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Filtration of interstellar H, O, N atoms through the heliospheric interface: Inferences on local interstellar abundances of the elements

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Abstract. In this Letter we report on our study of the filtration of interstellar atoms of hydrogen, oxygen and nitrogen in the interaction region between the solar wind and the local interstellar medium. 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 ions 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. We study the dependence of the filtration on the local interstellar proton and H atom number densities and evaluate the effects of charge exchange and electron impact ionization on the filtration. We explore the influence of electron temperature in the inner heliosheath on the filtration process. Using our filtration coefficients and SWICS/Ulysses pickup ion measurements we conclude $n_{\mathrm{OI,LIC}} = (7.8 \pm 1.3) \times 10^{-5}$ cm^{-3} and $n_{\mathrm{NI,LIC}} = (1.1 \pm 0.2) \times 10^{-5}$ cm^{-3}.

Key words. Sun: solar wind – interplanetary medium – ISM: atoms

1. Introduction

Interstellar atoms penetrate deep into the heliosphere after passing the heliospheric interface, the region of interaction of the solar wind with the interstellar plasma (Fig. 1). Being ionized inside the heliosphere the atoms create pickup ion populations. The velocity distributions of pickup ions are measured with the SWICS instrument on Ulysses and ACE and are reasonably well understood (Gloeckler et al. 2001). The pickup ions are convected by the solar wind magnetic field to the heliospheric termination shock (TS) and some of these pickup ions are accelerated at the TS to Anomalous Cosmic Rays (ACRs), which are observed by Voyager in the outer heliosphere and other spacecraft (e.g. ACE, Ulysses and Wind) in the inner heliosphere. Both pickup ion and ACR measurements allow one to study physical properties and the composition of the neutral components of the local interstellar gas (Gloeckler & Geiss 2003; Cummings et al. 2002). Densities of interstellar atoms of H, He, N, O, Ne near the termination shock are derived from the measured pickup ion spectra (Gloeckler & Geiss 2003). To get interstellar densities of the elements from those values one needs to know what affects these atoms as they pass through the heliospheric interface structure. In this Letter we will explore these processes and calculate the filtration factors, which are the ratios of the densities of the interstellar atoms at the TS and in the unperturbed LIC.

Since the 1970s it was realized that interstellar atoms penetrate through the heliospheric interface. The first determination of interstellar hydrogen was done by backscattered solar Lyman α radiation (e.g. Bertaux & Blamont 1971). Since that time considerable theoretical effort was directed towards examining the penetration of interstellar H atoms, which includes multi-component self-consistent modeling of the heliospheric interface (see Izmodenov et al. 2003 and references therein). Recently, the interest in heavier elements is increasing due to the successful measurements of heavier pickup ions and ACRs.

Numerical modeling of penetration of interstellar heavier elements into the heliosphere was previously done by Fahr (1991), Rucinski et al. (1993), Geiss et al. (1994), Fahr et al. (1995), Kausch & Fahr (1997), Izmodenov et al. (1997, 1999). Mueller & Zank (2003) modeled the penetration of He, C, N, O through the interface. However, the goal of all of the above

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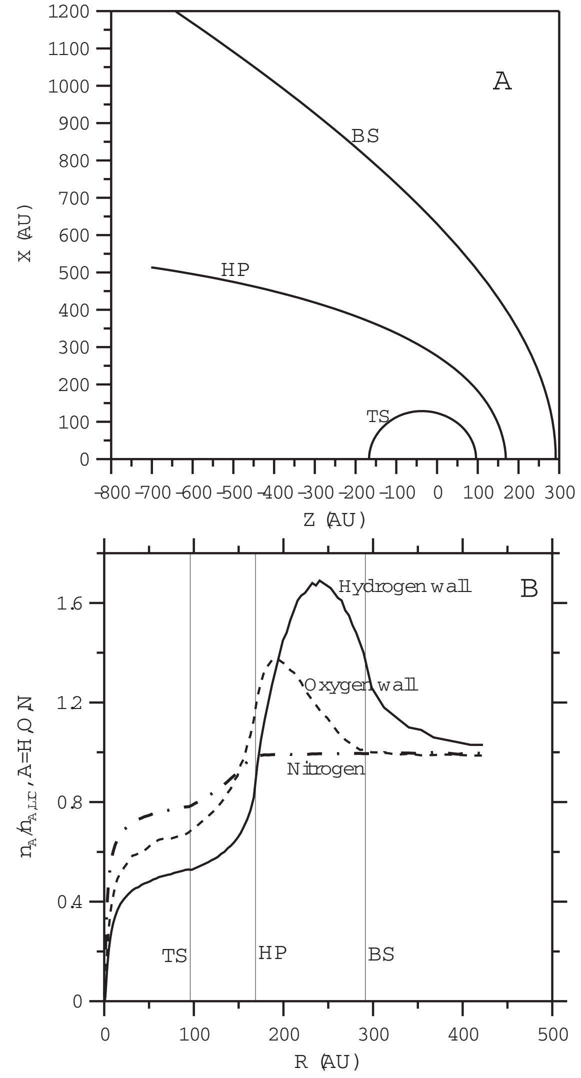

