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Extreme-ultraviolet diagnostics of pick-up ions in regions close to the solar corona

I. Feasibility of new observations

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Abstract. Recent investigations of pick-up ion data obtained with the AMPTE and the Ulysses spacecraft resulted in the discovery that, in contrast to previous expectation, pick-up ion velocity distribution can be anisotropic. Such anisotropy results from a smaller efficiency of pitch-angle scattering than usually assumed and translates into a larger scattering mean free paths than previously attributed to these particles. We demonstrate that existing and upcoming *in-situ* observations can be substantially supplemented by Earth-bound observations of the extreme-ultraviolet resonance glow of pick-up ions in the vicinity of the sun. The proposed observations, in combination with a theory of ions being picked-up by the heliospheric magnetic field close to the sun will not only allow us to obtain information about the anisotropy of the pick-up ion velocity distributions, but also to deepen our understanding of the physics of the accelerated solar wind and of the pick-up process of ions in this innermost region of the heliosphere not yet well explored.

Key words: plasmas – methods: observational – Sun: corona – Sun: UV radiation – interplanetary medium

1. Introduction and motivation

The existence of *Pick-Up Ions* (PUI), as a consequence of an ionization of neutral atoms of the *Local InterStellar Medium* (LISM) in the heliosphere, was already predicted almost 30 years ago (Semar 1970; Fahr 1971; Holzer 1972; Fahr 1973), long before their first detection. At that time it was already clear that interstellar neutral atoms, after ionization in the region of the supersonic solar wind, are immediately picked up by local electric induction forces and essentially convected outwards with the solar wind. But it remained unclear how PUI behave in velocity space while co-moving with the solar wind.

Meanwhile, these interstellar PUI have directly been detected by space probes. The first detection dates back to 1984/85 and was carried out with the plasma analyzer SULEICA (SUprathermaL Energy Ionic Charge Analyzer) onboard the earth-bound satellite AMPTE (see Möbius et al. 1985). In the years after 1985 many more identifications of cometary, lunar, planetary and interplanetary PUI followed. The perhaps best suited measurements for the study of the velocity space behaviour of these ions were performed recently with the SWICS (Solar Wind Ion Composition Spectrometer) instrument onboard the Ulysses space probe (Gloeckler et al. 1993,1994,1995; Geiss et al. 1994a,b).

From ongoing analyses of measurements obtained with SULEICA (Möbius et al. 1998) and SWICS (Gloeckler et al. 1995, Fisk et al. 1997) it has been concluded that PUI velocity distributions might be anisotropic. This finding has restarted the theoretical discussion the PUI behaviour in velocity space which originally began with papers by Wu & Davidson (1972), Hartle & Wu (1973), Wu et al. (1973), Wu & Hartle (1974).

As we demonstrate below, there is particular reason to expect PUI distributions to be anisotropic close to the sun. Two challenges, a theoretical and an observational one, invite to benefit from these particular distributions to learn more about the details of the behaviour of PUI in velocity space.

So, first, there is a theoretical challenge. In both the original and the more recent dicussion of the behaviour of PUI in velocity space, the innermost region of the heliosphere was excluded. The theory of the production, fluxes as well as velocity distributions of PUI has been developed within the framework of models being valid for heliocentric distances larger than 0.1 AU, i.e. about 20 solar radii (e.g. Vasyliunas & Siscoe 1976; Isenberg 1987; Bogdan et al. 1991; Rucinski et al. 1993; Rucinski & Bzowski 1995; Chalov et al. 1995 1997; Fichtner et al. 1996; Mall et al. 1996a; le Roux & Ptuskin 1998). The main reason for this limitation is the geometry and strength of the heliospheric magnetic field. In the sun's vicinity the field components perpendicular to the solar wind flow are small, i.e. the field is nearly radial, and its energy density is higher than that of the plasma, so that it is not frozen into the solar wind. These conditions have a profound influence on the pick-up process, because they are principally different from those farther out in the heliosphere and make several generally used concepts invalid.

Second, there is the observational challenge. Observations of PUI are, up to now, exclusively of direct nature. As mentioned above, a detection of these particles has been possible only with

Send offprint requests to: Hans-Jörg Fahr *in-situ* measurements made with the AMPTE (Möbius et al. 1985), Ulysses (Gloeckler et al. 1993,1994,1995) and, not yet fully confirmed, with the Voyager 1 & 2 (Decker et al. 1995) and Pioneer 10 (Intriligator et al. 1996) spacecraft. The AMPTE and Ulysses PUI data cover a heliocentric distance interval from 1 AU to about 5.4 AU (Jupiter's orbit) and are, thanks to Ulysses, not any longer limited to the ecliptic plane. Forthcoming missions with suitable instrumentation could potentially extend the region of *in-situ* PUI observations to even larger distances. For example, the Cassini spacecraft could be used also as a heliospheric probe (Mall et al. 1996b 1998) and improved measurements of PUI velocity distributions, in particular with respect to their anisotropies, could be obtained with the new Cluster II fleet (Möbius et al. 1996). However, the region close to the sun remains unreachable for these as well as other upcoming missions.

With the present paper we mainly deal with the second challenge, in order to check on the principal feasibility of PUI observations close to the sun. While nonetheless described in some detail below, the theoretical challenge will be subject of a subsequent study.

Indirect observations of PUI have already been suggested many years ago by Paresce et al. (1983). These authors explored the possibility to observe pick-up helium (He^{+}) in anti-solar direction via its 303.8 Å line. While they clearly recognized the dependence of the resonance signal on the details of the PUI velocity distribution, they found, despite a rather low intensity of the plasmaspheric 303.8 Å radiation in the Earth's shadow, that the expected signal from pick-up helium would be, most probably, below the detection threshhold. This result was based on the theoretical side on the assumption that He^{+} ions of interstellar origin, while being convected with the solar wind, would not be maintained at a suprathermal velocity level for a sufficiently long period, and on the experimental side on limited sensitivity and spectral resolution achievable with the instruments available at that time. Observations of regions of higher PUI density closer to the sun were not discussed for reasons of expected observational and instrumental limitations.

