Modeling of the tail region of the heliospheric interface

Dmitry Alexashov* and Vlad Izmodenov†

*Institute for Problems in Mechanis, Russian Academy of Sciences, Moscow, Russia
†Lomonosov Moscow State University, Department of Aeromechanics, Faculty of mechanics and mathematics, Vorob'evy gory, Glavnoe Zdanie MGU, 119899, Moscow, Russia

Abstract. The processes in the tail region of the interaction of the solar wind with the partially ionized local interstellar medium are investigated in a framework of the self-consistent kinetic gas dynamic model. It is shown that charge exchange of the hydrogen atoms with the plasma protons leads to suppression of the gas dynamic instabilities and disappearance the contact discontinuity at sufficiently large distances from the Sun. It is shown that the solar wind plasma temperature decreases and, ultimately, the parameters of the plasma and hydrogen atoms approach to the corresponding parameters of the pristine interstellar medium at large heliocentric distances.

INTRODUCTION

The solar wind interacts with partly ionized local interstellar cloud (LIC). The structure of the Solar Wind - LIC interaction region is shown in Figure 1. Contact discontinuity, or *the heliopause* (HP), separates solar wind and interstellar plasma. The heliopause is an obstacle to flow around by the supersonic (the Max number is about 10) solar wind, and also by the supersonic (the Max number is about 2) interstellar gas. A shock has to be formed in the case of supersonic flow. The supersonic solar wind passed through *the termination shock* (TS) to become subsonic. *The bow shock* is formed in the local interstellar cloud. The whole region of the solar wind interaction is called as *the heliospheric interface*. The interstellar H atoms interact with plasma component by charge exchange and strongly influence on the location of the shocks and the heliopause. The difficulty to model the interface is in large mean free path of the H atoms comparable with the size of the heliosphere. To describe interstellar H atom flow in the interface it is necessary to solve kinetic equation. Self-consistent model of the heliospheric interface was proposed in [1] and realized in [2]. Last paper also present first calculations in the region of the heliospheric interface. Figure 1 shows a comparison of locations of the two shocks and the heliopause for two cases with H atoms and without them. The discontinuities are significantly closer to the Sun in the case with atoms. In the tail region the structure of the flow changes qualitatively. The termination shock becomes more spherical and Mach Disk (MD), reflected shock (RS) and tangential discontinuity (TD) disappear (Figure 1).

The model of the heliospheric interface allows answering two fundamental questions: 1. Where is the edge of the solar system? 2. How far is the influence of the solar system on the surrounding interstellar medium?

To give an answer on the first question we need to give definition of the solar system boundary. It is naturally to assume the boundary is the heliopause, which separate solar wind and interstellar plasmas. Note, that the influence of the solar system on the interstellar medium is significantly far than the heliopause. Secondary interstellar atoms, which are result of the charge exchange of original interstellar atoms and solar wind protons, disturbed the interstellar gas upwind the bow shock (e.g. [3,4] and reference therein). However, the most of papers have studied the upwind region effects mainly. At the same time the study of the heliotail region has also significant interest. For the heliotail we cannot say that the heliopause is the heliospheric boundary. It is seen in Figure 1, the heliopause is not closed surface and the solar wind fills the whole space into the downwind direction. The goal of the present work is in the study the effect of charge exchange on the tail region of the heliospheric interface.

MODEL

To study the effect of charge exchange on the structure of the heliotail we used kinetic-gasdynamic model by Baranov and Malama [1-4]. To describe the charged component (electrons and protons) we solve hydrodynamic Euler equations, where the effect of charge exchange is taken into account in the right parts of these equations. To calculate the flow of interstellar H atoms in the helio-

