Evolution of pickup proton spectra in the inner heliosheath and their diagnostics by energetic neutral atom fluxes

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[1] The spatial evolution of pickup protons moving from the termination shock outward to the heliopause, after having suffered stochastic preacceleration in the supersonic solar wind, is studied taking into account ongoing velocity diffusion of the protons in the turbulent Alfvénic fluctuation field. Here only the upwind part of the heliosheath is considered. It is shown that spectra of pickup protons in the inner heliosheath are substantially different from those in the region inside the termination shock. Differential fluxes of energetic neutral atoms originating from pickup protons by charge exchange with interstellar hydrogen atoms in the inner heliosheath and arriving at 1 AU are calculated. It is shown that observations of energetic neutral hydrogen fluxes in a sufficiently wide energy range can be used to place strong limits on the level of solar wind turbulence near the termination shock and further downstream. *INDEX TERMS:* 2152 Interplanetary Physics: Pickup ions; 2124 Interplanetary Physics: Heliopause and solar wind termination; 2144 Interplanetary Physics: Interstellar gas; 2114 Interplanetary Physics: Energetic particles, heliospheric (7514); *KEYWORDS:* solar wind, pickup ions, outer heliosphere, energetic neutral atoms, interstellar atoms

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1. Introduction

[2] For quite some time pickup ions have been the subject of fairly ambitious theoretical and observational investigations. Both the theoretical and observational studies have been concentrated on pickup ions injected into the supersonic plasma flow of the solar wind. By solving adequate particle phase-space transport equations many kinetic features of the expected pickup ion distributions become predictable for this region [see, e.g., *Isenberg*, 1987; *Bogdan et al.*, 1991; *Chalov et al.*, 1995, 1997; *le Roux and Fichtner*, 1997; *Chalov and Fahr*, 1999]. Close to the termination shock and downstream of it the physical conditions for the pickup process are different from the inner heliospheric ones in many respects, for example, the plasma flow is decelerated and then becomes subsonic, its flow geometry is nonspherical, turbulence levels behave differently with distance. This merits separate studies of the phase-space behavior of pickup ions in the region downstream of the shock.

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[3] The hydrodynamic description of the pickup ions as a separate energetic fluid, besides the solar wind background fluid, has already led to very interesting new theoretical insights into the internal entropy generation process at the termination shock, the resulting shock compression ratio and the downstream flow conditions as discussed in papers by *Zank et al.* [1993], *Chalov and Fahr* [1994, 1995, 1997], *le Roux and Fichtner* [1997], or *Kausch and Fahr* [1997]. Depending on the degree of the shock modulation by dynamically involved anomalous cosmic rays (ACRs) and the pickup ion injection efficiency to the ACR regime nonclassical shock compression ratios can be expected. This was demonstrated more recently on the basis of a hydrodynamic multifluid counterflow simulation program [*Fahr et al.*, 2000; *Fahr*, 2000] in which a consistent system of differential equations for five dynamically coupled fluids, that is, protons, H-atoms, pickup ions, ACRs and galactic cosmic rays (GCRs) was simultaneously integrated.

[4] Since these features of the shock and of the downstream plasma flow are not yet an object of in situ observations by the NASA deep space probes, the question thus arises as to how these highly exciting, but purely

theoretical results could perhaps be checked observationally by use of remote sensing methods. With concern to this question, some interesting recommendations have been given to observe energetic neutral atoms (ENAs), which are due to protons decharged by H-atoms in regions beyond the termination shock [see *Gruntman*, 1992; *Hsieh and Gruntman*, 1993; *Czechowski and Grzedzielski*, 1998; *Funsten et al.*, 1994; *Fahr and Lay*, 2000; *Gruntman et al.*, 2001; *Izmodenov et al.*, 2001b]. It was demonstrated by *Fahr and Lay* [2000] that postshock pickup ions decharging on H-atoms produce ENAs, which in the spectral range between 10 and 100 keV/nuc can be used as a direct diagnostic tool to observationally study the shock structure and the downstream flow conditions. To carry out this diagnostic carefully, however, one needs a kinetic description of pickup ions in the region beyond the shock. In two recent papers these descriptions were presented with some limitations. *Czechowski et al.* [2001] have adopted as boundary conditions the postshock spectra given by *Fahr and Lay* [2000] and solved a transport equation on the basis of multifluid representation of the heliosheath flow, not including energy diffusion processes, which, however, can be very important in the inner heliosheath as we are going to show in the present paper. *Chalov and Fahr* [2000] not only considered pickup ions directly transmitted from the region upstream to that downstream of the shock, but also considered contributions from pickup ions, which are multiply reflected at and finally transmitted through the shock. They showed that the latter species of pickup ions lead to higher-energy ion populations everywhere off the upwind or downwind stagnation line. Only along the stagnation line this species does not appear downstream of the shock in the stationary field case because the reflection probability for the perpendicular shock vanishes. In this paper we concentrate on the study of the phase-space transport of pickup protons downstream of the shock along or close to the stagnation line up to the heliopause and include the effects of energy diffusion and of ongoing injection processes due to charge exchange processes of these pickup protons with H-atoms from the local interstellar medium (LISM).

2. Stochastic Acceleration of Pickup Protons in the Region Inside the Termination Shock

[5] In the region beyond the termination shock, but inside the heliopause, that is, in the inner heliosheath, pickup protons can be considered as consisting of two populations: (1) pickup protons that have been created in the supersonic solar wind and then have been convected into the heliosheath and (2) those that have been created in the heliosheath. The first species suffers stochastic acceleration by solar wind turbulence in the whole region from the Sun up to the termination shock [see *Fisk*, 1976; *Isenberg*, 1987; *Bogdan et al.*, 1991; *Chalov et al.*, 1995, 1997; *Fichtner et al.*, 1996; *le Roux and Ptuskin*, 1998] or suffers acceleration at propagating interplanetary shocks [*Giacalone et al.*, 1997]. Thus these pickup protons will have already a pronounced high velocity tail when they reach the termination shock.