Since that time, however, the situation has changed with respect to both theoretical expectations and experimental capabilities. While Paresce et al. (1983) believed high energy tails of PUI velocity distributions to be unlikely, we nowadays know that such tails exist (Gloeckler et al. 1994) and can be explained by various acceleration processes (Isenberg 1987; Williams et al. 1993; Chalov et al. 1995; 1997; Fichtner et al. 1996; Lee et al. 1996; Schwadron et al. 1996; Zank et al. 1996; le Roux & Ptuskin 1998). There has also been made progress on the experimental side, so that significantly improved detectors can be built (see e.g. Jelinsky et al. 1995). These new circumstances and the recent observations of the so far unknown, but highly interesting anisotropic structure of PUI velocity distribution functions form our main motivation to revive the idea of indirect observations of PUI via their extreme-ultraviolet (EUV) resonance glow and to utilize it in order to explore for the first time the properties of this particle population in close vicinity of the sun.

2. Anisotropic PUI velocity distributions

2.1. Observations

As mentioned in the previous section recent observations of PUI have revealed that their velocity distributions could be anisotropic.

First, Gloeckler et al. (1995) reported measurements of pick-up hydrogen made with the Ulysses spacecraft at high southern heliographic latitudes indirectly indicating pronounced anisotropies in velocity space. The detection of this asymmetry became possible with the first observation of PUI with velocities *lower* than the solar wind speed. Unlike previous observations in the ecliptic, where the low velocity wings of the solar wind ion distributions are preventing a detection of PUI below about 400 km/s, at higher latitudes the solar wind ion distributions are shifted to higher velocities with a maximum of about $700-800$ km/s, thus opening a detection window for PUI below the solar wind speed. Although an anisotropy of PUI velocity distributions could not be measured directly because of the missing angular resolution, Gloeckler et al. (1995) found nonetheless that the observed direction-averaged distributions could not be explained with the assumption of isotropy, but that, in the solar wind frame, pick-up hydrogen exhibits a pronounced radial streaming towards the sun with a speed several times the local Alfvén speed. Such anisotropy implies a smaller efficiency of pitch-angle scattering than usually assumed and translates into larger mean free paths (~ 1 AU) than previously attributed to these particles. Thus, these observations are contributing to the general problem of how to explain the long mean free paths of low rigidity particles in the solar wind (see e.g. Schlickeiser 1988, Fisk et al. 1997).

Second, Möbius et al. (1998) analyzed AMPTE data and found for periods of an almost radial heliospheric magnetic field a reduction of the pick-up helium flux that would be consistent with both anisotropic velocity distributions and a large mean free paths of PUI of about $0.3-1$ AU.

Indirectly, both observations point to the need of a refined modelling of PUI distributions, in general. This is even more so in view of forthcoming measurements to be made with the time-of-flight ion COmposition and DIstribution Function analyser (CODIF) being part of the Cluster Ion Spectrometry (CIS) experiment aboard the new Cluster spacecraft. As pointed out by Möbius (1996), the instrument covers the velocity space with a sufficiently high angular resolution to reveal directly anisotropies of the PUI velocity distribution.

2.2. Theory

Wu & Davidson (1972), Hartle & Wu (1973), Wu et al. (1973), Wu & Hartle (1974) were the first to theoretically study instabilities of the initial, in the rest frame of the solar wind toroidal PUI velocity distribution with respect to wave excitations. They showed that, due the excitation of electrostatic, electromagnetic or hydromagnetic waves, this initial ring distribution of PUI decays into a broadened distribution with reduced velocities $v_{\|}$ parallel and $v_{\perp}$ perpendicular to the heliospheric magnetic field. The decay time was found to be $\sim 3 \cdot 10^2\ s$ for the $v_\parallel$-and $\sim 4 \cdot 10^3\ s$ for the $v_\perp$-decay. Inasmuch these decays would count in terms of PUI resonance emission intensities in the EUV was, as stated above, quantitatively analysed by Paresce et al. (1983).

Although it was unpredictable from these studies into which form the initially toroidal PUI velocity distribution would develop, it was nevertheless tacitly assumed that, most probably, the torus would be transformed into a spherical shell by strong pitch-angle scattering. In addition, the distribution was expected to suffer adiabatic cooling operating in the expanding solar wind. The combined effect of both processes was first described by Vasyliunas & Siscoe (1976).

In the years following that publication it had generally been accepted that, caused by resonant interactions with ambient hydromagnetic wave fields (Isenberg 1987, Lee & Ip 1987; Fahr & Ziemkiewicz 1988; Bogdan et al. 1991), PUI velocity distributions first undergo a fast pitch-angle scattering towards isotropy. The energy diffusion of PUI by the second-order Fermi process, i.e. Fermi scattering, was described by Isenberg (1987), Bogdan et al. (1991), Chalov et al. (1995 1997), Chalov & Fahr (1996), Fichtner et al. (1996) also based on the expectation of isotropy, and it was demonstrated that PUI experience substantial acceleration while being convected outwards with the solar wind.

Lee & Ip (1987), however, also recognized that the growth rates γ for linear wave excitations by thermally broadened, toroidal PUI velocity distributions are strongly depending on the initial injection conditions, i.e the initial velocities $v_{o\parallel}$ and $v_{o\perp}$ since they were led, for pick-up hydrogen, to the expression:

$$\gamma = \sqrt{\frac{\pi}{8e}}\ \frac{v_A |v_{o\parallel}| \omega_i}{c^2}\ \left(\frac{\omega_i}{|\Omega_p|}\right)\ \left(\frac{v_{o\perp}}{\sigma_{th}}\right)^2 \tag{1}$$

where ω_i and σ_{th} are the plasma frequency and the thermal velocity spread of pick-up hydrogen, v_A and Ω_p are the local Alfvén speed and the proton gyrofrequency, and c the speed of light. Evidently, the growth rates vanish for vanishing velocities $v_{o\parallel,\perp}$, meaning that a toroidal distributions at pitch angle cosines $\mu = cos\,\theta = v_{o\parallel}/\sqrt{v_{o\parallel}^2 + v_{o\perp}^2} \approx 0$ and $\mu \approx 1$ are relatively stable. This did point to the fact that pitch-angle scattering not necessarily produces complete and isotropic shell distributions.

