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Spatial variation of pickup proton energy spectra in the inner heliosheath and fluxes of energetic neutral atoms

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Abstract

The spatial variation of pickup protons downstream the termination shock in the upwind direction is considered taking into account stochastic pre-acceleration in the supersonic solar wind. It is shown that energy spectra of pick-up protons in the inner heliosheath are considerably different from those in the region inside the termination shock due to efficient charge exchange reactions between the protons and interstellar hydrogen atoms and due to energy diffusion. Differential fluxes of energetic neutral atoms (ENAs) originating from the charge exchange process in the inner heliosheath are calculated at 1 AU. It is shown that observations of neutral hydrogen fluxes in the energy range from 1 to 100 keV can give important information on the level of solar wind turbulence in the inner heliosheath.

Keywords: Termination shock; Inner heliosheath; Energetic neutral atoms; Pickup proton energy spectra

1. Introduction

The structure of the interaction region between the solar wind and interstellar medium is influenced by the action of neutral hydrogen which, in the present view, constitutes the major mass portion of the multi-component local interstellar medium (LISM). Hydrogen atoms capable of penetrating deeply into the heliosphere essentially modify thermodynamical properties of the outer solar wind by creating a specific very hot population of pickup protons through charge exchange with solar protons, photoionization, and electron impact ionization.

Freshly created pickup ions have thermal velocities equal to the local solar wind speed. Hence one can expect that properties of pickup ions in the supersonic solar wind and in the inner heliosheath (the region between the termination shock and heliopause) are essentially different. While pickup ions in the supersonic solar wind have almost identical initial velocities which only slightly change with distance in the region from the Earth's orbit up to the termination shock due to deceleration of the solar wind in the outer heliosphere, the pickup-ion population in the inner heliosheath is composed of particles with different regions of origin and in consequence with essentially different initial velocities. Due to a rapid deceleration of the solar wind at the termination shock, pickup ions originating in the heliosheath have smaller velocities than pickup ions convected from the region inside the termination shock. This fact leads to very interesting features which appear in pickup proton spectra in the inner heliosheath as is shown below.

The charge exchange between pickup protons and interstellar hydrogen atoms in the heliosheath results in the origin of energetic neutral atoms (ENAs) which can

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reach inner parts of the heliosphere and can be detected by spacecraft. Such ENAs carry very important information on the outer heliosphere and can be used as an effective tool to study plasma properties in the heliosheath (see e.g. Gruntman et al., 2001).

2. Pickup proton spectra in the inner heliosheath

The governing Fokker–Planck transport equation for the isotropic velocity distribution function of pickup protons $f(t, \mathbf{r}, v)$ has the following form:

$$\frac{\partial f}{\partial t} + \boldsymbol{U}\frac{\partial f}{\partial \mathbf{r}} = \frac{1}{v^2}\frac{\partial}{\partial v}\left(v^2 D \frac{\partial f}{\partial v}\right) + \frac{v}{3}\frac{\partial f}{\partial v}\operatorname{div}\boldsymbol{U} + Q(\mathbf{r}, v) + S(\mathbf{r}, v), \quad (1)$$

where $\boldsymbol{U}(\mathbf{r})$ is the solar wind velocity; v is the magnitude of the pickup proton velocity in the solar wind rest frame; $D(\mathbf{r}, v) = D_A + D_m$ is the combined velocity diffusion coefficient consisting of two parts, D_A and D_m; and $Q(\mathbf{r}, v)$ is the local source of freshly ionized pickup protons. Coefficients D_A and D_m describe velocity diffusion of particles due to their interaction with small-scale Alfvénic turbulence with the correlation length $L_{A,E} \sim 0.01$ AU and large-scale magnetosonic fluctuations with spatial scales up to several AU which can contain interplanetary shock waves. Acceleration of particles by this latter type of fluctuations is equivalent to the second-order Fermi acceleration because in a first order of view, the acceleration at shock fronts is compensated by the deceleration in the following rarefaction waves (Toptygin, 1983). The term $S(\mathbf{r}, v)$ describes the charge exchange process between pickup protons and interstellar hydrogen atoms. This process does not change the number density of pickup protons but results in a redistribution of the energy in pickup proton spectra. The term $S(\mathbf{r}, v)$ can be written as

