Velocity distribution of interstellar H atoms in the heliospheric interface

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October 30, 2000

Abstract. In this paper we present first results of a numerical computation of the velocity distribution function of interstellar H atoms in the heliospheric interface, the region of the solar and interstellar wind interaction. The velocity distribution is a key tool to evaluate uncertainties introduced by various simplified models of the interface. We numerically solve the kinetic equation for gas of H-atoms self-consistently with the hydrodynamic equations for plasma. Neutral and plasma components are efficiently coupled by charge exchange. The interaction disturbs the atom velocity distribution, which is assumed to be Maxwellian in the circum-solar local interstellar medium. It is shown that besides "original" interstellar atoms, there are three other important atom populations originating in the heliospheric interface. Velocity distribution functions of these populations at the heliopause are presented and discussed.

Keywords: interstellar atoms, solar wind, heliospheric interface

1. Introduction

Interstellar atoms penetrate into the heliosphere through the heliospheric interface, the region of the solar wind and interstellar wind interaction. The measurements of these atoms through the reflected solar radiation and as pickup ions and anomalous cosmic rays on the Voyager, Pioneer, Ulysses, SOHO and HST spacecraft provide an opportunity of remote study of the heliospheric interface structure and properties of the local interstellar medium (LISM). Interstellar H atoms is the most abundant (about 90%) component of interstellar gas. These atoms interact with the solar wind and interstellar plasma component by charge exchange. The mean free path of the H atoms with respect to charge exchange with protons is comparable to the size of the heliospheric interface (e.g., Izmodenov et al., 2000). Under such conditions a kinetic description of neutrals is required to describe their essentially non-Maxwellian properties (Baranov et al., 1998). In this paper, we present first results of our modeling of the velocity distribution of interstellar hydrogen in the heliospheric interface. In our calculations we solve the kinetic Boltzmann equation for velocity distribution of H atoms. For the plasma component we use a hydrodynamic approach. Sources and sinks of mass, momentum and energy due to charge exchange with the atoms are taken into account self-consistently in the right part of the plasma Euler's equations. The self-consistent model of the heliospheric interface was developed by Baranov and Malama (1993). Later this model was applied to interpret different observational diagnostics of the interface (Izmodenov et al., 1999a,b).

2. Structure of the heliospheric interface

The fluid description assumed for the plasma component (protons and electrons) does not permit mutual penetration and mixture of the solar wind and interstellar charged particles. A contact discontinuity surface - the heliopause - forms and separates the solar wind and interstellar plasma components. The supersonic solar wind must go through a shock before reaching the interstellar plasma at the heliopause. This is the termination shock (TS). A bow shock in front of the heliopause decelerates the interstellar wind plasma.

The interstellar H atoms push the heliospheric plasma interface closer toward the Sun. The interaction with the atoms disturbs the plasma flows upstream the shocks. The solar wind is disturbed upstream of the TS by charge exchange with interstellar neutrals, while the interstellar plasma upstream the bow shock is disturbed by the charge exchange with newly created energetic atoms, which come from the supersonic solar wind region. Four regions with significantly different plasma properties can be recognized in the heliospheric interface: A) undisturbed interstellar plasma, B) disturbed interstellar plasma region, C) the heliosheath with the compressed and decelerated solar wind plasma, D) the supersonic solar wind upstream TS;

The velocity distributions of atoms newly created by charge exchange depend on local plasma properties. It is convenient to divide atoms into four different populations in the heliospheric interface depending on the place of their origin, as defined above, e.g. original (or primary) interstellar atoms form population A. The velocity distribution function $f_H(\vec{v}_H, \vec{r})$ is a sum of distribution functions of these populations: $f_H = f_{H,A} + f_{H,B} + f_{H,C} + f_{h,D}$. To calculate f_H we use the Monte-Carlo method with splitting of trajectories, which allows us to calculate these four distribution functions.

3. Results and Conclusions

To illustrate evolution of the velocity distributions we present (figure 1) $f_{H,i}$ as functions of V_z component of velocity at five locations in the heliospheric interface in the upwind direction. We use a cylindrical (z, x, ϕ) coordinate system with the Sun in the center. The symmetry axis (Oz) is assumed to be parallel to the Sun/LISM relative velocity vector, V_{LISM}. (Another presentation of the results - projections of the velocity distribution functions in (V_z, V_x)-plane of the phase space - can be found on the Web-page: http://194.190.131.172/∼izmod/Papers/2001/SSR-izmod/.)

