Interaction of Heavy Interstellar Atoms with the Heliosphere

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Abstract. Heavy elements including He, O, and others are present in the interstellar medium surrounding the heliosphere. They form the source for heavy pickup ions and anomalous cosmic rays in the heliosphere. Kinetic numerical models are used to study the entrance and the heliospheric distribution of neutrals and singly charged ions of helium and oxygen as they interact through charge exchange with the neutral and ionized hydrogen of the heliosphere. A representative hydrogen heliospheric model is used to study the heavy element distributions and charge exchange mean free paths, and obtain key results such as filtration ratios and increased heavy neutral densities (walls).

INTRODUCTION

The interaction region of the ionized solar wind with the partially ionized local interstellar medium (LISM) defines the heliosphere with its characteristic boundaries, the termination shock and the heliopause. The dominant particle species in the heliosphere are neutral hydrogen (H), protons and electrons. Consequently, numerical models to study the global heliosphere focus on the interaction of the solar wind hydrogen plasma with the interstellar hydrogen/proton wind. The self-consistent study of neutral H in the heliosphere is important since both neutral H and the plasma mutually influence each other in non-linear ways via charge exchange.

The solar wind and the LISM contain elements heavier than hydrogen as well. The direct solar wind includes heavy ions in various high charge states. The LISM is comprised of neutral heavy atoms and heavy ions in low charge states. The interstellar atoms can penetrate through the heliospheric boundaries into the inner heliosphere, where they, together with the corresponding pickup ions, serve as messengers from the LISM which is currently out of reach for in-situ measurements.

To study the LISM through the measurement of neutral heavy atoms and their singly charged heavy ions, it is necessary to know what changes the interstellar atom population undergoes on its path through the heliosphere. The dominant interactions are the charge exchange of a neutral atom A with the plasma proton background, $A + p \rightarrow A^+ + H$ (1), creating a singly charged heavy pickup ion, and the reverse process, $A^+ + H \rightarrow A + p$ (2), which creates a neutral heavy atom. Through process (2) the neutral hydrogen background influences the heavy interstellar ions outside the heliopause. Similarly, interstellar and solar wind hydrogen plasma depletes the original heavy neutral population and creates heavy pickup ions (equation 1), which are especially important as they relate to
direct measurements in the inner heliosphere, to anomalous cosmic rays (ACR), and to the possibility of energetic neutral atoms (ENA).

MODEL

This study uses a combination of two different models. The electron-proton plasma together with heliospheric neutral hydrogen originating in the LISM, are modeled self-consistently through a multi-fluid hydrodynamic method [1], with the inner boundary at 1 AU with steady solar wind parameters of density \( n_{p,SW} = 5 \, \text{cm}^{-3} \), velocity \( v_{SW} = 400 \, \text{km s}^{-1} \), and temperature \( T_{SW} = 10^5 \, \text{K} \). The outer boundary is at 1000 AU in the ISM, with \( n_H = 0.216 \, \text{cm}^{-3} \), \( n_p = 0.047 \, \text{cm}^{-3} \), \( v = 26 \, \text{km s}^{-1} \), and \( T = 7000 \, \text{K} \) being the interstellar hydrogen density, proton density, velocity, and temperature boundary parameters, respectively. The simulations couple neutral H with plasma through charge exchange, with a cross section taken from Fite et al. [2], and account for the Sun’s gravity, radiation pressure, and photoionization by the Sun’s UV radiation.

The second model used here is a kinetic direct Boltzmann solver [3] (modified from [4, 5, 6]) that tracks the flow of an interstellar neutral heavy atom species through the heliosphere, through direct calculations of representative atom trajectories. Simultaneously, the corresponding singly charged heavy ions species is accounted for in similar direct calculations. Along their trajectories, the two heavy element species are exchanging charge with protons or with neutral hydrogen, respectively, according to equations (1) and (2). The corresponding proton and H distributions are taken from the first model described above. The effects of photoionization and gravity on the heavy elements are taken into account as well, whereas the back-reaction effects of charge exchange (1) and (2) on the proton and neutral hydrogen distributions are neglected. This omission becomes potentially important for oxygen, and will be investigated in future studies.