The evolutionary tendencies of noncomplete shell distributions have been explicitly studied by Freund & Wu (1988) who demonstrated that shell distributions are the less unstable the more complete they become, meaning that a perfect completion of the shell and the development of an isotropic distribution is possibly a very long process. Therefore, and in view of the above mentioned observations, a brief discussion of models of anisotropic PUI velocity distributions is worthwhile.

The first two models of anisotropic PUI velocity distributions were already given in Gloeckler et al. (1995) and Möbius et al. (1998). However, the former authors themselves noted already the limitations of their diffusion model in the case of large anisotropies, and the latter treated the anisotropies in a two-stream model not allowing to obtain information about the structure of the actual velocity distribution. Pointing to these shortcomings, Isenberg (1997) made the next step towards a more comprehensive model of anisotropic distributions. He formulated an analytical model based on a hemispherical representation of PUI velocity distributions. Although still strongly simplifying the relevant physics by assuming an exactly radial heliospheric magnetic field and no scattering through a pitch-angle θ of $90^o (\Leftrightarrow \mu = cos\,\theta = cos\,90^o = 0)$, the model helps to understand the persistence of the observed anisotropy which appears hardly reduced by hydromagnetic wave-particle instabilities. It also allows one to explain the long mean free paths of these PUI as a consequence of no scattering through $\mu = 0$ (Fisk et al. 1997).

All three models were developed to understand PUI observations at 1 AU and beyond, i.e. in regions where, except for very high latitudes, the undisturbed heliospheric magnetic field becomes more and more azimuthal, periods of radial orientation are limited in time and the field is frozen into the solar wind. This is principally different at heliocentric distances smaller than 20 solar radii. Not only is the angle between the Parker spiral and the radial direction everywhere smaller than 6^o there, but also the fluctuations in the heliospheric magnetic field direction might be smaller because that close to the sun, in particular inside the Alfvénic surface, the quiet field is dynamically important and forcing, to some extent, a corotation of the solar wind plasma (see e.g. Marsch & Richter 1984). In addition, in that region the waves are mainly propagating in anti-solar direction. Therefore, one could expect anisotropies in the PUI velocity distributions in the vicinity of the sun to be more pronounced and to persist for longer periods of time. So, in order to study anisotropic distributions, observations of PUI in that region would be particularly worthwhile. In the following we present an investigation of the feasibility of observations of PUI densities and their velocity distributions in the vicinity of the sun.

3. EUV echoes from PUI

3.1. The HeII - 303.8 Å resonance glow

The diffuse 303.8 Å background has recently been observed with the Extreme UltraViolet Explorer (EUVE) (Jelinsky et al. 1995). The only emission lines detected were those of HeI and HeII at the wavelengths 587, 537 and 304 Å having intensities consistent with scattering of solar radiation in the geocorona or interplanetary space. A decade before, Paresce et al. (1983) demonstrated already that the intensity and spatial variation of the resonance line of singly ionized helium at 303.8 Å , as observed with the instrumentation available at that time, could generally be explained with solar HeII line emissions being resonantly back-scattered by thermal He^+ in the Earth's plasmasphere. However, for the anti-solar direction an excess signal was detected. All terrestrial sources like multiple scattering of the 303.8 Å line by He^+ in the Earth shadow, magnetospheric He^+ populating the plasma sheet or interstellar neutral helium penetrating the Earth's atmosphere could be ruled out. Amongst the extraterrestrial sources like a diffusive radiation background at 303.8 Å due to impact ionization, charge exchange or resonance scattering of HeI and HeII, respectively, the latter appeared as a potential candidate to explain the enhanced flux. While it was not possible to confirm this source as contributing significantly to the excess signal, and its more likely origin was seen in the 584 Å resonance emission of neutral helium unavoidably observed within the same channel due to bandpass limitations, the authors noted the important implications for the PUI theory if the 303.8 Å line would in fact be the main contributor.

In the light of both our present-day knowledge about suprathermal PUI velocity distributions and significantly improved instrument capabilities, a new approach to observations of the 303.8 Å line appears worthwile. In contrast to earlier measurements, as shown below, nowadays it appears promising to detect an excess signal produced by scattering pick-up helium in the sun's vicinity, i.e. even through the dayside plasmasphere.

3.2. Estimate of the HeII - 303.8 Å resonance intensity close to the sun

As a first step we perform an order of magnitude estimate. The intensity $I_{\rm obs}$ of a resonance emission emanated from an irradiated volume filled with an optically thin backscattering medium with a number density $n(\boldsymbol{r})$, that is observed by an instrument with detector surface F_D and angle of view Ω_D along a line of sight parameterized by s, can, in general, be computed from the following relation:

$$I_{\rm obs}(s) = \frac{F_D \Omega_D}{4\pi\,{\rm sr}}\,\sigma \int_{s_o}^{s} \Phi(\Theta) I_\odot(\boldsymbol{r}(s')) n_{\rm pui}(\boldsymbol{r}(s')) ds' \qquad (2)$$

