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ASTRONOMY AND ASTROPHYSICS

Neutral interstellar gas atoms reducing the solar wind Mach number and fractionally neutralizing the solar wind

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Abstract. Many stars are known to drive stellar winds of the solar wind type. Thus when moving through the ambient interstellar medium these stars not simply ionize this medium but also interact as moving stellar wind systems. Only neutral interstellar gas components can directly enter the inner stellar wind region and there undergo charge exchange reactions with the supersonic stellar wind protons. Thereby the dynamical identities of plasma and gas components are partially exchanged. The net effect is that energy is extracted from the wind plasma and transferred to newly created energetic neutral atoms (ENA) transporting the former wind energy over large distances into the distant interstellar medium. As example for stellar wind systems in general, in the following we study quantitatively the effect of a loading of the initial solar wind plasma with transcharged neutral atoms connected with the incorporation of suprathermal pick-up ions and an associated reduction of the effective solar wind sonic Mach number. In addition the removal of kinetic solar wind energy by neutralized solar wind protons leads to a nonclassical reduction of the solar wind ram pressure and thereby a reduction of the location of the heliospheric termination shock. Our results indicate that a substantial percentage of the original solar wind energy is converted into a global flow of energetic neutral atoms and that the effective solar wind Mach numbers in the outer heliosphere are drastically reduced if presently quoted neutral H-atom densities in the outer heliosphere of $0.1 \leq n_{\mathrm{H}\infty} \leq 0.3$ [cm^{-3}] are in fact prevailing.

Key words: inteplanetary medium – solar system: general – Sun: solar wind – plasmas

1. Introduction to the problem

For several decades the fact has been envisaged that neutral gas species of the local interstellar medium (LISM) at their flow towards the solar system enter the regime of supersonic heliospheric plasma, and are subject there to numerous processes, partly ionizing and recharging them. The most important loss process for LISM hydrogen atoms in the inner heliosphere is resonant charge transfer with solar wind protons. In view of the relevant charge exchange mean free paths, the appropriate method to describe theoretically this interaction scenario is a kinetic theory based on the Boltzmann-Vlasov integro-differential equation (see e.g. Fahr 1971, 1978; Holzer 1977; Thomas 1978; Wu & Judge 1979; Ripken & Fahr 1983; Fahr 1991; Osterbart & Fahr 1992; Baranov & Malama 1993, 1995; Ruciński & Bzowski 1995; Fahr 1996; Williams et al. 1997; Bzowski et al. 1997).

In view of fairly time-consuming computational efforts within these kinetic approaches more recently attempts have been also made to describe the problem of charge-exchange-coupled plasma-gas flows by hydrodynamic approaches in which not only the quasineutral plasma components, but also the neutral gas is treated as a hydrodynamic fluid characterized only by its lowest velocity moments, i.e. density, bulk velocity, and scalar pressure (Pauls et al. 1995; Whang 1996a, 1996b; Pauls & Zank 1997). These theoretical approaches are restricted in validity by the fact that only scalar temperatures or pressures are admitted and that higher velocity moments of the H-atom flow are neglected. Also the appearance of neutralized solar wind protons, i.e. H-atoms of about 1 keV energies is not taken into account. This thus generates the inherent problem that just one of the most important effects, namely that of neutralized, keV-energetic solar wind protons leaving the solar system in radial directions and removing this way primary solar wind kinetic energy, cannot adequately be taken into account in these approaches.

The effect of charge-exchange induced removals of keV-energies from the solar wind is, however, extremely important for the net result of the solar wind – interstellar medium interaction. In fact high percentages of the original solar wind energy are handed over to neutral keV-atoms and are removed from the solar system in this form. The first estimate of this energy loss from the heliosphere by neutral H-atoms was given in an early paper by Blum & Fahr (1970), where it was already recognized that at solar distances of about 100 AU more than 50 percent of the original solar wind kinetic energy may be transported out of the solar system by neutral keV-H-atoms. When this 'neutral form' is interacting with the ambient interstellar medium form, this may for instance cause a change of the temperature

Send offprint requests to: H.J. Fahr (UNF308@ibm.rhrz.uni-bonn.de) of the inflowing interstellar plasma at distances far ahead of the heliopause, as envisaged by Gruntman (1982).

2. Estimated fraction of neutralized solar wind

A quick estimate of the percentage ϵ of energy removed by neutral H-atoms from the solar wind flow is obtained with the argumentation given by Fahr (1990). One can calculate a critical radius $P_{\rm ex}$ of a cylinder coaxial with the LISM inflow vector $\boldsymbol{V}_{\rm LISM}$ within which LISM bulk atoms approaching the solar system would undergo a charge-exchange reaction with a solar wind proton with a probability of $\exp(-1)$. Over the solar activity cycle this radius only weakly varies around values of about 15 AU. Then the total production $\Pi_{\rm H-ENA}$ of keV-H-atoms (H-ENAs) per unit of time is given by:

$$\Pi_{\rm H-ENA} = n_{\rm LISM}\, V_{\rm LISM}\, (1-\chi_{\rm H})\, \tau_{\rm H} \left[\pi\, P_{\rm ex}^2\right] \qquad (1)$$

where $n_{\rm LISM} = n_{\rm H-LISM} + n_{\rm p-LISM}$ is the total LISM density added up from LISM H-atoms and LISM protons. The quantities $\chi_{\rm H}$ and $\tau_{\rm H}$ denote the degree of H-ionization in the LISM and the transmission of LISM H-atoms through the plasma interface ahead of the heliospheric shock (see e.g. Ripken & Fahr 1983; Fahr 1986, 1990, 1991; Osterbart & Fahr 1992; Ruciński et al. 1993). From Eq. (1) one can easily derive the global three-dimensional average of the percentage ϵ of neutralized solar wind as given by:

$$\begin{aligned} \epsilon &= \frac{\Pi_{\rm H-ENA}}{4\pi\, r_{\rm E}^2\, n_{\rm sE}\, V_{\rm sE}} \\ &= \frac{1}{4}\frac{n_{\rm LISM}}{n_{\rm sE}}\frac{V_{\rm LISM}}{V_{\rm sE}}\,(1-\chi_{\rm H})\,\tau_{\rm H}\left(\frac{P_{\rm ex}}{r_{\rm E}}\right)^2 \qquad (2) \end{aligned}$$

where $n_{\rm sE}$ and $V_{\rm sE}$ are solar wind density and velocity at heliocentric distance $r_{\rm E} = 1$ AU. For a completely neutral LISM (i.e. $\chi_{\rm H} = 0$, $\tau_{\rm H} = 1$) one obtains the result that $\epsilon \cong 1.0$ at $n_{\rm LISM} \cong 1.0$ cm^{-3}, i.e. the solar wind will be completely neutralized under such LISM conditions.

