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Interstellar oxygen in the heliospheric interface: influence of electron impact ionization

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Abstract. A fraction of the interstellar atoms crosses the interface between the solar wind and the ionized component of the local interstellar medium (the heliospheric interface), and enters the heliosphere. The number of penetrating atoms depends on the strength of the atom-plasma interaction, i.e. on the atom type.

In this paper we consider the penetration of the interstellar oxygen atoms, and we study in detail the influence of the electron impact ionization. It is shown that this process leads to a significant interstellar O-atom density decrease in the heated (by the termination shock) solar wind. A comparison between oxygen and hydrogen shows that in the heliosphere these two elements have abundances, temperatures and velocities that differ from the corresponding interstellar parameters. On the basis of these new model results, we compare the interstellar OI/HI ratio measured by the HST with the ratio inside the heliosphere which can be deduced from SWICS/Ulysses O^+ and H^+ pick-up data.

Key words: methods: numerical – atomic processes – hydrodynamics – Sun: solar wind – ISM: atoms – ISM: abundances

1. Introduction

Our solar system is moving through a partially ionized interstellar cloud. The ionized fraction of this local interstellar cloud (LIC) interacts with the expanding solar wind and forms the LIC-Solar Wind interface (or heliospheric interface). Interstellar atoms penetrate deeply in the heliosphere where they could be observed directly as atoms, pick-up ions or anomalous cosmic rays (ACR) and indirectly through backscattering of the solar radiation. However, gas-dynamical parameters of these neutrals suffer significant modifications during the crossing of the heliospheric interface. In particular, the flux of neutral atoms may decrease during the crossing of the heliospheric interface. This phenomenon, called "filtration" is due to the coupling of the atoms with the plasma in the interface, i.e. some of the atoms acquire the same motion as the ions and are diverted away from the heliosphere. The filtration factor is the ratio between the interstellar atom density inside the heliosphere, at a distance from the Sun large enough for the direct solar wind and EUV ionization to be negligible, and the initial interstellar neutral density outside the heliosphere, in the unperturbed interstellar medium. The filtration factor is then a measurement of the coupling with the plasma. Since such modifications depend on the type of atom through the charge-exchange cross-section, the relative abundances and the velocity distributions of different species inside the heliosphere are different from the original interstellar abundances and velocity distributions.

Interstellar hydrogen and helium are most interesting among the interstellar atoms due to their large cosmic abundances and the availability of observations. There has been recently an increasing interest in heavier elements of the LIC, in particular O, N, Ne, C. This interest in minor species is now growing due to the recent successful detection of pick-up and ACR ions, with 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 the protons. Very recently, Gruntman & Fahr (1998) proposed a mapping of the heliopause in the oxygen ion O^+ reson ance line (83.4 nm). O^+ in the heliospheric interface is strongly connected with the distribution of neutral oxygen.

Numerical modeling of interstellar oxygen penetration in the heliosphere (Fahr et al., 1995; Izmodenov et al., 1997; Kausch & Fahr, 1997) shows that the fraction of neutral oxygen penetrating into the heliosphere is rather high. It varies between 60–90% on the upwind side depending on the interstellar parameters and which theoretical model is actually used for the analysis. The above models included the effects of direct charge-exchange $O + H^+ \rightarrow O^+ + H$, reverse charge exchange reaction $H + O^+ \rightarrow H^+ + O$ and photoionization. Izmodenov et al. (1997) compared oxygen ion fluxes in the vicinity of the Sun deduced from the Ulysses measurements (Gloeckler et al., 1993) with recent nearby stars spectroscopic HST observations of the neutral oxygen to neutral hydrogen ratio in the Local Cloud (Linsky et al., 1995). The comparison has been made on the basis of the solution of the Boltzmann equation for interstellar atoms by means of a Monte-Carlo method. It has been shown that an additional filtration of atomic oxygen is required

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[⋆] Permanently at Moscow State University, Department of Aeromechanics and Gas dynamics, Faculty of Mechanics and Mathematics (izmod@ipmnet.ru) to reconcile these two types of observations on the basis of the kinetic model.

