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Letter to the Editor

# Energetic particles from the outer heliosphere appearing as a secondary pick-up ion component

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**Abstract.** In measured pick-up ion spectra a special spectral feature has been identified on the high side of the pick-up ion injection energy which cannot be explained as due to energy diffusion of primary pick-up protons originating from ionized interstellar H-atoms. As we can show, however, in the following article, this feature can be explained as a secondary pick-up ion feature due to ions originating from the charge exchange ionization of energetic neutral H-atoms entering the inner heliosphere and coming from their birth places in the heliosheath. It may thus be the case that energetic neutral H-atoms from the heliosheath region, searched for by experimenters for quite some time now, have already been seen as secondary pick-up ions in special features of measured distribution functions.

**Key words.** acceleration of particles – solar wind – interplanetary medium

## 1. Introduction to pick-up ion features

Interstellar neutral hydrogen from the local interstellar medium (LISM) penetrating deeply into the heliosphere and there undergoing ionization processes via charge exchange with solar wind protons and photoionization by solar EUV radiation is the source of a specific solar wind ion population called interstellar pick-up protons. Since the first detection of pick-up protons by the Solar Wind Ion Composition Spectrometer (SWICS) on the Ulysses spacecraft (Gloeckler et al. 1993) many interesting features of pick-up proton spectra have been observed. Under quiet solar wind conditions with low levels of MHD turbulence the velocity distribution of pick-up protons in the spacecraft rest frame is observed to fall off steeply beyond the cutoff, i.e. the pick-up ion injection point at twice the solar wind speed. High velocity tails beyond the cutoff are developed under disturbed solar wind conditions and at high levels of MHD turbulence due to efficient stochastic acceleration of protons occuring due to nonlinear interactions with solar wind turbulence (Gloeckler et al. 1994). However, some unexplained features have been detected more recently in pick-up ion spectra even under quiet conditions, namely about three orders of magnitude lower suprathermal tails extending to regions beyond the cutoff are observed (Gloeckler et al. 1993; Gloeckler 1996; Gloeckler & Geiss 1998; Gloeckler et al. 2000). As a challenge to theoreticians there are no clear explanations up to now of the origin of these suprathermal tail ions during quiet times.

In the present paper we show that these observed but unexpected suprathermal tails in pick-up proton distributions during quiet solar wind conditions can be qualitatively explained if one takes into account an additional, never looked-at source of pick-up protons resulting from energetic neutral atoms (ENAs) coming from the inner heliosheath. These ENAs are produced due to charge exchange reactions between accelerated pick-up protons downstream of the termination shock and LISM neutral atoms in the region between the termination shock and heliopause (Gruntman 1992; Hsieh & Gruntman 1993; Gruntman et al. 2001; Chalov & Fahr 2000). For the first time these ENAs have probably been detected by the High-Energy Suprathermal Time-of-Flight sensor (HSTOF) of the Charge, Element, and Isotope Analysis System (CELIAS) on the Solar and Heliospheric Observatory (SOHO) in the energy range between 60 to 100 keV/nuc (Hilchenbach et al. 1998; 2000). In the following we shall study how these ENAs reappear as pick-up protons. Here we consider only hydrogen atoms and pick-up protons.

## 2. Fluxes of energetic neutral atoms from the inner heliosheath

In the present paper we start from considering pick-up ion distributions in the ecliptic plane near the upwind direction. Hence

*Send offprint requests to*: S. V. Chalov, e-mail: chalov@ipmnet.ru we are interested first in ENA fluxes arriving at points lying on the LISM wind axis which is parallel to the LISM velocity vector (points $A$ in Fig. 1). An expression for the directional differential flux of ENAs from the inner heliosheath, $j_{\rm ENA}$ (in units of: $\rm cm^{-2}\,s^{-1}\,sr^{-1}\,keV^{-1}$) can be given by (Gruntman 1992)

$$j_{\rm ENA}(r,\theta,E) = \int_{S_{\rm TS}}^{S_{\rm HP}} j_{\rm PUI}(\boldsymbol{\xi},E)\sigma(E)\,n_{\rm H}(\boldsymbol{\xi})P_{\rm A}(\boldsymbol{\xi},E)\,{\rm d}s\,, \qquad (1)$$