$$S(\mathbf{r}, v) = -\sigma_{ex}(u) n_H u \left[f(\mathbf{r}, v) - \frac{n_{PUI}}{4\pi v^2}\delta(v - U_H) \right], \quad (2)$$

where σ_{ex} is the charge exchange cross-section, n_H is the number density of atoms, U_H is the relative velocity of a hydrogen atom with respect to the local wind frame, and $u(v)$ is the average relative velocity of pickup protons with velocity v with respect to hydrogen atoms.

The source term Q as well as the plasma velocity and density fields have been calculated in the frame of the two-dimensional model of the solar wind interaction with the partly ionized LISM developed by Baranov and Malama (1993, 1995). Kinetic and hydrodynamic approaches have been used to describe the motion of the neutral and plasma components, respectively. As ionization processes, the charge exchange, photoionization, and electron impact ionization have been taken into account. Fig. 1 shows the spatial distribution of hydrogen atoms in the upwind direction normalized to the

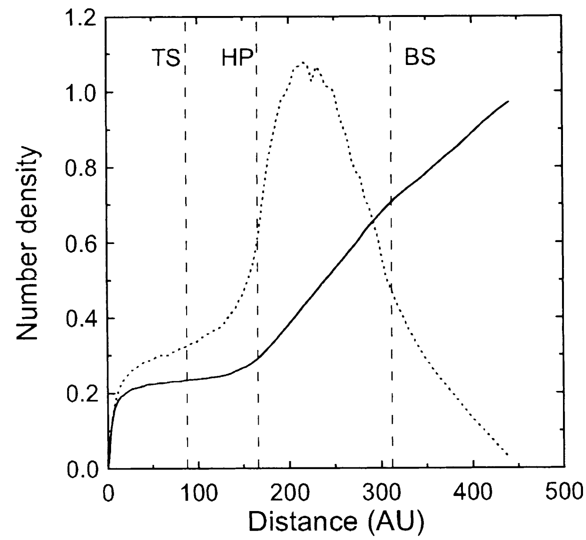

Fig. 1. Number density of hydrogen atoms in the upwind direction normalized to the their LISM number density. Solid line shows primary interstellar atoms, dotted line shows atoms created in disturbed interstellar plasma.

number density of neutral hydrogen in the LISM. The solid line shows the number density of primary interstellar atoms, while the dotted line shows the number density of atoms created in disturbed interstellar plasma. Positions of the termination shock, heliopause, and bow shock are indicated by the vertical dashed lines. For typical parameters of the solar wind ($U_E = 430$ km s^{-1}, $n_{pE} = 6.5$ cm^{-3}) and at $V_{LISM} = 25.6$ km s^{-1}, $n_{H,LISM} = 0.2$ cm^{-3}, $n_{p,LISM} = 0.05$ cm^{-3} the termination shock, heliopause, and bow shock are located in the upwind direction at 88, 166 and 312 AU, respectively. The jump of the plasma density at the termination shock is equal to 2.8. In the following only the upwind region of the heliosheath will be considered. The process of charge exchange between solar wind protons and hydrogen atoms and electron impact ionization of the atoms result in a dramatic change of the relative contribution of pickup and solar protons to the total plasma number density in the heliosheath as can be seen in Fig. 2. Note that importance of the ionization by electron impact in shocked solar wind plasma has been emphasized by Baranov and Malama (1996).