Electron impact ionization in the heated post-shocked solar wind was considered by Izmodenov et al. as possibly responsible for the stronger filtration of the interstellar oxygen in the heliospheric interface. The influence of electron impact on interstellar oxygen filtering has been taken into account for the first time by Fahr et al. (1995). These authors have done it in a simplified way, by multiplying the charge-exchange cross-section by a number larger than one, this number being taken constant throughout the whole interface, which is equivalent to the implicit assumption that the electron impact ionization rate does not vary as a function of temperature.

Here we calculate explicitly the interstellar oxygen filtration with and without electron impact ionization in the frame of the two-shock heliospheric interface model of Baranov & Malama (1993, 1995, 1996). To compute the interstellar oxygen density in the interface, we use a Monte-Carlo method with the splitting of the trajectories developed by Malama (1991).

2. Model

Because the mean free path of the interstellar atoms is comparable with the characteristic size of the interface, the kinetic Boltzmann's equation has to be solved (see Eq. 1 in Izmodenov et al. 1997). The equation takes into account the solar gravitation, the direct charge exchange $O+H^+ \rightarrow O^+ + H$, the reverse charge exchange $H + O^+ \rightarrow H^+ + O$, the photoionization and the electron impact ionization.

The study of the influence of the electron impact ionization on the interstellar hydrogen atom filtration has been done self-consistently on the basis of the two-shock heliospheric interface model by Baranov & Malama (1996). It is shown in this work that hydrogen filtration due to electron impact ionization is not significant. However, these authors have discovered that electron impact ionization influences the plasma flow in the region between the termination shock (TS) and the heliopause (HP). Indeed, when electron impact ionization is taken into account, there appears a strong density gradient in the whole region of compressed solar wind (see Fig. 3 in Baranov & Malama 1996).

For oxygen the situation is different, because due to its small cosmic abundance neutral oxygen doesn't influence the plasma flow. At the same time the electron impact ionization rate at electron temperatures relevant to the interface is larger for oxygen than for hydrogen (Fig. 1), because these elements have the same first ionization potential P_1, but oxygen has two electrons on the outer orbit and six electrons on the inner orbit (the second ionization potential is also rather s all for oxygen).

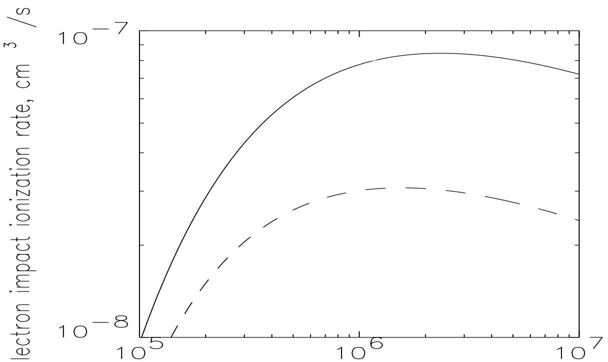

Fig. 1. Electron impact ionization rates for oxygen (solid curve) and hydrogen (dashed curve) as functions of electron temperature.

Lotz (1967) has proposed an empirical formula with three free parameters as a representation of experimental results on the electron impact ionization cross-section. More recently, Arnaud & Rothenflug (1985) have presented a representation of Brook et al. (1978) measurements of the cross section for O atoms. Comparisons between their formula with Lotz (1967) formula show that there is a small difference, which is unimportant to the goals of the present paper. In our calculations we use the more simple formula of Lotz (1967):

$$\beta_e(T_e) = \frac{2}{P_1}\sqrt{\frac{2}{P_1 m_e \pi}}a\sqrt{\lambda}\cdot$$
$$\{q_1(E_1(\lambda) - b\cdot e^c\frac{\lambda}{\lambda+c}E_1(\lambda+c)) + \tag{1}$$
$$\frac{q_2}{\beta}(E_1(\beta\lambda) - b\cdot e^c\frac{\lambda}{\lambda+c}E_1(\beta(\lambda+c)))\}$$

Here a,b,c, q_1,q_2, P_1,P_2 are constant numbers. For oxygen (resp. hydrogen) $q_1 = 2(1)$,$q_2 = 6(0), P_1 = 13.6(13.6), P_2 = 28.5(0), a = 2.8(4.0), b = 0.92(0.6), c = 0.19(0.56)$. λ and E_1 are functions of the electron temperature: $\lambda = \frac{P_1}{kT_e}$, $E_1(\lambda) = \int_1^\infty \frac{e^{-\lambda t}}{t}dt$, and $\beta = \frac{P_2}{P_1}$.