where $r$ is the distance of the point of observation $A$ from the Sun, $\theta$ is the off-axis angle which defines the direction of the line of sight, $j_{\rm PUI}(\boldsymbol{\xi},E)$ is the spectral flux of pick-up protons with energy $E$, $\sigma(E)$ is the charge exchange cross section for pick-up protons colliding with hydrogen atoms with a relative energy $E$, $n_{\rm H}(\boldsymbol{\xi})$ is the number density of interstellar neutral hydrogen atoms. Here we assume axissymmetry with respect to the upwind axis and therefore take the ENA fluxes to be independent on the roll angle. The term $P_{\rm A}(\boldsymbol{\xi},E)$ describes the extinction of ENAs between the point $A$ of observation and the point of their birth $O$. The integration in Eq. (1) extends from the termination shock ($s = S_{\rm TS}$) to the heliopause ($s = S_{\rm HP}$) along the line of sight originating at $A$ with a differential line element d$s$. The extinction $P_{\rm A}(\boldsymbol{\xi},E)$ is given by

$$P_{\rm A}(\boldsymbol{\xi},E) = \exp\left(-\int_A^O \beta(t)\,{\rm d}t\right), \qquad (2)$$

where $\beta(t)$ is the total loss rate resulting from charge exchange and photoionization. Assuming that $\beta = \beta_{\rm E}(r_{\rm E}/\xi)^2$ and taking into account that ${\rm d}t = {\rm d}s/w$ where $\xi$ is the distance of a hydrogen atom from the Sun and $w$ is its velocity (see Fig. 1) we obtain

$$P_{\rm A}(\boldsymbol{\xi},E) = P(r,\theta,E)\,, \quad P(r,\theta,E) = \exp\left(-\frac{\beta_{\rm E} r_{\rm E}^2}{wr}\frac{\theta}{\sin\theta}\right). \qquad (3)$$

To derive Eq. (3) the condition $r \ll R_{\rm TS}$ has been used. From Eqs. (1) and (3) one can then obtain

$$j_{\rm ENA}(r,\theta,E) = F(\theta,E)P(r,\theta,E)\,, \qquad (4)$$

where

$$F(\theta,E) = \int_{S_{\rm TS}}^{S_{\rm HP}} j_{\rm PUI}(\boldsymbol{\xi},E)\sigma(E)n_{\rm H}(\boldsymbol{\xi})\,{\rm d}s\,. \qquad (5)$$

In order to find the flux $F(\theta,E)$ it is necessary to know the spatial and energy distribution of pick-up protons in the inner heliosheath. Recently the spatial evolution of pick-up protons in the upwind part of the inner heliosheath has been studied by Chalov et al. (2003) taking into account stochastic acceleration of the protons by solar wind turbulence in the supersonic solar wind and in the heliosheath. Here we will make use of pick-up proton spectra calculated by Chalov et al. (2003) to find $F(0,E)$ in the case when the efficiency of stochastic acceleration is low. Since no theoretical and observational information on spatial and energy distribution of pick-up protons in the whole region of the inner heliosheath is available at present, we simplify our study here by assuming that $F(\theta,E) = F(0,E)$. If the ENA flux entering the inner heliosphere is known, then one can easily calculate the number density $n_{\rm ENA}(r)$ of these ENAs which then can be used to calculate the sources of freshly created pick-up

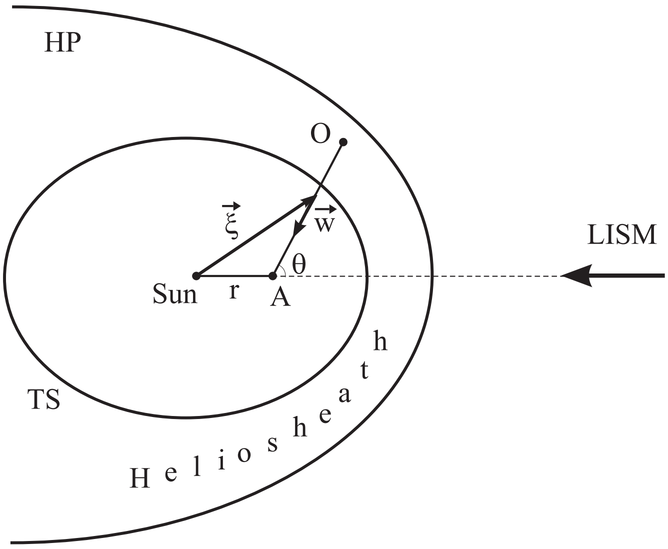


**Fig. 1.** Schematic illustration of the heliosphere and its interface to the interstellar medium.

protons of the "second kind", i.e. secondary pick-up protons. The number density is given by

$$n_{\rm ENA}(r) = 2\pi\int_0^\pi\int_{E_1}^{E_2}\frac{j_{\rm ENA}(r,\theta,E)}{w}\sin\theta\,{\rm d}\theta{\rm d}E\,, \qquad (6)$$

where the energy range of ENAs will be defined below.

