Pre-accelerated pick-up ions, anomalous cosmic rays, and the associated ENA fluxes

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Abstract

Pick-up ions (PUIs) are expected to be preaccelerated up to energies around 100 keV upstream of the heliospheric shock. At the shock they split into two populations, one convected downstream, and one being reflected and partly undergoing diffusive acceleration towards MeV energies to form the anomalous cosmic rays (ACRs). Both populations are subject to charge exchange processes with interstellar H-atoms producing energetic neutral atoms (ENAs) in the region beyond the heliospheric shock. The ENAs can penetrate into the inner solar system and thus communicate the distant plasma conditions to the Earth's orbit where these particles can be observed. In the present contribution we combine the models of the evolution of pre-accelerated PUI spectra inside and outside the heliospheric termination shock and calculate the corresponding ENA flux from transcharging. The results are compared to the ENA fluxes associated to ACR transcharging.

1 Introduction

After the recognition of the potential of observations of so-called energetic neutral atoms (ENAs) as an indirect diagnostic for various particle populations and a direct diagnostic for the region of subsonic solar wind beyond the heliospheric shock (Hsieh et al. 1992), such ENA measurements have been successfully performed with the SOHO spacecraft (Hilchenbach et al. 1998, Czechowski et al. 1999). The observed ENA hydrogen fluxes in the interval $55 - 80\ keV$ as recorded with the CELIAS/HSTOF instrument on SOHO appear to be consistent with the general expectation of higher fluxes from the downwind direction of the heliosphere, i.e. from the heliotail. This expectation is based on numerical studies of the spatial ACR distribution beyond the heliospheric shock (e.g. Czechowski et al. 1995, Czechowski and Grzedzielski 1998) exhibiting the highest densities in downwind direction.

Recently, it has been shown that a fraction of PUIs, which are injected with energies of about $1\ keV$ into the solar wind plasma, probably experience a significant preacceleration up to several hundred keV (Chalov, Fahr and Izmodenov 1995, 1997; Fichtner et al. 1996, le Roux and Ptuskin 1998) or even up to the MeV regime (Jokipii & Giacalone 1998). If so, they are suitably located in velocity space to contribute to the observed ENA fluxes. Here, we address the question how important this PUI contribution is in order to correctly interpret the observed ENA spectra.

2 The Model

To determine the ENA fluxes one needs to know the phase space distributions of the associated plasma species, here PUIs and ACRs. While for the region beyond of the heliospheric shock those of the latter were computed by Czechowski, Fichtner and Kausch (1999), no comparable study has been performed for PUIs so far.

2.1 Phase space distributions of PUIs We start out from the phase space distributions of preaccelerated PUIs computed by Chalov, Fahr and Izmodenov (1995), who solved the PUI transport equation with the method of stochastic differential equations. They obtained differential particle fluxes $\Phi_{pui}(r, \vartheta, w)$ connected to the phase space distribution function via

$$f_{pui}(r, \vartheta, w) = \frac{1}{2\pi u_0} \frac{1}{\sqrt{w}} \Phi_{pui}(r, \vartheta, w) \tag{1}$$

with r, ϑ and w denoting the heliocentric distance, the angle between the upwind direction and the direction to the point $\vec{r}$, and the normalized kinetic energy of the particles given by $w = (v/u_0)^2$ with $u_0 = 450\ km/s$ being the solar wind speed at 1 AU. v is the particle speed.

In order to use the results of Chalov, Fahr and Izmodenov (1995) as an input for the ENA flux model (see below), a fitting procedure has been used. The differential particle fluxes, which were computed for the upwind direction ($\vartheta = 0$) and are shown in Figure 3 in Chalov, Fahr and Izmodenov (1995), can be fitted and converted to the phase space distribution:

$$f_{pui}^{up}(X, w) = \frac{1}{2\pi u_0} \frac{1}{\sqrt{w}} C_\gamma(X) w^\gamma exp\left(-C_\kappa(X)\left(w - w_0\right)^\kappa\right) \tag{2}$$

with $0.1 < X = r/r_{sh} < 1$ and $r_{sh} = 89.7\ AU$ denoting the heliocentric shock distance, with the parameters $\gamma = -0.1145, \kappa = 2/3, w_0 = 0.833$ and the auxiliary functions $C_\gamma(X) = 10^{4.3141} X^{-0.3363}$ and $C_\kappa(X) = 2.011 X^{0.202}$. This fit was obtained for normal turbulence levels, i.e. the standard case of dissipationless wave propagation discussed in Chalov, Fahr and Izmodenov (1995).

