Astron. Astrophys. 334, 337–354 (1998)

ASTRONOMY AND ASTROPHYSICS

Minor helium components co-moving with the solar wind

Daniel Ruciński[1], **Maciej Bzowski**[1], **and Hans-Jörg Fahr**[2]

[1] Space Research Centre of the Polish Academy of Sciences, Bartycka 18A, PL-00716 Warsaw, Poland
[2] Institut für Astrophysik und Extraterrestrische Forschung der Universität Bonn, Auf dem Hügel 71, D-53121 Bonn, Germany

Received 18 March 1997 / Accepted 5 January 1998

Abstract. We revisit the problem of the minor $^4\mathrm{He}$ components in the solar wind. It is shown that due to interactions of neutral interstellar atoms or interplanetary dust-desorbed atoms and molecules with the solar wind ions and with solar EUV radiation various sorts of secondary neutral and ion helium populations are produced, enriching the original content of helium species in the solar wind. Basing on numerical modeling we show that besides the well known He^+ pickup population one can expect measurable amounts of other minor constituents, such as: He^{++} pickup ions, He^+ ions of solar wind characteristics, and energetic (~ 4 keV) neutral He atoms. We provide estimates of their expected fluxes and discuss their radial variations. It is shown that the doubly charged He^{++} pickup population may typically contribute ~ 2–3% to the total helium pickup flux and it demonstrates (similarly to the He^+ pickup component) a pronounced downwind–upwind anisotropy resulting from the gravitational focusing of the interstellar helium. Similar fluxes, of the order of $\sim 10^2$–10^3 $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at 1 AU, are expected for the energetic neutral helium component, created due to the double charge-exchange between the solar wind alpha particles and the interstellar helium atoms. According to our calculations, this component may be the dominant constituent of the Neutral Solar Wind (NSW) up to distances of ~ 0.4–0.6 AU on the upwind side, ~ 0.5–1.0 AU in the sidewind direction, and even up to ~ 2–4 AU in the downwind region, depending on the phase of the solar cycle. Another minor component discussed in the paper are the 'solar' He^+ ions, with the properties inherited from the former solar wind alpha particles after their transcharge on the neutral H and He interstellar atoms or on the neutral dust-desorbed H atoms and H_2 molecules, or after their radiative recombination. It is shown that in the outer regions (beyond ~ 3–4 AU) the decharging of alphas on neutral hydrogen is the dominant source of the 'solar' He^+ ions. Their predicted abundance in the solar wind due to this mechanism remains in good agreement with recent estimates of the upper limit of the solar He^+ /He^{++} ratio determined from SWICS measurements on Ulysses carried out in 1991–1993. At smaller distances ($R < 1$–2 AU) a significant contribution to the solar He^+ abundance is expected also from other mechanisms, mainly from the radiative recombination, and closer to the Sun possibly from the decharge of alphas on dust-desorbed hydrogen atoms and molecules. Extending our calculation to the outer heliospheric regions ($R \sim 70$–100 AU) we conclude that the content of the most abundant He^+ pickup component may reach a noticeable fraction up to ~ 15–35% of the abundance of the original solar wind alphas, the 'solar' He^+ ions may contribute at ~ 1–3% of the solar wind alpha level, and the content of He^{++} pickup and neutral energetic He atoms is typically between ~ 0.5% and 1.0% of the alphas abundance.

Key words: interplanetary medium – solar wind – atomic processes

1. Introduction

The ionization state of the expanding multi-ion solar wind is considered to be mainly determined by the physical processes operating in the lower corona. The systematic decrease of the number of ionization and recombination acts with the heliocentric distances cause that beyond some small distance from the Sun (somewhat different for various ions) – typically of ~ 1.5–$5R_\odot$ – the ionization state is essentially frozen-in, and provides general information about the coronal electron temperature (Hundhausen et al., 1968; Arnaud and Rothenflug, 1985; Geiss et al., 1995b; von Steiger, 1996). Such 'freezing-in' of ionization states remains basically constant during the solar wind outflow into the interplanetary space. However, some residual ionization processes and recombination are still acting. Furthermore, interactions of the solar wind and solar EUV radiation with the gaseous and dusty matter in the interplanetary space can produce some changes in the ion abundances within the solar wind. Although they change only marginally the content of the most abundant original solar wind ions (H^+, He^{++} , e), they lead to the creation of several secondary minor components, enriching the composition of the solar wind. The most spectacular observational evidence of the existence of such newly created ions in the solar wind was the detection of the various pickup ions during AMPTE/IRM (Möbius et al., 1985,1988) and Ulysses missions (Gloeckler et al., 1993; Geiss et al., 1994). It is worth to note that despite very low abundances of the minor/secondary components monitoring of them may provide a useful tracer of