[6] The transport of these pickup protons in the solar wind is governed by the following Fokker-Planck equation for the pitch angle-averaged isotropic velocity distribution function $f(t, \mathbf{r}, v)$:

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

where $\mathbf{U}(\mathbf{r})$ is the solar wind velocity, v is the magnitude of the pickup proton velocity in the solar wind rest frame, $D(\mathbf{r}, v)$ is the velocity diffusion coefficient, and $Q(\mathbf{r}, v)$ is the source of freshly ionized pickup protons. The term $S(\mathbf{r}, v)$ describes the charge exchange process between pickup protons and interstellar H-atoms. This latter process does not of course change the number density of pickup protons but results in a redistribution of the energy in pickup proton spectra. Nevertheless, this term is ignored in the region of the supersonic solar wind but it is very important in the heliosheath and is taken into account here.

[7] *Chalov et al.* [1997] considered the combined effects of small-scale Alfvénic and large-scale magnetosonic fluctuations on the formation of pickup ion spectra, so that $D = D_A + D_m$, where D_A and D_m describe the velocity diffusion owing to the interaction of pickup ions with Alfvénic and with magnetosonic turbulences, respectively. We assume here that Alfvénic turbulence has a power law spectrum and is composed of dispersionless, unpolarized waves with equal intensities in the forward and backward directions of propagation. Under the given assumptions and following the derivations by *Isenberg* [1987] the velocity diffusion coefficient D_A derived from the quasi-linear theory of the cyclotron resonant wave-particle interaction can be written as

$$D_A = D_{A0}\frac{U_E^3}{r_E}\left(\frac{v}{U_E}\right)^{\gamma-1}\left(\frac{r}{r_E}\right)^{\gamma-\alpha+\delta(1-\gamma)}, \tag{2}$$

where

$$D_{A0} = \frac{\pi^2(\gamma-1)}{\gamma(\gamma+2)}\left(\frac{v_A}{U_E}\right)^2\left(\frac{qBL_A}{2\pi m_p cU}\right)_E^{2-\gamma}\frac{r_E}{L_{AE}}\frac{\langle\delta B_{AE}^2\rangle}{B_E^2}. \tag{3}$$

γ is the spectral index of turbulence ($\gamma = 5/3$ below), v_A is the Alfvénic velocity, q and m_p are the charge and mass of the proton, B is the magnitude of the mean interplanetary magnetic field, L_A is the correlation length of Alfvénic turbulence, and $\langle\delta B_A^2\rangle$ is the mean squared amplitude of magnetic fluctuations. For our further derivations it was adopted that

$$B = B_E\frac{r_E}{r}, \quad \langle\delta B_A^2\rangle = \langle\delta B_{AE}^2\rangle\left(\frac{r_E}{r}\right)^{\alpha}, \quad L_A = L_{AE}\left(\frac{r}{r_E}\right)^{\delta}. \tag{4}$$

[8] The spatial behavior of the correlation length and mean squared amplitude of Alfvénic fluctuations in the outer heliosphere are presently not well understood. *Zank et al.* [1996] and *le Roux et al.* [1999] proposed a model of the radial evolution of the energy density in magnetic fluctuations and their correlation length taking into account (1) the generation of waves by stream-stream interactions and by pickup ions and (2) the damping of waves due to

turbulent dissipation and stochastic acceleration of pickup ions. The spatial behavior of the fluctuations that they obtained differs from predictions of the WKB theory assuming the fluctuations evolve according to a linear wave convection without sources and sinks of spatially distributed wave power. However, since we are mainly interested in the evolution of pickup proton spectra in the region of the heliosheath and in order to keep an as small number of free parameters as possible, we assume that $\delta = 1$ [*Jokipii*, 1973] and $\alpha = 3$ [*Hollweg*, 1974] can be used in equation (4) according to the WKB theory. According to *Jokipii and Coleman* [1968] we adopt $L_{AE} = 1.3 \times 10^{11}$ cm.

[9] In addition to Alfvénic fluctuations with $L_{AE} \sim 0.01$ AU, large-scale oscillations in the magnitudes of the solar wind velocity and magnetic field with spatial scales up to several AU are observed. As a rule these oscillations are connected with corotating interaction regions and merged interaction regions, and contain the structures of large-scale interplanetary shock waves. It has been demonstrated by *Toptygin* [1983] that acceleration of particles by this 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. The corresponding energy diffusion coefficient can be written in the form

$$D_m(v) = \frac{v^2}{9}\int_0^\infty \langle \nabla \cdot \delta\mathbf{U}_m(\mathbf{r}, t) \nabla \cdot \delta\mathbf{U}_m(\mathbf{r}, t-\tau)\rangle \, d\tau \qquad (5)$$

under the two following assumptions: (1) the mean free path of particles with respect to scattering by short-wavelength Alfvénic fluctuations, $\Lambda_\parallel$, is much less than the correlation length of large-scale fluctuations, L_m, that is, $\Lambda_\parallel \ll L_m$, and (2) the time of diffusive propagation of particles over the distance L_m, $\tau_{dif} \cong L_m^2/K_\parallel$, is much larger than $\tau_{conv} \cong L_m/U$, the convective time for the passage of the distance L_m, that is,

$$\tau_{dif}/\tau_{conv} = 3UL_m/v\Lambda_\parallel \gg 1, \qquad (6)$$

where $K_\parallel = v\Lambda_\parallel/3$ is the spatial diffusion coefficient corresponding to short-wavelength Alfvénic turbulence. In equation (5) $\delta\mathbf{U}_m$ is the large-scale fluctuation of the solar wind velocity and brackets $\langle \ldots \rangle$ denote a large-scale correlation average. It can be shown then that

$$D_m = D_{m0}\frac{U_E^3}{r_E}\left(\frac{v}{U_E}\right)^2\left(\frac{r_E}{r}\right)^\beta, \qquad (7)$$

where

$$D_{m0} = \frac{\langle \delta U_m^2\rangle_E^{1/2}/U_E}{9L_m/r_E}, \qquad (8)$$

and it was assumed that

$$\langle \delta U_m^2\rangle = \langle \delta U_m^2\rangle_E\left(\frac{r_E}{r}\right)^{2\beta}. \qquad (9)$$

With regards to the correlation length of large-scale fluctuations it seems to be reasonable to assume that L_m is the mean distance between large-scale interplanetary shock waves. From observations of the Pioneer and Voyager spacecraft and from numerical simulations of the evolution of recurrent solar wind structures in the distant heliosphere [*Whang and Burlaga*, 1988; *Whang and Burlaga*, 1990; *Richardson et al.*, 2001] one can obtain that $L_m = 3$ AU and $\beta = 0.7$.

