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Effects of charge exchange in the tail of the heliosphere

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Abstract

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

Keywords: Heliosphere; Tail of the heliosphere; Charge exchange; Partially ionized interstellar medium

1. Introduction

The Sun and the solar system are presently moving in the partly ionized local interstellar cloud (LIC) (e.g. Lallement, 1996). Direct measurements of interstellar atoms of helium (Witte et al., 1996) by GAS/Ulysses experiment show that the velocity of relative Sun-LIC motion is about 26 km/s, and the local interstellar temperature is about 6500 K. Other interstellar parameters, such as interstellar ionization state, densities of neutral and charged components, magnitude and direction of the interstellar magnetic field, can be determined by remote space experiments. These are measurements of backscattered solar Lyman α radiation on board the SOHO, Voyager, Pioneer spacecraft, of the pickup ions on board the Ulysses and ACE spacecraft, of solar wind properties at large heliocentric distances by Voyager, of absorption of Lyman α spectra toward nearby stars, and of heliospheric fluxes of energetic neutral atoms (ENA). An adequate theoretical model of the solar wind interaction with LIC is needed to interpret the remote experiments. Theoretical concept of the solar wind interaction with the local interstellar cloud was proposed in the pioneer papers by Parker (1961) and Baranov et al. (1971). During last 30 years the model was significantly advanced by several research groups (for recent reviews see, e.g. Izmodenov, 2000, 2003; Zank, 1999).

The structure of the Solar Wind – LIC interaction region is shown in Fig. 1. Contact discontinuity, or *the heliopause* (HP), separates the solar wind and interstellar plasmas. The heliopause is an obstacle for both the supersonic solar wind with sonic Mach number ~10 and the supersonic interstellar gas with sonic Mach number – if the local magnetic field is weak enough – of the order of 2.

A shock has to be formed in the case of supersonic flow around an obstacle. The supersonic solar wind passes through *the termination shock* (TS) to become subsonic. *The bow shock* decelerates the local interstellar gas from supersonic to subsonic. The whole region of the solar wind interaction is called *the heliospheric interface.*

Note, however, that in the case when the effect of interstellar atoms is not taken into account, the qualitative picture of the tail flow pattern is more complex.

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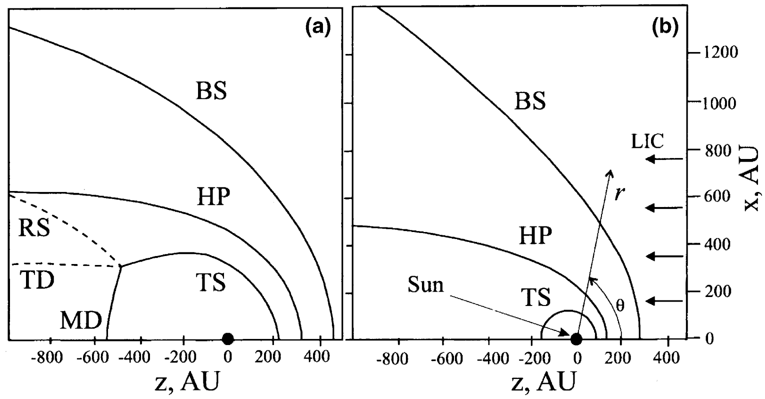

Fig. 1. The structure of the solar wind interaction with the interstellar medium. HP is the heliopause, TS is the heliospheric termination shock, BS is the bow shock, MD is the Mach disk, TD is the tangential discontinuity, RS is the reflected shock. (a) corresponds to the case with no H atoms, while (b) corresponds to the solution when interstellar H atoms are taken into account.

The solar wind flow is subsonic in the nose part of the region between the termination shock and the HP. Then the flow passes through the sonic line (Baranov and Malama, 1993) and becomes supersonic. This results in formation of the Mach disk (MD), tangential discontinuity (TD) and reflected shock (RS) in the tail region (Fig. 1(a)). The Mach disk, tangential discontinuity and reflected shock may disappear due to influence of the interstellar magnetic field (Pogorelov and Semenov, 1997; Linde et al., 1998; Aleksashov et al., 2000) or galactic cosmic rays (e.g. Myasnikov et al., 2000; Fahr et al., 2000). We do not consider these components in this paper.