Fig. 1. A) Sketched is the idealized structure of the heliospheric interface (the region of interaction of the solar wind with the LIC) based on results of model 6 in Table 1. **B)** Distribution of hydrogen, oxygen and nitrogen into the upwind direction along the axis of symmetry.

cited studies was to demonstrate the effect or effects of filtration in the interface in general. Recently, Cummings et al. (2002) have developed a new set of ionization rates for 11 elements of interstellar atoms and estimated filtration factors for these elements.

In this Letter we use our new advanced model of the heliospheric interface to perform a comparative study of the penetration through this interface of three interstellar elements – hydrogen, oxygen and nitrogen. Interstellar H and O having large charge exchange cross sections will have their flux altered in the outer heliosheath, the region between the bow shock and the heliopause. As shown by Izmodenov et al. (1999) electron impact ionization may be important for interstellar O atoms, while it is negligible for H atoms. For N atoms, the charge exchange cross section is negligibly small in the considered range of energies, while electron impact ionization plays an important role (Cummings et al. 2002).

2. Model

In this work we use our most advanced global model of the heliospheric interface, which takes into account the effects of interstellar helium ions and solar wind alpha particles (Izmodenov et al. 2003) in addition to the proton and H atom components (Baranov et al. 1991; Baranov & Malama 1993; Izmodenov et al. 2001; see, also, for review Izmodenov 2001). All plasma components (electrons, protons, pickup ions, interstellar helium ions, and solar wind alpha particles) are considered as one-fluid with the total density ρ and bulk velocity v. This one-fluid approximation assumes that all ionized components have the same temperature T. Although this assumption cannot be made in the case of the solar wind, the one-fluid model is based on mass, momentum and energy conservation laws and predicts plasma bulk velocity and locations of the shocks very well. The effect of this assumption on the filtration factors is discussed later in the paper.

The boundary conditions are the following. At the Earth orbit we assume that the solar wind is spherically symmetric, which makes our model axisymmetric, and we use IMP 8 data averaged over several solar cycles for the solar wind parameters: $n_{\rm p,E}$ = 7.39 cm^{-3}, $V_{\rm sw,E}$ = 432 cm^{-3}. The number density of solar wind alpha particles is assumed to be 2.5% of the solar wind proton number density.

Among the interstellar parameters influencing the heliospheric interface structure, the LIC velocity relative to the Sun and the temperature of the local interstellar gas are now well established by direct measurements of interstellar helium atoms with the GAS instrument on Ulysses (Witte et al. 1996). Unlike interstellar hydrogen, the atoms of interstellar helium penetrate the heliospheric interface nearly undisturbed, because of negligible strength of the coupling with protons due to the small cross sections of elastic collisions and charge exchange. Based on these measurements we take in this paper the temperature of the interstellar gas to be 6500 K and the speed of the LIC relative to the Sun as 26.4 km s^{-1}. The remaining three input parameters required to calculate the heliospheric interface structure are the number densities of interstellar protons, $n_{\rm p,LIC}$, of interstellar helium ions, $n_{\rm He^+,LIC}$, and of H atoms, $n_{\rm H,LIC}$.

For O-atoms we took into account both the direct O + p → O$^+$ + H and the reverse O$^+$ + H → O + H$^+$ charge exchange and electron impact ionization. We neglect charge exchange for N-atoms, since it is estimated that it may result only in a ~1% of filtration (Cummings et al. 2002) due to the small cross section of both direct and reverse charge exchange reactions. In our calculations we use Voronov's formula for electron impact rate coefficients for O and N (Voronov 1997). For charge exchange cross sections for oxygen we use formula given by Stancil et al. (1999). The number density of oxygen ions in the undisturbed LIC is determined by the ionization balance condition n(OII)/n(HII) = 8/9 × n(OI)/n(HI). This condition is very close to the condition, which can be derived from model 17 of Slavin & Frisch (2002). To calculate the number density of oxygen ions we solve the continuity equation for this component (Izmodenov et al. 1997).

Using our model and boundary conditions described above, we performed parametric studies by varying the interstellar

Table 1. Results of parametric calculations.