For a more realistic situation with $\chi_{\rm H} \geq 0$; $\tau_{\rm H} \leq 1.0$ one may obtain values $\epsilon \leq 1.0$. However, in view of the huge discrepancies among derived values of the hydrogen density $n_{\rm H\infty}$ in the outer heliosphere (i.e. after filtration of hydgrogen gas through the heliospheric interface region) as well as in values of $\chi_{\rm H}$ quoted in the literature, it may be highly interesting to study the implied consequences for the value ϵ in more detail. On the one side, derived from solar wind deceleration values there is a recent claim by Richardson et al. (1995) for a low H-atom density in the distant heliosphere of only $n_{\rm H\infty} = 0.05\,{\rm cm}^{-3}$, also supported by different derivations from interplanetary Lyman-Alpha measurements (see e.g. Chassefière et al. 1986 and Quémerais et al. 1992). On the other hand, there are competing derivations from interplanetary Lyman-Alpha observations and H^+ pick-up ion data from Ulysses, pointing to values of $n_{\rm H\infty} \cong 0.1$–$0.3$ cm^{-3} (Ajello et al. 1994; Quémerais et al. 1994, 1995; Puyoo et al. 1997; Gloeckler et al. 1997). This discrepancy in the determination of $n_{\rm H\infty}$ could not been dissolved up to the present. On the other hand, as demonstrated above, values of the order of $n_{\rm H\infty} \geq 0.3$ cm^{-3} will have severe implications for the fraction ϵ of primary solar wind plasma converted into a neutral H-ENA atom flow. Due to the relevance of this problem for the reduction of solar wind velocities, Mach numbers and ram pressures we shall carry out quantitative calculations for different hydrogen densities $n_{\rm H\infty}$ to determine clear ranges for the degree of neutralization of the solar wind.

3. Relative densities of pickup protons and solar wind deceleration

Here we start out from a conventional stationary "hot" kinetic model describing the heliospheric density distribution of interstellar hydrogen as developed by Fahr (1971), Thomas (1978), and Wu & Judge (1979), used here in the form applied by Ruciński et al. (1993) for the calculation of H-atom densities and H^+ pick-up ion production rates. Although alternative and simpler H-density models published and used by Axford (1972) or Vasyliunas & Siscoe (1976) (so called "cold classical models") are analytical, and therefore less time-consuming, but they do not take into account the thermal spread in the velocity distribution of the incoming interstellar H-atoms, and thus describe the inflow of a purely homogeneous cold gas. In consequence, as shown by Ruciński & Bzowski (1996), these "cold models" deliver significantly inaccurate H-densities, especially in the region close to the Sun and in an extended part of the downwind hemisphere, and for that reason we decided not to use them in our present study.

Thus, all our present calculations were performed on the basis of the aforementioned hot kinetic model for the following assumed parameters, which characterize the interstellar gas and the solar wind, respectively: $V_{\rm H\infty} = 20\,{\rm km/s}$; $T_{\rm H\infty} = 10000\,{\rm K}$; $\mu = 1$ (ratio of the solar radiation pressure to the solar gravitational force); $n_{\rm s}\,(r_{\rm E}) = 8$ cm^{-3}; $V_{\rm s}\,(r_{\rm E}) = 450$ km/s, where $r_{\rm E}$ = 1 AU.

The relevant charge exchange cross-section connected with the adopted solar wind velocity of 450 km/s at the Earth's orbit is equal to $\sigma_{\rm ex} \cong 1.664 \cdot 10^{-15}$ cm^2 (Barnett et al. 1990) and together with other assumed solar wind parameters this leads to a charge exchange rate at 1 AU $\beta(r_{\rm E}) = 6 \cdot 10^{-7}$ s^{-1}. The photoionization of H-atoms, which contributes in a minor degree (typically by 10 to 20 percent) to the total H-ionization rate, was neglected in our present considerations.

In our calculations we have considered values for the outer heliospheric H-atom density (i.e. the one resulting after filtration inside the heliospheric interface) of between $n_{\rm H\infty} = 0.1$ cm^{-3} and $n_{\rm H\infty} = 0.25$ cm^{-3}. The resulting local heliospheric H-atom profiles along the upwind, crosswind and downwind directions are displayed in Fig. 1. One should notice that even at large heliocentric distances of $r \cong 70$–100 AU the downwind density is still significantly lower than the assumed value $n_{\rm H\infty}$.

Using these local hydrogen densities and generally plausible local hydrogen charge exchange rate, we can then calculate pick-up proton production rates and associated fluxes $\Phi_{\rm pi}$ of such pick-up protons (see e.g. Ruciński et al. 1993). In the com-