For a comparison of ENA spectra resulting from the transcharging of PUIs and ACRs beyond the shock, it is necessary to convert the upstream PUI phase space distribution (2) to the downstream side of the heliospheric shock. Neglecting a reflection of PUIs at the electrostatic shock potential, the two effects to be considered are an increase of (a) the total density and (b) the magnetic field by the compression ratio s, implying the assumption of a perpendicular shock. Due to the conservation of the magnetic moment of PUIs passing over the shock there is a jump in their kinetic energy characterized by $v_{\perp,do}^2 = s v_{\perp,up}^2$, which for an isotropic f_{pui} gives $< v_\perp^2 >= (2/3) v^2$ and, thus, $v_{do}^2 = s v_{up}^2$. The conservation of the differential flux across the shock surface, one obtains with $f_{pui}^{up}(1, v_{up}) d^3 v_{up}\, u_{up} = f_{pui}^{do}(1, v_{do}) d^3 v_{do}\, u_{do}$ the result $f_{pui}^{do}(1, w) = s^{-1/2} f_{pui}^{up}(1, w/s)$.

From these considerations one derives from equation (2) the following post-shock PUI spectrum:

$$f_{pui}^{do}(1, w) = \frac{1}{2\pi u_0} \frac{1}{\sqrt{w}} C_\gamma(1) \left(\frac{w}{s}\right)^\gamma exp\left(-C_\kappa(1)\left(\frac{w - w_0}{s}\right)^\kappa\right) \tag{3}$$

For the computations we use a compression ratio $s = 3.2$ in upwind and 4.0 in downwind direction (following the self-consistent model results obtained by Kausch (1998)).

2.2 Phase space distributions of ACRs The ACR distributions were computed from the model presented in Czechowski, Fichtner and Kausch (1999), i.e. a power law spectrum ($j_{ACR} \sim E_{kin}^{-1.41}$) at the shock was assumed. The flux levels were matched to those found by Stone, Cummings and Webber (1996) such that the anomalous proton flux is $7 \cdot 10^4\ m^{-2} s^{-1} sr^{-1} MeV^{-1}$ at $E_{kin} = 100\ keV$.

In the next section, we compare, on the basis of equations (2) and (3) the fluxes of ENAs resulting from transcharging of preshock (upstream) and postshock (downstream) PUIs with those originating from ACRs.

3 The ENA fluxes

3.1 The ENA model The flux of ENAs, j_{ENA} at the location $\vec{x}_0$ from a direction $\vec{s}$ is computed from a model also used by Czechowski et al. (1999). The basic equation reads

$$j_{ENA}(\vec{x}_0, \vec{s}, E) = \int j_{PUI,ACR}(\vec{x}, \vec{s}, E) \sum_k (\sigma_{ik} n_k)\ (1 - D)\, dl \tag{4}$$

with $j_{PUI,ACR} = p^2 f_{PUI,ACR}$ denoting the differential flux of PUIs or ACRs, $E = p^2/(2m)$ and the charge exchange cross section σ_{ik} for an ion (i) and an atom (k). The atom number density is n_k. The extinction factor $(1 - D) \sim 1$ describes the (small) loss of ENAs during propagation from their source region to the detector. Finally, l obeys the relation $\vec{x} = \vec{x}_0 - \vec{s}\, l$.

3.2 PUI-ENAs from downstream of the shock

Figure 1 shows the ENA spectra resulting from a transcharging of PUIs (described by equation (3)) and ACRs in the region beyond the heliospheric shock. The upper line of each pair corresponds to the downwind direction.