As was mentioned above the population of pickup protons in the heliosheath is composed of protons of local origin and of those which have been convected into the heliosheath from the region inside the termination shock, hence having suffered by stochastic acceleration in the supersonic solar wind. The efficiency of the acceleration depends on the magnitudes of fluctuations of the solar wind velocity and magnetic field. In the following the magnitudes of Alfvénic and magnetosonic fluctuations at the Earth's orbit will be described by $\zeta_{AE} = \langle \delta B_{AE}^2 \rangle / B_E^2$ and $\zeta_{mE} = \langle \delta U_{mE}^2 \rangle^{1/2} / U_E^2$, respec-

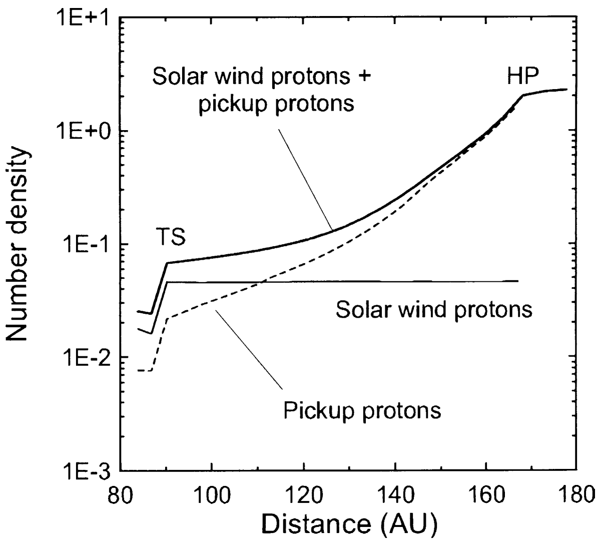

Fig. 2. Number densities of solar wind and pickup protons in the inner heliosheath in the upwind direction normalized to the interstellar proton number density. The positions of the termination shock and heliopause are indicated.

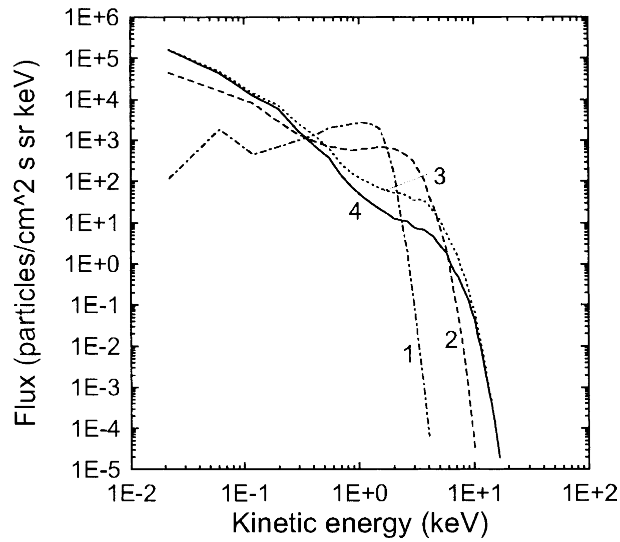

Fig. 3. Spatial behaviour of differential pickup proton fluxes in the heliosheath in the solar wind rest frame at $\zeta_{AE} = 0.05$, $\zeta_{mE} = 0$ and $\zeta_{AH} = 0.4 \times 10^{-3}$. 1–90, 2–145, 3–160, 4–164 AU. The termination shock and heliopause are located at 88 and 166 AU, respectively.

tively. For an extended discussion of the diffusion coefficients D_A and D_m from Eq. (1) and spatial evolution of small-scale Alfvénic and large-scale magnetosonic turbulence in the supersonic solar wind see Chalov (2000) and Chalov et al. (2003). With regard to turbulence in the heliosheath, in order to keep as few free parameters as possible, we assume here that only Alfvénic turbulence play a role in the region downstream of the termination shock and that its relative level, $\zeta_{AH} = \langle \delta B_A^2 \rangle / B^2$, behaves as a constant. At the termination shock the assumption of the conservation of the energy of particles in the de Hoffman–Teller frame and the assumption that the magnetic moment of a particle is the same before and after the interaction with the shock are used here. The latter assumption is a fairly good approximation for quasi-perpendicular shocks in the case when $r_g/\Lambda_\parallel \ll 1$ (r_g is the gyroradius, $\Lambda_\parallel$ the parallel mean free path of particles). This inequality is valid in the energy range considered here.