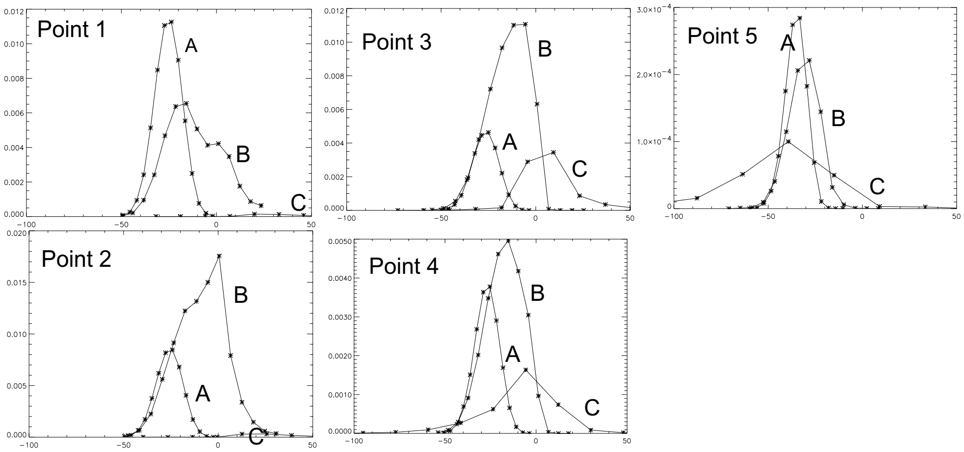

Figure 1. Distributions of H atoms, $f_{i,H}$ (i=A,B,C), are shown as functions of V_z for fixed values of $V_x = U_x$ and $V_\phi = U_\phi = 0$. U_x, U_ϕ are x and ϕ components of the vector of bulk velocity of H atoms. The values are normalized to dimensionless number density: $\int f_{i,H}(\vec{r},\vec{v})d\vec{v} = n_{i,H}(\vec{r})/n_{H,LIC}$. Point 1 is located in the disturbed interstellar medium at the bow shock, point 2 is located inside the hydrogen wall, point 3 is at the heliopause, point 4 is at the termination shock, point 5 is at the Earth orbit. All points are located in the upwind direction.

The velocity distributions are not Maxwellian for all introduced populations of H atoms. Interstellar atoms with smaller velocities preferably charge exchange with protons. This so-called "selection" effect is clearly seen in the velocity distribution of population A (primary interstellar atoms). The originally Maxwellian distribution is disturbed for velocities $V_z > -20 km/s$. (The minus sign of V_z means approaching to the Sun.) The cause of the selection is the smaller mean free paths of slow atoms compared with fast atoms. At the heliopause, the selection causes an effective increase of the bulk velocities of 2-3 km/s. Outside the heliopause atoms of populations C and D have velocities directed outward from the Sun. These atoms propagate in the disturbed interstellar medium and can reach the regions upstream the bow shock. In the interstellar medium, the velocity distribution of population C - atoms originated in the heliosheath - can serve as remote diagnostics of the three-dimension shape of the heliopause. The heliopause shape is reflected in the velocity distribution of population C. Inside the termination shock the atoms of population C directed toward the Sun, can be measured directly in the vicinity of the Sun as heliospheric ENAs (see, Hilchenbach et al, 1998; Izmodenov et al., this volume). Outside the termination shock, the velocity distribution of population D -neutral solar wind - is proportional to $(R_{TS}/R)^2$ and, practically does not depend on direction.

Complete analyzes of the evolution of the velocity distribution function in the heliospheric interface (Izmodenov et al., 2001) allows us to make the following conclusions:

1. Velocity distribution functions of the four introduced populations are not Maxwellian in the heliosphere.

2. The H atom velocity distribution function is significantly disturbed at large distances from the Sun, even at the bow shock and beyond.

3. Slow particles are preferably charge exchanged with the plasma protons. This effect of so-called selection, makes the velocity distributions of primary and secondary interstellar atoms asymmetric with respect to $V_z = U_{z,bulk}$.

4. Velocity distributions of both primary and secondary H atoms are dependent on the geometry of the interface region and, in particular, on the angle to the upwind direction.

5. Atoms of population C penetrate deeply into the solar wind. In the downwind cavity, the number density of this population is even larger than the number densities of interstellar populations, which may be important for interpretations of pick-up ions and Ly-α measurements. This population is a good tracer of the termination shock and the heliopause shapes for measurements from both inside and outside the heliosphere.

Acknowledgements

This work was supported in part by U.S. Civilian Research & Development Foundation (CRDF) Award # RP1-2048, the Russian Foundation for Basic Research Grants # 98-01-00955, INTAS-CNES Grant # 97-0512 and the International Space Science institute (ISSI) in Bern.

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