov et al. (2004). It was found that

A. $54 \pm 4\%$ of interstellar hydrogen atoms, $68 \pm 3\%$ of interstellar oxygen and $78 \pm 2\%$ of interstellar nitrogen penetrate through the interaction region into the interface. In the case of a lower electron temperature in the heliosheath $81 \pm 2\%$ and $89 \pm 1\%$ of interstellar oxygen and nitrogen penetrate, respectively.
B. Using the filtration coefficients and SWICS/Ulysses pickup ion measurements we conclude that $n_{\mathrm{OI,LIC}} = (7.8 \pm 1.3) \times 10^{-5}$ cm^{-3} and $n_{\mathrm{NI,LIC}} = (1.0 \pm 0.2) \times 10^{-5}$ cm^{-3}.
C. The local interstellar OI/HI and NI/OI ratios are $(\mathrm{OI/HI})_{\mathrm{LIC}} = (4.3 \pm 0.5) \times 10^{-4}$ and $(\mathrm{NI/OI})_{\mathrm{LIC}} = 0.13 \pm 0.01$. The obtained interstellar OI/HI ratio is slightly lower than the ratio $(4.8 \pm 0.48) \times 10^{-4}$ determined by Linsky et al. (1995) from spectroscopic observations of stellar absorptions.

Acknowledgements I thank the referee of the paper for numerous corrections that improved the paper significantly. I thank Johannes Geiss, George Gloeckler, Rosine Lallement, Yuri Malama and Dmitry Alexashov for their valuable contributions to the work reported in this paper. Especially I would like to thank Johannes Geiss for very pleasant, fruitful and brainstorming discussions during my visit to ISSI. Friendly recommendations and advice of Johannes helped me a lot in both my scientific and not scientific life. I also thank all staff of ISSI for the hospitality during my visits. A part of presented work was done in the frame of Russian–French cooperation (PICS program) under RFBR grant 05-02-22000_CNRS_a. The research was also supported by RFBR grant 07-02-01101-a.

References

D. Alexashov, S.V. Chalov, A. Myasnikov, V. Izmodenov, R. Kallenbach, Astron. Astrophys. **420**, 729–736 (2004) ,
V.B. Baranov, M.G. Lebedev, Y.G. Malama, Astrophys. J. **375**, 347–351 (1991)
V.B. Baranov, Y.G. Malama, J. Geophys. Res. **98**, 15157–15163 (1993)
V.B. Baranov, Y.G. Malama, Space Sci. Rev. **78**, 305–316 (1996)
V.B. Baranov, V.V. Izmodenov, Fluid Dyn. **41**, 689–707 (2006)
A.C. Cummings, E.C. Stone, C.D. Steenberg, Astrophys. J. **578**, 194–210 (2002a)
A.C. Cummings, E.C. Stone, C.D. Steenberg, Astrophys. J. **581**, 1413 (2002b)
H.-J. Fahr, Astron. Astrophys. **241**, 251–259 (1991)
H.J. Fahr, R. Osterbart, D. Rucinski, Astron. Astrophys. **294**, 587–600 (1995)
J. Geiss, G. Gloeckler, U. Mall, R.von Steiger, A.B. Galvin, K.W. Ogilvie, Astron. Astrophys. **282**, 924–933 (1994)
G. Gloeckler, J. Geiss, Adv. Space. Res. **34**, 53–60 (2004)
V. Izmodenov, Space Sci. Rev. **97**, 385–388 (2001)
V. Izmodenov, D. Alexashov, Astron. Lett. **29**, 58–63 (2003)
V. Izmodenov, R. Lallement, Y.G. Malama, Astron. Astrophys. **317**, 193–202 (1997)
V.V. Izmodenov, R. Lallement, J. Geiss, Astron. Astrophys. **344**, 317–321 (1999)
V.V. Izmodenov, Y.G. Malama, A.P. Kalinin, M. Gruntman, R. Lallement, I.P. Rodionova, Astrophys. Space Sci. **274**, 71–76 (2000)
V.V. Izmodenov, M. Gruntman, Y. Malama, J. Geophys. Res. **106**, 10681–10690 (2001)
V.V. Izmodenov, Y.G. Malama, G. Gloeckler, J. Geiss, Astrophys. J. **594**, L59–L62 (2003)
V. Izmodenov, Y.G. Malama, G. Gloeckler, J. Geiss, Astron. Astrophys. **414**, L29–L32 (2004)
V. Izmodenov, D. Alexashov, A. Myasnikov, Astron. Astrophys. **437**, L35–L38 (2005a)
V. Izmodenov, Y.G. Malama, M.S. Ruderman, Astron. Astrophys. **429**, 1069–1080 (2005b)
V.V. Izmodenov, D.B. Alexashov, AIP Conf. Proc. **858**, 14–19 (2006)
V.V. Izmodenov, R. Kallenbach (eds), The physics of the heliospheric boundaries, ISSI Scientific Report 5, 2007
T. Kausch, H.J. Fahr, Astron. Astrophys. **325**, 828–838 (1997)
R. Lallement, Space Sci. Rev. **78**, 361–374 (1996)
R. Lallement, Science **307**, 1447–1449 (2005)
J.L. Linsky, B.E. Wood, Astrophys. J. **463**, 254 (1996)
J.L. Linsky, A. Dipas, B.E. Wood et al., Astrophys. J. **476**, 366 (1995)
Y.G. Malama, V.V. Izmodenov, S.V. Chalov, Astron. Astrophys. **445**, 693–701 (2006)
E. Möbius, M. Bzowski, S. Chalov, H.-J. Fahr, G. Gloeckler, V. Izmodenov, R. Kallenbach, R. Lallement, D. McMullin, H. Noda, Astron. Astrophys. **426**, 897–907 (2004)

H.-R. Mueller, G.P. Zank, AIP Conf. Proc. **679**, 89–92 (2003)
A.V. Myasnikov, V. Izmodenov, D. Alexashov, S. Chalov, J. Geophys. Res. **105**, 5179–5188 (2000)
M. Opher, E.C. Stone, P.C. Liewer, Astrophys. J. **640**, L71–L74 (2006)
N.V. Pogorelov, G.P. Zank, T. Ogino, Astrophys. J. **644**, 1299–1316 (2006)
E. Quémerais, R. Lallement, J.-L. Bertaux, D. Koutroumpa, J. Clarke, E. Kyrola, W. Schmidt, Astron. Astrophys. **455**, 1135–1142 (2006)
J.D. Richardson, Y. Liu, C. Wang, Adv. Space Res. (2007, submitted)
D. Rucinski, H.-J. Fahr, S. Grezedzielski, Planet. Space Sci. **41**, 773–783 (1993)
J.D. Slavin, P.C. Frisch, Astrophys. J. **565**, 364–379 (2002)
P.C. Stancil, D.R. Schultz, M. Kimura et al., Astron. Astrophys. Suppl. **140**, 225–234 (1999)
G.S. Voronov, At. Data Nucl. Data Tables **65**, 1–30 (1997)
M. Witte, M. Banaszkiewicz, H. Rosenbauer, Space Sci. Rev. **78**, 289–296 (1996)
M. Witte, Astron. Astrophys. **426**, 835–844 (2004)
G. Zank, Space Sci. Rev. **89**, 413–688 (1999)