We assume that the plasma picks up the new oxygen ions immediately after their creation by ionization processes, i.e. ionized atoms acquire immediately the velocity and the temperature of the solar wind. In these conditions, the number density of ions obeys the continuity equation. The ionization balance that probably prevails in the unperturbed medium determines the number density of oxygen ions at the outer boundary.

The boundary conditions for the proton number density, the bulk velocity and the Mach number of the solar wind at the Earth's orbit are taken as $n_{p,E} = 7\,\mathrm{cm}^{-3}, V_E = 450\,\mathrm{km\,s}^{-1}, M_E = 10$.

In the unperturbed LIC we use $V_{p,LIC} = 25\,\mathrm{km\,s}^{-1}$, $T_{p,LIC} = 5600\,\mathrm{K}$. These values are close to the most recent determinations of interstellar He parameters obtained by Witte et al. (1996) with the GAS instrument on Ulysses. These authors give an interstellar helium velocity 24.6 ± 1.1 km s^{-1} and a helium temperature of $5800 \pm 700\,\mathrm{K}$. Our numerical experiments show that the increase of the interstellar temperature up to 6700 K and the interstellar velocity up to 25.6 km s^{-1}, that correspond to the temperature and velocity deduced from ground-based and UV spectra of nearby stars observations (Lallement, 1996), doesn't change the structure of the interface significantly.

The interstellar H atom number density $n_{H,LIC} = 0.2\,\mathrm{cm}^{-3}$ has been deduced by Gloeckler et al. (1997) using the new SWICS pick-up results and an interstellar HI/HeI ratio

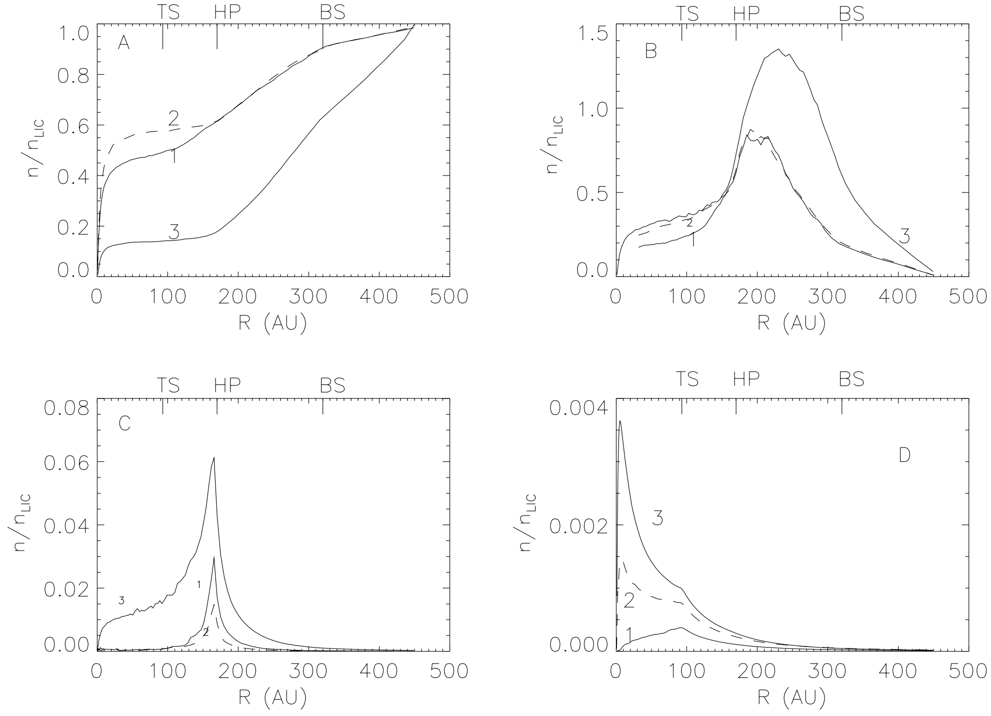

Fig. 2. Neutral oxygen number density in the upwind direction for primary interstellar atoms - population 4 (A), secondary interstellar atoms - population 3 (B), "subsonic solar" atoms - population 2 (C) and " supersonic solar" atoms - population 1 (D). Plotted values are normalized to the oxygen atom number density in unperturbed interstellar medium. Curves 1 correspond to calculations for oxygen where electron impact ionization has been taken into account, curves 2 are the results without electron impact, curves 3 are the relevant normalized densities of hydrogen populations. Positions of the TS, HP, BS are shown.