Here, $n_{\rm pui}(\boldsymbol{r})$ is the number density of PUI and

$$I_\odot(\boldsymbol{r}) = I_o \left(\frac{r_o}{r}\right)^2 = I_E \left(\frac{r_E}{r_o}\right)^2 \left(\frac{r_o}{r}\right)^2 \qquad (3)$$

denotes the intensity of the external radiation source, i.e. the sun. While the index '*o*' indicates quantities taken at a reference distance of $(r_o = 10\, r_\odot)$, the index '*E*' refers to the Earth' orbit. There is no generally accepted value for the intensity of the 303.8 Å line at Earth. For example, Hall et al. (1963) give $I_E = 2.5 \cdot 10^9 \, \frac{\rm Photons}{\rm cm^2 s}$, Heroux & Hinteregger (1978) state $I_E = 6.9 \cdot 10^9 \, \frac{\rm Photons}{\rm cm^2 s}$, and, more recently, $I_E = 6 \cdot 10^9 \, \frac{\rm Photons}{\rm cm^2 s}$ was given (Meier 1991, see also references therein). More recent measurements are expected to come up from SOHO/EIT observations (e.g. Moses et al. 1997). For our estimate we adopt the lowest value, so that for the solar 303.8 Å line we have

$$\begin{aligned} I_o = I_E \left(\frac{r_E}{r_o}\right)^2 &= 2.5 \cdot 10^9 \, \frac{\rm Photons}{\rm cm^2 s} \cdot \left(\frac{215}{10}\right)^2 \\ &= 1.1 \cdot 10^{12} \, \frac{\rm Photons}{\rm cm^2 s} \end{aligned} \qquad (4)$$

and, therefore, we find

$$I_{\rm obs}(s) = \frac{F_D \Omega_D}{4\pi\,{\rm sr}} \sigma I_o \int_{s_o}^{s} \left(\frac{r_o}{r(s')}\right)^2 n_{\rm pui}(\boldsymbol{r}(s')) ds' \qquad (5)$$

The resonance absorption cross section for photon scattering at the 303.8 Å line center is given by $\sigma = 2.7 \cdot 10^{-15} cm^2$ (Mitchel & Zemanski 1934, Paresce et al. 1983). The phase function $\Phi(\Theta)$ of the scattering process is depending on the angle Θ between the line of sight and the illumination direction, but is set equal to one here.

Introducing three dimensionless quantitites:

$$\boldsymbol{x} = \frac{\boldsymbol{r}}{r_o}\,; \qquad t = \frac{s}{r_o}\,; \qquad f(\boldsymbol{r}) = \frac{n_{\rm pui}(\boldsymbol{r})}{n_{\rm pui,max}}$$

allows for the formulation:

$$\begin{aligned} I_{\rm obs}(t) &= \frac{F_D \Omega_D}{4\pi\,{\rm sr}} \sigma I_o r_o n_{\rm pui,max} \int_{t_o}^{t} \frac{f(\boldsymbol{x}(t'))}{x^2(t')} dt' \\ &= \frac{F_D \Omega_D}{4\pi\,{\rm sr}} \sigma I_o r_o n_{\rm pui,max}\, \eta \end{aligned} \qquad (6)$$

Using (i) as typical instrumental characteristics $F_D = 1\, cm^2$ and $\Omega_D = 10^{-3}$ sr (see e.g. Chakrabarti et al. 1982; Paresce et al. 1983; Fahr & Lay 1984), (ii) $n_{\rm pui,max} = 3.5 \cdot 10^{-3}\ cm^{-3}$ as a typical PUI number density at $(r_o = 10\, r_\odot)$ (e.g. Rucinski et al. 1993), (iii) the assumption that the main emission comes from PUI in the region $[t_o = 10\, r_\odot, t = 20\, r_\odot]$, and (iv) the approximation (see the appendix A)

$$\eta = \int_{t_o}^{t} \frac{f(\boldsymbol{x}(t'))}{x^2(t')} dt' \approx 1.6 \qquad (7)$$

one obtains the estimate

$$I_{\rm obs} \approx 930 \, \frac{\rm Photons}{\rm s} \qquad (8)$$

This corresponds (with 1 Rayleigh = $\frac{10^6}{4\pi} \, \frac{\rm Photons}{\rm cm^2\ s\ sr}$) to

$$I_{\rm obs} = 930 \cdot 10^3 \cdot 1 \, \frac{\rm Photons}{\rm cm^2 s\ sr} \, \frac{4\pi}{10^6} \, \frac{\rm s\ sr\ cm^2}{\rm Photons} = 11.6\ {\rm R} \qquad (9)$$

The facts that this value is higher than the maximum intensity coming from the dayside geocorona (~ 8 R, see Paresce et al. 1983, Fahr & Lay 1984) and that it represents a lower limit with respect to the chosen line intensity motivate us to proceed with the analysis and to perform a more detailed check for a refined scenario.

4. Numerical computation of the expected radiation intensity

After the rather crude, but encouraging order of magnitude estimate obtained in the previous section we now turn to a refined computation of the He^+-resonance glow at regions close to the solar corona. For the present purpose it suffices to calculate the He^+ density from a model developed by Rucinski & Fahr (1989) and Rucinski et al. (1993). The local production of He^+ PUI is proportional to the number of interstellar neutral He atoms in a local volume at a given location in the heliosphere. The distribution of these neutrals results from the well established so-called *hot kinetic model* (Fahr 1971,1978; Thomas 1978; Wu & Judge 1979) generalized to include electron impact ionization

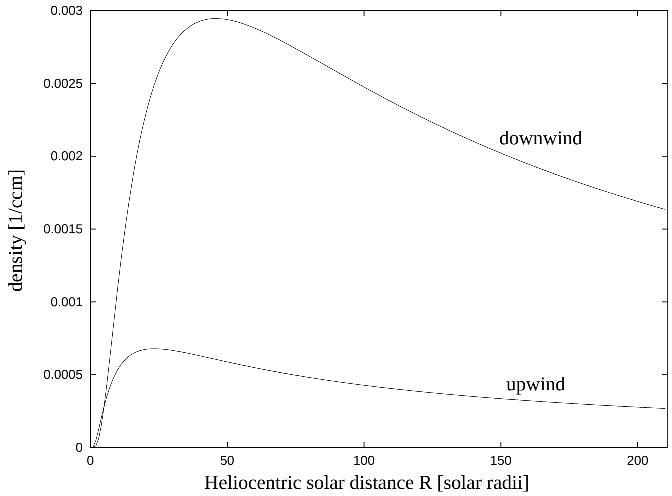

Fig. 1. The pick-up helium densities in upwind and downwind direction.