[10] The source term Q and the solar wind velocity $\mathbf{U}$ in equation (1) have been calculated in the consistent frame of the two-dimensional model of the solar wind interaction with the partly ionized interstellar medium developed by *Baranov and Malama* [1993, 1995, 1996], *Baranov et al.* [1998], and *Izmodenov et al.* [2001a]. 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.

[11] To describe the interaction of pickup protons with the termination shock we assume here that the magnetic moment of particles is conserved at the shock crossing. The latter assumption is fulfilled in the case when the influence of magnetic fluctuations on the velocity space coordinates of a single particle at its shock crossing is unimportant, more precisely, when the pitch angle scattering mean free path is larger than the local gyroradius. While two-dimensional calculations were carried out for the region of the supersonic solar wind, the evolution of pickup proton distributions in the heliosheath as considered here is restricted to the upwind direction only. In this case the termination shock normal is perpendicular to the upstream magnetic field, and thus reflection of particles due to the abrupt changes of the magnetic field over the shock does not take place. The cross-field diffusion is not taken into account in our model, which is also very limited at energies below 100 keV.

[12] As was shown by *Jokipii* [1987, 1992] only diffusive acceleration at the quasi-perpendicular solar wind termination shock has a high enough acceleration rate to produce ACRs and the acceleration is determined primarily by diffusion normal to the ambient magnetic field. The condition that the diffusive approximation is valid and that particles are able to again diffuse upstream to encounter the shock can be written in the form

$$\Lambda_\parallel/r_g < w/V_{sh}, \qquad (10)$$

where r_g is the gyroradius, V_{sh} is the shock velocity, and w is the velocity of a particle. Condition (10) leads to stringent constraints for low-energy particles. For instance, for protons with energies $\cong$100 keV in front of the termination shock condition (10) gives $\Lambda_\parallel < 0.1$ AU. The assumption of such small values of $\Lambda_\parallel$ near the termination shock is, however, rather problematic. It is known that even at 1 AU the parallel mean free path of ions with energies of around 1 keV, at least during some periods, can reach values of 1 AU [*Gloeckler et al.*, 1995; *Fisk et al.*, 1997]. On the other hand, the high level of turbulence that is required to fulfill the above mentioned inequality, as we show below, leads to efficient stochastic acceleration of pickup ions in the heliosheath and to very high fluxes of ENAs at 1 AU in the energy range up to 100 keV. Thus one can conclude that

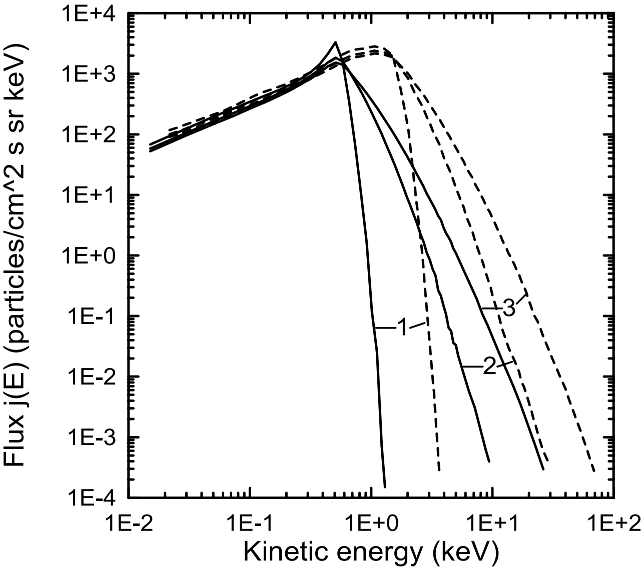

Figure 1. Upstream (solid lines) and downstream (dashed lines) fluxes of pickup protons in the solar wind rest frame in the vicinity of the termination shock for different levels of large-scale turbulence: 1 — $\zeta_{mE} = 0$; 2 — $\zeta_{mE} = 0.3$; 3 — $\zeta_{mE} = 0.5$.

the injection of protons in the process of diffusive shock acceleration at the upwind part of the termination shock (i.e., perpendicular shock) apparently only takes place at energies above 100 keV, that is, in the energy range that is not considered in this paper.

[13] It should be noted that in the flanks of the termination shock where the shock, because of its departure from sphericity, is quasi-perpendicular, reflections are probable, and there it can considerably modify the downstream proton spectra as was shown by *Chalov and Fahr* [2000]. For instance, at energies above 50 keV downstream spectra of pickup protons are essentially modified by multiple reflections at the angle counted from the upwind direction of ~30° [*Chalov*, 2000]. The longitudinal variation of pickup proton spectra at high energies (ACRs), however, will be smoothed by diffusion along the magnetic field lines.

