Astron. Astrophys. 363, L21–L24 (2000)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

Keplerian injection velocities reflected in helium pick-up ion spectra

S.V. Chalov[1] **and H.J. Fahr**[2]

[1] Institute for Problems in Mechanics of the Russian Academy of Sciences, Prospect Vernadskogo 101-1, 117526 Moscow, Russia (chalov@ipmnet.ru)

[2] Institut für Astrophysik und extraterrestrische Forschung der Universität Bonn, Auf dem Hügel 71, 53121 Bonn, Germany (hfahr@astro.uni-bonn.de)

Received 25 September 2000 / Accepted 27 October 2000

Abstract. It is usually assumed that pick-up ions at the event of their production, seen in the solar rest frame, have peculiar velocities which are negligible with respect to solar wind velocities. This assumption, however, is no more valid for pick-up ion injections at small solar distances. As we are showing here, the He^+ - pick-up ion spectra to be expected at distances inside 1 AU clearly reflect the fact that ion injection took place with non-negligible velocities due to the Keplerian motion of parent He atoms entering from the interstellar medium, as was already recognized in SOHO CELIAS measurements by Möbius et al. (1999). We demonstrate that these injection signatures are less pronounced under conditions of high-speed compared to those of low-speed solar winds and are variable with the off-upwind angle. Careful study of these injection features can help to identify the actual He ionization rate.

Key words: acceleration of particles – Sun: solar wind – inteplanetary medium – ISM: atoms, ions

1. Introduction

Recently Möbius et al. (1999) have presented observations of He^+ pick-up ions obtained with SOHO CELIAS CTOF in 1996 for the time period when the Earth was on the upwind side of the interstellar medium flow. As shown in this paper the high-velocity cut-off of the pick-up ion spectra in the solar rest frame is at higher values compared to the standard value $V/U_{\rm SW} = 2$. In contrast analogous He^+ data obtained with AMPTE SULEICA in 1985 on the downwind side show a shift of the cut-off to lower velocities. It has also been demonstrated that the normalized value of the shift is anticorrelated with the solar wind velocity. Möbius et al. (1999) consider these shifts as due to a manifestation of the interstellar neutral helium velocity at the injection point in the inner heliosphere.

When modelling the pick-up ion transport in the heliosphere the authors usually assume that initial velocities of freshly created ions, since considered to be small compared to solar wind velocities, in the solar wind frame simply are equal to the negative local solar wind velocity. This assumption is valid as long as the solar wind velocity is considerably larger than the peculiar velocities of the parent neutral He atoms. In the inner heliosphere, however, the He atoms suffer considerable acceleration by the solar gravity. The effect of acceleration due to the absence of radiation pressure is more pronounced for neutral helium as compared to neutral hydrogen atoms. The effect of the proper motions of parent He atoms on velocities of freshly created He^+ pick-up ions in the resulting spectra thereby is different on the upwind and downwind hemispheres as has been shown by Möbius et al. (1999).

In the present paper we study pick-up helium velocity distributions in the ecliptic plane on the basis of solutions of the Fokker-Planck type transport equation for anisotropic distribution functions taking into account the actual velocities of He^+ pick-up ions at the moment of their injection and also all relevant physical phase-space transport processes occurring after injection, like adiabatic cooling and focusing, pitch-angle scattering, and energy diffusion.

2. Theoretical model of He^+ pick-up ion transport

The transport equation describing the phase-space evolution of the gyrotropic velocity distribution function $f(r,\varphi,v,\mu)$ of pick-up ions in the radial solar wind moving with velocity $U_{\rm SW}$ can be written in the following form (see Chalov & Fahr 1998, 1999):

$$\begin{aligned}\frac{\partial f}{\partial t} &+ (U_{\rm SW}+v\mu\chi)\frac{\partial f}{\partial r} \\ &+ \left(\frac{1-3\mu^2}{2}\frac{1-\chi^2}{r}-\frac{1-\mu^2}{r}\right)\times U_{\rm SW}v\frac{\partial f}{\partial v} \\ &+ \frac{1-\mu^2}{2}\left[\frac{v}{r^2}\frac{\mathrm{d}}{\mathrm{d}r}\left(r^2\chi\right)+\frac{2\mu U_{\rm SW}}{r}-3\mu U_{\rm SW}\frac{1-\chi^2}{r}\right]\frac{\partial f}{\partial \mu} \\ &= \hat{S}f+Q(r,\varphi,v,\mu)\,, \end{aligned} \tag{1}$$

where v and μ are the velocity and cosine of the ion pitch-angle in the solar wind frame, χ is the cosine of the angle between