The interstellar H atoms interact with the plasma component by charge exchange and strongly influence locations of the shocks and the heliopause and the structure of the heliospheric interface. The main difficulty to model the heliospheric interface is a large mean free path of the H atoms with respect to charge exchange. The mean free path is comparable with the characteristic size of the heliosphere. Therefore, to describe interstellar H atom flow in the heliospheric interface it is necessary to solve a kinetic equation. A self-consistent two-component (plasma and H atoms) model of the heliospheric interface was proposed by Baranov et al. (1991) and realized by Baranov and Malama (1993). The latter paper also presented the first numerical simulations of the heliotail. Fig. 1 compares the geometrical pattern – locations of the two shocks and the heliopause – for the model that takes into account the influence of interstellar H atoms, with the model that does not take into account the neutral component. It is seen that the discontinuities are significantly closer to the Sun in the case with atoms. In the heliotail region the structure of the plasma flow changes qualitatively. The termination shock becomes more spherical and the Mach disk (MD), reflected shock (RS) and tangential discontinuity (TD) disappear (Fig. 1). Effects of H atoms on the heliospheric interface structure including the disappearance of the Mach disk were also studied in Pauls et al. (1995), Zank et al. (1996), Lipatov et al. (1998), Mueller et al. (2000).

The model of the heliospheric interface allows one to answer two fundamental questions: 1. Where is the edge of the solar system plasma? 2. How far downstream can the influence of the solar wind be felt on the surrounding interstellar medium?

To give answer to the first question we need to define the solar plasma system boundary. It is natural to assume the boundary is the heliopause that separates the solar wind and interstellar plasmas. Note, that the influence of the solar system on the interstellar medium extends significantly farther than the heliopause. Secondary interstellar atoms, which result by charge exchange of the original interstellar H atoms and solar wind protons, disturb the interstellar gas upwind of the bow shock. Detailed studies of mutual influences of charge and neutral components in the heliospheric interface were done in Baranov and Malama (1993, 1995, 1996), Baranov et al. (1998), Izmodenov et al. (1999, 2000, 2001). However, these papers were mainly focused on the upwind region. At the same time the study of the heliotail region has also significant interest. In the heliotail we cannot assume the heliospheric boundary to be a well defined closed surface. Rather, as it is indicated in Fig. 1, the heliopause may not close and the solar wind may fill up the whole space in the downwind direction.

The goal of this work is to study the structure of the tail region of the heliospheric interface. We focus on the effects of the charge exchange process on the tail region.

2. Model

To study the effect of charge exchange on the structure of the heliotail we used the kinetic gas-dynamical model by Baranov and Malama (1993). In this model the solar wind at the Earth's orbit is assumed to be spherically symmetric and not varying with time. The interstellar flow is also assumed to be constant parallel flow. Under these conditions the flow in the interaction region is axisymmetric.

To describe the charged component (electrons and protons) we solve hydrodynamic Euler equations, where the effect of charge exchange is taken into account on the right-hand sides of these equations. To calculate the flow of interstellar H atoms in the heliospheric interface we solve the kinetic equation (e.g. Izmodenov et al., 2001).

The main process of the plasma-neutral coupling is the charge exchange process $H + H^+ \rightarrow H^+ + H$. Photoionization and electron impact ionization are also taken into account. The interaction of charged and neutral components results in exchange of mass, momentum and energy between these components. The source term $Q = (q_1, q_{2,z}, q_{2,r}, q_3)$ is on the right-hand side of the Euler equation for the charged component. Here $q_1, \vec{q}_2 = (q_{2,z}, q_{2,r}), q_3$ are sources of mass, momentum and energy, respectively. The source terms are integrals over the H atom velocity distribution function f_H:

$$q_1 = n_H \cdot (\beta_i + \beta_{impact}), \quad n_H = \int f_H(\mathbf{w}_H)\,d\mathbf{w}_H, \tag{1}$$

