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Variations of interstellar H atom parameters in the outer heliosphere: solar cycle effects

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Abstract

In this paper, we study response of the heliospheric plasma interface, the region of the solar wind interaction with the local interstellar medium, to 11-year solar cycle variations of the solar wind. We explore how the solar wind variations influence interstellar H atoms in the heliospheric interface, which are coupled to plasma by charge exchange. We develop the self-consistent model, where the kinetic equation for interstellar H atom velocity distribution function is solved self-consistently with the gas dynamic equations for the charged (electrons and protons) component. It is shown that the termination shock location varies within ±7 AU, the heliopause variation is ~2 AU, and the bow shock variation is negligible. The important new result is that at large heliocentric distances the density of the interstellar H atoms varies within ~10% with solar cycle. The variation of density increases closer to the Sun up to 30% at 5 AU.

Keywords: Outer heliosphere; Solar cycle effects; Interstellar H atom; Heliosphere plasma interface

1. Introduction

More than 30 years (three solar cycles) observations of the solar wind show that its momentum flux varies by factor of 2 from solar maximum to solar minimum (Gazis, 1996; Richardson, 1997). It was shown theoretically that such variations of the solar wind momentum flux strongly influence the heliospheric interface structure (e.g., Karmesin et al., 1995; Wang and Belcher, 1999; Baranov and Zaitsev, 1998; Zank, 1999; Zaitsev and Izmodenov, 2001; Scherer and Fahr, 2003a,b; Zank and Mueller, 2003).

Most of global models studying the solar cycle effects ignored the interstellar H atom component or took into account this component by using simplified fluid approximations. These simplifications were done because it is difficult to solve 7D (time, three dimensions in space, three dimensions in velocity-space) kinetic equation for the interstellar H atom component. Kinetic description of interstellar atoms is necessary due to their large mean free path comparable with the size of the heliospheric interface. Recently, it has been shown explicitly by Izmodenov et al. (2001) that the velocity distribution function of interstellar atoms is not Maxwellian. Fluid and multi-fluid approaches for interstellar H atoms are not valid and may result in incorrect solutions and incorrect interpretations of observational data. At the same time, the momentum flux variations of the solar wind may have significant effect on distribution of interstellar H atoms in the heliosphere due to coupling of the atom and plasma components by charge exchange.

The qualitative pattern of the heliospheric interface is shown in Fig. 1(a). The solar wind plasma decelerates and turns to the tail in the termination shock (TS), the interstellar plasma decelerates and turns outward the axis of symmetry in the bow shock (BS). The heliopause (HP), which is contact discontinuity, separates these two

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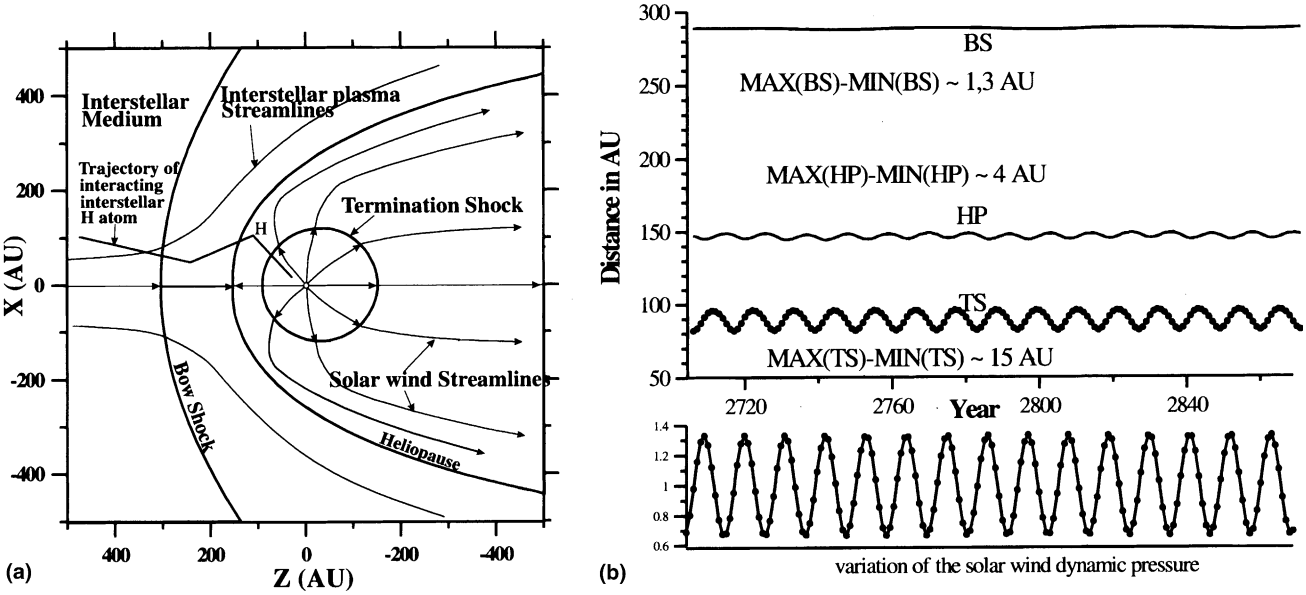