## 3. Inclusion of secondary pick-up protons originating from heliosheath ENAs

Immediately after the ionization of primary and secondary hydrogen, the newly appearing protons undergo the action of electro-inductive forces in the magnetized solar wind and linear and nonlinear wave-particle interactions. The governing transport equation describing the pitch-angle anisotropic velocity distribution function of pick-up protons can be written in the following form (see e.g. Chalov & Fahr 1998):

$$\frac{\partial f}{\partial t} + (U_{\rm SW} + v\mu\chi)\frac{\partial f}{\partial r} + \left(\frac{1-3\mu^2}{2}\frac{1-\chi^2}{r} - \frac{1-\mu^2}{r}\right)U_{\rm SW}v\frac{\partial f}{\partial v}$$
$$+\frac{1-\mu^2}{2}\left[\frac{v}{r^2}\frac{\rm d}{{\rm d}r}\left(r^2\chi\right) + \frac{2\mu U_{\rm SW}}{r} - 3\mu U_{\rm SW}\frac{1-\chi^2}{r}\right]\frac{\partial f}{\partial\mu}$$
$$= \hat{S}\,f + Q_{\rm ENA}(r,v,\mu) + Q_{\rm H}(r,v,\mu)\,, \qquad (7)$$

where $U_{\rm SW}$ is the solar wind speed, $v$ and $\mu$ are the speed and cosine of the proton pitch-angle in the solar wind rest frame, $\chi$ is the cosine of the angle between the radial direction and Parker's interplanetary magnetic field, $\hat{S}\,f$ is the Fokker-Planck diffusion operator describing the effects of pitch-angle scattering and energy diffusion, $Q_{\rm ENA}$ and $Q_{\rm H}$ are the sources of pick-up protons originating due to ionization of ENAs and of LISM H-atoms, respectively. These sources can be written in the following form:

$$Q_{\rm ENA}(r,v,\mu) = \frac{n_{\rm ENA}(r)\beta_{\rm E}(r_{\rm E}/r)^2}{2\pi U_{\rm SW}^2}\,q_{\rm ENA}(v,\mu)\,, \qquad (8)$$

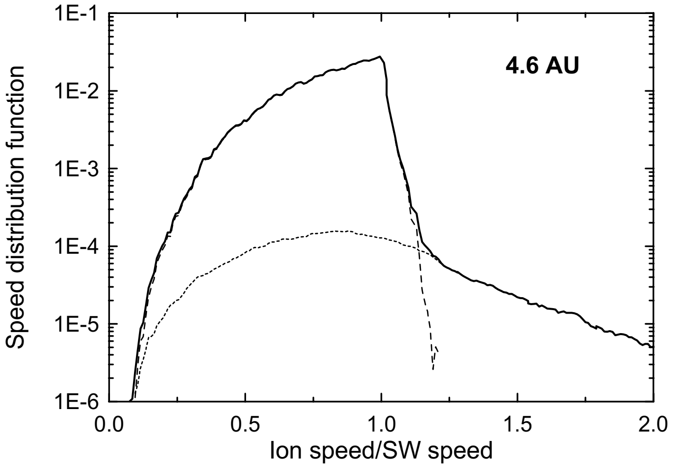


**Fig. 2.** The dimensionless speed distribution functions $F_v$ of pick-up protons originating from LISM atoms (dashed curve) and from ENAs (dotted curve) at low level of turbulence with $\langle \delta B_E^2 \rangle / B_E^2 = 0.01$. The solid curve is the total speed distribution function.

$$Q_H(r, v, \mu) = \frac{n_H(r)\beta_E(r_E/r)^2}{2\pi U_{SW}^2}\,\delta(v - U_{SW})\delta(\mu - \mu_0(r))\,. \qquad (9)$$

In Eq. (9) the $\delta$-functions imply that the solar wind-frame speeds of freshly injected pick-up protons originating from LISM H-atoms are equal to the solar wind speed $U_{SW}$ (since velocities of the H-atoms can be ignored) and their initial pitch-angles are determined by the local magnetic field configuration. The term $q_{ENA}(v, \mu)$ in Eq. (8) is a complicated function of its arguments. An explicit expression for this function is not used in our model. The method of its calculation is shortly described in the next paragraph.

In order to solve Eq. (7) we transform it to an equivalent system of ordinary stochastic differential equations which describes trajectories of protons in phase-space (see Chalov & Fahr 1998). The initial velocity (magnitude and direction) of a proton originating from a ENA is chosen from the probability distribution which can be found on the basis of the ENA flux $j_{ENA}(r, \theta, E)$ given by Eq. (4). Then this velocity is transformed into the solar wind rest frame to find the initial values of the speed $v$ and the pitch-angle $\mu$ of the proton.