[14] To solve equation (1), the method of transforming this partial differential equation of second order into stochastic differential equations has been used [see, e.g., *Chalov et al.*, 1997]. Figure 1 shows upstream (solid lines) and downstream (dashed lines) fluxes of pickup protons in the vicinity of the termination shock, which is located at 88 AU in the upwind direction for typical parameters of the solar wind: U_E = 430 km s^{-1}, n_{eE} = 6.5 cm^{-3}, v_A = 50 km s^{-1}, $\zeta_{AE} = 0.05$ (= $\langle \delta B_{AE}^2 \rangle / B_E^2$). Curves 1, 2, and 3 correspond to ζ_{mE} = 0; 0.3; and 0.5 (= $\langle \delta U_{mE}^2 \rangle^{1/2} / U_E$), respectively. These values of ζ_{mE} correspond to different magnitudes of large-scale oscillations at 1 AU observed at different extended periods [e.g., *Balogh et al.*, 1999]. The values ζ_{AE} and ζ_{mE} govern the efficiency of stochastic acceleration by small-scale Alfvénic and large-scale magnetosonic fluctuations, respectively (see equations (3) and (8)). It can be seen from Figure 1 that pickup protons arriving at the termination shock can attain pronounced high-energy tails upstream and downstream of the shock depending on the characteristic parameters of the solar wind turbulence.

3. Transport of Pickup Protons in the Inner Heliosheath

[15] In the upwind region, downstream of the termination shock up to the heliopause, the behavior of the velocity distribution function of pickup protons can be described by a spherically symmetric version of equation (1). At V_{LISM} = 25.6 km s^{-1}, $n_{H,LISM}$ = 0.2 cm^{-3}, $n_{p,LISM}$ = 0.05 cm^{-3} considered here and solar wind parameters as stated in the previous section the heliopause is located at 166 AU. Not very much is known about the presence and properties of magnetosonic or Alfvénic turbulences in the heliosheath, thus to keep the smallest number of free parameters possible, we may simplify our study here by assuming that only Alfvénic turbulences play a role in the region downstream of the shock.

[16] Since the spatial behavior of the solar wind velocity and density in the heliosheath is quite different from that in the supersonic solar wind the velocity diffusion coefficient D_A now has a form different from equation (2). No exact information on the strength of the heliosheath magnetic field as a function of distance is available at present, because no relevant MHD counterflow simulations for the realistic case of an LISM H-atom presence are published in the literature so far. Hence we prefer to replace the dependence on B in the diffusion coefficient D_A by a dependence on the Alfvén velocity v_A and the plasma density n_p setting: $B = v_A\sqrt{4\pi m_p n_p}$. Then instead of equations (2)–(4) we obtain the diffusion coefficient D_A in the following form:

$$D_A = D_{A0}\frac{U_E^3}{r_E}\left(\frac{v}{U_E}\right)^{\gamma-1}\left(\frac{n_p(r)}{n_{pE}}\right)^{1-\gamma/2}, \tag{11}$$

where now

$$D_{A0} = \frac{\pi^2(\gamma-1)}{\gamma(\gamma+2)}\left(\frac{v_A}{U_E}\right)^{4-\gamma}\left[\frac{qr_E}{c}\left(\frac{n_{pE}}{\pi m_p}\right)^{1/2}\right]^{2-\gamma}\times\left(\frac{r_E}{L_A}\right)^{\gamma-1}\frac{\langle\delta B_A^2\rangle}{B^2}. \tag{12}$$

Downstream from the termination shock toward the stagnation point at the heliopause both the density n_p and the frozen-in magnetic field B increase, the increase with distance, however, most probably being different for these two quantities. Although the proton number density is calculated in the frame of our model, the magnitude of the magnetic field can be found only as a result of the solution of a self-consistent magnetohydrodynamical problem of the interaction between the solar wind and the partly ionized interstellar medium. Not knowing anything better, we assume here that the quantities v_A, L_A, and $\zeta_A = \langle \delta B_A^2 \rangle / B^2$ behave as constants in the heliosheath ($v_A = v_{AH}$, $L_A = L_{AH}$, $\zeta_A = \zeta_{AH}$), that is, they are assumed to be distance-independent along the upwind axis.

[17] The term $S(\mathbf{r}, v)$ in equation (1), which describes the redistribution of the energy of pickup protons due to their

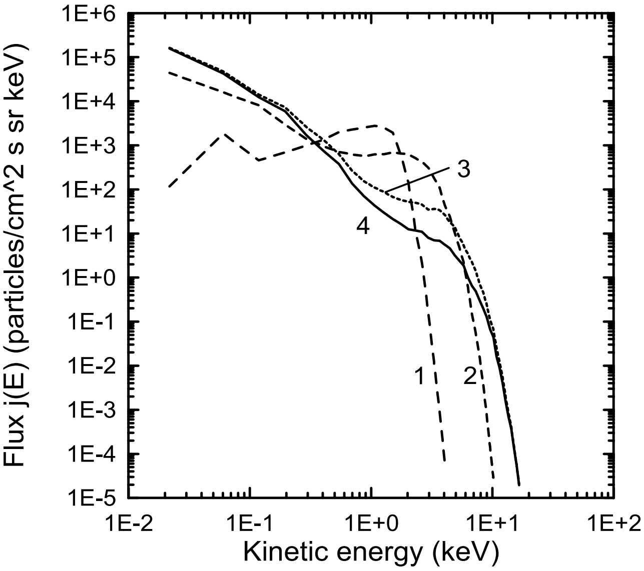

Figure 2. Spatial evolution of downstream pickup proton fluxes in the solar wind rest frame at $\zeta_{mE} = 0$ and $\zeta_{AH} = 0.4 \times 10^{-3}$. 1–90 AU, 2–145 AU, 3–160 AU, 4–164 AU. The termination shock and heliopause are located at 88 AU and 166 AU, respectively.

consecutive charge exchange reactions with interstellar H-atoms, can be written as

$$S(\mathbf{r}, v) = -\sigma_{ex}(u) n_H u \Big[f(r, v) - \frac{n_{PUI}}{4\pi v^2} \delta(v - U_H) \Big], \qquad (13)$$

where σ_{ex} is the charge-exchange cross section, n_H is the number density of atoms, $U_H = U + V_{LISM}$ is the relative velocity of a LISM H-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 H-atoms and is calculated to equal $U + v^2/3U$ for $U \geq v$ and to $v + U^2/3v$ for $U \leq v$. For simplicity, the thermal velocities of H-atoms are ignored here. The local density of pickup ions is given by $n_{PUI} = 4\pi \int v^2 f dv$.