of 13 ± 1 (the average value of the ratio towards the nearby white dwarfs).

Unfortunately there are no direct ways to measure the circumsolar interstellar electron (or proton) density. There have been measurements of the average electron density in the LIC toward nearby stars. However, resulting densities range from 0.05 (-0.04,+0.14) cm^{-3} up to 0.3 (-0.14, +0.3) cm^{-3} depending on the ions used for the diagnostics or on which line-of-sight is probed (e.g., Lallement & Ferlet, 1997). The most precise, temperature independent value is $0.11\,\mathrm{cm}^{-3}$ toward the star Capella (Wood & Linsky, 1997). In addition, what is measured is always averaged over large distances, while the ionization degree in the local interstellar medium is very likely highly variable and out of ionization equilibrium (e.g., Vallerga, 1998). Therefore there is a need for indirect observations which can bring stringent constraints on the plasma density and on the shape and size of the interface. In our calculations we use for the interstellar proton number density $0.07\,\mathrm{cm}^{-3}$, which is upper limit recently given by Izmodenov et al. (1999). These authors have tried to reconcile the SWICS Ulysses pick-up ion data, $Ly-\alpha$ measurements, and low-frequencies radio emissions on the basis of the two-shock heliospheric interface model, and have concluded that the most likely value for the proton density in the LIC is in the range $0.04\,\mathrm{cm}^{-3} < n_{P,LIC} < 0.07\,\mathrm{cm}^{-3}$.

The simulations were performed for a number density of oxygen in the unperturbed LIC $n_{O,LIC}$ equal to $9.6 \cdot 10^{-5}\,\mathrm{cm}^{-3}$. This corresponds to a ratio of oxygen to hydrogen number densities $\frac{n_{O,LIC}}{n_{H,LIC}}$ of $4.8 \cdot 10^{-4}$ (Linsky et al., 1995). This is the most recent determination of OI/HI relative abundance measurements in the LIC. Since the influence of the oxygen on the protons and H atoms is negligible, in the case of a different O/H abundance ratio, oxygen atoms and ions density distributions can be obtained from the present results by simply multiplying by the appropriate constant.

3. Results of model calculations

Interstellar atoms in the heliosphere can be divided into four different populations depending on which region of the interface they originate from. Indeed, after charge-exchange with the protons, parameters of the newly created (secondary) atoms strongly depend on the local plasma parameters. The heliospheric interface can be divided into 4 regions with very different plasma properties: the supersonic solar wind up to the TS (region 1), the compressed and heated solar wind in the region between the TS and HP (region 2), the compressed interstellar medium between the HP and the BS (region 3) and the unperturbed interstellar medium (region 4). In correspondence with these regions, we divide the interstellar neutrals into 4 populations.

Fig. 2 displays number densities of all populations of interstellar atoms as a function of heliocentric distance in the direction anti-parallel to the interstellar flow vector (the upwind direction). Curves 1 on the figure correspond to calculations including electron impact ionization. The comparison of these curves with dashed lines (where the electron impact ionization is not taken into account) shows that the main effect of the electron impact ionization appears in the compressed solar wind (in the region between the TS and the BS). Indeed, according to the Baranov-Malama model, the solar wind plasma is mostly heated in this region. It is assumed in the model that electrons and protons have the same temperature. The temperature reaches $1–2 \cdot 10^6$ K in the compressed solar wind. For primary interstellar atoms (population 4, Fig. 2a) the effect of additional filtration due to electron impact ionization is about 9%. For secondary interstellar population (population 3, Fig. 2b) the effect is even larger, about 15% of additional filtration. These two interstellar populations are the densest in the heliosphere, and thus their filtration is the most important number. Figs. 2c and 2d show number densities of hot oxygen born between the TS and the HP (population 2), and energetic oxygen atoms born in the supersonic solar wind (population 1). It is seen from the comparison of curve 1 and curve 2 in Fig. 2c that the number density of population 2 increases due to the electron impact. At the HP the increase is about factor of two. As a matter of fact, electron impact ionization increases the number density of oxygen ions, and reverse charge exchange $H+O^+ \to H^+ + O$ leads to additional hot oxygen neutrals.