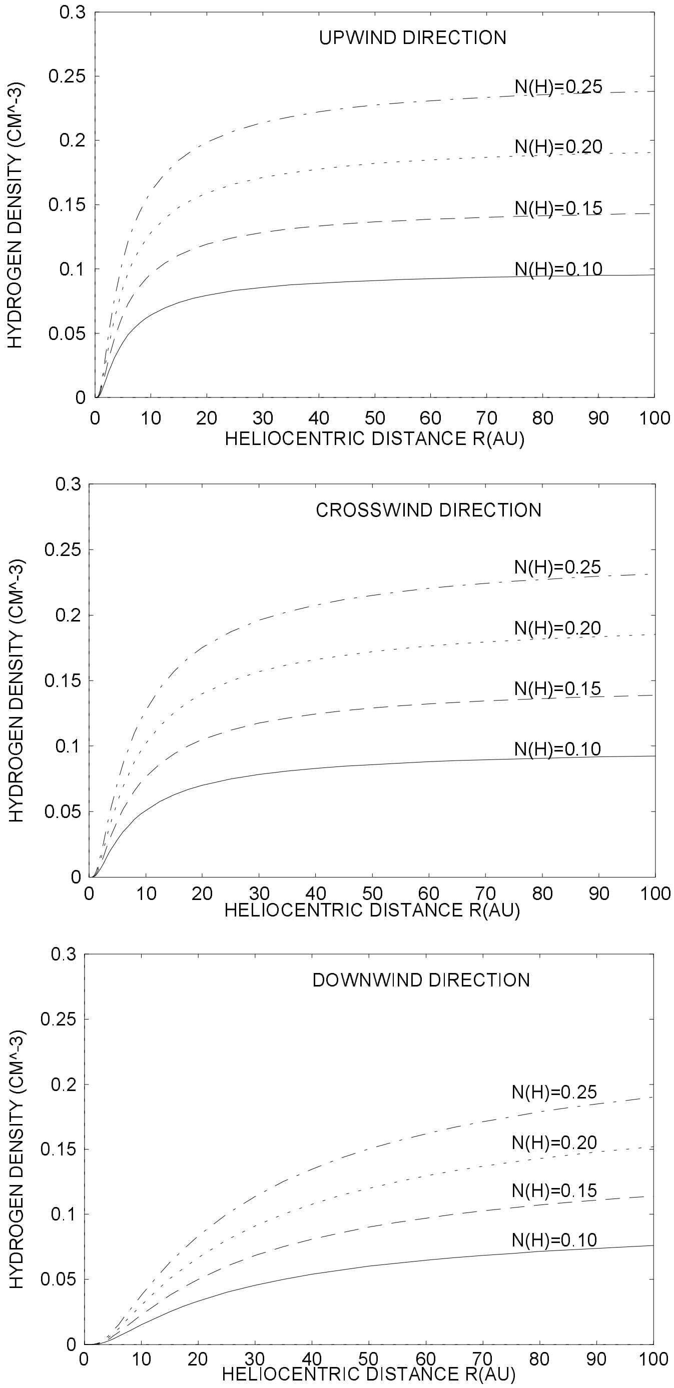

Fig. 1. Heliospheric hydrogen densities shown as function of the distance from the Sun, calculated for different values: $n_{\mathrm{H}\infty} = 0.1$; 0.15; 0.2; 0.25 cm^{-3}; upper panel – upwind direction, middle panel – crosswind direction, lower panel – downwind direction.

putation of these production rates we do not take into account the change of the charge exchange cross section due to changing velocities of the pick-up ion loaded wind. This is reasonably justified a posteriori in view of the fact that within the range of velocities covered here, i.e. 450 km/s to 350 km/s, (as seen in Fig. 3), the charge exchange cross section changes only by about 10 percent. Thus even an iteration on this point to reach consistency in the calculated cross section would only help us to include a second order effect compared to linear effects included here.

Since pick-up protons and solar wind protons are assumed to move with the same bulk velocity V_{s} the ratio ξ of the pick-up protons to the total number of solar wind protons hence is given by:

$$\xi\left(\boldsymbol{r}\right) = \frac{\phi_{\mathrm{pi}}}{\phi_{\mathrm{p}} + \phi_{\mathrm{pi}}} = \frac{n_{\mathrm{pi}}}{n_{\mathrm{p}} + n_{\mathrm{pi}}} = \frac{n_{\mathrm{pi}}}{n_{\mathrm{s}}} \tag{3}$$

where the total (i.e. original + pick-up) solar wind proton density was defined by: $n_{\mathrm{s}} = n_{\mathrm{p}} + n_{\mathrm{pi}}$.

The following relations are used now to describe partial densities of pick-up protons and original solar wind protons:

$$n_{\mathrm{p}} = n_{\mathrm{s}}\left(1 - \xi\right); \; n_{\mathrm{pi}} = n_{\mathrm{s}}\,\xi. \tag{4}$$

In a radial solar wind outflow geometry the relative abundance $\xi\left(\boldsymbol{r}\right)$ of pick-up protons is described by the following continuity equation:

$$\frac{1}{r^2}\frac{\partial\left[r^2\,\xi\left(\boldsymbol{r}\right)\,n_{\mathrm{s}}\left(\boldsymbol{r}\right)\,V_{\mathrm{s}}\left(\boldsymbol{r}\right)\right]}{\partial r} = \beta\left(\boldsymbol{r}\right)\,n_{\mathrm{H}}\left(\boldsymbol{r}\right) \tag{5}$$

where $\beta\left(\boldsymbol{r}\right)$ is the local charge exchange frequency given by:

$$\beta\left(\boldsymbol{r}\right) = \sigma_{\mathrm{ex}}\,n_{\mathrm{p}}\left(\boldsymbol{r}\right)\,V_{\mathrm{s}}\left(\boldsymbol{r}\right) = \sigma_{\mathrm{ex}}\,n_{\mathrm{s}}\left(\boldsymbol{r}\right)\,\left[1 - \xi\left(\boldsymbol{r}\right)\right]V_{\mathrm{s}}\left(\boldsymbol{r}\right). \tag{6}$$

In connection with the total flux conservation, i.e. $r^2\,n_{\mathrm{s}}\,V_{\mathrm{s}} = \mathrm{const}$, one obtains from Eq. (5) the following differential equation for the abundance function $\xi\left(\boldsymbol{r}\right)$:

$$\frac{1}{1 - \xi\left(\boldsymbol{r}\right)}\frac{\partial\,\xi\left(\boldsymbol{r}\right)}{\partial r} = \sigma_{\mathrm{ex}}\,n_{\mathrm{H}}\left(\boldsymbol{r}\right) \tag{7}$$

which is solved by:

$$\xi\left(\boldsymbol{r}\right) = 1 - \exp\left[-\int_{r_0}^{r}\sigma_{\mathrm{ex}}\,n_{\mathrm{H}}\left(\boldsymbol{r'}\right)\,\mathrm{d}r'\right]. \tag{8}$$

Here r_0 is a place close to the Sun where the abundance $\xi\left(\boldsymbol{r}_0\right)$ is totally negligible. In Fig. 2 we show curves for $\xi\left(\boldsymbol{r}\right)$ along the upwind, crosswind, and downwind axes for various interstellar gas densities $n_{\mathrm{H}\infty}$.