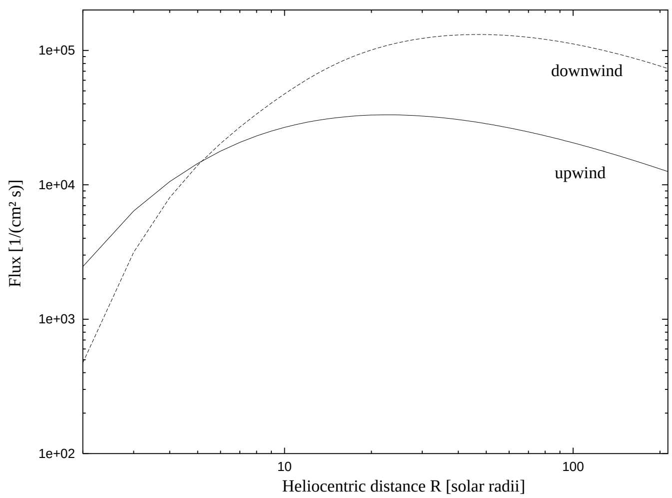

Fig. 2. The pick-up helium fluxes in upwind and downwind direction.

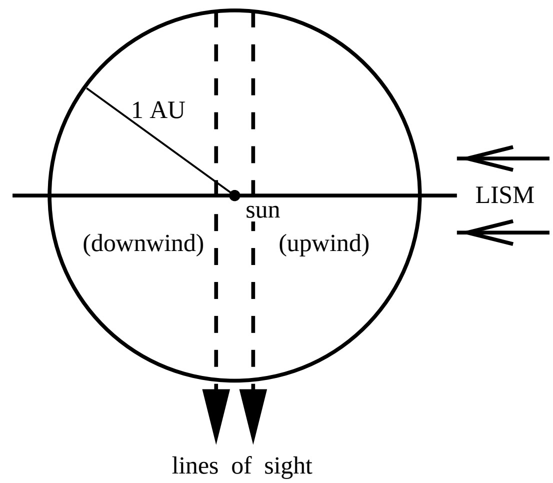

Fig. 3. The line of sights (for an observer on Earth) chosen for the results of Fig. 4.

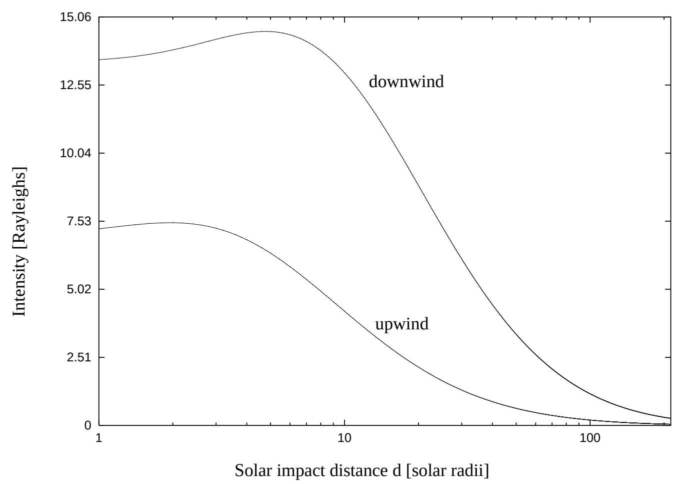

Fig. 4. The resonance glow (as seen from Earth) associated with pick-up helium densities given in Fig. 1 shown as function of the solar impact distance d, i.e. the distance of the point on the line of sight closest to the sun.

processes, which are not decreasing with increasing heliocentric distance like $1/r^2$ (see Rucinski & Fahr 1989; Rucinski et al. 1998), and is described by:

$$n(\boldsymbol{r}) = \int\int\int \quad f_\infty(\boldsymbol{v}_\infty(\boldsymbol{r},\boldsymbol{v})) \times exp\left(-\int_\infty^s \beta_t(s^{'})\frac{ds^{'}}{v^{'}}\right)\, d\boldsymbol{v} \tag{10}$$

where $f_\infty(\boldsymbol{v}_\infty(\boldsymbol{r},\boldsymbol{v}))$ represents the unperturbed velocity distribution function of interstellar He atoms entering the solar system with a velocity $\boldsymbol{v}_\infty(\boldsymbol{r},\boldsymbol{v})$ and later reaching the space point $\boldsymbol{r}$ with a velocity $\boldsymbol{v}$. The exponential function describes the total losses of He atoms along their trajectories $s(\boldsymbol{r})$ due to a local total loss frequency $\beta_t(\boldsymbol{r})$. This frequency is represented as a sum of the contributions from all relevant loss processes, i.e. for He it is given by the expression:

$$\beta_t(\boldsymbol{r}) = \beta_{ph}(\boldsymbol{r}) + \beta_{el}(\boldsymbol{r}) \tag{11}$$

where the two terms on the right-hand side denote the loss frequency resulting from photo- and electron impact ionization, respectively.