Fig. 1. (a) Structure of the heliospheric interface, the region of the interaction of the solar wind and the Local Interstellar Cloud. (b) Upper panel: Time variations of the locations of the termination shock, bow shock and the heliopause in the upwind direction. Low panel: variations of the solar wind momentum flux, $\rho_E V_E^2$, with time.

plasma flows. Hydrogen atoms newly created by charge exchange have the velocities of their ion partners in the charge-exchange collisions. Therefore, the parameters of these new atoms depend on the local plasma properties. It is convenient to distinguish four different populations of H atoms: (1) atoms created in the supersonic solar wind, (2) atoms originating in the heliosheath and known as heliospheric ENAs (Gruntman et al., 2001), (3) atoms created in the disturbed interstellar wind and (4) original (or primary) interstellar atoms.

2. Model

In this work, we advance the heliospheric interface model developed by the Moscow group (Baranov and Malama, 1993, 1996; Izmodenov et al., 2003b) by introducing 11-year solar cycle variations of the solar wind in the model. Goal of this paper is to explore theoretical aspects of non-stationary interaction of the solar wind and the local interstellar cloud. The results presented here cannot be directly applied to interpretation of observational data.

We consider all the plasma components (electrons, protons and pickup ions) as one fluid with total density ρ and bulk velocity $\vec{v}$. It is assumed that all ionized components have the same temperature T. Plasma is quasineutral, i.e., $n_e = n_p$. Magnetic field is ignored in the paper. Protons interact with the H atoms by charge exchange. Hydrodynamical equations for charged component are solved self-consistently with kinetic equation for the H atom component.

Governing equations for charged component are the following:

$$
\begin{aligned}
&\frac{\partial \rho}{\partial t} + \mathrm{div}(\rho\vec{v}) = q_1, \\
&\frac{\partial \rho\vec{v}}{\partial t} + \mathrm{div}(\rho\vec{v}\vec{v} + p\hat{I}) = \vec{q}_2, \qquad (1) \\
&\frac{\partial E}{\partial t} + \mathrm{div}([E + p]\vec{v}) = q_3.
\end{aligned}
$$

Here ρ is the total density of the ionized component, p is the total pressure of ionized component, $E = \rho(\varepsilon + \vec{v}^2/2)$ is the total energy per unit volume, $\varepsilon = p/(\gamma - 1)\rho$ is the specific internal energy, $\hat{I}$ is the unit matrix. Temperature of the plasma is determined from the equation of state $p = 2n_p kT$. Right parts q_1, $\vec{q}_2$, q_3 are sources of mass, momentum and energy due to charge exchange of H atoms and protons, photoionization and electron impact ionization (Baranov and Malama, 1993).

The velocity distribution of H atoms $f_H(\vec{r}, \vec{w}_H, t)$ is calculated from the linear kinetic equation:

$$
\begin{aligned}
&\frac{\partial f_H}{\partial t} + \vec{w}_H \cdot \frac{\partial f_H}{\partial \vec{r}} + \frac{\vec{F}}{m_H} \cdot \frac{\partial f_H}{\partial \vec{w}_H} \\
&\quad = -f_H \int |\vec{w}_H - \vec{w}_p| \sigma_{ex}^{HP} f_p(\vec{r}, \vec{w}_H)\, d\vec{w}_p \\
&\qquad + f_p(\vec{r}, \vec{w}_p) \int |\vec{w}_H^* - \vec{w}_H| \sigma_{ex}^{HP} f_H(\vec{r}, \vec{w}_H^*)\, d\vec{w}_H^* \\
&\qquad - (\nu_{ph} + \nu_{impact}) f_H(\vec{r}, \vec{w}_H). \qquad (2)
\end{aligned}
$$