Fig. 2 shows also the distributions of interstellar hydrogen populations in the heliospheric interface. It can be seen when comparing O and H curves that the "oxygen wall" (the increase in density of population 3, Fig. 2b) is less pronounced than the "hydrogen wall". However, the ratio of oxygen number density of population 3 at the TS (the TS is about at 100 AU Upwind) to the interstellar number density is almost the same as for hydrogen. It is also interesting to note that due to the larger oxygen mass the maximum density in the oxygen "wall" is closer to the HP than for hydrogen. Nevertheless, the density of primary interstellar atoms (population 4) in the outer heliosphere (Fig. 2) and the filtration factor (the ratio of atom number density in the out r heliosphere to atom number density in the LIC) of oxygen are larger than for hydrogen. The filtration factors are equal to 0.7 and 0.475 for oxygen and hydrogen correspondently. This is due to the smaller charge-exchange cross section for oxygen. Larger primary oxygen penetration into the heliosphere with almost the same penetration for the secondary interstellar atoms could lead to significant difference between the properties of the interstellar oxygen and hydrogen in the heliosphere, because the secondary atoms are more heated and decelerated. Hopefully this difference will be measured in future experiments.

4. Comparison of OI/HI interstellar and heliospheric ratios

The most accurate comparison between interstellar and heliospheric oxygen makes use of Hubble Space Telescope (HST) nearby star observations on one hand, and Ulysses SWICS O^+ pick-up data on the other. The most appropriate HST data in the solar environment are those of Linsky et al. (1995). These authors have measured both neutral oxygen and neutral hydrogen column densities along the line-of-sight towards the star Capella. Towards this target located at 12 pc, only one velocity cloud component produces interstellar absorption lines, the one corresponding to our Local Cloud (Lallement & Bertin, 1992). As a consequence, relative abundances deduced from column density calculations towards this star directly apply to the LIC (and not to companion clouds) and are the most representative of the extra-heliospheric gas. According to the Linsky et al. data the neutral oxygen to neutral hydrogen ratio OI/HI is known with a rather small uncertainty of the order 10%:

$$\frac{n(OI)_{LIC}}{n(HI)_{LIC}} = 4.8 \cdot 10^{-4}$$

Recently, on the basis of SWICS/Ulysses oxygen pick-up ion data, Gloeckler & Geiss (1999) have concluded that the neutral oxygen and hydrogen number densities in the outer heliosphere are equal to $n_{HEL}(OI) = (7.8 \pm 1.4) \cdot 10^{-5}\,\mathrm{cm}^{-3}$ and $n_{HEL}(HI) = 0.115 \pm 0.025\,\mathrm{cm}^{-3}$ respectively.

The neutral oxygen to neutral hydrogen ratio in the interstellar medium is linked to the ratio in the heliosphere by:

$$\frac{n(OI)_{HEL}}{n(HI)_{HEL}} = \frac{\alpha_O}{\alpha_H} \cdot \frac{n(OI)_{LIC}}{n(HI)_{LIC}} \tag{2}$$

Here α is the filtration factor.

Using SWICS/Ulysses results by Gloeckler & Geiss (1999) and HST data by Linsky et al. (1995) we conclude that

$$0.75 < \frac{\alpha_O}{\alpha_H} < 2.16 \tag{3}$$

with the mean value $\frac{\alpha_O}{\alpha_H} = 1.46$.