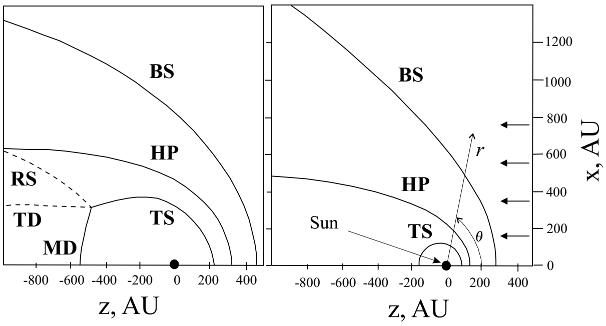

FIGURE 1. The structure of the heliospheric interface is the region of the solar wind interaction with the interstellar medium.

spheric interface we solve kinetic equation:

$$\mathbf{w}_{\mathrm{H}} \cdot \frac{\partial f_{\mathrm{H}}(\mathbf{r},\mathbf{w}_{\mathrm{H}})}{\partial \mathbf{r}} + \frac{\mathbf{F}}{m_{\mathrm{H}}} \cdot \frac{\partial f_{\mathrm{H}}(\mathbf{r},\mathbf{w}_{\mathrm{H}})}{\partial \mathbf{w}_{\mathrm{H}}} \quad (1)$$

$$= -f_{\mathrm{H}}(\mathbf{r},\mathbf{w}_{\mathrm{H}}) \int |\mathbf{w}_{\mathrm{H}} - \mathbf{w}_p| \sigma_{ex}^{\mathrm{HP}} f_p(\mathbf{r},\mathbf{w}_p) d\mathbf{w}_p$$

$$+ f_p(\mathbf{r},\mathbf{w}_{\mathrm{H}}) \int |\mathbf{w}_{\mathrm{H}}^* - \mathbf{w}_{\mathrm{H}}| \sigma_{ex}^{\mathrm{HP}} f_{\mathrm{H}}(\mathbf{r},\mathbf{w}_{\mathrm{H}}^*) d\mathbf{w}_{\mathrm{H}}^*$$

$$-(\beta_i + \beta_{\mathrm{impact}}) f_{\mathrm{H}}(\mathbf{r},\mathbf{w}_{\mathrm{H}}).$$

Here $f_{\mathrm{H}}(\mathbf{r},\mathbf{w}_{\mathrm{H}})$ is velocity distribution function of H atoms; $f_p(\mathbf{r},\mathbf{w}_p)$ is locally Maxwellian velocity distribution of protons; $\mathbf{w}_p$ and $\mathbf{w}_{\mathrm{H}}$ is individual velocities of protons and H atoms, respectively; $\sigma_{ex}^{\mathrm{HP}}$ is the cross section of the charge exchange of H atoms and protons; β_i is the photoionization rate; m_{H} is the mass of H atom; β_{impact} is the electron impact ionization;and $\mathbf{F}$ is the sum of the solar gravitation and radiation pressure forces.

The main process of the plasma-neutral coupling is charge exchange. Photoionization and electron impact ionization are also taken into account in equation (1). The interaction of the charged and neutral components results in exchange of mass, momentum and energy between the components. The expressions for the source terms into the right parts of Euler equations are given in [2].

For boundary conditions in the unperturbed LIC we assume that velocity $V_\infty = 25$ km/s, interstellar H atom and proton number densities are 0.2 cm^{-3} and 0.07 cm^{-3}. The temperature of the LIC was assumed 6000 K. Velocity, number density and Max number at the Earth orbit are 450 km/s, 7 cm^{-3} and 10, respectively. Velocity distribution function of H atoms is assumed to be Maxwellian.

Euler equations with the source terms were solved self-consistently with the kinetic equation for H atoms. To get the self-consistent solution we used the iterative method. The kinetic equation was solved by Monte-Carlo method with splitting of trajectories. Unlike the previously published papers based on Baranov-Malama model, we performed the calculations in extended computation region toward the heliotail. We performed computations up to 50000 AU along the axis of symmetry and up to 5000 AU in the perpendicular to the symmetry axis direction. To estimate divergence of chosen numerical scheme we used different computational grids. A dependence of the numerical solution from outer boundary conditions was estimated by variation of the computational domain in the tail region.