Calculations of fluxes of pick-up protons in the upwind part of the inner heliosheath carried out by Chalov et al. (2003) are based on the two-dimensional kineto-hydrodynamic model of the interaction between the solar wind and the partially ionized LISM developed by Baranov & Malama (1993). The solar wind parameters at 1 AU and LISM parameters which they adopted, and also are adopted here, are the following: $U_{SW} = 430$ km s$^{-1}$, $n_{pE} = 6.5$ cm$^{-3}$, $V_{LISM} = 26.6$ km s$^{-1}$, $n_{H,LISM} = 0.2$ cm$^{-3}$, $n_{p,LISM} = 0.05$ cm$^{-3}$ (see e.g. Gloeckler & Geiss 2001; Izmodenov et al. 2003). Furthermore we assume that $\beta_E = 6 \times 10^{-7}$ s$^{-1}$ and the energy range of ENAs under consideration is 0.02 keV $\le E \le$ 5 keV (i.e. $E_1 = 0.02$ keV and $E_2 = 5$ keV in Eq. (6)). Figure 2 then shows calculated dimensionless pitch-angle averaged speed distribution functions $F_v$ in the solar wind rest frame at $r = 4.6$ AU which are defined as

$$F_v = \frac{2\pi U_{SW} v^2 f_v}{n_{H,\infty}}\,, \qquad f_v = \int_{-1}^{1} f\,\mathrm{d}\mu\,. \qquad (10)$$

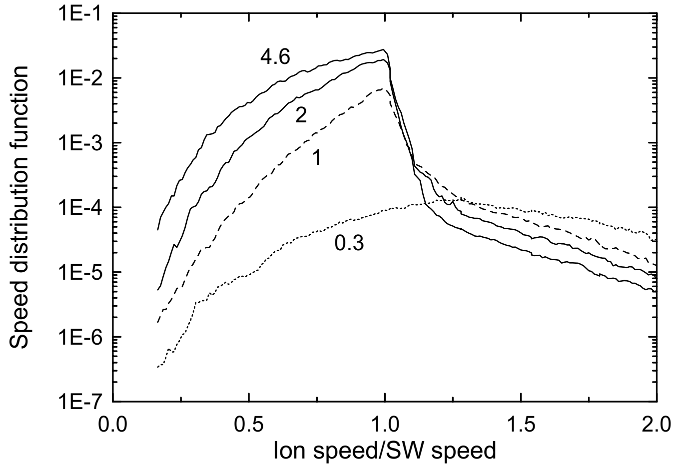


**Fig. 3.** The spatial evolution of the total speed distribution function of pick-up protons. The numbers denote the distance from the Sun in AU.

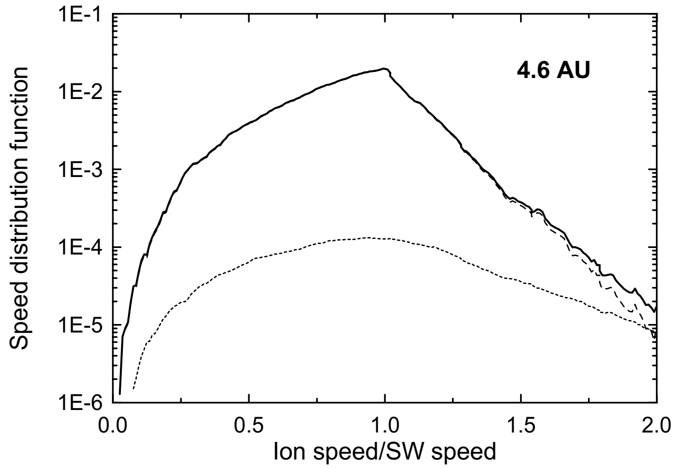


**Fig. 4.** Same as Fig. 2, but for increased level of turbulence with $\langle \delta B_E^2 \rangle / B_E^2 = 0.05$.

The dashed and dotted curves represent the velocity distributions of pick-up protons originating from LISM H-atoms and H-ENAs, respectively. The solid curve shows the total speed distribution function. One clearly can see the abrupt decrease of the velocity distribution of primary pick-up protons originating from LISM H-atoms above the injection speed $v = U_{SW}$ due to negligible velocity diffusion. Note that the level of slab Alfvénic turbulence in the case presented in Fig. 2 is low with $\langle \delta B_E^2 \rangle / B_E^2 = 0.01$. The suprathermal tail appearing is formed by secondary pick-up protons originating from ENAs. Figure 3 shows the evolution of the total pick-up velocity distribution with increasing solar distance. At small distances (0.3 AU) almost all pick-up protons are of ENA origin. When the distance from the Sun increases the relative contribution of ENA pick-up protons decreases with respect to primary pick-up protons and at large solar distances it is only manifest in the form of suprathermal tails.