In the following we now aim at the calculation of the solar wind deceleration in the outer heliosphere due to pick-up ion loading and to the action of pick-up ion pressure. Using formula (18) from the paper by Fahr & Fichtner (1995), the solar wind deceleration due to pick-up proton loading and to the action of pick-up ion pressure can be given by:

$$\frac{\mathrm{d}V_{\mathrm{s}}}{\mathrm{d}r} = \frac{2}{3 + \xi}\frac{V_{\mathrm{s}}}{r}\,\left[\xi - 2\sigma_{\mathrm{ex}}\,n_{\mathrm{H}}\,r\,\left(1 - \xi\right)\right] \tag{9}$$

where the relations given in Eq. (4) were used to describe partial densities of pick-up protons and solar wind protons, and where V_{s}, and n_{H}, σ_{ex} denote the local solar wind bulk velocity, local neutral hydrogen density, and charge exchange cross section, respectively.

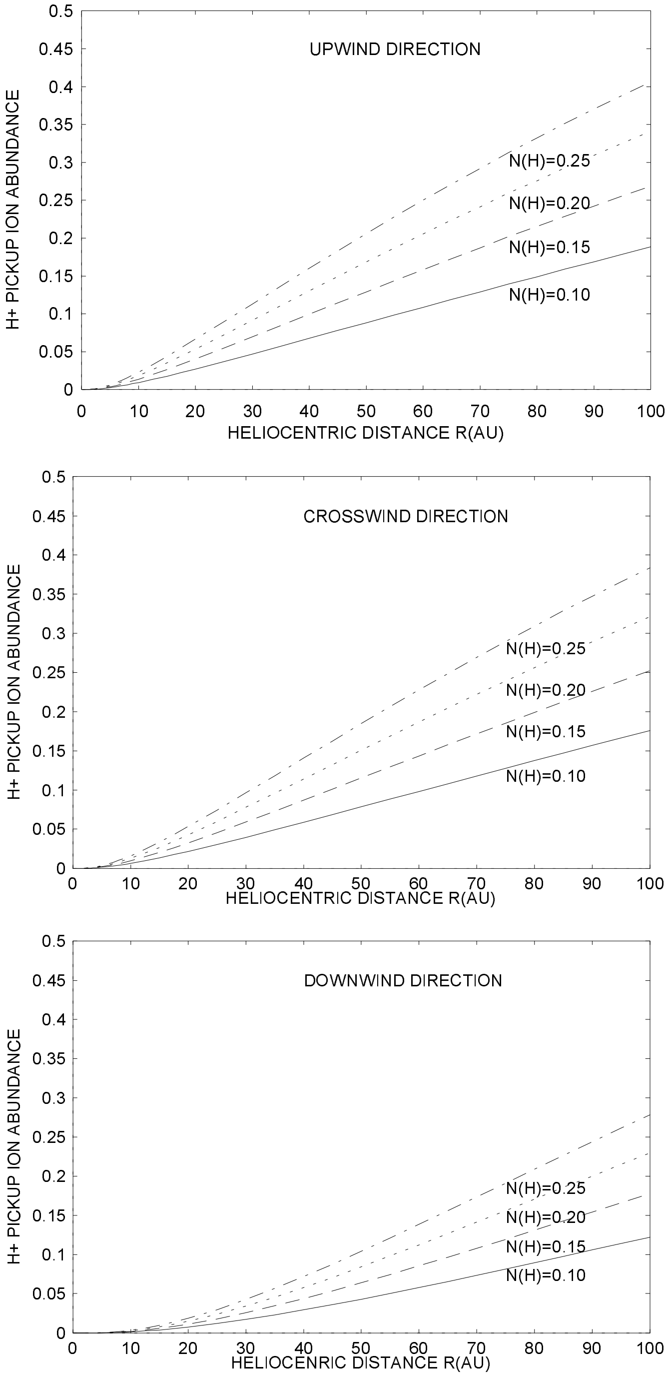

Fig. 2. Relative pick-up proton abundance $\xi(\boldsymbol{r})$ as function of the heliocentric distance for different values of $n_{\mathrm{H}\infty}$ (same as used in Fig. 1); upper panel – upwind direction; middle panel – crosswind direction; lower panel – downwind direction.

From Eq. (9) one can then obtain the following differential equation:

$$\frac{\mathrm{d}}{\mathrm{d}r}\ln V_{\mathrm{s}} = \frac{2}{3+\xi}\,\frac{1}{r}\left[\xi - 2\sigma_{\mathrm{ex}} n_{\mathrm{H}}\, r\,\left(1-\xi\right)\right] \tag{10}$$

which after integration yields the local solar wind velocity $V_{\mathrm{s}}(\boldsymbol{r})$ in the form:

$$V_{\mathrm{s}}(\boldsymbol{r}) = V_{\mathrm{s0}}\,\exp\left[\int_{r_0}^{r}\frac{2}{3+\xi}\,\frac{1}{r'}\left[\xi(\boldsymbol{r}') - 2\sigma_{\mathrm{ex}}\, n_{\mathrm{H}}(\boldsymbol{r}')\, r' \times \right.\right.$$
$$\left.\left. \times\;\left(1-\xi(\boldsymbol{r}')\right)\right]\,\mathrm{d}r'\right]. \tag{11}$$

In Fig. 3 we show the resulting velocity V_{s} of the decelerated solar wind along the upwind, crosswind, and downwind axis, respectively, for various assumed hydrogen densities $n_{\mathrm{H}\infty}$, using the $\xi(\boldsymbol{r})$ values calculated earlier and displayed in Fig. 2.