QUALITATIVE ANALYSIS

In present work we consider effect of the charge exchange process ($H + H^+ \rightarrow H^+ + H$) on the plasma flow in the tail region of the heliospheric interface. The supersonic solar wind passes through the heliospheric termination shock, where its kinetic energy transfers to the thermal energy. Let us assume now that the heliopause surface is parallel to the direction of interstellar flow. In this case the solar wind can be considered as a flow in the nozzle with constant cross-section. Our computations show that the solar wind pressure downstream the termination shock is several times smaller than the interstellar pressure. Under these conditions the solar wind flow decelerates and has some minimal value at infinity. The minimal value is determined by the parameters of the solar wind downstream the termination shock and the interstellar pressure. Neither the interstellar proton number density nor the relative Sun-LISM velocity does not determine the minimal velocity. Therefore, in the case with no atoms in the frame of hydrodynamic approach it is possible to find solution where the solar wind (and, therefore, the solar system) extended in the heliotail up to infinity. Such a qualitative consideration can be easily generalized, when the heliopause is not parallel to the axis of symmetry. Then the solar wind flow can be considered as a flow in convergent or expanding nozzle.

Qualitatively other situation is realized in the case with interstellar atoms. Our calculations show that in the case the pressure is larger than the interstellar pressure. The solar wind should be accelerated in this case by the pressure gradient. However, interstellar atoms play significant role due to charge exchange. Due to large mean free path the interstellar atoms fulfill the heliotail. Part of original (or primary) interstellar atoms increases with the heliocentric distance. The temperature (7000 K) and velocity (25 km/s) of interstellar atoms are smaller than the velocity (100 km/s) and temperature (100000 K) of the post shocked solar wind. New protons, which are born from interstellar H atom, have smaller average and thermal velocities than original solar protons. Therefore, the charge exchange process leads to effective cooling and deceleration of the solar wind. Since the part of primary

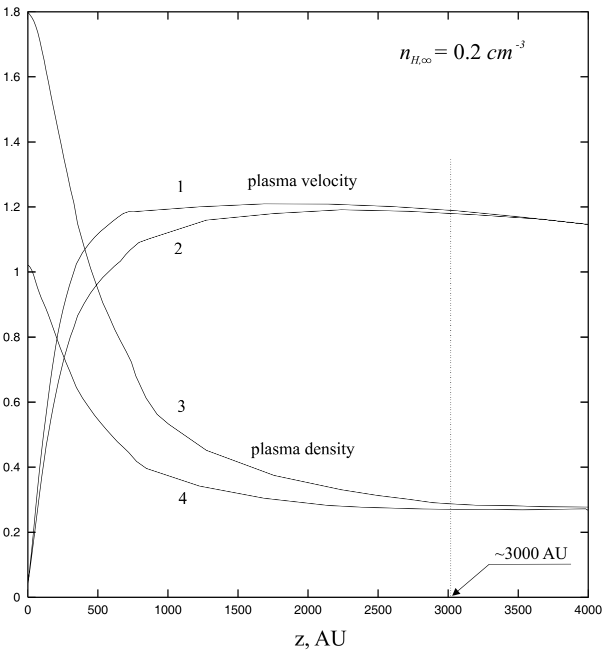

FIGURE 2. Velocities (curves 1 and 2) and densities (curves 3 and 4) from both sides of the heliopause as a function of the heliocentric distance along the heliopause. Curves 2 and 3 correspond to interstellar side; curves 1 and 4 correspond to solar wind side. The velocities and temperatures are normalized to their interstellar values.