---

Send offprint requests to: S.V. Chalov the radial direction and large-scale interplanetary magnetic field which is assumed to have the Parker spiral configuration (in the paper an outward pointing magnetic field is adopted), $\hat{S}f$ is the scattering operator applied to the function f and describing effects of pitch-angle scattering and energy diffusion (for more details see Chalov & Fahr 1998, 1999), Q is the local production rate of pick-up ions, and φ is longitude, i.e. the off-upwind angle of the position. The second term on the left-hand side of Eq. (1) describes the convective motion with the solar wind velocity and the streaming of particles along the magnetic field lines due to the anisotropy of the pitch-angle distribution. The third term corresponds to the adiabatic cooling, and the fourth one to adiabatic focusing.

In order to calculate the number density of neutral interstellar helium in the heliosphere we make use of the modified cold model by Feldman et al. (1972) which takes into account the thermal spread of the particle trajectories also describing the density enhancement near the axis of the focusing cone. The modified cold model has been chosen in view of its simplicity. It provides explicit analytic expressions for the neutral helium distribution. On the other hand, the model is reasonable to study the influence of the bulk flow of interstellar helium on pick-up ion spectra. Hence the local production rate is assumed to have the form:

$$Q = \frac{P(r_{\rm E})(r_{\rm E}/r)^2}{2\pi U_{\rm SW}^2}\left[n_{\rm d}(r,\varphi)\delta\left(v - |\boldsymbol{u}_{\rm d}(r,\varphi) - \boldsymbol{U}_{\rm SW}|\right) \times \delta\left(\mu - \mu_{\rm d}(r,\varphi)\right) + n_{\rm i}(r,\varphi)\delta\left(v - |\boldsymbol{u}_{\rm i}(r,\varphi) - \boldsymbol{U}_{\rm SW}|\right) \times \delta\left(\mu - \mu_{\rm i}(r,\varphi)\right)\right], \quad (2)$$

where $P(r_{\rm E})$ is the He-ionization rate at $r_{\rm E} = 1$ AU, $n_{\rm d,i}$ are the number densities of helium atoms following hyperbolic direct and indirect orbits, respectively, $\boldsymbol{u}_{\rm d,i}$ are the velocities of the atoms at the point of ionization, and $\mu_{\rm d,i}$ are the corresponding initial pitch-angles which are determined by the local configuration of the interplanetary magnetic field. For more details concerning the number density of neutral helium and the explicit form of the scattering operator $\hat{S}$ see Chalov & Fahr (1999).

Since on the upwind side of the interstellar medium flow $n_{\rm i} \ll n_{\rm d}$ it can be seen from Eq. (2) that the velocity of atoms is added to the solar wind velocity at the determination of the initial velocity of pick-up ions on the upwind side and subtracted on the downwind side.

To solve Eq. (1) numerically the method of stochastic differential equations (SDEs) is applied describing trajectories of individual ions in phase space (for the general theory of SDEs and the application of SDEs to pick-up ion transport see Gardiner 1990 and Chalov & Fahr 1998, respectively). Concerning the LISM parameters of helium and the actual ionization rate the following values are adopted in our calculations (see Witte et al. 1996): $T_\infty = 7000$ K; $V_\infty = 25.3$ km s^{-1}; $P(r_{\rm E}) = 6.8\,10^{-8}$ s^{-1}. To specify pitch-angle scattering and energy diffusion coefficients determining the scattering operator $\hat{S}$ we adopt here that $\langle\delta B_{\rm E}^2\rangle/B_{\rm E}^2 = 0.01$. This level of Alfvénic turbulence corresponds to quiet conditions in the solar wind. Here $\langle\delta B_{\rm E}^2\rangle$ and $B_{\rm E}$ are the mean-squared amplitude of Alfvénic fluctuations and the magnitude of the large-scale interplanetary magnetic field at 1 AU.