The interstellar helium and oxygen boundary values used in this study are taken from model 17 of Slavin and Frisch [7] who calculate the abundances and ionization states of all relevant elements in the nearby ISM taking into account measured interstellar column densities and models for the radiation environment in the Local Interstellar Cloud and its interface with the hot Local Bubble. Their model 17 is one of several models favored by measurements of pickup ion spectra [8]. The number densities used here are \( n_O = 1.6 \times 10^{-4} \, \text{cm}^{-3} \) and \( n_{O^+} = 6.6 \times 10^{-5} \, \text{cm}^{-3} \) for oxygen in the LISM, and \( n_{He} = 0.017 \, \text{cm}^{-3} \) and \( n_{He^+} = 0.017 \, \text{cm}^{-3} \) for helium in the LISM. The large \( He^+ \) mass density exceeds that of the protons [9], a fact which is not yet taken into account in the plasma modeling here. Both the interstellar \( He^{++} \) and \( O^{2+} \) densities are significantly smaller than those of their respective singly charged ion counterpart, and hence are not modeled here. The interstellar velocity and temperature for helium and oxygen is assumed to be the same as those for interstellar hydrogen.

For the charge exchange cross sections of reactions (1) and (2), we use power law fits to experimental data described in the literature, for He [10], and O [11]. These cross sections are similar to those compiled recently by Cummings et al. [12]. Of particular interest is that the oxygen cross sections do not fall off at lower relative velocities as do the other heavy elements including helium. Therefore, oxygen is rather tightly coupled
to hydrogen, and charge exchange between the outer simulation edge and the bow shock already alters the oxygen ionization state, so that the densities become $n_O = 1.7 \times 10^{-4}$ cm$^{-3}$ and $n_{O^+} = 6.2 \times 10^{-5}$ cm$^{-3}$, respectively. As the back reactions onto the hydrogen distributions are neglected, the ionization state of hydrogen is unaltered in spite of this process.

**RESULTS**

**Hydrogen.** The structure of the hydrogen distribution as calculated by the multifluid model, is shown in Figure 1 through two-dimensional grayscale maps of the parallel plasma velocity component (panel C), plasma temperature (panel D), plasma density (panel G), and density of neutral H (panel H). The plasma shock boundaries, the termination shock (TS), the heliopause (HP), and the bow shock (BS) are clearly identifiable as sharp temperature gradients in the plasma temperature panel (D). The extent of the heliosphere in the nose direction (stagnation axis) is $\sim 99$ AU to the TS, $\sim 148$ AU to the HP, and $\sim 285$ AU to the bow shock. The TS extends tailward to a maximum distance of $\sim 216$ AU. The neutral number density reaches values as high as $0.5$ cm$^{-3} = 2.32 n_{H, LISM}$ in the hydrogen wall (132% overdensity). The wall is confined between the HP and BS and has a width of $\sim 100$ AU on the stagnation axis. Owing to charge exchange losses, the neutral number density falls to $0.098$ cm$^{-3}$ by the time the neutral flow reaches the TS in the nose direction, which represents 45% of the interstellar value (the filtration ratio).

**Helium.** Figure 1, panels A and B, show the helium results obtained using the Boltzmann code, with the above hydrogen distribution as a constant background. Corresponding to the low charge exchange cross section of neutral He, interstellar He atoms enter the heliosphere almost unimpeded, and there is no density enhancement discernible in the neutral He density data exhibited in panel A. The variability of the field expresses the limited statistical accuracy of the particle method. There is a depletion of neutral He due to photoionization around the Sun, which is erased downwind of the Sun by gravitational focusing. The associated helium cone occupies a scale that is too small to be resolved in Figure 1A (true also for the analogous oxygen cone in panel E). Singly ionized interstellar helium, shown in panel B, is excluded from the interior of the heliopause by its coupling to the hydrogen plasma component. Because the charge exchange rate is so low, He$^+$ is the best example of a distribution of interstellar test particles that follow the hydrogen plasma flow. There are no significant losses or gains of He$^+$ outside the heliopause, and the interior heliosphere is left with a very low density of ions created from neutrals via charge exchange (pickup ions). The overdensity of He$^+$ results from its strong coupling to the surrounding proton – electron plasma. As the hydrogen plasma is decelerated at the bow shock and further decelerated adiabatically upwind of the heliopause (see panel C), direct interstellar He$^+$ is accordingly decelerated in the region between the bow shock and heliopause (the outer heliosheath) and diverted around the heliosphere, unable to cross the heliopause. Like the interstellar hydrogen plasma, the flow stagnates where the symmetry axis crosses the heliopause. The arrangement of panels B and D underscores the alignment of the helium
FIGURE 1. Grayscale maps characterizing the helium distribution in the heliosphere (A: neutral He density, B: He$^+$ density), and the oxygen distribution (E: neutral O density, F: O$^+$ density). For comparison, proton maps of density (G), parallel velocity (C), and temperature (D), as well as neutral hydrogen density (H), are given.
ion overdensity with bow shock and heliopause, and a weak production of pickup ions in heliosheath and heliotail.