4. The effective solar wind Mach number

Paying attention to the fact that the solar wind is a multifluid plasma with protons, pick-up's and electrons being tightly bound by electromagnetic forces and thus moving outwards with the same bulk velocity one is advised to consider the effective solar wind Mach number rather than the proton or electron Mach number. As discussed by Fahr et al. (1997), the respective effective sound velocity $C^{\star}$ for the multifluid solar wind as characterized above is thus given by:

$$C_{\mathrm{s}}^{\star 2} = \frac{\partial P^{\star}}{\partial\rho} = \frac{\partial P^{\star}}{\partial r}\,\frac{\partial r}{\partial\rho} = \frac{\frac{\partial}{\partial r}\left[P_{\mathrm{p}} + P_{\mathrm{e}} + P_{\mathrm{pi}}\right]}{\frac{\partial\rho}{\partial r}} \tag{12}$$

where the effective pressure $P^{\star}$ is given by the sum of the pressures P_{p} (protons), P_{e} (electrons), and P_{pi} (pick-up ions) of the relevant components, respectively.

The effective solar wind Mach number $M_{\mathrm{s}}^{\star}$ with the help of Eq. (12) is given in the following form:

$$M_{\mathrm{s}}^{\star 2} = \left(\frac{V_{\mathrm{s}}}{C_{\mathrm{s}}^{\star}}\right)^2 = \frac{V_{\mathrm{s}}^2\,\frac{\partial\rho}{\partial r}}{\frac{\partial}{\partial r}\left(P_{\mathrm{p}} + P_{\mathrm{e}} + P_{\mathrm{pi}}\right)}. \tag{13}$$

The proton and electron pressures are here represented in the LTE ideal-gas approximation, whereas the pick-up ion pressure is represented in the form given by Fahr & Fichtner (1995):

$$P_{\mathrm{pi}} = \frac{1}{3} m_{\mathrm{p}}\, n_{\mathrm{pi}}\, V_{\mathrm{s}}^2 \tag{14}$$

assuming an isotropized complete-shell distribution for the pick-up protons. Introducing the abundance function ξ we then can bring Eq. (13) into the form:

$$M_{\mathrm{s}}^{\star 2} = \frac{m_{\mathrm{p}}\, V_{\mathrm{s}}^2\,\frac{\partial n_{\mathrm{S}}}{\partial r}}{\frac{\partial}{\partial r}\left[n_{\mathrm{s}}\left(kT_{\mathrm{e}} + (1-\xi)\; kT_{\mathrm{p}} + \frac{\xi}{3}\, m_{\mathrm{p}}\, V_{\mathrm{s}}^2\right)\right]}. \tag{15}$$

In the above expression (15) for the effective Mach number, the solar wind electron and proton temperatures T_{e} and T_{p} were introduced. This expression can be transformed to the following form:

$$M_{\mathrm{s}}^{\star 2} = \frac{m_{\mathrm{p}}\, V_{\mathrm{s}}^2}{\left[kT_{\mathrm{e}} + (1-\xi)\; kT_{\mathrm{p}} + \frac{\xi}{3}\, m_{\mathrm{p}}\, V_{\mathrm{s}}^2\right] + \frac{n_{\mathrm{s}}\,\Gamma}{\frac{\partial n_{\mathrm{s}}}{\partial r}}} \tag{16}$$

where the function Γ is expressed by:

$$\Gamma(\boldsymbol{r}) = \frac{\partial kT_{\mathrm{e}}}{\partial r} + \left[1-\xi(\boldsymbol{r})\right]\frac{\partial kT_{\mathrm{p}}}{\partial r} -$$

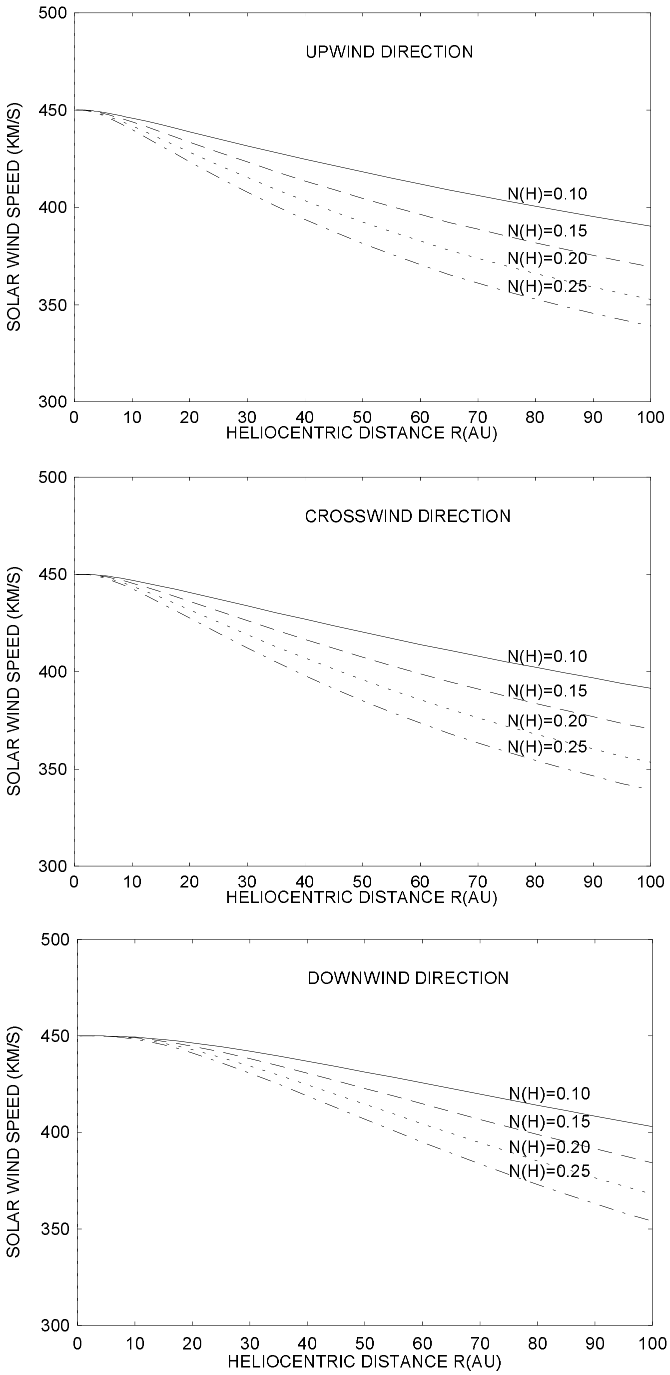

Fig. 3. The solar wind velocity $V_{\rm s}\,(\boldsymbol{r})$ as function of the heliocentric distance for different values of $n_{\rm H\infty}$ (same as in Fig. 1): upper panel – upwind direction; middle panel – crosswind direction; lower panel – downwind direction.