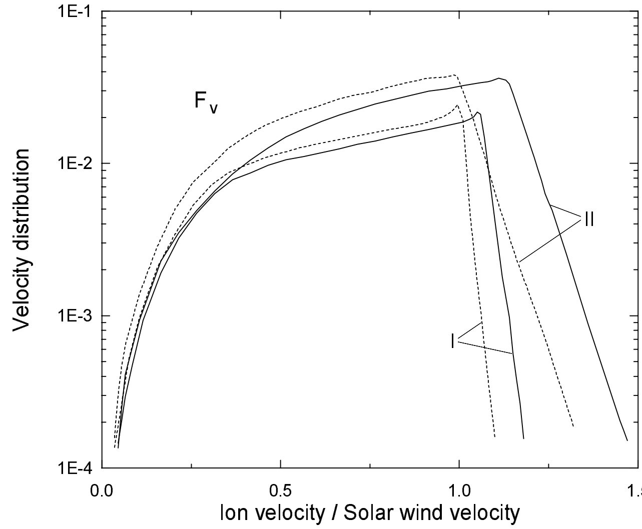

Fig. 1. The velocity distribution function $F_{\rm v}$ at $r = 1$ AU and $\varphi = 0°$. I – $U_{\rm SW} = 700$ km s^{-1}, II – $U_{\rm SW} = 350$ km s^{-1}. The solid curves are velocity distributions for the case when the actual injection velocities of He$^+$ pick-up ions are taken into account, the dashed curves correspond to the case when $u = 0$.

3. Discussion of results

For the purpose of displaying our results we shall first define pitch-angle integrated and normalized velocity distribution functions of pick-up ions, i.e. $F_{\rm v}$, $F_{\rm v}^{(+)}$, and $F_{\rm v}^{(-)}$ by the following formulae:

$$F_{\rm v} = \frac{2\pi U_{\rm SW} v^2 f_{\rm v}}{n_\infty({\rm He})}, \qquad F_{\rm v}^{(+)} = \frac{2\pi U_{\rm SW} v^2 f_{\rm v}^{(+)}}{n_\infty({\rm He})}, \qquad F_{\rm v}^{(-)} = \frac{2\pi U_{\rm SW} v^2 f_{\rm v}^{(-)}}{n_\infty({\rm He})}, \quad (3)$$

where

$$f_{\rm v}(r,\varphi,v) = \int_{-1}^{1} f\,{\rm d}\mu, \qquad f_{\rm v}^{(+)}(r,\varphi,v) = \int_{0}^{1} f\,{\rm d}\mu, \qquad f_{\rm v}^{(-)}(r,\varphi,v) = \int_{-1}^{0} f\,{\rm d}\mu. \quad (4)$$

The normalization is chosen so that

$$\int_0^\infty F_{\rm v}\,{\rm d}\left(v/U_{\rm SW}\right) = n_{\rm PU}/n_\infty({\rm He}). \quad (5)$$

Fig. 1 shows the velocity distribution function $F_{\rm v}$ at $r = 1$ AU on the upwind side ($\varphi = 0°$; the angle φ is measured from the upwind direction). The curves labeled I and II correspond to high velocity ($U_{\rm SW} = 700$ km s^{-1}) and low velocity ($U_{\rm SW} = 350$ km s^{-1}) solar wind, respectively. The solid curves are velocity distributions for the case when the actual injection velocities of He$^+$ pick-up ions are taken into account, while the

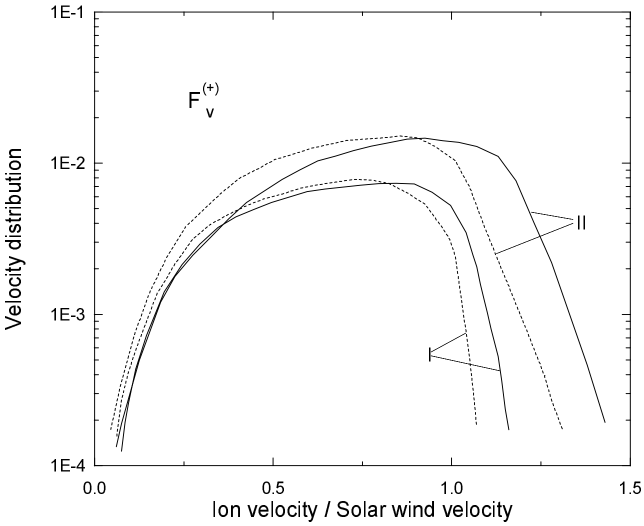

Fig. 2. The same as Fig. 1, but for $F_{\rm v}^{(+)}$.