Here $\vec{w}_p$ and $\vec{w}_H$ are the individual proton and H atom velocities, respectively, and $\vec{F}$ is the sum of the solar gravitational force and the solar radiation pressure force, f_{p} is locally Maxwellian velocity distribution function with the parameters $(n_{\mathrm{p}}, \vec{v}, T)$, which are determined by solution of the Euler equations (1). $\sigma_{\mathrm{ex}}^{\mathrm{HP}}$ is the charge-exchange cross-section. v_{ph} and v_{impact} are photoionization and electron impact ionization, respectively. Numerical values for $\sigma_{\mathrm{ex}}^{\mathrm{HP}}$, v_{ph} and v_{impact} are given in Izmodenov et al. (1999). The plasma and neutral components interact mainly by charge exchange. Photoionization, solar gravitation, and radiation pressure, which are taken into account in Eq. (2), are important at small heliocentric distances. Electron impact ionization may be important in the inner heliosheath, the region between the termination shock and the heliopause. Note, that photoionization rate and solar radiation pressure may vary with the solar cycle. At present we do not include solar cycle variations of these parameters in our model, but we plan to do it in the nearest future.

The boundary conditions for Eqs. (1) are following. At the Earth orbit, we assume that the solar wind is spherically symmetric. It makes our model axissymmetric. At the Earth orbit, we assume model solar cycle variations of the solar wind number density, bulk velocity and temperature:

$$\begin{aligned} n_{\mathrm{pE}} &= n_{\mathrm{pE},0}(1 + \delta_n \sin \omega t), \\ v_{\mathrm{E}} &= v_{\mathrm{pE},0}, \\ T_{\mathrm{E}} &= T_{\mathrm{E}0} = \mathrm{const.} \end{aligned} \tag{3}$$

For the solar wind disturbances (3) the ratio of maximum to minimum momentum flux $\Delta = (1+\delta_n)/(1-\delta_n)$. Following Baranov and Zaitsev (1998), we made calculations for $\delta_n = 1/3$ such that $\Delta \approx 2$. In this paper, we consider variations of the solar wind density, which is sufficient for purposes of this paper. Effects of realistic solar cycle were studied by us in Izmodenov et al. (2003a).

Averaged over several solar cycles IMP 8 data were used: $n_{\mathrm{pE},0} = 7.39\ \mathrm{cm}^{-3}$, $V_{\mathrm{pE},0} = 432\ \mathrm{cm}^{-3}$. In the undisturbed interstellar medium at the outer boundary, we choose the following parameters of interstellar gas $V_{\mathrm{LIC}} = 26.4$ km/s, $T_{\mathrm{LIC}} = 6500$ K, $n_{\mathrm{H,LIC}} = 0.2\ \mathrm{cm}^{-3}$, $n_{\mathrm{H,LIC}} = 0.04\ \mathrm{cm}^{-3}$. The choice of the interstellar velocity and temperature is based on recent observations of the interstellar He atoms by GAS/Ulysses (Witte, private communications, 2003). The choice of $n_{\mathrm{H,LIV}}$ and $n_{\mathrm{p,LIC}}$ is based on analysis of the backscattered Lyman-alpha intensities and pickup ion measurements (see, e.g., Lallement, 1999; Izmodenov et al., 1999).

To solve the Euler equations (1) self-consistently with the kinetic equation (2) we used iterative procedure. In the first step of this iterative procedure, the Euler equations (1) with the constant source terms $q_1, \vec{q}_2, q_3$ were solved with the boundary conditions (3). The source terms were taken from the stationary solution with averaged solar wind parameters. We performed calculations over 300 solar cycles. As a result, we got distribution of the plasma parameters. We analyzed this distribution and found that there is the 11-year periodicity only. In the second step, we solved the kinetic equation (2) by Monte Carlo method with splitting of trajectories (Malama, 1991). To increase statistical efficiency of the method, we assume periodicity in our Monte Carlo calculations with the time period $t_{\mathrm{period}} = 66$ years. To get small statistical errors, we averaged statistical results over $t_{\mathrm{mc}} = 1$ year. Here we used distribution of the plasma parameters for last 66 years obtained in the first step. As a result, we obtained the periodic (66 years) $q_1, \vec{q}_2, q_3$ source terms. In the third step, we solved the Euler equations (1) with the boundary conditions (3) and the periodic source terms obtained in the second step. Again, we performed gas dynamic calculations over 300 solar cycles. Analysis of the plasma distributions shows the 11 year periodicity only. Then we solved kinetic equation (2) by Monte Carlo method with distribution of the plasma parameters for last 66 years obtained in the third step. We continued this process of iterations until the results of two subsequent iterations are practically coinciding.