$$- \left(kT_{\rm p} - \frac{1}{3} m_{\rm p}\, V_{\rm s}^2\right) \frac{\partial \xi\,(\boldsymbol{r})}{\partial r} + \qquad (17)$$
$$+ \frac{2}{3}\xi\,(\boldsymbol{r})\; m_{\rm p}\, V_{\rm s}\,(\boldsymbol{r})\; \frac{\partial V_{\rm s}\,(\boldsymbol{r})}{\partial r}.$$

With Eqs. (7) and (11) the above expression can further be evaluated and it yields:

$$\begin{aligned}\Gamma\,(\boldsymbol{r}) \;=\; & \frac{\partial kT_{\rm e}}{\partial r} + [1-\xi\,(\boldsymbol{r})] \times \\ & \times \left[\frac{\partial kT_{\rm p}}{\partial r} - \left(kT_{\rm p} - \frac{m_{\rm p}\,V_{\rm s}^2}{3}\right)\sigma_{\rm ex}\,n_{\rm H}\,(\boldsymbol{r})\right] + \\ & + \frac{2}{3}\xi\,(\boldsymbol{r})\; m_{\rm p}\,V_{\rm s}^2\,(\boldsymbol{r}) \times \\ & \times \frac{2\,\{\xi\,(\boldsymbol{r}) - 2\sigma_{\rm ex}\,n_{\rm H}\,(\boldsymbol{r})\;r\;[1-\xi\,(\boldsymbol{r})]\}}{(3+\xi\,(\boldsymbol{r}))\;r}.\end{aligned} \qquad (18)$$

From the law of conservation of the total solar wind proton flux, and with the use of Eq. (10) one can in addition derive the remaining differential expression in the denominator of Eq. (16) yielding:

$$\frac{1}{n_{\rm s}}\,\frac{\partial n_{\rm s}}{\partial r} = -\frac{2}{r}\left[1 + \frac{2}{3+\xi}\left(\xi - 2\sigma_{\rm ex}\,n_{\rm H}\,r\;(1-\xi)\right)\right]. \qquad (19)$$

For a numerical evaluation of expression (16) with the use of Eqs. (18) and (19) one also needs the solar wind temperatures $T_{\rm e}$ and $T_{\rm p}$ as functions of the heliocentric distance. Due to the fact that solar wind protons are converted into pick-up protons, i.e. they undergo a loss process, it is clear that their temperature cannot behave as adiabatic since the solar wind proton flow under these conditions behaves as a non-isentropic flow (see e.g. Whang 1996a):

$$\frac{\partial}{\partial r}\left[\ln\!\left(\frac{P_{\rm p}}{\rho_{\rm p}^{5/3}}\right)\right] = -\frac{\beta}{V_{\rm s}}. \qquad (20)$$

For negligible plasma heating and for negligible charge exchange rates (i.e. at small and large solar distances) the solar wind plasma flow should behave isentropic. It should give there rise to a fall-off of the proton pressure according to: $P_{\rm p} \cong r^{-2\gamma}$, with $\gamma = 5/3$ as the adiabatic factor. As observational data from VOYAGER-1/2, however, reveal (see Lazarus et al. 1995; Whang 1995), the solar wind proton pressure already at moderate solar distances falls off, in fact, less steep pointing to a heating process in these regions. In principle, the correct, i.e. consistent temperature profile should be derived in iterative runs of our description of the pick-up ion loaded solar wind. However, the corrections entering our calculations from iteratively corrected temperature profiles, as can easily be proven in the frame of the present theoretical approach, are of second order and do not need consideration here.

A fairly clear indication of the non-adiabaticity of the expanding solar wind proton plasma is for instance clearly reflected in the proton temperature measurements carried out with VOYAGER-1/2 and Pioneer-10/11 (see e.g. Richardson et al. 1996). In contrast to an adiabatic behaviour we thus decide to use proton temperatures here which are observationally well supported by VOYAGER-2 measurements and are given by Richardson et al. (1996) in the following form:

$$T_{\rm p}\,(r) = T_{\rm p}\,(r_{\rm E})\,\left(\frac{r_{\rm E}}{r}\right)^{\alpha_{\rm p}} \cong 44600 \cdot \left(\frac{r}{r_{\rm E}}\right)^{-0.46}\;[{\rm K}]. \qquad (21)$$

The solar wind electron temperatures $T_{\rm e}\,(r)$ can for instance be obtained with the help of ULYSSES results published by

Scime et al. (1994). These authors give temperatures separately for core ($T_{\rm ec}$) and halo ($T_{\rm eh}$) electrons in the following form:

$$T_{\rm ec}\left(r\right) = 1.3 \cdot 10^5 \left(\frac{r}{r_{\rm E}}\right)^{-0.85} \ [{\rm K}] \tag{22}$$

and

$$T_{\rm eh}\left(r\right) = 9.2 \cdot 10^5 \left(\frac{r}{r_{\rm E}}\right)^{-0.38} \ [{\rm K}]. \tag{23}$$

Since typical abundances of core and halo electrons were found to be (see Feldman et al. 1975, 1979): $A_{\rm c} \cong 0.96$ and $A_{\rm h} \cong 0.04$, for our purposes here, in lack of any better information one may thus reasonably well represent the effective electron temperature by the following combined expression:

$$T_{\rm e}\left(r\right) = A_{\rm c}\, T_{\rm ec}\left(r\right) + A_{\rm h}\, T_{\rm eh}\left(r\right). \tag{24}$$

Together with the expressions (21) and (24) now the expression (16) for the effective Mach number $M_{\rm s}^{\star}\left(\boldsymbol{r}\right)$ can be numerically evaluated. In Fig. 4 these effective Mach numbers are shown along the upwind, crosswind, and downwind directions for various intestellar adopted hydrogen gas densities $n_{{\rm H}\infty}$ in the outer heliosphere, covering the range 0.1–0.25 cm^{-3}.