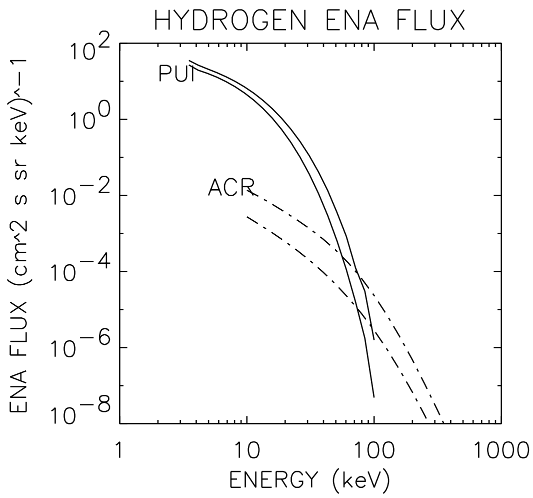

Figure 1: *The spectra of hydrogen ENAs at* 1 AU *resulting from transcharging of PUIs (solid lines) and ACRs (dash-dotted lines) in the upwind (ACR-ENAs: lower curve; PUI-ENAs: upper curve) and downwind direction downstream of the shock.*

Obviously, the flux of ENAs above a kinetic energy of about $100\,keV$ is mainly originating from ACRs. Below there is a dominant contribution from those resulting from charge exchange with PUIs: at an energy of $50\,keV$ the flux of PUI-ENAs is already an order of magnitude higher than that of ACR-ENAs.

The differences between the upwind and the downwind direction are a direct consequence of the spatial distribution of ACRs and PUIs in the heliosheath. The higher ENA fluxes from downwind are, however, not due to higher densities there, but rather due to the extended transcharging region.

The ACR distribution was computed from the basic cosmic ray transport equation and is discussed in detail in Czechowski, Fichtner and Kausch (1999). The fluxes of ENAs from the downwind direction are typically higher than the upwind fluxes by a little less than one order of magnitude.

The spatial PUI density distribution has been obtained with a hydrodynamic multifluid model (Kausch 1998, Kausch, Fahr and Scherer 1999), who took into account the influence of all major species, i.e. neutrals, pick-up ions, anomalous and galactic cosmic rays with the solar wind, and determined with a self-consistent description the large-scale structure of the heliosphere as well as the large-scale distribution of all mentioned species. The flux difference between upwind and downwind direction is not so pronounced as in the case of ACRs.

3.3 PUI-ENAs from upstream of the shock

We now extend the study to ENAs resulting from preshock PUIs. The ENA spectra of Figure 2 were obtained on the basis of equation (2).

Shown are, for three heliocentric distances of the heliospheric shock, the upwind fluxes in the low energy range $0 - 5\ \ keV$. At about $3.5\,keV$ the flux levels of the preshock PUI-ENAs are similar to those of postshock PUI-ENAs. However, for lower energies the flux increases significantly by about two orders of magnitude. Comparing the spectra of Figure 1 and 2, it is evident that at such low energies the preshock PUI-ENAs appear to dominate the total flux, while above $5\ keV$ the postshock PUI-ENAs take over.

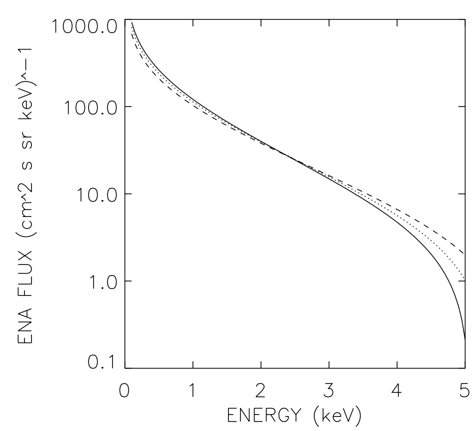

Figure 2: *The spectra of hydrogen ENAs resulting from preshock PUIs in upwind direction for a shock at 50, 70 and 90 AU (dashed, dotted and solid line).*

The difference in the flux levels between the three cases shown is not very strong, reflecting the fact that losses of ENA propagating from the outer to the inner heliosphere are almost negligible, i.e. the parameter D in equation (4) is small.

While not performed explicitly here, a computation of hydrogen PUI-ENA fluxes from the downwind direction should be expected to result in somewhat lower fluxes, as in the case of ENAs produced from transcharging with postshock PUIs discussed above.

4 Conclusions

The spectrum of ENAs can be divided into three different regions. At low energies of about $0-3\,keV$ it is dominated by ENAs originating from preshock PUIs upstream of the heliospheric shock. At intermediate energies of $3-100\,keV$ the ENAs resulting from a transcharging of postshock PUIs dominate. Finally, above about $100\,keV$ the ACR population provides the highest fluxes.

It is interesting to note that about $100\,keV$ the postshock PUI-ENAs and ACR-ENAs have similar flux levels. So, it is quite possible that PUI-ENAs contribute to the ENA fluxes recently observed with SOHO (Czechowski et al. 1999).

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