Send offprint requests to: D. Ruciński

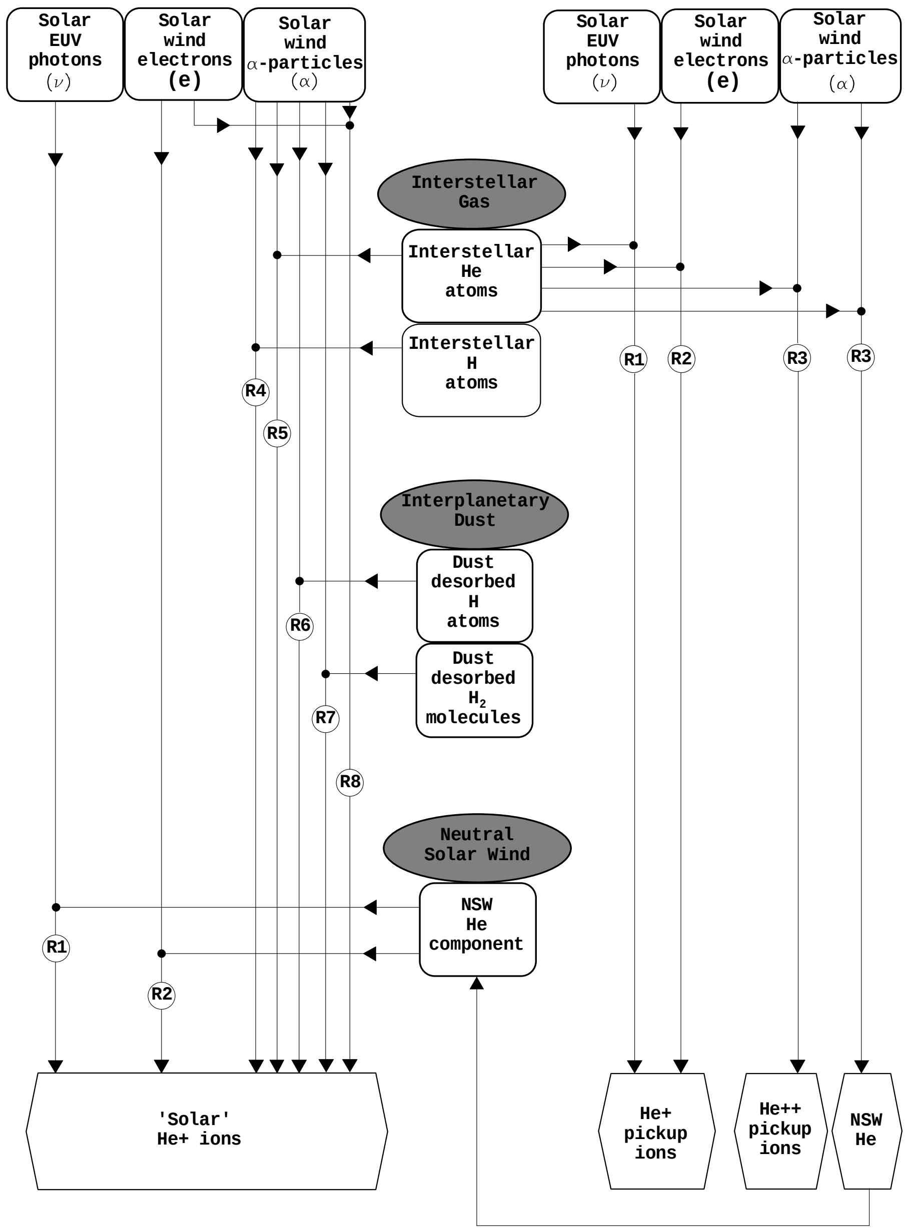

Fig. 1. The reaction diagram

various physical processes occurring in the heliosphere. In particular, the determination of their abundance may on one hand serve as a diagnostics of the temperature in the inner corona, and on the other hand it may indicate possible contributions of the non-solar sources (e.g. interstellar gas, cometary and meteoroid debris, dust grains, etc.) to their content in the solar wind (see e.g. Bochsler, 1992). As proved by recent studies related to pickup ion observations, the monitoring of such species may lead not only to the determination of densities of the relevant interstellar neutral species in the outer heliosphere (Geiss et al., 1994; Gloeckler, 1996), but, when observed continuously over a longer period of time in favourable spatial conditions, also to the derivation of temperature and velocity of the interstellar gas (Möbius et al., 1995, 1996; Möbius, 1996).