[18] Since parameters of solar wind turbulence are unknown in the heliosheath we will consider ζ_{AH} as a free parameter. At first, let us consider the case of a very low level of turbulence in the heliosheath. The magnitude of Alfvénic fluctuations and the correlation length just in front of the termination shock (r = 88 AU) can be calculated in this case from equation (4). Analytical relations derived from conservation arguments and connecting upstream and downstream values of $\langle \delta B_A^2 \rangle$ [see *Chalov and Fahr*, 2000] lead to the following values in the heliosheath: $\zeta_{AH} = 0.4 \times 10^{-3}$ and $L_{AH}/r_E = 0.73$. Such a low level of turbulence is realized in the case when no generation of waves in the region upstream of the termination shock takes place and when turbulence are simply convected from the inner region of the heliosphere outward.

[19] Figure 2 first shows downstream fluxes of pickup protons (in the solar wind rest frame) at different distances from the Sun for the case when the upstream spectrum at the termination shock is given by curve 1 of Figure 1 (i.e., large-scale magnetosonic fluctuations in the supersonic solar wind are absent: $\zeta_{mE} = 0$) and when $\zeta_{AH} = 0.4 \times 10^{-3}$, $L_{AH}/r_E = 0.73$. The spectrum given by curve 1 is close to that just downstream of the shock (see dashed curve 1 in Figure 1) except for a peak at low energies, which now appears in Figure 2. The peak is formed because of ionization of interstellar atoms in the downstream region (charge exchange with solar wind protons, photoionization, and electron collision ionization) and due to charge exchange between interstellar atoms and pickup protons, which results in the creation of energetic neutral atoms and cold pickup protons with velocities close to the local solar wind velocity (see equation (13)).

[20] The relative contribution of pickup protons with different regions of creation to the resulting downstream fluxes can be seen in Figure 3, which shows downstream fluxes of pickup protons originating in the supersonic solar wind (solid lines) and in the heliosheath (dashed lines) at 98 AU (lines 1) and 164 AU (lines 2). Subsequent spatial evolution of pickup proton spectra in the heliosheath given by curves 2, 3, and 4 in Figure 2 have the following interesting features. Firstly, the high-energy tail shifts to higher energies. This shift is not connected with the stochastic acceleration, which is not effective at such low levels of Alfvénic turbulence (calculations give identical spectra at much lower values of ζ_{AH}), but is a consequence of the adiabatic heating due to the compression of decelerated plasma when it moves from the termination shock to the heliopause. Secondly, there is a spectral gap at medium energies (about several keV), which is more pronounced at large distances (close to the heliopause). This gap is formed because of charge exchange of pickup protons with interstellar atoms, which results in a spectral energy redistribution: protons with low energies are created while medium-energy protons are removed. This process is one of the important reasons for the increase of spectral fluxes at low energies, which is clearly seen in Figure 2. The

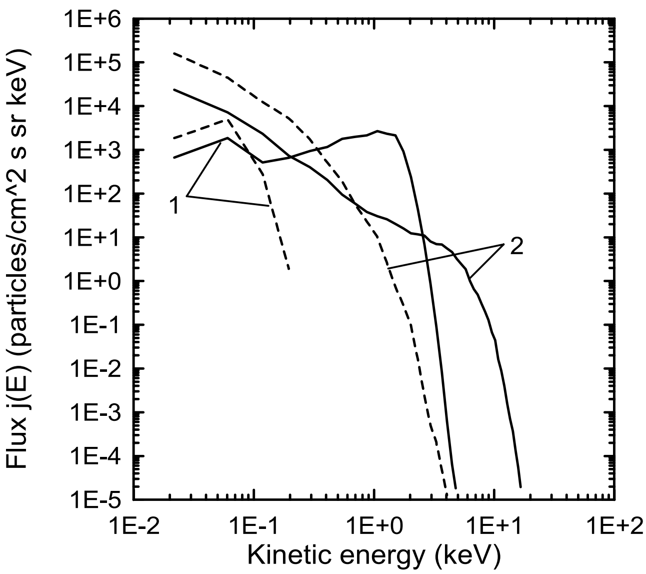

Figure 3. Downstream fluxes of pickup protons originated in the supersonic solar wind (solid lines) and in the heliosheath (dashed lines) at 98 AU (lines 1) and 164 AU (lines 2). $\zeta_{mE} = 0$ and $\zeta_{AH} = 0.4 \times 10^{-3}$.

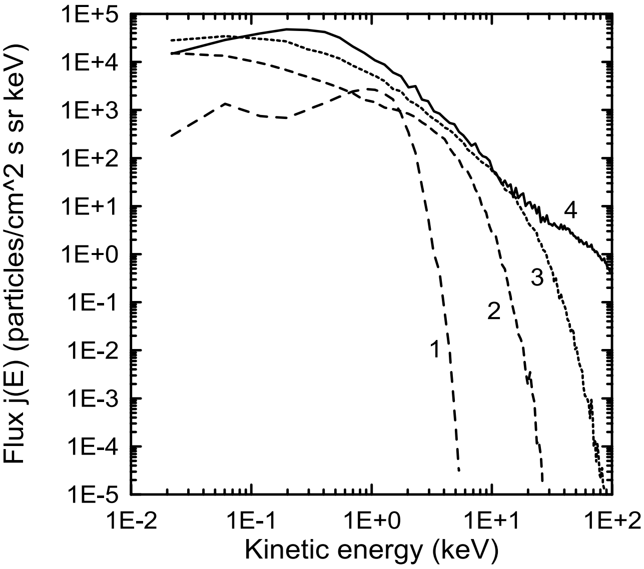

Figure 4. The same as Figure 2 but with enhanced level of turbulence in the heliosheath: $\zeta_{AH} = 0.7 \times 10^{-2}$. 1–90 AU, 2–125 AU, 3–145 AU, 4–164 AU.