While $\beta_{ph}(\boldsymbol{r})$ with a distance dependence of $1/r^2$ allows for an analytic expression of the extinction, this is not the case for the losses due to electron ionizations, and, therefore, one finds:

$$n(\boldsymbol{r}) = \int\int\int \quad f_\infty(\boldsymbol{v}_\infty(\boldsymbol{r},\boldsymbol{v})) \times exp\left(-\frac{\beta_{ph}(s)r^2\theta(s)}{P(s)\boldsymbol{v}_\infty(\boldsymbol{r},\boldsymbol{v})}\right) \times exp\left(-\frac{\int_\infty^s \beta_{el}(s^{'})r^2(s^{'})d\theta(s^{'})}{P(s^{'})\boldsymbol{v}^{'}_\infty(\boldsymbol{r},\boldsymbol{v})}\right) d\boldsymbol{v} \tag{12}$$

where θ is the angle between the upwind direction and the direction to a location $\boldsymbol{r}(s)$ on a particle's trajectory.

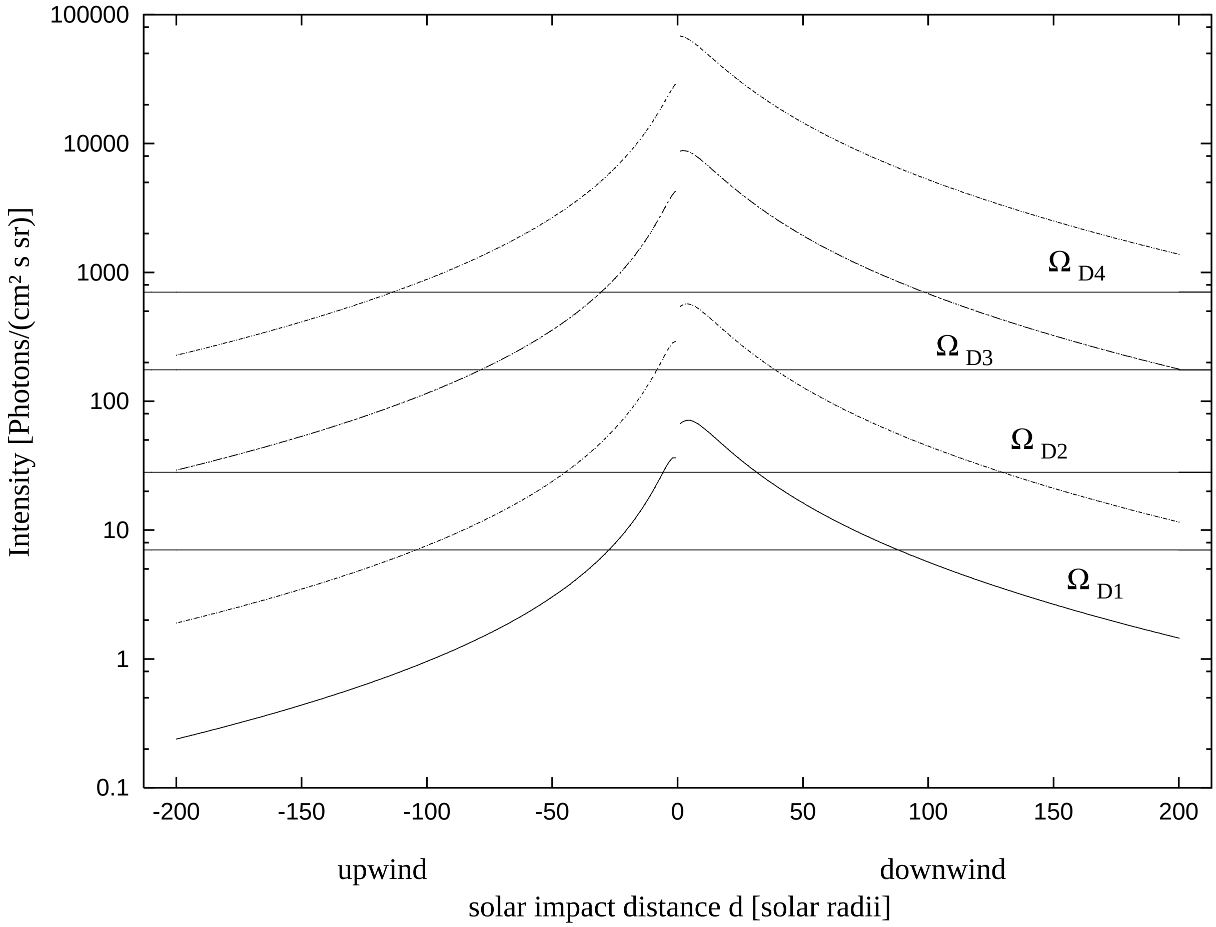

Fig. 5. The total 303.8 Å resonance glow of solar coronal pick-up helium and of the geocorona seen with an Earth-bound instrument as a function of the impact distance d for different fields of view Ω_{Di} with diameters $r_i = 1, 2, 5, 10\, r_\odot$ at the impact point ($1r_\odot \approx 0.5^o$). The four horizontal lines indicate the corresponding geocoronal He^+ background which is, as an upper limit, assumed to be 8 Rayleighs.

With this density distribution of interstellar neutrals, one can calculate the local production rate of He^+ PUI

$$P(\boldsymbol{r}) = n(\boldsymbol{r})\beta_t(\boldsymbol{r}) \tag{13}$$

and their related flux $F(\boldsymbol{r})$ in the following form:

$$F(\boldsymbol{r}) = \int_{r_{in}}^{r} n(\boldsymbol{r}^{'})\beta_t(\boldsymbol{r}^{'}) \left(\frac{r^{'}}{r}\right)^2 dr^{'} \tag{14}$$

obtained as solution of a flux continuity equation formulated for a spherically symmetric flux geometry. r_{in} is taken as that inner distance where the PUI flux vanishes.

Figs. 1 and 2 depict the pick-up helium densities and fluxes obtained with Eqs. (12) and (14), respectively, adopting $r_{in} = 1\, r_\odot$ and $u_{\rm pui} = u_{\rm sw}$ = 450 km/s as well as $v_\infty = 25$ km/s, $T_\infty = 7000$ K and $n_{He,\infty} = 0.014$ cm^{-3}s for the LISM (Witte et al. 1996). The total loss frequency at $r = r_E = 1$ AU is assumed to be $\beta_{t,E} = 1.0 \cdot 10^{-7}{\rm s}^{-1}$. For further details see Rucinski & Fahr (1989).