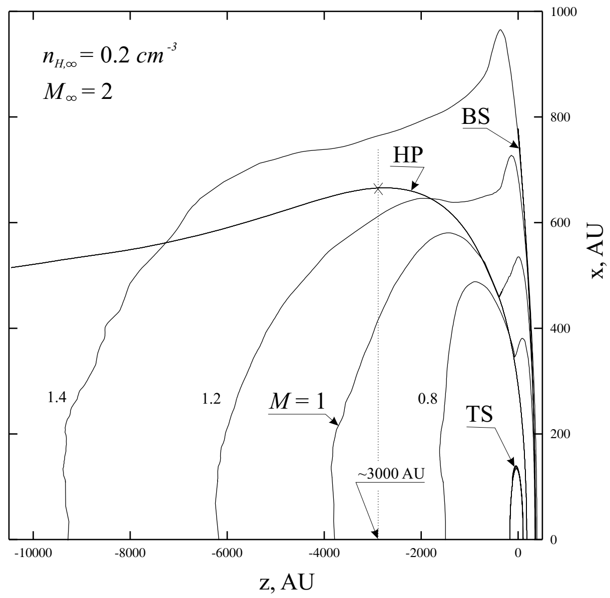

FIGURE 3. Isolines of Mach number M. It is seen that on the distances more than 4000 AU into the heliotail direction the solar wind flow is supersonic. The Mach number increases with increase of the heliocentric distance and approaches its interstellar number.

interstellar atoms increases with the increasing of the heliocentric distance, it is naturally to expect approaching of the solar wind velocity, density and temperature to their interstellar values.

Despite a number of assumptions, given qualitative analysis is confirmed by our numerical calculations. In the next section we present and discuss results of numerical calculations.

RESULTS AND DISCUSSION

Distributions of plasma parameters in the heliospheric tail region are presented in figures 2 and 3. In figure 2 we present distribution of density and velocity of plasma from both sides of the heliopause. In the classical hydrodynamics there are two conditions for tangential discontinuity. The conditions are 1) no mass transport through the discontinuity, 2) balance of pressures on the both sides of the discontinuity. These conditions permit a jump of density and tangential velocity through the heliopause. In the case with H atoms the jump of density and pressure will become weaker with increasing the distance along the heliopause due to mass transport caused by charge exchange. For $z \approx -3000$ AU, where z is the distance along the axis of symmetry and sign "-" means the direction along the interstellar flow direction, the jump of density and tangential velocity disappears (Figure 2). The velocity of the solar wind is about 100 km/s downstream the termination shock. Then the velocity becomes smaller due to new inject by charge exchange protons and approaches the value of interstellar velocity. The solar wind becomes also cooler due to charge exchanges. It is interesting to see whether the solar wind becomes supersonic due to effective cooling. Figure 3 shows isolines of Mach numbers in the heliospheric interface. The solar wind passes through the sound velocity at about 4000 AU, then the Mach number increases approaching its interstellar value. The heliopause is also shown in Figure 3. The line $z = -3000$ AU shows the region where there is no jump of density and velocity through the heliopause.

Figure 4 represents the densities, velocities and temperatures of the interstellar hydrogen along the different downwind directions. The angle θ in Figure 4 is the angle between line-of-sight and upwind directions (Figure 1). Parameters of H atoms are approaching their interstellar values on distances less than 20000 AU for all line-of-sights. The approaching is faster for smaller θ. It is interesting to note, that the hydrogen wall, the increase of H atom number density in the region between the heliopause and the bow shock [1-3] is visible even for large $\theta \approx 150 - 170^o$.

To get numerical solution of the heliotail plasma becomes possible due to charge exchange. It is important