Fig. 3 shows differential fluxes of pickup protons (in the solar wind rest frame) in the inner heliosheath at different distances from the Sun (see also Chalov et al., 2003). Acceleration by large-scale magnetosonic fluctuations in the supersonic solar wind is not taken into account here, $\zeta_{AE} = 0.05$ and $\zeta_{AH} = 0.4 \times 10^{-3}$. Such a low level of turbulence in the heliosheath can be realized in the case when no generation of waves at the termination shock takes place and fluctuations are simply convected from the inner heliosphere outwards. The spectrum given by curve 1 is close to that just downstream of the shock (it is not shown here) except for a peak at low energies. The peak is formed due to ionization of interstellar atoms downstream of the termination shock through charge exchange with solar protons, photoionization, and electron impact ionization, and due to charge exchange between interstellar atoms and pickup protons resulting in the creation of ENAs and cold pickup protons with velocities close to the local solar wind velocity which is less than the upstream velocity by a factor of 3. Curves 2, 3 and 4 show subsequent spatial evolution of pickup proton spectra in the heliosheath. One can see that the high-energy tail shifts to higher energies with increasing distance. This shift, however, is not connected with stochastic acceleration in the heliosheath which is not effective at such low levels of Alfvénic turbulence. Rather this shift is a consequence of adiabatic heating due to the convergence of the plasma mass flow in the region between the termination shock and heliopause. The other interesting feature which can be seen in Fig. 3 are gaps in the spectra at medium energies which are pronounced at large distances (close to the heliopause). The formation of gaps is explained by charge exchange of pickup protons with interstellar atoms which leads to a energy redistribution in the spectra, namely, low-energy protons are created while medium-energy protons are removed. This process is one of the reasons for the increase of fluxes at low energies which is seen in Fig. 3. The other reason for an increase, as was already mentioned above, is the production of low-energy pickup protons due to charge exchange of solar wind protons with hydrogen atoms.

Fig. 4 shows pickup proton fluxes near the heliopause in the cases with low $\left(\zeta_{AH} = 0.4 \times 10^{-3}\right)$ and enhanced $\left(\zeta_{AH} = 0.7 \times 10^{-2}\right)$ levels of Alfvénic turbulence in the heliosheath. In addition, pre-acceleration of pickup

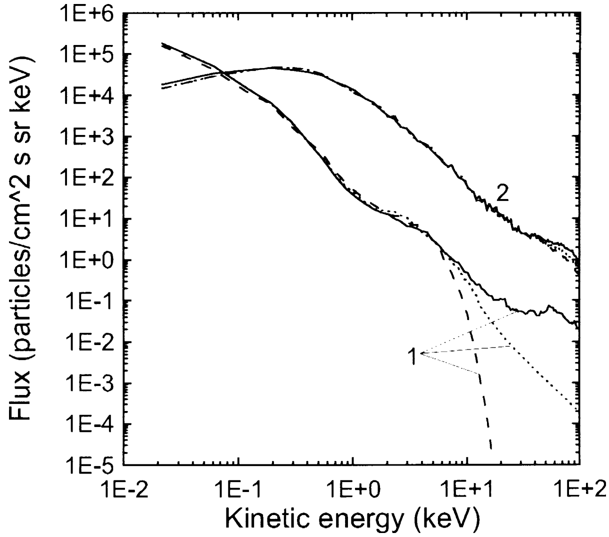

Fig. 4. Pickup proton fluxes near the heliopause at low level of turbulence in the heliosheath with $\zeta_{AH} = 0.4 \times 10^{-3}$ (curves 1) and enhanced level with $\zeta_{AH} = 0.7 \times 10^{-2}$ (curves 2). Dashed lines – $\zeta_{mE} = 0$, dotted lines – $\zeta_{mE} = 0.3$, solid lines – $\zeta_{mE} = 0.5$. In all cases $\zeta_{AE} = 0.05$.