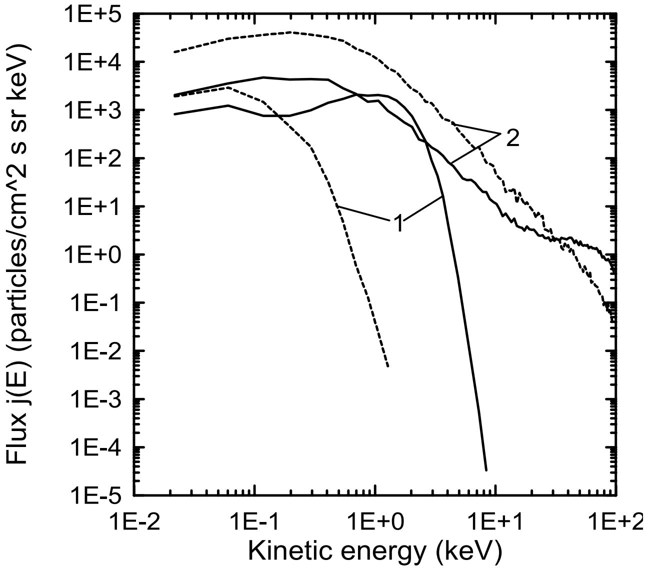

Figure 5. The same as Figure 3 but with enhanced level of turbulence in the heliosheath: $\zeta_{AH} = 0.7 \times 10^{-2}$.

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 H-atoms in the heliosheath. The fact that the gap is pronounced at medium energies and absent at high energies is explained by the decrease of the charge exchange cross section with energy.

[21] Finally one should note that if one compares effects of cooling and heating of pickup protons in the heliosheath, the former effect will be dominant over the latter, namely, the mean squared value of pickup proton velocity in the solar wind rest frame decreases with distance. The decrease is connected with the production of low-energy pickup protons and spectral energy redistribution, as discussed above.

[22] Let us assume now that local generation of Alfvénic waves takes place upstream of and at the termination shock. As a result the level of turbulence in the heliosheath will be enhanced as compared with the case considered above. Figures 4 and 5 show spectral fluxes of pickup protons in the heliosheath at different distances from the Sun with the same initial flux at the termination shock like in Figures 2 and 3 ($\zeta_{mE} = 0$) but with a more than 10 times enhanced level of turbulence in the heliosheath ($\zeta_{AH} = 0.7 \times 10^{-2}$) and with a reduced value of the correlation length ($L_{AH}/r_E = 4.2 \times 10^{-2}$). One can see in Figures 4 and 5 that the high-energy tails of pickup protons, due to the effective stochastic acceleration, now are considerably more populated than those in Figures 2 and 3. Note that stochastic acceleration in the upwind portion of the heliosheath is much more effective than in the inner heliosphere under identical parameters of solar wind turbulence. This fact is connected with the convergence of the plasma flow in the former case, so that adiabatic cooling can not be considered now as a competing mechanism. The spectral gap can now only be seen near the heliopause where the local charge exchange rate is very high because of large number densities of both the interstellar H-atoms and the pickup protons. At smaller distances the gap is smoothed because of efficient velocity diffusion.

[23] Furthermore in Figures 6 and 7 fluxes of pickup protons are shown in the heliosheath at $\zeta_{mE} = 0.3$ (i.e., the acceleration by large-scale magnetosonic fluctuations in the supersonic solar wind is taken into account; see curves 2 in Figure 1) and $\zeta_{AH} = 0.4 \times 10^{-3}$ (low level of turbulence in the heliosheath) and $\zeta_{AH} = 0.7 \times 10^{-2}$ (enhanced level of turbulence), respectively. Note that the latter level of Alfvénic turbulence is, nevertheless, essentially lower than the one in the inner heliosphere.

[24] It has been shown in this section that the spatial evolution of pickup proton spectra in the inner heliosheath is considerably different from the spatial behavior of the

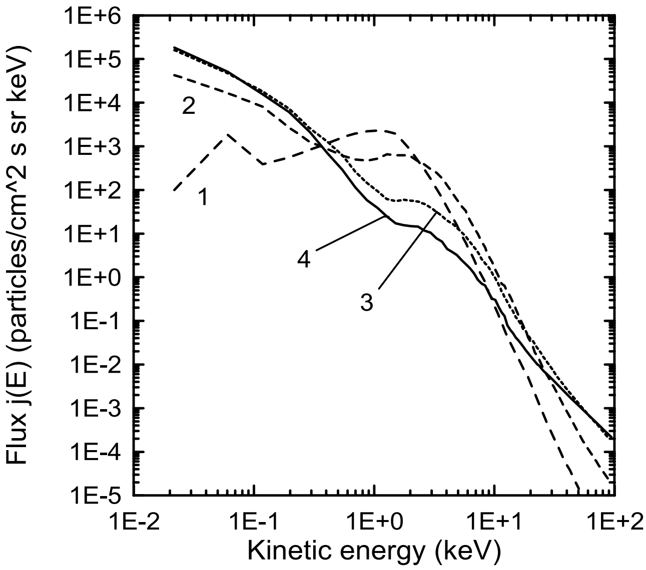

Figure 6. The same as Figure 2 but acceleration of pickup protons by large-scale turbulence in the supersonic solar wind is taken into account with $\zeta_{mE} = 0.3$.