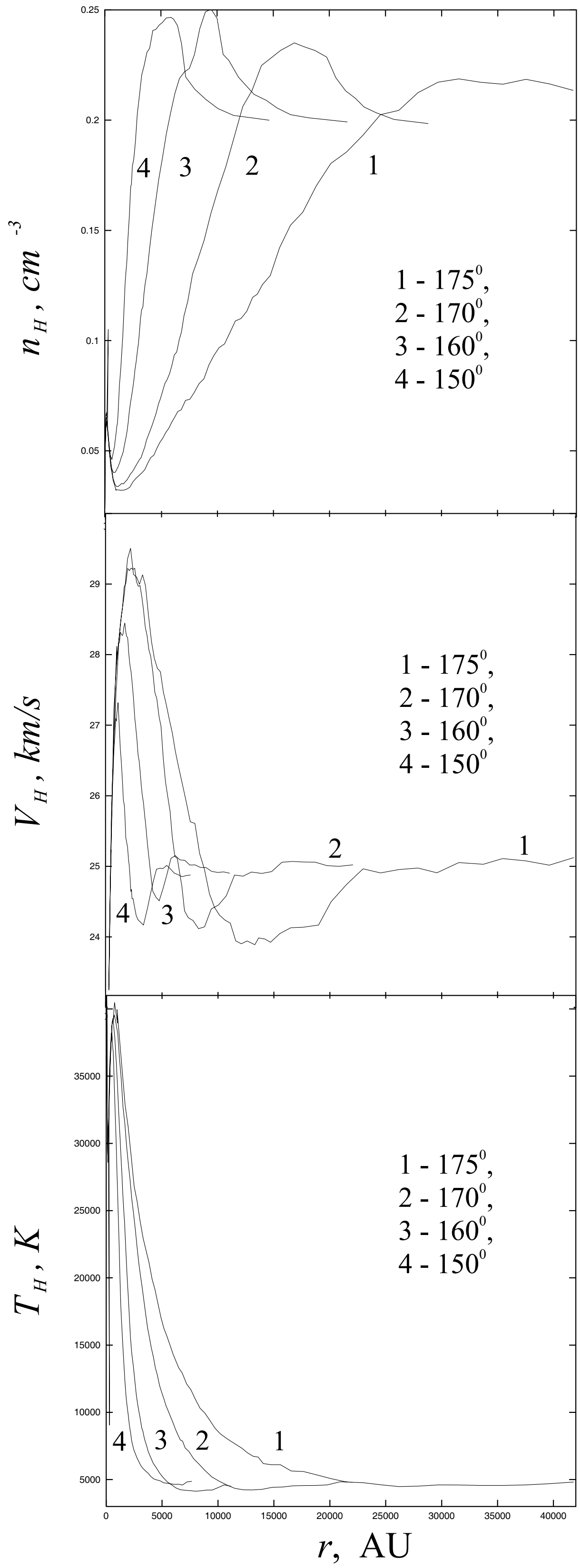

FIGURE 4. Number density, velocity and temperature of the interstellar H atom along downwind lines of sights θ = 150, 160, 170, 175 degrees.

that the solar wind is supersonic at the outer boundary. This allows fulfilling correct boundary conditions.

In this work we considered influence of the charge exchange process only. In future, influences of different hydrodynamic and plasma instabilities, interstellar and heliospheric magnetic fields on the heliotail structure must to be considered.

SUMMARY

In this paper we consider effects of charge exchange on the structure of the heliotail region. In particular, it was shown that

1. The charge exchange process change the solar wind - interstellar interaction flow qualitatively in the tail region. The termination shock becomes more spherical and Mach disk, reflected shock and tangential discontinuity disappear (Figure 1). The jumps of density and tangential velocity through the heliopause becomes smaller into the tail and disappears at about 3000 AU.
2. Parameters of solar wind plasma and interstellar H atoms are approaching their interstellar values. It allows to estimates of influence of the solar wind, and, therefore, the solar system size into the downwind direction as about 20000- 40000 AU. Unlike the upwind direction the solar system boundary has diffusive nature in downwind.
3. The supersonic character of the solar wind flow in the heliotail allows us to perform correct numerical calculations. This is not possible in the case without H atoms.

ACKNOWLEDGMENTS

This work has been done in the frame of International Space Science Institute Team "The Physics of the Heliotail". This work was supported in part by INTAS Awards 2001-0270, RFBR grants 01-02-17551, 02-02-06011, 02-02-06012, 01-01-00759, CRDF Award RP1-2248, and International Space Science Institute in Bern.

REFERENCES

1. Baranov, V.B., Lebedev, M.G., and Malama, Yu.G., *Astrophys. J.* **375**, 347 (1991).
2. Baranov V.B., Malama Yu.G., *J. Geophys. Res.* **98**, 15,157 (1993).
3. Izmodenov, V. V.,*Astrophys. Space Science* **274** 55-69, 2000.