Because of the relatively high abundance of helium in the solar wind and in the interstellar wind, of the variety of possible newly-created secondary helium components, and of the observational search for such ('pickup' and 'solar') minor ions, we decide to revisit in the present paper the question of the expected enrichment of the solar wind in various $^4\mathrm{He}$ ion and neutral species. Basing on numerical modeling, in the following sections we discuss the yield of the production of He^+ and He^{++} pickup ions, the expected abundance of He neutral component in the solar wind, and several mechanisms leading to possible increase of the 'solar' He^+ abundance, including: charge-exchange of solar wind α-particles with interstellar H and He atoms, charge-exchange of alpha particles with dust-originated H and H_2 inside the Earth's orbit, radiative recombination of solar wind alphas and (photo)ionization of the helium component of the Neutral Solar Wind (NSW). A schematic overview of the whole network of the considered reactions leading to the creation of the abovementioned components is shown in Fig. 1.

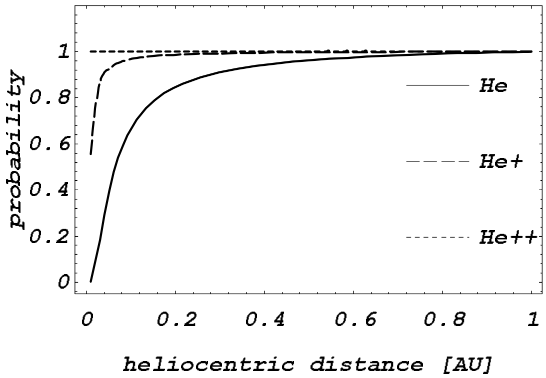

Fig. 2. Probability of the survival against the change of the charge state of the energetic He atoms, He^{+} ions, and He^{++} ions, reaching 1 AU and born at the heliocentric distance r from the Sun.

Although in this study we focus mainly on typical situations for the Earth's orbit and/or for the region penetrated by Ulysses ($\sim$ 1–5 AU), we provide also relevant estimates of the expected modifications of the helium abundance in the solar wind for the outer heliosphere – i.e. for the distances of the possible location of the termination shock ($R \sim$ 70–100 AU).

2. Method of modeling

2.1. Distribution of interstellar neutrals

Since most of the minor helium components considered in the paper originate from various ionization processes acting on interstellar neutral He and H atoms, the local distribution of these species in the interplanetary space is one of the key factors determining the production of the secondary helium components. In our approach we assume that the distribution of neutral interstellar gases is described according to the classical "hot" kinetic model (Fahr, 1971; Wu and Judge, 1979) with the modification introduced by Ruciński and Fahr (1989) allowing to include explicitly the electron impact ionization, with its rate not varying like $1/r^2$ with heliocentric distance. This process, although of secondary importance for H and He, contributing by up to $\sim 8\%$ and $\sim 15\%$ to their total ionization rate at 1 AU (Ruciński et al., 1996), correspondingly, should not be neglected in the vicinity of the Sun, because its role systematically increases with the decrease of the heliocentric distance.

The calculations reported were performed for the values of the basic interstellar neutral H and He parameters close to the termination shock (density n_∞, bulk velocity V_{B}, temperature T) and for the relevant quantities characterizing the efficiencies of the most important interactions with the solar wind plasma and EUV radiation (ionization rates β_i, radiation pressure μ) specified in Table 1. The parameters are consistent with the values determined from the studies by Bertaux et al. (1985), Quémerais et al. (1994), and Witte et al. (1996).

In the table, $\beta_{\mathrm{phot}}\,(1\,\mathrm{AU})$, $\beta_{\mathrm{ch-ex}}\,(1\,\mathrm{AU})$, and $\beta_{\mathrm{el}}\,(1\,\mathrm{AU})$ denote the photoionization, charge-exchange, and electron impact ionization rates at 1 AU, respectively, and μ is the ratio of the solar Lyman-α radiation pressure to the solar gravitational force. While the photoionization and charge-exchange rates vary like $1/r^2$ with the heliocentric distance, the electron impact rate deviates from such simple dependence. To calculate this rate at an arbitrary distance r from the Sun, we apply here the general solution for the bi-maxwellian ("core" + "halo") population of the solar wind electrons, as developed by Ruciński and Fahr (1989). Generally, it can be written in the form:

Table 1. Adopted parameters of interstellar hydrogen and helium near the termination shock

	Hydrogen	Helium
n_∞	0.14 cm^{-3}	0.014 cm^{-3}
V_{B}	20 km/s	25 km/s
T_∞	8 000 K	7 000 K
μ	1.0	0.0
$\beta_{\mathrm{phot}}\,(1\mathrm{AU})$	$1.0 \cdot 10^{-7}\,\mathrm{s}^{-1}$	$1.0 \cdot 10^{-7}\,\mathrm{s}^{-1}$
$\beta_{\mathrm{ch-ex}}\,(1\mathrm{AU})$	$4.5 \cdot 10^{-7}\,\mathrm{s}^{-1}$	negligible
$\beta_{\mathrm{el}}\,(1\mathrm{AU})$	$4.3 \cdot 10^{-8}\,\mathrm{s}^{-1}$	$1.1 \cdot 10^{-8}\,\mathrm{s}^{-1}$

$$\beta_{\mathrm{el}} = C_0\, A_1 \left[-\frac{C_1}{\alpha_1} \mathrm{Ei}\,(-\alpha_1) + \frac{G_1}{\phi_1} \mathrm{Ei}\,(-\phi_1) - \right. \\ \left. - \frac{C_2}{\alpha_2} \mathrm{Ei}\,(-\alpha_2) + \frac{G_2}{\phi_2} \mathrm{Ei}\,(-\phi_2) \right], \quad (1)$$

where the first two terms designated by index 1 correspond to the contribution from the "core" population, and the last two (with index 2) refer to the contribution from the "halo" component. Ei is the exponential integral function and, according to Ruciński and Fahr (1989), the functional dependences are defined as follows:

$$\begin{aligned} A_1 &= \frac{8\pi}{m_{\mathrm{e}}^2}, \\ C_1 &= n_{\mathrm{c}} \left(\frac{m_{\mathrm{e}}}{2\pi\, kT_{\mathrm{c}}} \right)^{\frac{3}{2}}, \\ C_2 &= n_{\mathrm{h}} \left(\frac{m_{\mathrm{e}}}{2\pi\, kT_{\mathrm{h}}} \right)^{\frac{3}{2}}, \\ \alpha_1 &= \frac{P_i}{kT_{\mathrm{c}}}, \\ \alpha_2 &= \frac{P_i}{kT_{\mathrm{h}}}. \end{aligned} \quad (2)$$

where m_{e} is the electron mass, k is the Boltzmann constant, n_{c} and n_{h} are the "core" and "halo" electron densities, T_{c} and T_{h} denote, coprrespondingly, the "core" and "halo" electron temperatures, and P_i is the ionization potential of the considered species. All remaining quantities from Eq. (1) referring to the electron impact ionization of H, He, and He^{+} are listed in the relevant columns of Table 2.

Our current numerical calculations, including computation of the electron impact rate, were performed for the conditions of a relatively slow solar wind with $V_{\mathrm{SW}} = 450$ km/s, being in good agreement with the conditions met by Ulysses during the

Table 2. Numerical values of the coefficients in the formula for electron impact ionisation

	H	He	He^+
P_i	13.6 eV	24.6 eV	54.4 eV
C_0	$4.0 \cdot 10^{-14}$	$8.0 \cdot 10^{-14}$	$4.4 \cdot 10^{-14}$
ϕ_1	$\alpha_1 + 0.56$	$\alpha_1 + 0.46$	$\alpha_1 + 0.60$
ϕ_2	$\alpha_2 + 0.56$	$\alpha_2 + 0.46$	$\alpha_2 + 0.60$
G_1	$1.050 \cdot C_1$	$1.188 \cdot C_1$	$0.692 \cdot C_1$
G_2	$1.050 \cdot C_2$	$1.188 \cdot C_2$	$0.692 \cdot C_2$

in-ecliptic phase of its mission (Phillips et al., 1995; Marsden, 1996).