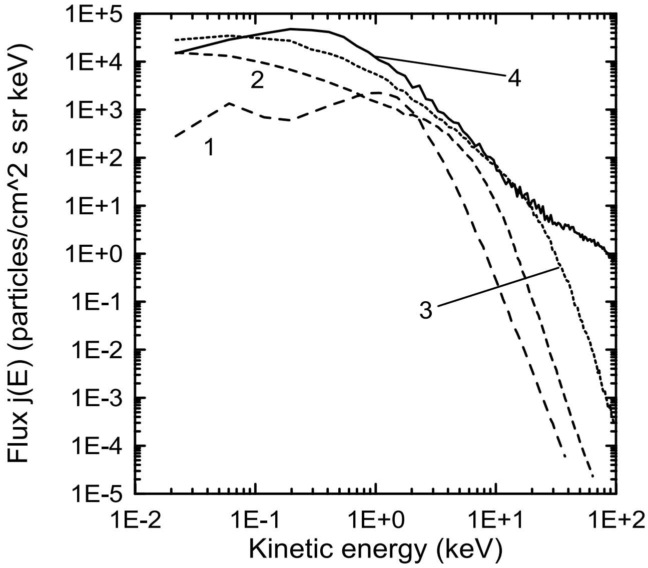

Figure 7. Downstream pickup proton fluxes at $\zeta_{mE} = 0.3$ and enhanced level of turbulence in the heliosheath: $\zeta_{AH} = 0.7 \times 10^{-2}$. 1–90 AU, 2–125 AU, 3–145 AU, 4–164 AU.

spectra in the supersonic solar wind. Some interesting features like spectral gaps and phenomena of cooling of pickup protons due to charge exchange with interstellar H-atoms have been emphasized in the upper paragraphs. These typical spectral features since reflecting many interesting details of prevailing heliosheath physics could perhaps be made an object of observational investigations. In the next section we shall consider such possibilities.

4. Energetic Neutral (H-) Atoms From the Inner Heliosheath

[25] Interstellar pickup protons in the inner heliosheath with spectral distributions given in Figures 2–7 suffer charge exchanges with interstellar atoms. As a product of such charge exchange reactions H-atoms (ENAs) with velocities represented by the pickup distribution functions are created, which can then partly enter the inner heliospheric regions and can be detected there. The relevant process behind this ENA production is described by the term $S(\mathbf{r}, v)$ (see equation (13)) in equation (1) and there leads to energy redistribution in pickup proton spectra as was already mentioned above. At the same time, however, the former, parent pickup protons are converted into hydrogen atoms with nearly the same velocities as the responsible protons had before. These heliospheric ENAs from beyond the termination shock can be detected even at the orbit of the Earth with the use of appropriate detectors [see *Gruntman et al.*, 2001]. The first detections of such ENAs in the energy range between 60 to 100 keV/nuc even seem to have been successfully carried out with the SOHO/CELIAS instrument [*Hilchenbach et al.*, 1998, 2000].

[26] After their creation ENAs move on nearly straight ballistic trajectories suffering losses by ionization, which is mainly important in the inner heliosphere. At the orbit of the Earth ENAs from the inner heliosheath can be registered and serve as a powerful tool to carry out a remote diagnostic of the plasma properties in distant regions of the heliosheath. A numerical expression for the directional differential flux of H-ENAs from the inner heliosheath in (cm^{-2} s^{-1} sr^{-1} keV^{-1}) can be given by [see *Gruntman*, 1992, 1997; *Hsieh and Gruntman*, 1993; *Gruntman et al.*, 2001]

$$j_H(\mathbf{r}_0, E) = \int_{s_{sh}}^{s_{hp}} j_{PUI,H}(\mathbf{r}, E)\sigma(E)n_H(\mathbf{r})\exp[-D(\mathbf{r}, E)]\, ds, \quad (14)$$

where $j_{PUI,H}(\mathbf{r}, E)$ is the spectral flux of pickup protons with energy E (in the solar rest frame), $n_H(\mathbf{r})$ is the number density of neutral hydrogen, $\sigma(E)$ is the charge exchange cross section for pickup protons colliding with H-atoms. The extinction of ENAs between the point $\mathbf{r}_0$ of observation and the point of their birth at $\mathbf{r}$ is given by $D(\mathbf{r}, E) = \int\beta(t)dt$, where $\beta(t)$ is the total loss rate resulting from charge exchange, photoionization, and electron impact ionization processes. The integration in equation (14) extends from the termination shock ($s = s_{sh}$) to the heliopause ($s = s_{hp}$) along the line of sight originating at $\mathbf{r}_0$ with a differential line element ds. Like *Gruntman et al.* [2001] we assume that the ionization rate is inversely proportional to the square of the distance from the Sun and adopt the value $\beta_E = 6 \times 10^{-7}$ s^{-1} at 1 AU in our calculations of ENA fluxes.

[27] Figure 8 shows differential fluxes of H-ENAs from the inner heliosheath at 1 AU originating from pickup protons. Curves labeled 1 and 2 show the fluxes in the case

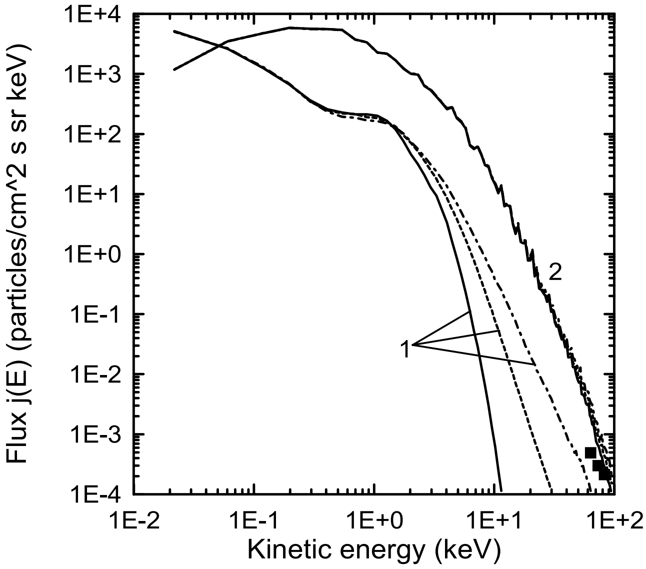

Figure 8. Differential fluxes of ENAs from the inner heliosheath at 1 AU originated from pickup protons at low level of turbulence in the heliosheath with $\zeta_{AH} = 0.4 \times 10^{-3}$ (curves 1) and enhanced level with $\zeta_{AH} = 0.7 \times 10^{-2}$ (curves 2). Solid lines show the fluxes in the case when preacceleration of the pickup protons by large-scale turbulence in the supersonic solar wind is not taken into account ($\zeta_{mE} = 0$). Dashed lines correspond to $\zeta_{mE} = 0.3$ and dash-dotted lines to $\zeta_{mE} = 0.5$. The filled squares in the right bottom corner are fluxes of ENAs from the apex direction observed with SOHO/CELIAS at 1 AU [*Hilchenbach et al.*, 2000].