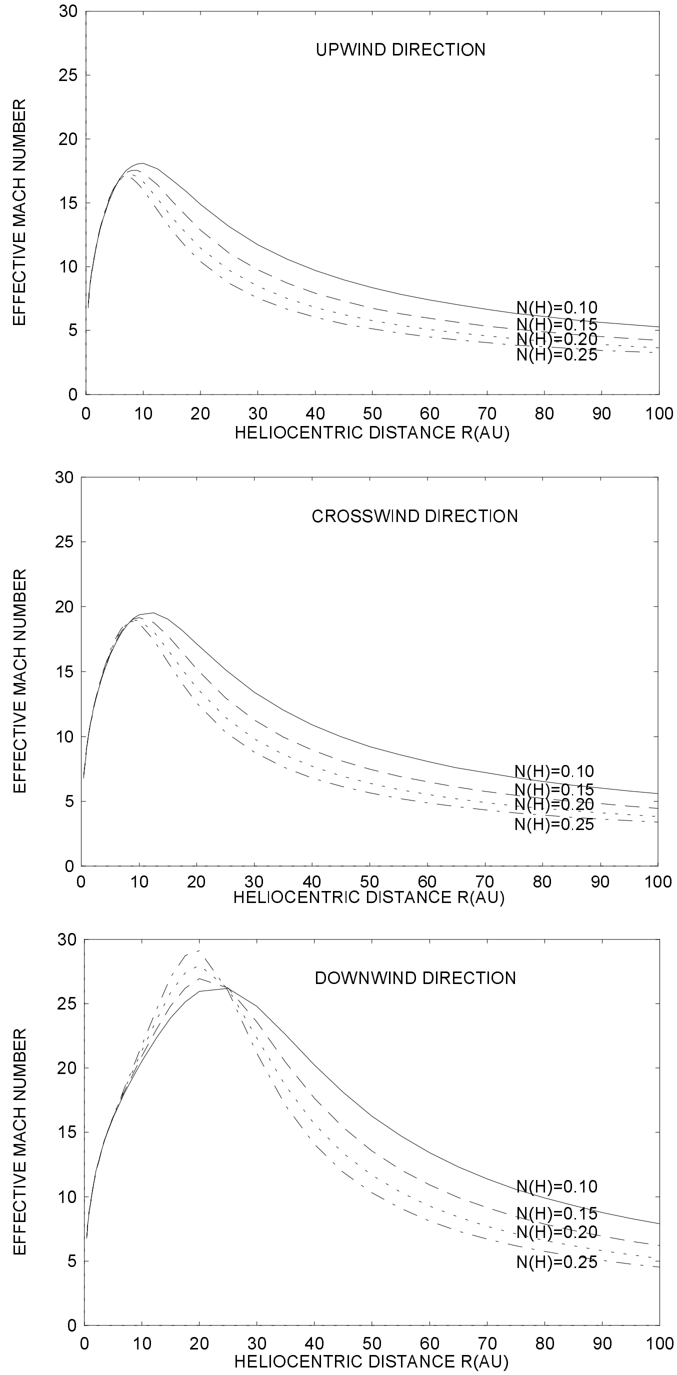

Fig. 4. The effective solar wind Mach number $M_{\rm s}^{\star}$ as function of the heliocentric distance for different values of $n_{{\rm H}\infty}$ (same as in Fig. 1): upper panel – upwind direction; middle panel – crosswind direction; lower panel – downwind direction.

5. Discussion of results

As we have shown in Fig. 2, the relative abundance of pick-up protons is strongly increasing with solar distance. This increase is especially pronounced in the distant upwind heliosphere, where within the range of interstellar gas densities discussed in this paper abundance values can reach $0.15 \le \xi \le 0.4$, meaning that about 15 to 40 percent of the total solar wind flux at larger distances appears in the form of pick-up protons. This on the other hand also means that about the same percentage of the original solar wind energy flux eventually has been converted into an energy flux which is carried out of the solar system by neutral energetic H-atoms.

In Fig. 5 we have displayed as a function of the interstellar gas density $n_{{\rm H}\infty}$ the percentage of the original solar wind energy flux reappearing at a distance of 80 AU in the form of an energy flux of neutralized solar wind protons (ENAs) in the upwind, crosswind and downwind directions. These ENAs then can deeply penetrate into the ambient interstellar medium, interacting there only via secondary charge exchange reactions with the LISM plasma component flowing towards the solar system. For LISM plasma densities of the order of $n_{\rm p-LISM} = 0.1\,{\rm cm}^{-3}$ (see e.g. Gloeckler et al. 1997; Izmodenov et al. 1999) one arrives at a mean penetration depth of the order of 200 AU, meaning that within a circumsolar LISM environment of this size the energy carried by the neutralized solar wind will be deposited as thermal energy in the ambient LISM plasma due to aforementioned secondary charge exchange reactions. The effect of a preheating of the LISM plasma during its flow towards the heliopause will be numerically treated by us in a forthcoming paper.

Since about 15 to 40 percent of the original solar wind energy is removed from the heliosphere by neutral atoms, the remaining solar wind ram pressure is consequently reduced to a value between 85 to 60 percent, which causes the solar wind termination shock to move inwards to about 92 and 77 percent of its “vacuum value”, respectively (see e.g. Axford 1972).