#	$n_{\rm H,LIC}$ cm^{-3}	$n_{\rm p,LIC}$ cm^{-3}	R(TS) AU	$F_{\rm H,TS}{}^a$	$F_{\rm O,TS}$	$F_{\rm N,TS}$
1	0.16	0.032	109	0.58	0.72 (0.84)	0.80 (0.90)
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] $F_{A,\rm TS} = n_{A,\rm TS}/n_{A,\rm LIC}$ (A = H, O, N) are the filtration factors of interstellar H, O, N atoms, respectively.

proton, $n_{\rm p,LIC}$ and atomic hydrogen, $n_{\rm H,LIC}$, number densities in the ranges of 0.032–0.07 cm^{-3} and 0.16–0.2 cm^{-3}, respectively. We made calculations for 13 models with $n_{\rm p,LIC}$ and $n_{\rm H,LIC}$ listed in Table 1. The interstellar helium ion number density was calculated by using an interstellar helium atom number density of 0.015 cm^{-3} (Gloeckler & Geiss 2003; Witte, private communication) and the standard universal ratio of the total H to He, $(n_{\rm p,LIC} + n_{\rm H,LIC})/(n_{\rm He^+,LIC} + n_{\rm He,LIC}) = 10$.

3. Results

Figure 1b 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. An increase in the density of H atoms in the region between the bow shock and heliopause is known as “hydrogen wall”, which was predicted theoretically by Baranov et al. (1991) and, then, was observationally shown to exist in Lyman alpha absorption toward α Cen by Linsky & Wood (1996). The hydrogen wall is formed by secondary interstellar atoms, which are created by charge exchange of primary interstellar atoms with protons decelerated in front of the HP. Analogously, the oxygen wall is due to charge exchange process $\rm O^+ + H \rightarrow O + H^+$ (Izmodenov et al. 1997). Since the interstellar atom has the velocity of its ion companion in charge exchange reaction, which is decelerated and heated by the BS, the bulk velocity of secondary atoms is smaller and the effective kinetic temperature is higher as compared with those of the primary interstellar atom. Because of the higher thermal velocity and smaller bulk velocity of the secondary population, fewer atoms penetrate through the HP. This effect is known as filtration by charge exchange which we define to be the density ratio $n_{A,\rm TS}/n_{A,\rm LIC}$ (A = H, O, N).

Atoms, which penetrate through the interface, can be ionized by hot solar wind electrons in the inner heliosheath, the region between the TS and HP. This results in additional filtration in the inner heliosheath region (Izmodenov et al. 1999). For interstellar N-atoms charge exchange is negligible and all filtration is due to electron impact ionization. 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. A correct treatment requires a multi-component solar wind model, which is currently under development. To estimate the effect of a change in electron temperature on the filtration factor, we also performed calculations with models, where the one-fluid model electron temperature was arbitrarily divided by a factor of 3.

Table 1 summarizes the filtration factors for all 13 models. It shows the location of the TS, and the filtration factors, which are the ratios of the number densities of interstellar atoms at the TS to their densities in the LIC, $n_{A,\rm TS}/n_{A,\rm LIC}$ (A = H, O, N). The main conclusion, which can be made based on results shown in the table, is that the filtration factors do not vary significantly with variation of interstellar densities $n_{\rm H,LIC}$ and $n_{\rm p,LIC}$. We find that 54 ± 4% of interstellar hydrogen atoms, 68 ± 3% of interstellar oxygen and 78 ± 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 ACR or pickup ion data, is not very sensitive to variations in the modeling of the LIC/SW interaction.

Gloeckler & Geiss (2003) derived from Ulysses pickup ion observations that $n_{\rm OI,TS} = (5.3 \pm 0.8) \times 10^{-5}$ cm^{-3} and $n_{\rm NI,TS} = (7.8 \pm 1.5) \times 10^{-5}$ cm^{-3}. Dividing these values by the averaged of Table 1 filtration factors, we obtain $n_{\rm OI,LIC} = (7.8 \pm 1.3) \times 10^{-5}$ cm^{-3} and $n_{\rm NI,LIC} = (1.1 \pm 0.2) \times 10^{-5}$ cm^{-3}.

4. Summary and conclusions

We have studied the penetration of the interstellar atoms of H, O, N into the heliosphere through the heliospheric interface. We performed a parametric study by varying local interstellar proton and atom number densities. It was found that

1. 54 ± 4% of interstellar hydrogen atoms, 68 ± 3% of interstellar oxygen and 78 ± 2% of interstellar nitrogen penetrate through the interaction region into the interface. In the case of a lower electron temperature in the heliosheath 81 ± 2% and 89 ± 1% of interstellar oxygen and nitrogen penetrate, respectively.

2. Using our 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 $n_{\mathrm{NI,LIC}} = (1.1 \pm 0.2) \times 10^{-5}$ cm^{-3}.

3. Finally, we obtain the local interstellar OI/HI and NI/OI ratios, which are $(\mathrm{OI/HI})_{\mathrm{LIC}} = (4.3 \pm 0.5) \times 10^{-4}$ and $(\mathrm{NI/OI})_{\mathrm{LIC}} = 0.13 \pm 0.01$. Our 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.

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