$$\vec{q}_2 = \int (\beta_i + \beta_{impact})\mathbf{w}_H f_H(\mathbf{w}_H)\,d\mathbf{w}_H + \int\int u\sigma_{ex}^{HP}(u) \times (\mathbf{w}_H - \mathbf{w}_p) f_H(\mathbf{w}_H) f_p(\mathbf{w}_p)\,d\mathbf{w}_H\,d\mathbf{w}_p, \tag{2}$$

$$q_3 = \int (\beta_i + \beta_{impact}) \frac{w_H^2}{2}(\mathbf{w}_H)\,d\mathbf{w}_H + \frac{1}{2} \times \int\int u\sigma_{ex}^{HP}(u)(\mathbf{w}_H^2 - \mathbf{w}_p^2) f_H(\mathbf{w}_H) f_p(\mathbf{w}_p)\,d\mathbf{w}_H\,d\mathbf{w}_p. \tag{3}$$

Here $u = |\mathbf{w}_H - \mathbf{w}_p|$ is the relative atom-proton velocity, $f_H(\mathbf{r}, \mathbf{w}_H)$ is the velocity distribution function of H atoms; $f_p(\mathbf{r}, \mathbf{w}_p)$ is the locally Maxwellian velocity distribution of protons; $\mathbf{w}_p$ and $\mathbf{w}_H$ are the individual velocities of protons and H atoms, respectively; σ_{ex}^{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 rate; and $\mathbf{F}$ is the sum of the solar gravitation and radiation pressure forces.

For boundary conditions in the unperturbed LIC we adopt the velocity $V_{LIC} = 25$ km/s, interstellar H atom and proton number densities are 0.2 and 0.07 cm^{-3}. The temperature of the LIC was assumed 6000 K. Velocity, number density and sonic Mach number of the solar wind 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 term $\vec{Q}$ 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 (Malama, 1991). Unlike the previously published papers based on Baranov–Malama model, we performed the calculations in an extended computation region toward the heliotail. We performed computations up to 50,000 AU along the axis of symmetry and up to 5000 AU in the direction perpendicular to the axis of symmetry. To estimate the divergence of the chosen numerical scheme we used different computational grids. Dependence of the numerical solution on outer boundary conditions was estimated by variation of the computational domain in the tail region.

3. Qualitative analysis

In this work we consider the effect of the charge exchange processes ($H + H^+ \rightarrow H^+ + H$) on the plasma flow in the tail region of the heliopause interface. The supersonic solar wind passes through the heliospheric termination shock, where its kinetic energy changes mainly into thermal energy. Let us assume now that in the tail region the surface of the heliopause is parallel to the direction of the interstellar flow. This is supported by our numerical simulations. Under this assumption the solar wind can be considered to be a flow in a nozzle with constant cross-section. Our computations show that in the case with no H atoms the solar wind thermal pressure downstream of the termination shock is several times smaller than the interstellar pressure. In a nozzle with constant cross-section the solar wind flow decelerates and has some minimal velocity at infinity. The minimal value is determined by the parameters of the solar wind downstream of the termination shock and the interstellar thermal pressure. Neither the interstellar proton number density nor the relative Sun-LIC velocity do 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 plasma) extends in form of a heliotail up to infinity. Such a qualitative consideration can be easily generalized, when the heliopause is not parallel to the axis of symmetry.

Qualitatively different situation is encountered in the case when interstellar H atoms are taken into account. Our calculations show that in this case the solar wind pressure downwind of the termination shock is larger than the interstellar pressure. The solar wind should be accelerated in this case by the pressure gradient.

However, due to charge exchange interstellar atoms play a significant role. Because of their large mean free path they fill up the heliotail. Among the heliospheric H atoms the portion of original (or primary) interstellar atoms increases significantly with heliocentric distance.