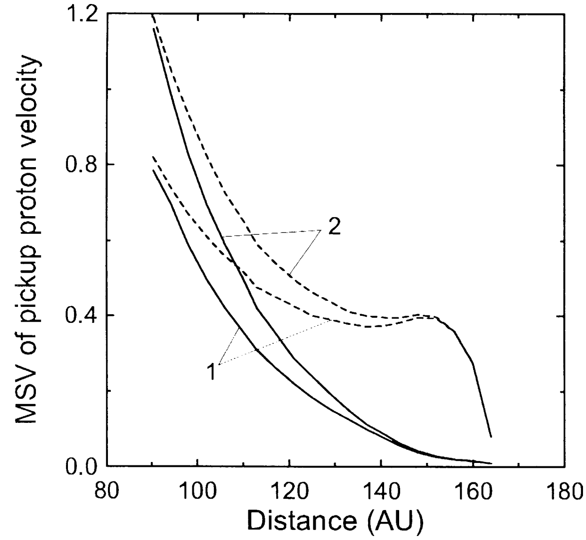

Fig. 5. Spatial distribution of mean-squared values of pickup proton velocities in the solar wind rest frame normalized to the solar wind velocity squared at 1 AU. solid lines correspond to the low level of turbulence in the heliosheath, dashed lines to the enhanced level. Curves 1 show distributions in the case when acceleration of pickup protons by large scale turbulence in the supersonic solar wind is not taken into account ($\zeta_{mE} = 0$) and curves 2 show distributions in the case when $\zeta_{mE} = 0.5$.

protons by large-scale fluctuations in the supersonic solar wind with different magnitudes is now taken into account. The magnitude of Alfvénic turbulence at the Earth's orbit is the same as in Fig. 3 ($\zeta_{AE} = 0.05$). As is mentioned above the low level of turbulence in the heliosheath is realized in the case when no generation of waves takes place and fluctuations are simply convected from the inner heliosphere into the heliosheath. In the case with the enhanced level of turbulence, local or spatially distributed generation of Alfvénic turbulence in the vicinity of the termination shock or in the heliosheath is assumed. The generation of turbulence at the shock can be associated with different kinds of instabilities taking place due to the presence of high-energy particles. The specific mechanisms of such generation are not considered in the present paper. Here we do no more than study the response of pickup proton spectra to the enhanced level of turbulence in the heliosheath. In this respect our model is not self-consistent. One can see in Fig. 4 that the high-energy tails in pickup proton spectra are considerably more populated than those in Fig. 3 due to the effective stochastic acceleration in the heliosheath and the pre-acceleration in the supersonic solar wind. Note that stochastic acceleration in the upwind region of the heliosheath is much more effective than in the inner heliosphere under identical parameters of solar wind turbulence due to the convergence of the plasma flow in the region between the termination shock and heliopause. Note however that in spite of the formation of the high-energy tails, the effect of cooling of the pickup proton population in the heliosheath due to production of low-energy particles is dominant. Namely, the mean-squared value of pickup proton velocities in the solar wind rest frame decrease with distance as is seen in Fig. 5.