While at larger heliocentric distances both the He^+-density and flux are higher in downwind than in upwind direction as a consequence of gravitational focusing, the opposite is true for the region close to the solar corona. There, the higher extinctions of helium atoms along their way to the downwind axis overcompensate the focusing effect.

From the densities, we can compute the corresponding He^+ 303.8 Å resonance glow intensities. For these computations we have chosen lines of sights like those indicated in Fig. 3 and assumed as before that the main contribution comes from close to the sun (see also Sect. 3.2 and Fig. A.1). The resulting resonance glow intensities as seen from Earth are shown in Fig. 4.

In order to visualize the feasibility of the actual measurements of this glow, the total glow intensity that can be seen by an Earth-bound instrument is of interest. This total glow intensity of backscattered radiation from these pick-up helium ions and of the geocorona has to be compared to that of the plasmaspheric intensity alone. Fig. 5 gives such intensities expected to be received by a detector close to Earth when looking with variable solar offset angles along the upwind and the downwind axis, respectively. For the solar He^+ 303.8 Å line emission we have taken the values given in the previous section. The intensities were calculated for a line of sight of the detector starting at the position of the Earth in its vernal equinox ($\alpha = 0, \delta = 0$). The

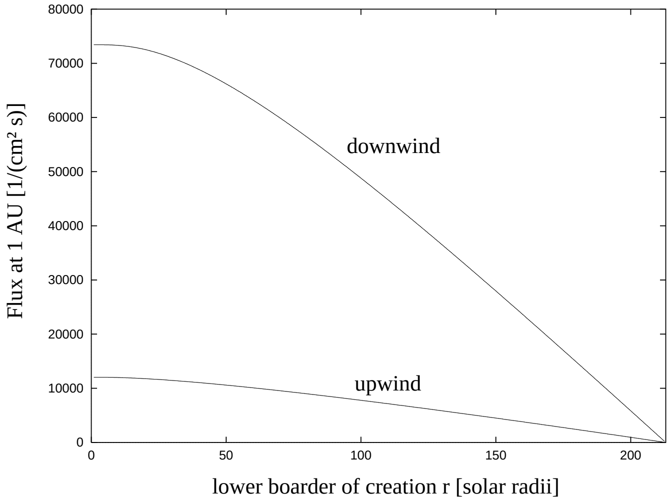

Fig. 6. The dependence of the pick-up helium flux at 1 AU on the lower integration boundary r_{in}.

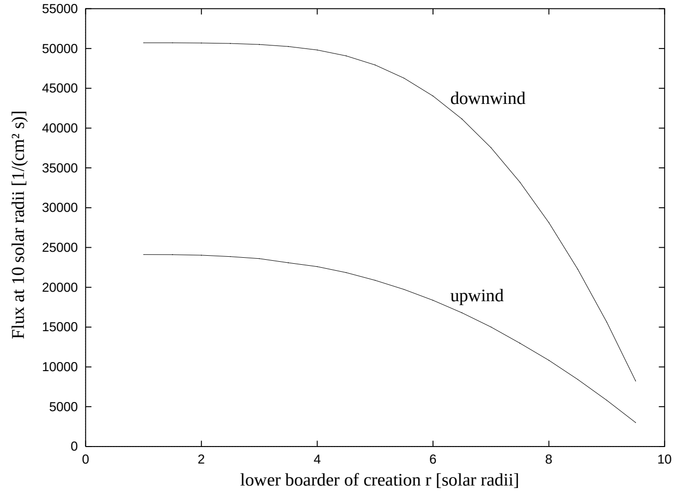

Fig. 7. The dependence of the pick-up helium flux at $10\,r_\odot$ on the lower integration boundary r_{in}.

solar offset angle is measured with the impact distance d of the line of sight in units of $r_\odot$. The angle of view of the observing instrument is also measured in units of $r_\odot$ indicating the diameter of the field of view at the impact point of the line of sight. The horizontal lines indicate the plasmaspheric He^+ 303.8 Å foreground emission assumed to produce an 8 Rayleigh emissivity on the dayside (see e.g. Chakrabarti et al. 1982; Paresce et al. 1983; Fahr & Lay 1984). Given that this value is rather an upper limit than an average value means that actual circumstances might be even more favorable for the proposed observations (Vallerga 1998, private communication). It is clearly noticeable that at small solar offsets the solar coronal He^+ glow contribution dominates over the geocoronal foregound. This again allows to conclude that observations of He^+ resonance emissions can be used as a valuable diagnostic to identify He^+ densities and velocities close to the solar corona.

5. The significance of PUI velocity distributions

As mentioned before, because of the strength and almost radial orientation of the heliospheric magnetic field close to the solar corona, the pick-up process does not operate there in the manner that is usually assumed. If, however, PUI are not readily picked-up, their bulk velocity $u_{\rm pui}$ not only differs from the solar wind velocity $u_{\rm sw}$, but might even vanish at some heliocentric distance $r_{in} > r_\odot$. This would translate into a vanishing PUI flux at the distance defining the lower limit r_{in} of the integral in Eq. (14). In other words, the inner boundary for the flux computation is not clearly defined in the aforementioned calculations.

In particular close to the upwind direction, the injection of He^+ PUI may easily cause negative values of $u_{\rm pui}$ at solar distances $r \le r_{in}$ meaning that PUI produced in this region are not moving outwards, but inwards towards the solar corona. While not knowing its exact value, we may still investigate the influence of r_{in} on the resulting flux $F(\boldsymbol{r})$.