The temperature (6000 K) and velocity (25 km/s) of the primary interstellar atoms are smaller than the velocity (100 km/s) and temperature (100,000 K) of the post shocked solar wind. New protons that are born from the interstellar H atoms 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. On the one hand, solar wind acceleration by the pressure gradient and, on the other, solar wind deceleration by charge exchange may result in the heliopause being not always parallel to the symmetry axis (changing cross-section of the nozzle). Since the fraction of primary interstellar atoms increases with increasing heliocentric distance, it is natural to expect that solar wind velocity, density and temperature will approach their interstellar values.

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

4. Results and discussion

Results of our calculations confirm the qualitative analysis given above. Distributions of plasma paramters in the heliotail region are presented in Fig. 2. Fig. 2(a) shows sonic Mach numbers along the different downwind directions. The angle θ in Figs. 2(a, b) and 3 is the angle between line-of-sight and upwind directions (Fig. 1). The solar wind becomes cooler due to charge exchange (Fig. 2(b)). It is interesting to observe how the solar wind in the tail becomes again supersonic due to effective cooling (Figs. 2(a) and (b)). The velocity of the solar wind is about 100 km/s downstream of the termination shock. Then the velocity becomes smaller due to new protons injected by charge exchange and approaches the value of interstellar velocity. The interstellar sonic Mach number is ~2. The solar wind passes through the sound velocity at about $z \approx -4000$ AU, where z is the distance along the axis of symmetry and sign "−" means the direction toward the heliotail, and then the sonic Mach number increases further approaching eventually its interstellar value (Fig. 2(a)).

Fig. 2(c) presents the distributions of density and velocity of plasma along the heliopause. The parameters are shown from both interstellar and solar wind sides of the heliopause. In classical hydrodynamics two conditions determine the 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 interstellar H atoms the jump of density and pressure becomes weaker with increase of the distance calculated along the heliopause from its nose (denoted s in Fig. 2(c)). This is due to mass transport caused by charge exchange. For $z \approx -3000$ AU the jump of density and tangential velocity disappears (Fig. 2(c)).

Fig. 3 represents the densities, velocities and temperatures of the interstellar hydrogen along different downwind directions. Parameters of H atoms approach their interstellar values at distances less than 20,000 AU for all lines-of-sight. The approach 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 (Baranov et al., 1991; Izmodenov, 2000), is visible even for large $\theta \approx 150°–170°$.