Our methods allows to get-solution of the system of the nonlinear equations (1) and (2) fulfilling boundary conditions (3). Since uniqueness of the solution for this system is not proven, we cannot exclude that other solutions of this system of equations may exist. These solutions may have period different from 11 years. Note, that our numerical method for the Euler equations does not have any assumption. However, our numerical solution has no period different from 11 years.

3. Results

We have found that qualitative features of the nonstationary heliospheric interaction established early (Karmesin et al., 1995; Wang and Belcher, 1999; Baranov and Zaitsev, 1998; Zank, 1999; Zaitsev and Izmodenov, 2002; Scherer and Fahr, 2003a,b) are confirmed by our calculations. Fig. 1(b) demonstrates variation of the TS, HP and BS positions on the axis of symmetry for the case when $\delta_n = 1/3, \Delta = 2$. One can see that $\max(R_{\mathrm{TS}}) - \min(R_{\mathrm{TS}}) \sim 15$ AU or TS varies at about 7.5 AU from the mean location. Variation of the HP is smaller. It is about 2 AU. Variation of the BS is negligible. Comparison of the TS fluctuations with variation of the solar wind momentum flux (lower panel) shows ~2-year delay in the response of the TS to the momentum flux variation.

Fig. 1(b) presents results of our calculations for 15 solar cycles, which is 165 years. Averaging of these results over 11 years gives a constant within 0.1–0.5% of variations. These variations are induced by statistical errors in the right part of Euler equations and become smaller with smaller statistical errors of the source terms calculated by Monte Carlo.

Fig. 2 shows distribution of the proton number density along the axis of symmetry between the BS and HP at two different time moments. One can see a sequence of shocks and rarefaction waves moving from the HP to the BS similar to one obtained by Baranov and Zaitsev (1998), Zank (1999), Zaitsev and Izmodenov (2001), Scherer and Fahr (2003a,b). The amplitudes of these waves decrease while they propagate away from the Sun due to increase of their surface areas and interaction between the shocks and rarefaction waves.

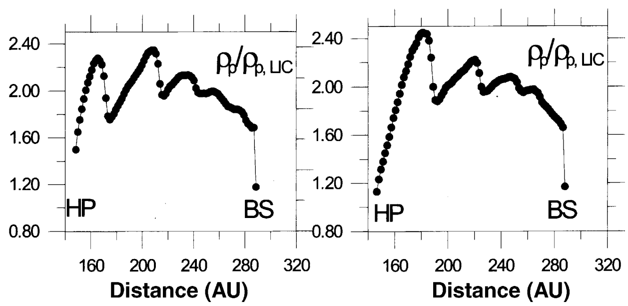

Fig. 2. The distribution of plasma parameters number density in the region between the heliopause and the bow shock for two different time periods. Dots are shown in order to present resolution of our grid in this region.

Fig. 3 presents our new results on time-variations of the interstellar H atom parameters at the TS in the upwind direction. The variations of both primary and secondary H atom number densities are within 10% at the TS (A) and increase up to 30% at the 5 AU (B). These variations need to be taken into account in interpretations of measurements of H atoms in the inner heliosphere. However, we do not see strong variations of the velocity and temperature of H atoms at the TS in our results. If such variations exist they are certainly less than statistical errors of our Monte Carlo calculations.

Note, that our results for 11 year variations of the H atom number densities are different from the results of fluid (Scherer and Fahr, 2003a,b) and multi-fluid model (Zank, 1999; Zank and Mueller, 2003). This difference might be due to uncertainties introduced by fluid or multi-fluid approaches. Validity of fluid approach to be used is determined by simple general criteria, that Knudsen number $Kn = 1/L \ ll \ 1$, where l and L are the mean free path of the particles and characteristic size of the problem, respectively. For stationary problem the distance between the HP and BS, which is approximately 100 AU, can be chosen as characteristic size of the problem. The mean free path of H atoms in the region is ~ 50 AU. Therefore, $Kn_{\text{stationary}} \sim 0.5$. The results of kinetic and fluid approaches were compared by Baranov and Zaitsev (1998). Izmodenov et al. (2001)