when the level of turbulence in the heliosheath is (1) low with $\zeta_{AH} = 0.4 \times 10^{-3}$, and (2) enhanced with $\zeta_{AH} = 0.7 \times 10^{-2}$, respectively. Solid lines correspond to the case when preacceleration of pickup protons by large-scale magnetosonic turbulence in the supersonic solar wind is not taken into account ($\zeta_{mE} = 0$; curves 1 in Figure 1 for fluxes at the termination shock). Dashed lines correspond to $\zeta_{mE} = 0.3$ (curves 2 in Figure 1 for fluxes at the termination shock) and dash-dotted ones correspond to $\zeta_{mE} = 0.5$ (curves 3 in Figure 1). One can see in Figure 8 that fluxes of H-ENAs are very sensitive to the level of solar wind turbulence in the inner heliosheath over the whole range of energies. On the other hand, at the lowest level of turbulence in the heliosheath ENA fluxes do not depend on the value of ζ_{mE} (preacceleration efficiency in the supersonic solar wind) at energies near and below 1 keV, while the strong dependence of the fluxes on ζ_{mE} at large energies exists. At the enhanced level of turbulence in the heliosheath fluxes of ENAs do practically not depend on the value of ζ_{mE}. The squares in the right bottom corner in Figure 8 are fluxes of H-ENAs from the apex direction observed with SOHO/CELIAS at 1 AU [*Hilchenbach et al.*, 2000]. As we have mentioned above, downstream spectra of pickup protons are modified by multiple reflections at the angle counted from the upwind direction of $\sim 30°$. This angle is large than the field of view of the High-Energy Suprathermal Time-of-Flight sensor (HSTOF) of the CELIAS [*Hilchenbach et al.*, 1998].

[28] It can be clearly concluded from these results that combined observations of ENA fluxes in the energy range near 1 keV and at energies of several tens of keV can give strong limits to the level of solar wind turbulence near the termination shock and in the inner heliosheath, which are very important to understand the mechanism of energization of pickup ions at the termination shock and the physics of the multifluid plasma in the heliosheath. For instance, the value $\zeta_{AH} = 0.7 \times 10^{-2}$ is likely to be the largest possible level of Alfvénic turbulence in the heliosheath. Otherwise fluxes of ENAs with energies above several tens of keV would be essentially higher than those actually observed at 1 AU (see Figure 8). Besides, a temporal change in the parameters of solar wind turbulence in the inner heliosheath (e.g., due to the solar cycle) would be reflected in the corresponding variations of ENA fluxes.

5. Conclusions

5.1. Pickup Protons

[29] In this paper we studied the spatial evolution of pickup proton spectra in the upwind part of the inner heliosheath. Continuous production of pickup protons by charge exchange of solar protons with interstellar H-atoms, by photoionization, and by electron impact ionization were taken into account. Energy diffusion and charge exchange of pickup protons with hydrogen atoms resulting in an energy redistribution in their spectra are also taken into account. The following have been shown in the paper:

[30] 1. The spatial behavior of pickup proton spectra in the heliosheath is essentially different from that in the supersonic wind. Formation of spectral gaps at medium energies and phenomena of cooling of pickup protons due to charge exchange with interstellar hydrogen atoms take place in the heliosheath.

[31] 2. The total pickup proton population consists of particles with different regions of origin. The high-energy part of spectra consists of protons originating in the supersonic solar wind. Pickup protons originating in the inner heliosheath form the low-energy population.

[32] 3. Energy spectra of pickup protons strongly depend on the level of Alfvénic turbulence. At low levels of Alfvénic turbulence the adiabatic heating due to compression of the plasma flow becomes more important in the formation of high-energy tails of pickup spectra than stochastic acceleration. At high levels of Alfvénic turbulence of course stochastic acceleration becomes important and even much more effective than in the inner heliosphere under identical parameters of solar wind turbulence.

5.2. H-ENAs From the Inner Heliosheath

[33] We used the pickup proton spectra to calculate differential fluxes of H-ENAs at 1 AU in energy range from 0.1 keV up to 100 keV. These H-ENAs are formed because of charge exchange of pickup protons with interstellar H-atoms in the inner heliosheath. This study is important in order to understand what we can learn about the heliospheric interface from future space ENAs experiments [e.g., *Gruntman et al.*, 2001]. The following have been shown in the paper:

[34] 1. The H-ENA fluxes at 1 AU are very sensitive to the level of solar wind Alfvénic turbulence in the inner heliosheath over the whole range of energy and can serve as a good diagnostics of Alfvénic turbulence in the heliosheath and, therefore mechanisms of the turbulence generation at the termination shock.

[35] 2. The fluxes can experience time variations due to variations in the parameters of solar wind turbulence with the solar cycle.

[36] 3. Fluxes of H-ENAs with energies above 60 keV observed with SOHO/CELIAS at 1 AU [*Hilchenbach et al.*, 1998, 2000] can be explained if it is considered that they are formed by charge exchange of accelerated pickup protons with H-atoms in the inner heliosheath. There are at least two possible ways to produce high-energy tails in pickup proton spectra, which are required to explain the observations, namely, stochastic acceleration in the inner heliosheath and acceleration by large-scale turbulence in the supersonic solar wind. These two ways, however, lead to considerably different fluxes of H-ENAs at lower energies (e.g., at 1 keV).

[37] In addition, we argue that combined observations of ENA fluxes at energies near 1 keV and at energies of several tens of keV can give important new information on spectral properties of pickup protons and on the parameters of the solar wind turbulence in the inner heliosheath.

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