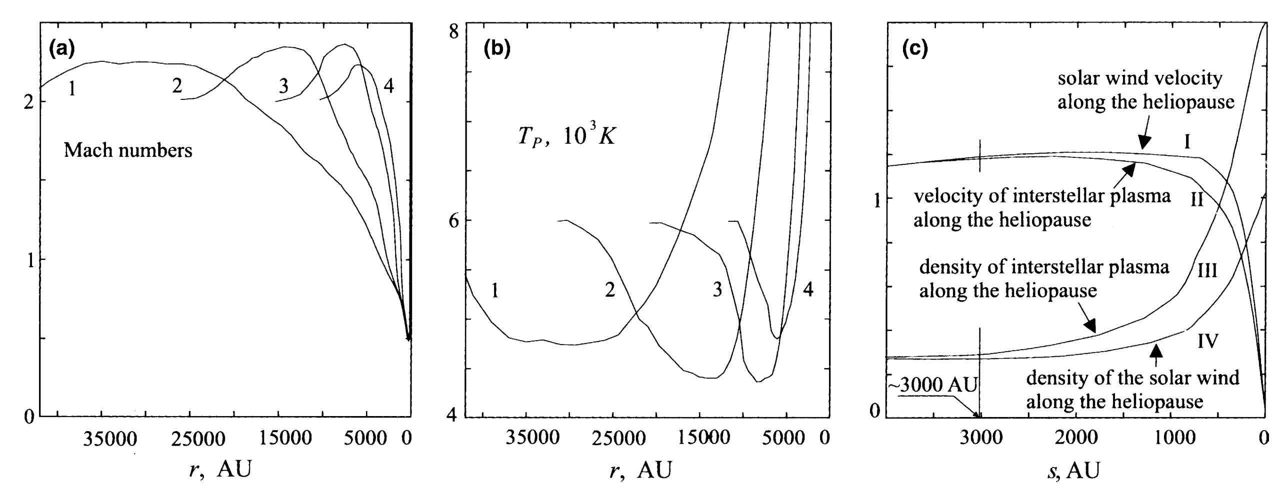

Fig. 2. The distribution of plasma parameters in the heliotail: sonic Mach number (a) and temperature (b) along downwind lines-of-sights $\theta = 150$ (curves 4), 160 (curves 3), 170 (curves 2), 175 (curves 1) degrees; (c) velocities (curves I and II) and densities (curves III and IV) from both sides of the heliopause as a function of the heliocentric distance along the heliopause. Curves II and III correspond to interstellar side; curves I and IV correspond to solar wind side. The velocities and densities are normalized to their interstellar values.

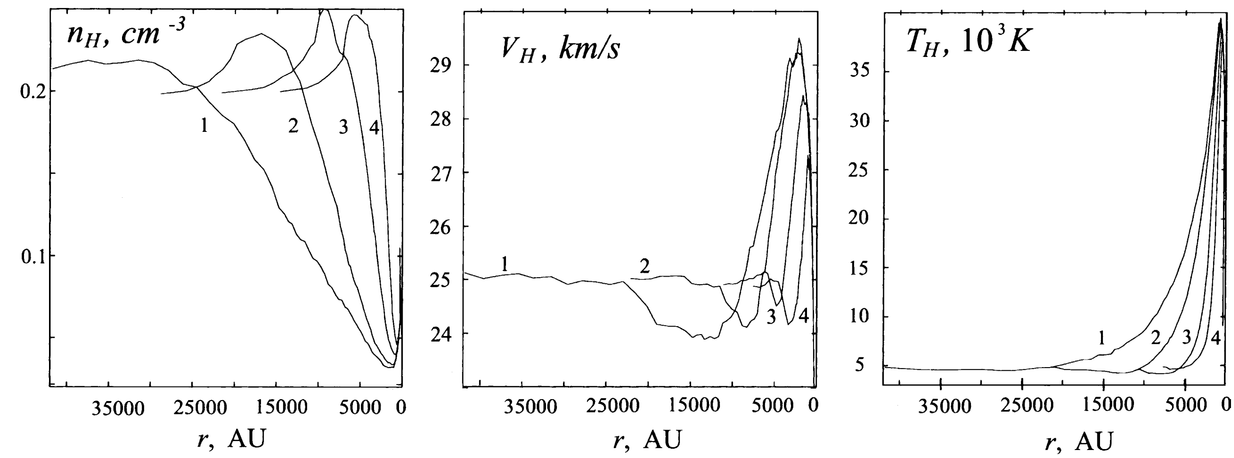

Fig. 3. Number density, velocity and temperature of the interstellar H atom along downwind lines-of-sights $\theta = 150$ (curves 4), 160 (curves 3), 170 (curves 2), 175 (curves 1) degrees.

It is important to note that it became possible to obtain the numerical solutions for heliotail plasma because charge exchange processes make the flow supersonic at the outer boundary. This allows to satisfy correct boundary conditions.

In this work we considered influence of charge exchange only. In the future, influences of different hydrodynamic and plasma instabilities, interstellar and heliospheric magnetic fields on the heliotail structure should be considered. The processes of magnetic reconnection can be also important in the heliosheath.

5. 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 changes the solar wind – interstellar interaction flow qualitatively in the tail region. As it was shown early (e.g. Baranov and Malama, 1993) the termination shock becomes more spherical and the Mach disk, reflected shock and tangential discontinuity disappear. The jumps of density and tangential velocity across the heliopause become smaller in the heliotail and disappear at about 3000 AU.
2. Parameters of solar wind plasma and interstellar H atoms approach their interstellar values at large heliocentric distances. This allows to estimate the influence of the solar wind, and, therefore, the solar system size into the downwind direction as about 20,000–40,000 AU. Unlike upwind, the solar system downwind boundary has diffusive nature in the heliotail.
3. The supersonic character of the solar wind flow in the heliotail allows us to perform correct numerical calculations, which are not possible in the case without H atoms.

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