**Oxygen.** The charge exchange cross sections of \((\text{He}, \text{H})\) and \((\text{O}, \text{H})\) are very different, both in the way they depend on the particle energy, and in magnitude, with the helium exchange cross section lower than that of oxygen by three to seven orders of magnitude for relative velocities relevant in the heliosphere. Therefore, the oxygen results are drastically different from those of helium.

Panel E of Figure 1 shows the two-dimensional density distribution of neutral O, and singly charged \(\text{O}^+\) is displayed in panel F. It is obvious that many features of the global heliosphere seen in hydrogen also appear with oxygen, in particular an oxygen wall in a narrow region upwind of the heliopause. It traces the familiar shape of the heliopause. Singly charged oxygen shows a qualitatively similar accumulation even though the ion overdensity corresponds to a pile-up at the heliopause, and, as a separate feature, there is an overdensity of ions downstream of the bow shock. Interstellar \(\text{O}^+\) ions behave in principle like the \(\text{He}^+\) particles in the way outlined above, with an overdensity due to the plasma deceleration. The high density decelerated oxygen ions just upwind of the heliopause encounter an overdensity in neutral hydrogen, the hydrogen wall, allowing frequent charge exchange (equation 2) that produce slow neutral oxygen atoms forming the oxygen wall. The densities of the two interaction partners are laid out next to each other in panels F and H in Figure 1. The charge exchange mean free path (mfp) for \(\text{O}^+\) varies over the width of the hydrogen wall, ranging from 60 AU down to 10 AU as the plasma velocity decreases. It is important to note that neutral oxygen crossing the heliopause into the heliosphere is comprised of both primary interstellar oxygen (albeit depleted by slight losses), and secondary neutral oxygen in a slower velocity state.

Despite the nominal losses of \(\text{O}^+\) due to efficient charge exchange in the hydrogen wall, the \(\text{O}^+\) density increases continually with decreasing distance to the heliopause as the ions are decelerated by the decelerated hydrogen plasma. Both this density increase and the gradient in mfp combine to make the neutral oxygen wall relatively thin. In addition, the overdensity of protons in the outer heliosheath combines with neutral oxygen to increase the \(\text{O}^+\) density downstream of the bow shock (see the neighboring panels E and G of Figure 1). However, given that the corresponding O charge exchange mfp is \(\sim 500\) AU in the outer heliosheath, this process is not very efficient.

Downwind of the oxygen wall, the O charge exchange mfp is \(\sim 2600\) AU in the inner heliosheath, so that neutral O is only gradually depleted by charge exchange with plasma protons. It is in the inner heliosheath where losses due to electron impact ionization may be important [12, 13], which are not included here. Photoionization is included, however, and exponentially depletes neutral O around the Sun. In the extended tail, neutral O gets slowly depleted by charge exchange with mfps larger than 1000 AU. This decrease (and an associated increase in pickup \(\text{O}^+\) that is too faint to appear in panel F) can be seen in the extended heliotail in Figure 1 beyond \(\sim -150\) AU.

Finally, in the off-axis side lobe region for oxygen (Figure 1E) there is a large, pronounced overdensity of neutral oxygen, flaring outward from the heliopause about 200 AU downwind of the Sun’s position (and 400 AU off axis). Since the \(\text{O}^+\) distribution shows a corresponding decrease of ion density, this neutral material is the product of charge exchange with neutral hydrogen (equation 2). Because of a high interstellar neutral H density and a low plasma density, oxygen ions experience frequent charge
exchange to form neutral atoms, whereas the reverse reaction is suppressed by the dearth of interstellar protons. This process is not relevant for other elements such as helium.

The neutral oxygen wall reaches densities as high as $3.1 \times 10^{-4} \text{ cm}^{-3} = 1.85 n_{O,LISM}$ (85% overdensity). The charge exchange losses of neutrals are made up by secondary neutrals, so that the neutral number density remains at $1.7 \times 10^{-4} \text{ cm}^{-3}$ (about 100%) even for the TS in the nose direction (no filtration). This upper bound for filtration is modified when electron impact ionization is included [12, 13]. All these oxygen results are specific to the chosen boundary parameters; studies addressing the sensitivity to the hydrogen parameters have been carried out elsewhere [3, 14].

**SUMMARY**

In summary, the results emphasize the importance of the charge exchange cross sections to the filtration and distribution of interstellar neutral heavy atoms in the heliosphere. Elements weakly coupled to H such as He, but also Ne, Ar, and even C [3], experience only modest losses when traversing the heliosphere, and filtration is not sensitive to the details of the H background. Elements coupled more strongly to H, such as O and N, are sensitive to the background H distribution, and react more strongly in the form of neutral walls and changed filtration ratios.

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**REFERENCES**