From the results presented in Sect. 3 we conclude that $\alpha_H = 0.475$ and $\alpha_O = 0.7$. Thus the ratio $\frac{\alpha_O}{\alpha_H} = 1.47$ is in perfect agreement with the mean value from Gloeckler & Geiss (1998) and Linsky et al. (1995) results. Now, how sensitive is this calculated ratio to the ionization fraction $\frac{n_{p,LIC}}{n_{H,LIC}}$ of the circumsolar gas? A parametric study of the interstellar hydrogen filtration has been done by Izmodenov et al. (1999) which answers this question in case of H (i.e. models and filtrations were computed for various values of the ionization fraction). A similar research could be done for interstellar oxygen. However, Izmodenov et al. (1999) have shown that a large increase (from $\frac{n_{p,LIC}}{n_{H,LIC}} = \frac{1}{5}$ to $\frac{n_{p,LIC}}{n_{H,LIC}} = 1$) of the ionization fraction of the circumsolar gas changes the hydrogen filtration factor by only 20%. For this reason we think that the ratio $\frac{\alpha_O}{\alpha_H}$ will not be very sensitive to interstellar ionization. Now, the OI/HI filtration ratio (3) has a rather large uncertainty (about 50%). As a consequence it seems impossible at the present time to use the interstellar oxygen as a very good diagnostics of the interstellar proton number density and the interstellar magnetic field, as it has been done for hydrogen (Izmodenov et al., 1999). New and more precise experimental data are needed to do it.

In the present calculations we have used two-shock heliospheric interface model by Baranov & Malama (1993, 1995, 1996). The possible existence of a one-shock heliospheric interface is also discussed in the literature. Indeed, in the case of a rather strong interstellar magnetic field ($B_{LIC} > 2.1\,\mu G$ for $n_{p,LIC} = 0.04\,\mathrm{cm}^{-3}$) the speed of the fast magneto-sonic wave in the LIC is larger than the relative Sun-LIC velocity. In this case the interstellar flow is sub-magnetosonic flow and there is no bow shock. Gayley et al. (1997) have modified the equation of state of the gas to simulate the effect of an interstellar magnetic field. For their one-shock model the authors also have qualitatively the same picture: the hydrogen wall, the filtration in the heliospheric interface. However, there are quantitative differences with the two-shock models. Moreover, Williams et al. (1997), Baranov et al. (1998) have shown that there are non-negligible differences between kinetic and multi-fluid models.

Thus, using one-shock or two-shock multifluid model (versus kinetic Monte-Carlo model) could lead to some quantitative (but not qualitative!!!) changes.

5. Conclusions

We have investigated the effect of the electron impact ionization on the filtration of the interstellar oxygen in the heliospheric interface. On the basis of the investigation we conclude:

1. Electron impact ionization acts on the interstellar oxygen penetrating in the heliosphere and leads to non-negligible additional filtration of the oxygen atoms in the region of the compressed and heated solar wind.
2. In our model, about 70% of interstellar oxygen penetrate in the heliosphere through the heliospheric interface. For the same solar and interstellar parameters only 47.5% of interstellar hydrogen penetrate in the heliosphere. Thus we conclude that the heliospheric relative abundance of OI to HI is larger than the interstellar abundance.
3. As it has been discussed in Sect. 3, the electron impact ionization leads to the increase of the number density of hot energetic neutrals (population 2) in the compressed solar wind (comparison of curves 1 and 2 in Fig. 2c). This is a consequence of the reverse charge-exchange reaction ($H + O^+ \rightarrow H^+ + O$ and could be important for the heliopause mapping in the oxygen ion O^+ resonance line recently proposed by Gruntman & Fahr (1998).
4. Only 30% of interstellar O atoms in the heliosphere are secondary atoms, while for hydrogen they are about 70%. These secondary interstellar atoms are created in the region between the BS and the TS by charge-exchange with the heated and stopped interstellar protons. The secondary atoms have a smaller velocity and a larger temperature compared with the primary atoms. As a consequence, in the heliosphere, interstellar oxygen atoms have a larger temperature and a smaller velocity than interstellar hydrogen atoms.
5. The comparison of the HST-GHRS spectroscopic data of Capella (Linsky et al., 1995) with heliospheric pick-up ion measurements shows a rather good agreement between data and theory. However, the accuracy of the filtration factor ratio derived from the experimental data is still too uncertain to allow a determination of the interstellar plasma density in an independent way.

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