3. Fluxes of energetic neutral atoms from the heliosheath

Interstellar pickup protons in the inner heliosheath suffer charge exchanges with interstellar atoms which are described by the term $S(\mathbf{r}, v)$ in Eq. (1). The charge exchange process results in the formation of low-energy pickup ions and high-energy hydrogen atoms. After their creation ENAs move on nearly straight ballistic trajectories suffering losses by ionization and can enter into the inner heliosphere where they could be observed (Gruntman, 1992, 1997; Hsieh and Gruntman, 1993; Gruntman et al., 2001). Fig. 6 shows calculated differential upwind fluxes of ENAs at the Earth's orbit originating from pickup protons in the inner heliosheath. Curves 1 and 2 show the fluxes in the cases when the level of turbulence in the heliosheath is low with $\zeta_{AH} = 0.4 \times 10^{-3}$ and enhanced with $\zeta_{AH} = 0.7 \times 10^{-2}$, respectively. Solid lines show the fluxes in the case when $\zeta_{mE} = 0$, that is, when pre-acceleration of pickup protons by large-scale turbulence in the supersonic solar wind is not taken into account. Dotted lines correspond to $\zeta_{mE} = 0.3$ and dashed lines correspond to $\zeta_{mE} = 0.5$. The squares in the right bottom corner show fluxes of energetic neutral hydrogen from the upwind direction observed with SOHO/CELIAS at the Earth's orbit (Hilchenbach et al., 2000).

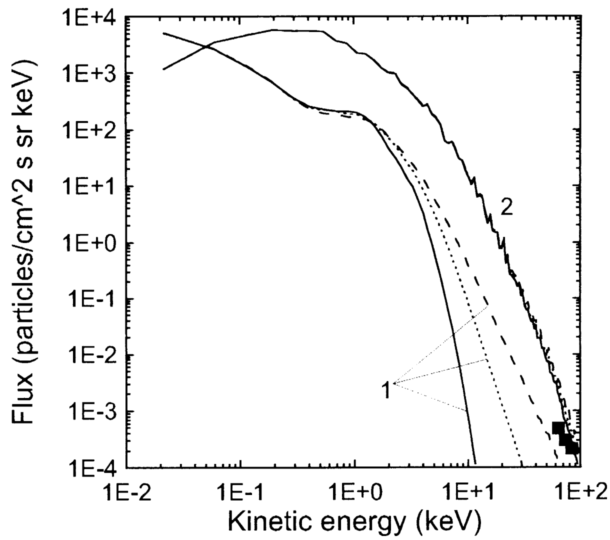

Fig. 6. Upwind fluxes of energetic hydrogen atoms at the Earth's orbit originated from pickup protons at low level of turbulence in the heliosheath with $\zeta_{AH} = 0.4 \times 10^{-3}$ (curves 1) and enhanced level with $\zeta_{AH} = 0.7 \times 10^{-2}$ (curves 2). Solid lines correspond to $\zeta_{mE} = 0$, dotted lines to $\zeta_{mE} = 0.3$ and dashed lines to $\zeta_{mE} = 0.5$. In all cases $\zeta_{AE} = 0.05$. The squares in the right bottom corner are fluxes of energetic hydrogen atoms from the upwind direction observed with SOHO/CELIAS.

The main feature of the fluxes in Fig. 6 is their strong dependence on the level of Alfvénic turbulence in the heliosheath over the whole range of energies. At the low level of turbulence in the heliosheath one can see also the strong dependence of the fluxes at energies above several keV on efficiency of acceleration by large-scale turbulence (ζ_{mE}) Note that diffusive shock acceleration at the termination shock is only possible through the cross-field diffusion since the shock is almost perpendicular in the upwind direction. This acceleration mechanism, however, is likely to be operating only if energies of particles exceed 100 keV (see discussion in Chalov et al., 2003). Thus observations of ENA fluxes in the energy range from 1 to 100 keV can provide a great deal of information on distant solar wind plasma and acceleration mechanisms of pickup protons at and beyond the termination shock.

4. Conclusions

The main conclusions of the paper are the following:

1. Pickup protons constitute the major portion of protons in the upwind part of the inner heliosheath.
2. Spectral shapes of pickup protons in the heliosheath are essentially different from those in the region inside the termination shock.
3. In spite of formation of high-energy tails owing to stochastic acceleration, the total population of pickup protons in the heliosheath experiences cooling due to production of low-energy pickup protons.
4. Fluxes of energetic neutral hydrogen from the inner heliosheath are very sensitive to the level of solar wind turbulence in this region.

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