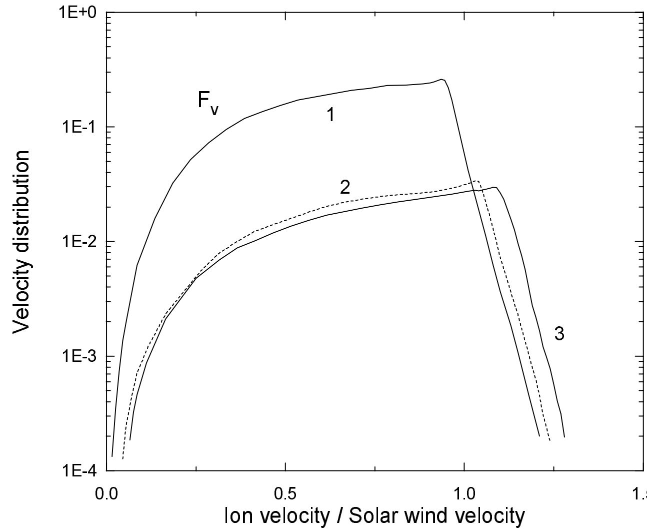

Fig. 3. The velocity distribution function $F_{\rm v}$ at $r = 1$ AU, $U_{\rm SW} = 450$ km s^{-1}, and different values of longitude: 1 – $\varphi = 180°$, 2 – $\varphi = 90°$, 3 – $\varphi = 0°$. The peculiar velocities of He^+ pick-up ions relative to the Sun are taken into account.

dashed curves show the corresponding distributions for the case when injection takes place with $u = 0$ in the source term given by Eq. (2) (i.e. vanishing injection velocity in the solar frame). One can clearly see the shift of the maximum of the distribution to higher velocities in the first case. The shift is larger for the slow solar wind than for the fast solar wind.

Due to technical characteristics of the CTOF sensor it is only possible to detect pick-up He^+ ions in the antisunward sector (in the solar wind frame). Therefore in Fig. 2 we show similar distributions as in Fig. 1 but for pick-up ions only with positive μ-values, so these ions move in the antisunward direction at 1 AU. One can principally see the same features of velocity distributions as in Fig. 1, however, the distributions in Fig. 2 are more smoothly shaped, and the sharp peaks seen in Fig. 1 and formed by freshly created ions from distributions $F_{\rm v}^{(-)}$ are absent here.

The interesting feature in Figs. 1 and 2 is the more pronounced high velocity tail formed due to stochastic acceleration of pick-up ions by solar wind turbulence in the slow solar wind as compared to the spectrum resulting for the case of the fast solar wind. An anticorrelation of He^+ abundances of the suprathermal tail with the solar wind velocity has in fact been observed with SOHO STOF and WIND STICS (Klecker et al. 2000; see also Fisk 2000). One of the possible reasons for this effect is that in the low velocity solar wind pick-up ions undergo diffusive acceleration for a longer time period before they reach a solar distance of 1 AU (see also Chalov & Fahr 1999). Thus diffusive acceleration will operate more efficiently under low velocity solar wind conditions.

It should be pointed out, however, that direct comparison of calculated velocity distributions with observations is only possible on the base of those specific μ-integrated distributions which are accessible to each concrete instrument, so our present results give only general effects of the interstellar helium motion on pick-up ion velocity distributions.

Fig. 3 shows velocity distributions $F_{\rm v}$ at $r = 1$ AU and $U_{\rm SW} = 450\,{\rm km\,s^{-1}}$ for different longitudes (upwind, crosswind and downwind) for the case when the correct injection velocities of He^+ pick-up ions relative to the Sun are taken into account. The large number density of pick-up ions on the downwind side $(\varphi = 180°)$ is connected with the well-known focusing effect of the Sun. Besides of differences in number densities of pick-up ions on upwind and downwind sides a longitudinal dependence of positions of maxima in their velocity distributions is clearly seen in Fig. 3. The maximum is shifted to higher velocities on the upwind side and to lower velocities on the downwind side in accordance with results by Möbius et al. (1999).

One can conclude that the effect of neutral He gas motion on He^+ pick-up ion velocity distribution is more pronounced in regions closer to the Sun due to the more pronounced gravitational acceleration of atoms. Fig. 4 where velocity distributions $F_{\rm v}$ at various solar distances, i.e. at 0.5 AU, 1 AU, and 2 AU, are presented clearly illustrates this effect.