The r_{in}-dependence of the He^+-fluxes in upwind and downwind direction at the two distances $r = 10\,r_\odot$ and $r = 1$ AU $= 215\,r_\odot$ are shown in Figs. 6 and 7, respectively. While the fluxes at 1 AU are rather insensitive to a variation of r_{in} in the range $1 < r_{in} < 20\,r_\odot$, those at $10\,r_\odot$ exhibit a strong dependence. Evidently, the correct choice of the inner boundary is only relevant for PUI flux computations close to the solar corona. Returning to the notion that $u_{\rm pui} < u_{\rm sw}$ close to the corona, the PUI densities shown in Fig. 1 have to be upscaled by

$$\tilde{n}_{\rm pui} = n_{\rm pui}\,\frac{u_{\rm sw}}{u_{\rm pui}} \tag{15}$$

On the other hand, the full illumination of PUI by the central solar line as adopted in the calculations shown in Figs. 4 and 5 can only be expected if $0 \le u_{\rm pui} \le u_c = 100$ km/s is valid, with u_c corresponding to the solar line width, i.e. $\Delta\lambda_c = 0.1\text{Å}\ \ \lambda_o\,\frac{u_c}{c}$. Otherwise the solar illumination has to be reduced by the factor:

$$\frac{\tilde{I}_\odot}{I_\odot} \approx exp\left[-\left(\frac{\Delta\lambda_{\rm pui}}{\Delta\lambda_c}\right)^2\right] = exp\left[-\left(\frac{u_{\rm pui}}{u_c}\right)^2\right] \tag{16}$$

This, finally, allows to conclude that the intensities plotted in Fig. 4 are fairly sensitive to the actual PUI velocity $u_{\rm pui} = u_{\rm pui}(\boldsymbol{r})$ by means of the function:

$$\tilde{I}_{303.8}(\boldsymbol{r}) \approx I_{303.8}(\boldsymbol{r})\,\left(\frac{u_{\rm pui}(\boldsymbol{r})}{u_{\rm sw}}\right)\,exp\left[-\left(\frac{u_{\rm pui}(\boldsymbol{r})}{u_c}\right)^2\right] \tag{17}$$

This emphasizes the interesting fact that observations of He^+ glow intensities in the vicinity of the sun are not only a diagnostic tool to study PUI densities but also their unknown bulk velocities and, thus, indirectly their velocity distribution.

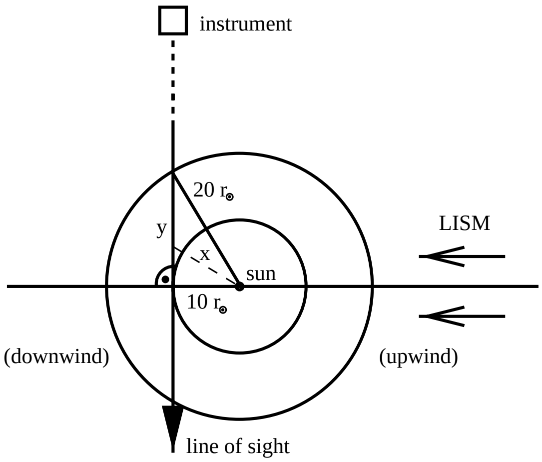

Fig. A1. Geometry used for the approximate evaluation of the integral (A3).

6. Summary and conclusions

We have demonstrated the feasibility of an indirect detection of thermodynamic properties of pick-up helium ions via their 303.8 Å resonance glow in the vicinity of the sun.

Such observations of the resonance glow would represent the first indirect detection of interstellar pick-up ions at all and supplement the existing direct *in-situ* observations obtained with several spacecraft. Furthermore, they would offer a very good diagnostic to explore the actual structure of the velocity distributions of pick-up ions, in particular their recently discussed substantial anisotropies. Such anisotropies are expected to be pronounced in regions close to the solar corona, because there the heliospheric magnetic field is dynamically important and quasi-radial.

While the latter condition is already recognized as a cause of anisotropic velocity distributions, the former gives rise to question the efficiency of the pick-up process. After having established with the present study that an indirect observation of interstellar helium ions close to the sun is feasible via the resonance glow of solar extreme-ultraviolet radiation, the subject of a forthcoming paper will be a thorough investigation of the pick-up process and of the phase space behaviour of such ions.

Appendix A: estimate of the integral factor η

For the case of a PUI number density distribution being symmetric with respect the line of sight, the integral can readily be evaluated. Such symmetry occurs if the line of sight is perpendicular to the *upwind-downwind* or *heliospheric axis*.

Then, the integral can be divided into two equal parts and it is useful to introduce a new independent variable (see Fig. A.1)

$$y = t - t_o \tag{A1}$$

and to observe that

$$x^2 = 1 + y^2 \tag{A2}$$

so that the integral reads:

$$\eta = \int_{t_o}^{t} \frac{f(\boldsymbol{x}(t'))}{x^2(t')} dt' = 2 \int_0^y \frac{f(y')}{1 + y'^2} dy' \tag{A3}$$

Assuming that the PUI produced very close to the Sun are convected with the solar wind flowing radially at asymptotic velocity translates into a PUI number density scaling inversely proportional with the square of the heliocentric distance

$$f(y) = \frac{1}{1 + y^2} \tag{A4}$$

This is, while simplifying, reasonable for the present estimate and yields:

$$\eta = 2 \int_0^y \frac{1}{(1 + y'^2)^2} dy' = 2 \left[\frac{y'}{2(1 + y'^2)} + \frac{1}{2} \, arctan \, y' \right]_o^y \tag{A5}$$

Finally, considering only the shell between $r = r_o = 10 r_\odot (\Rightarrow y = 0)$ and $r = 20 r_\odot (\Rightarrow y = \sqrt{300} \approx 17)$ to be contributing to the observed intensity, one finds:

$$\eta \approx \frac{17}{1 + 17^2} + arctan \, 17 \approx \frac{1}{17} + 1.51 \approx 1.6 \tag{A6}$$

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