In Sect. 3, we have shown (Fig. 3) the pick-up ion induced deceleration of the solar wind in different heliospheric directions. As it can be seen the deceleration is more pronounced on the upwind side compared to the downwind side, but in-

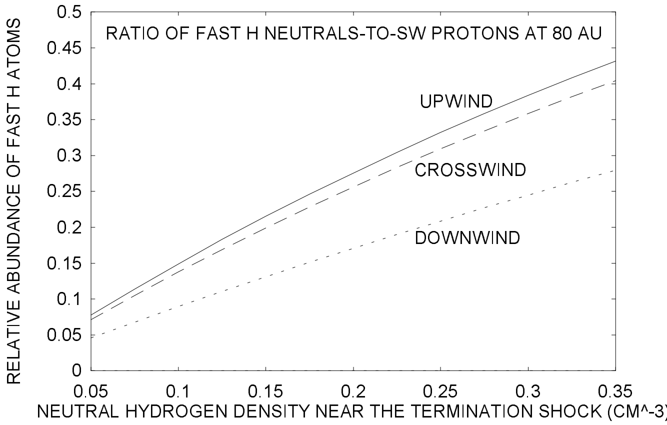

Fig. 5. The percentage ξ of the original solar wind neutralized by heliospheric charge exchange reactions with H atoms for upwind, crosswind, and downwind positions at 80 AU from the Sun is shown as function of the neutral hydrogen density $n_{\mathrm{H}\infty}$.

terestingly enough it is clearly less pronounced than predicted in earlier papers by Holzer & Leer (1973), Fahr (1973), Isenberg (1986) or Lee (1997). The reason is that in none of these papers the action of the pick-up ion pressure was adequately taken into account, which, however, partly compensates for the decelarative action of the pure mass loading of the expanding solar wind. In the approach of Fahr & Fichtner (1995), used in our present study, it is assumed that the pick-up ions due to the effective interaction with interplanetary Alfvénic turbulences are quickly enough pitch-angle scattered into a completely randomized distribution function leading to a pressure P_{pi}, which is not polytropically related to the pick-up ion density n_{pi}, but is proportional to $n_{\mathrm{pi}}\,V_{\mathrm{s}}^2$. This leads to interesting consequences concerning the interstellar gas densities $n_{\mathrm{H}\infty}$, which can be inferred from the measured solar wind deceleration.

Richardson et al. (1995), using the analytic deceleration law presented by Lee (1995) and later published by Lee (1997), derive from the fact of a 7-percent deceleration of the solar wind observed at an upwind position of 40 AU, a value of $n_{\mathrm{H}\infty} = 0.05$ cm^{-3} only. In contrast to this result, based on our numerical results presented in this paper, we can conclude that for the same degree of deceleration we would infer much higher densities of $n_{\mathrm{H}\infty} \cong 0.15$ cm^{-3}. These latter densities derived within context presented here seem to be much better conciliated with many independent density derivations published recently by Ajello et al. (1994), Quémerais et al. (1995) and Gloeckler et al. (1997), or density assumptions used by authors like Baranov & Malama (1993), Pauls & Zank (1996) or Izmodenov et al. (1999), all of them lying in a narrow range ($\pm 20\%$) around 0.15 cm^{-3}. On the other hand our results indicate that the simple analytic deceleration algorithm developed by Lee (1997) does not adequately account for the complete effect of a solar wind pick-up ion loading.

Finally, referring to the problem of the behaviour of the effective solar wind Mach numbers (see Fig. 4), we would like to emphasize the fact that their values due to the pressure of pick-up protons and to the associated solar wind deceleration are very much reduced in the outer regions of the heliosphere. As one may notice from these figures solar wind Mach numbers $M_{\mathrm{s}}^{\star}$, after reaching maximum values of about 18 (upwind) and 30 (downwind) at distances of about 10 to 20 AU, then start falling off monotonically to values of about 5 or even lower at the position of the expected termination shock. This expresses the fact that the shock may be much weaker than thought earlier on the basis of a monofluid shock transition and is a result which is also confirmed by several "solar wind–interstellar plasma" interaction models, like those published by Baranov & Malama (1993, 1995) or similar considerations by Fisk (1996), in which the effect of pick-up ions was estimated. The upstream Mach numbers found in all of these papers, including this one here, point to the values of the order of 5, though following the argumentation of Cummings & Stone (1995, 1996) or Stone et al. (1996) derived from measured spectral indexes κ of Anomalous Cosmic Ray (ACR) spectra it should be rather around 2.5. In the unmodulated part of the spectra of the shock accelerated ACR's, according to a theory by Drury (1983) the spectral index κ should be related with the shock compression ratio s simply by (see Potgieter & Moraal 1988):

$$\kappa = \frac{s+1}{1-s} \tag{25}$$

where the corresponding compression ratio $s = s^{\star}$ of the classical Rankine-Hugoniot shock on the other hand is connected with the upstream effective Mach number $M_{\mathrm{s1}}^{\star}$ by:

$$s^{\star} = \frac{(\gamma+1)\ M_{\mathrm{s1}}^{\star\,2}}{2+(\gamma-1)\ M_{\mathrm{s1}}^{\star\,2}}. \tag{26}$$

First there are several reasons why the effective Mach number may be even more reduced than calculated in this paper. One of them is that the pick-up protons do not experience only pitch-angle scattering in the interplanetary magnetic field turbulences, but also undergo energy diffusion processes by Fermi-2 interaction processes with these turbulences. As it was shown in papers by Isenberg (1987), Bogdan et al. (1991), Chalov et al. (1995, 1997) energetic shoulders are then generated in the pick-up ion distribution functions, which in effect lead to higher pick-up ion pressures than considered in this paper and consequently to even lower upstream Mach numbers.

Another reason for a further reduction of the compression ratio has been discussed in papers by Chalov & Fahr (1994, 1997). They point to the fact that the termination shock instead of being classical Rankine-Hugoniot shock is likely to be an ACR-modulated shock, which depending on the ACR injection rate at the shock leads to strongly reduced compression ratio s. For a strongly ACR-modulated shock, which is symbiotic with a shock precursor, the theory of Drury (1983) and Potgieter & Moraal (1988) anyway does not apply for ACR spectra, and thus Eq. (25) cannot at all be used to derive a shock compression ratio s, as done by Cummings & Stone (1995, 1996) or Stone et al. (1996).

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