When the level of solar wind turbulence is increased, the effect of velocity diffusion becomes important and suprathermal tails formed by secondary pick-up protons can be hidden due to the presence of accelerated primary pick-up protons as

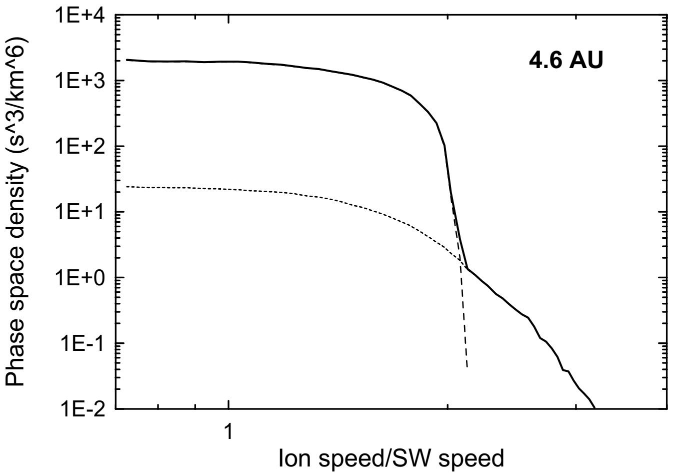


**Fig. 5.** The phase-space densities of pick-up protons for the case shown in Fig. 2, but in the solar rest frame.

is demonstrated in Fig. 4. Thus the best conditions to observe ENA pick-up protons are given for quiet solar wind conditions with low levels of turbulence when the velocity diffusion process is not important. Finally Fig. 5 shows the phase-space densities of pick-up protons for the case shown in Fig. 2, but now in the solar rest frame which is roughly identical with the spacecraft frame. From the qualitative comparison of the calculated phase-space density with pick-up proton spectra observed by SWICS Ulysses under quiet solar wind conditions (Gloeckler et al. 1993; Gloeckler 1996; Gloeckler & Geiss 1998) one can conclude that the observed suprathermal tails can be explained as originating via charge exchange processes between solar wind protons and ENAs from the inner heliosheath. On the basis of the present results we could not, however, dare to carry out quantitative comparison of our calculations with observed spectra, since our model is simplified by the assumption that an isotropic ENA inflow from the heliosheath prevails with spectral intensities similar to those calculated by us for the upwind direction reflecting in our assumption that $F(\theta, E) = F(0, E)$.

## 4. Conclusions

The above presented results have shown that the suprathermal tails in pick-up proton spectra observed by SWICS Ulysses under quiet solar wind conditions when velocity diffusion is negligible can be explained as secondary pick-up ion features if one takes into account an additional source of pick-up protons connected with ENAs from the inner heliosheath. Hence one can state that ENAs from the heliosheath region for which experimenters are searching at present have already been seen as secondary pick-up ion features. The contribution of ENA pick-up protons to the total spectra of pick-up protons is more pronounced at small distances from the Sun. Suprathermal features formed by ENA pick-up protons are not identifyable as an outstanding spectral structure when at higher turbulence levels the presence of accelerated LISM pick-up protons predominates the spectral region beyond the injection border.

It is important to emphasize that quiet-time suprathermal tails are also seen in velocity distributions of $He^+$ and $He^{++}$ (e.g. Gloeckler et al. 2000). Recent detection of energetic neutral helium of probable heliospheric origin (Shaw et al. 2000) gives grounds to expect that the $He^+$ quiet-time suprathermal tails have the same origin as the pick-up $H^+$ tails. It is very likely that the mechanism of formation of the $He^{++}$ suprathermal tails is quite different. However, a contribution from ENAs to the $He^{++}$ suprathermal tails is also possible. Really, $He^+$ ions created from ENAs close to the Sun have large components of velocities along magnetic field lines. Since the radial component of the interplanetary magnetic field close to the Sun is larger than the longitudinal one, the $He^+$ ions will move towards regions of high EUV and solar wind flux where the double ionization rate is high. The inward-directed movement will continue until efficient pitch-angle scattering stops it. However, in order to estimate the efficiency of $He^{++}$ production from ENAs it is necessary to construct an adequate numerical model.

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