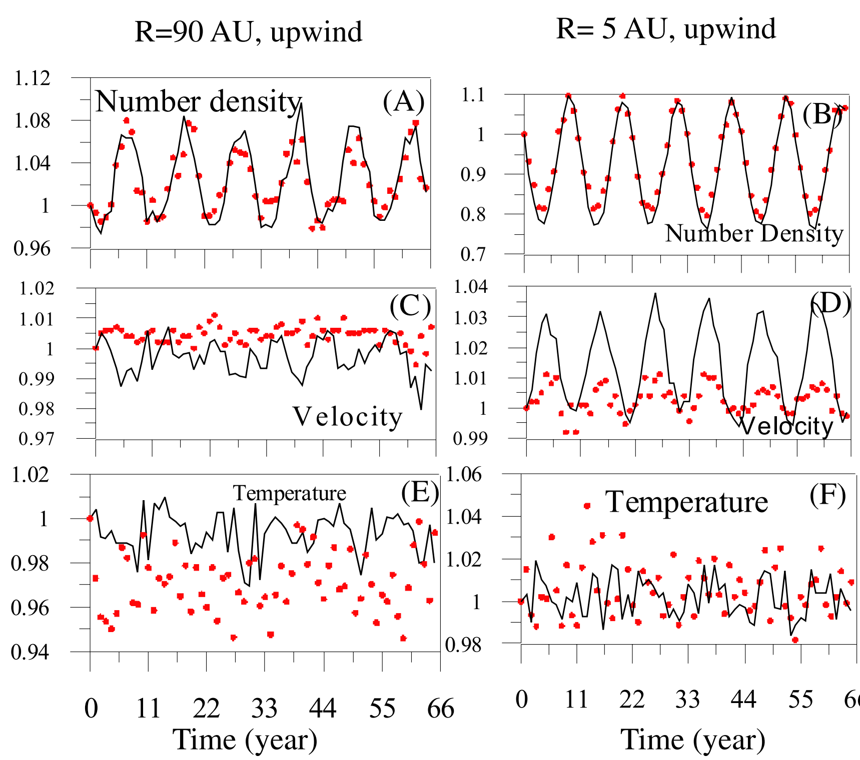

Fig. 3. Time-variation of the interstellar H atom parameters at $R \sim 90$ AU (left column) and at 5 AU (right column) in the upwind direction. (A,B) H atom number density, (C,D) bulk velocity of H atoms and (E,F) Kinetic temperature of H atoms. Solid curves and dots correspond to primary and secondary populations of interstellar H atoms, respectively.

have shown explicitly that the velocity distribution function of H atoms is not Maxwellian anywhere in the interface. For the time-dependent problem considered in this paper the characteristic size, L, is determined as half of wavelength of plasma fluctuations. In the region between the HP and BS $L \sim 20$ AU. Therefore, $Kn_{\mathrm{time}} \sim 2$ and fluid approaches become even less appropriate as compared with stationary model. This fundamental reason could be the cause of the large discrepancy between our results and results obtained by Zank and Mueller (2003) and Scherer and Fahr (2003b) who used the multi-fluid approaches.

4. Summary

We developed the non-stationary self-consistent model of the heliospheric interface and used it to explore the solar cycle variations of the interface. We obtained the periodic solution of system of the Euler equations (1) for plasma, and the kinetic equation (2) for interstellar H atoms with the periodic boundary conditions (3) for the solar wind at the Earth's orbit. The period of the solution is 11 years.

Our basic results for the plasma component confirm the results presented previously. The results can be summarized as: (1) the solar cycle variation of the TS location is within 7–10%; (2) the variation of the bow shock location is negligible; (3) there is a sequence of shocks and rarefaction waves in the region between the heliopause and the bow shock.

For the interstellar H atom component, we obtain the following new results: (1) variation of filtration of the interstellar atoms is within 10%; (2) there is no significant variations of their temperature and bulk velocity. The solar cycle variations of filtration of the interstellar H atoms should be taken into account in interpretations of observational data such as pickup ions, backscattered Lyman-alpha radiation.

Note that in this paper we present first results of our non-stationary model of the heliospheric interface. More results and their detailed discussion will be presented in our future papers (e.g., Izmodenov et al., 2004).

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