4. Conclusions

We have shown that He^+ pick-up ion spectra observed at solar distances of the order of 1 AU or smaller clearly reflect the fact that these pick-up ions are injected into phase-space with non-negligible Keplerian velocities. This phenomenon becomes manifest by the fact that, when judged in the solar wind rest frame, the peaks of spectral densities are shifted to values larger (upwind hemisphere) or smaller (downwind hemisphere) than 1 if the spectra are studied as functions of velocities normalized by the solar wind velocity $U_{\rm SW}$. Hereby the hemispherical behaviour is clearly explained since in the upwind hemisphere He^+ ions are injected into the solar hemisphere of the velocity space leading to higher initial relative velocities, whereas on the

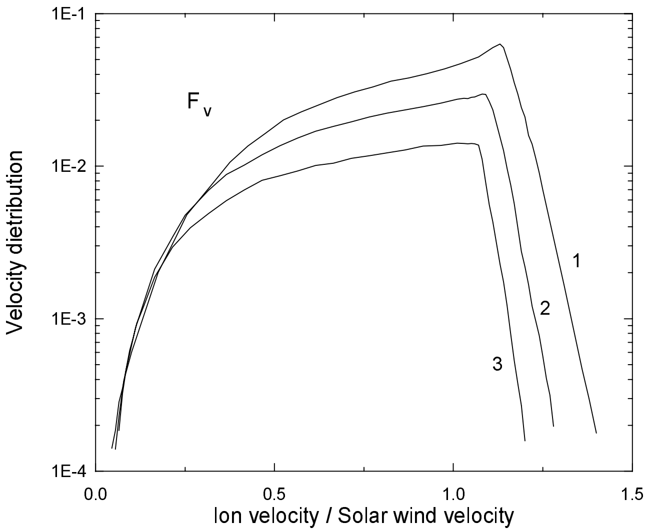

Fig. 4. The radial dependence of F_{v} at $\varphi = 0°$ and $U_{\mathrm{SW}} = 450$ km s^{-1}: 1 – $r = 0.5$ AU, 2 – $r = 1$ AU, 3 – $r = 2$ AU.

downwind hemisphere injection occurs into the antisolar hemisphere leading to smaller initial relative velocities with respect to the solar wind frame. In the upwind hemisphere the spectral peak in addition shifts to higher velocities the closer to the sun the spectrum is taken, reflecting clearly the increase of the Keplerian injection velocities with decreasing distances from the Sun.

Furthermore one may recognize that the slope of the high velocity wings of the spectra are less steep in the case of low velocity solar winds. This in our calculations clearly arises because the diffusive acceleration process (Fermi-2) operates more efficiently (longer particle exposure periods) in the low velocity wind. There may, however, even be an additional reason why this phenomenon comes up connected with the fact that the turbulence levels $\langle \delta B^2 \rangle / B^2$ in the low velocity wind and the degree of turbulence isotropy $\epsilon\ (= I^-/I^+)$ are larger in low velocity solar winds making diffusive acceleration even more effective (see Chalov & Fahr 1998, 1999). However, to support this hypothesis more concrete evidence from observations is needed.

Acknowledgements. This work was partially carried out while S.V.Chalov during his stay in 2000 was a guest at the Institute for Astrophysics and Extraterrestrial Research of the University of Bonn. The authors are grateful to the Deutsche Forschungsgemeinschaft (DFG) for the financial support of this stay in the frame of a bi-national cooperation project with grant number: 436 RUS 113/110/6-2 and in the frame of the DFG project with number Fa-97/24-2. S.V.Chalov was also partially supported by the Russian Foundation for Basic Research (RFBR) Grants 98-01-00955, 98-02-16759, 99-02-04025, and INTAS-CNES Grant No 97512 “The Heliosphere in the Local Interstellar Cloud”.

The authors thank the referee for helpful remarks.

References

Chalov S.V., Fahr H.J., 1998, A&A 335, 746

Chalov S.V., Fahr H.J., 1999, Solar Phys. 187, 123

Feldman W.C., Lange J.J., Scherb F., 1972, in: The solar wind, eds. C.P. Sonnett, P.J.Jr. Coleman, J.M. Wilcox, NASA, SP 308, p.684

Fisk L.A., 2000, ACE Symposium “The Acceleration and Transport of Energetic Particles Observed in the Heliosphere”, Indian Wells, California, 5–8 January 2000. Book of Abstracts

Gardiner C.W., 1990, Handbook of Stochastic Methods (2d ed., New York: Springer)

Klecker B., Bogdanov A.T., Hilchenbach M., et al., 2000, COSPAR Colloquium on “The Outer Heliosphere: The Next Frontiers”, Potsdam, Germany, 24–28 July 2000. Book of Abstracts, p.29

Möbius E., Litvinenko Y., Grünwaldt H., et al., 1999, Geophys. Res. Lett. 26, 3181

Witte M., Banaszkiewicz M., Rosenbauer H., 1996, Space Sci. Rev. 78, 289