The proton density at 1 AU assumed in our calculations is: $n_{\rm p} = n_{\rm e} = 6$ cm^{-3}, and the solar wind n_α / n_p ratio is equal to 0.04. Considering a spherically symmetric flow of the solar wind with the conservation of the mass flux, we adopt for the purpose of the electron impact calculations the following simple dependencies of electron density ("core" and "halo") and temperature as a function of the heliocentric distance from the Sun:

$$n_{\rm c,h}\left(r\right) = n^0_{\rm c,h} r^{-2}; \quad T_{\rm c,h}\left(r\right) = T^0_{\rm c,h} r^{-\gamma}, \tag{3}$$

where the quantities with the superscript "0" denote, respectively, the "core" and "halo" densities and temperatures at 1 AU, and distance r is expressed astronomical units (AU). According to the Ulysses observations (Scime et al., 1994) we adopt $T^0_{\rm c} = 1.3 \cdot 10^5$ K and $T^0_{\rm h} = 9.2 \cdot 10^5$ K, correspondingly. The aforementioned assumption of the total electron density at 1 AU of 6 cm^{-3}, with typical proportion of 96% for core and 4% for halo, leads to the densities: $n^0_{\rm c} = 5.76$ cm^{-3} and $n^0_{\rm h} = 0.24$ cm^{-3} for these two electron populations.

The value of the exponent γ in the temperature dependence is still known with a relatively large uncertainty for the regions inside 1 AU, where the electron impact ionization is really important. For the sake of consistency, we adopt in our calculations $\gamma = 0.394$, as determined from the Helios observations of the slow (400–500 km/s) solar wind at 0.3–1.0 AU (Marsch et al., 1989), i.e. relevant for the same range of the solar wind speed as assumed in the present study. This value is only slightly different from $\gamma = 1/3$ adopted in the earlier model calculations by Ruciński and Fahr (1989). It remains also in reasonable agreement with the range of that parameter derived from Vela, Mariner and Voyager 2 observations (Montgomery et al., 1968; Ogilvie and Scudder, 1978; Sittler et al., 1981). Outside 1 AU the adopted dependence is still in very good agreement with the slope determined recently from the Ulysses in-ecliptic observations (1.2–5.4 AU) for the "halo" component (see Scime et al., 1994). Also for the "core" component it does not deviate much from the determinations based on total data set of Ulysses thermal noise measurements performed between 1.1 and 3.3 AU (Maksimovic et al., 1996). Although, according to the Ulysses SWOOPS measurements between 1.2 and 5.4 AU, the "core" temperature seems to decrease steeper (Scime et al., 1994), we have to stress that because the electron impact effect is anyway of secondary importance and its contribution to the losses of neutrals becomes less and less significant outside 1 AU, the adopted assumption on the value of γ, even if somewhat deviates there from the result of Scime et al. (1994), it does not affect in any significant degree the results of our calculations.

Other possible ionization processes, due to their low rates, contribute only marginally (by less than 3%) to the total rate and therefore we neglect them in the present study as generally unimportant for destruction of interstellar neutrals.

2.2. Survival probability of newly created minor He species

When discussing problems of ionization in the context of production of minor helium components one should notice that ionization effects play generally a multiple role. Besides being responsible for destruction of interplanetary neutrals (reflected by the "loss rate"), they also contribute to the creation of specific types of minor constituents. Finally, they may also lead to the subsequent destruction of some fraction of these newly-born species during their outward convection with the solar wind from the place of their birth to the point of observation. While the production rates for specific components will be specified in the appropriate sections of the paper, where particular mechanisms are discussed, here we briefly analyze the survival probabilities of newly created He atoms, He^+ and He^{++} ion components against ionization and decharging processes during their outward flow with the solar wind.

The probability that a species i born at a distance r from the Sun reaches a final point R can be described as:

$$P_i = \exp\left[- \int_r^R \frac{\beta_i\left(r'\right) {\rm d}r'}{V_{\rm SW}} \right], \tag{4}$$

where $\beta_i\left(r'\right)$ is the total loss rate for the considered species at the heliocentric distance r', and $V_{\rm SW}$ is the solar wind speed, assumed in our calculation to be constant and equal to 450 km/s, and thus reflecting the slow solar wind regime.

For the helium component of the Neutral Solar Wind (NSW) and for the original neutral interstellar helium, the relevant ionization rates $\beta_i\left(r'\right)$, consisting mainly of the contributions due to photoionization $\beta^{\rm He}_{\rm phot}$ and the electron impact effect $\beta^{\rm He}_{\rm el}$, are just identical. Thus the probability of survival of an NSW He atom can be described as:

$$P^{\rm He} = \exp\left[- \int_r^R \frac{\beta^{\rm He}_{\rm phot}\left(r'\right) + \beta^{\rm He}_{\rm el}\left(r'\right)}{V_{\rm SW}} {\rm d}r' \right]. \tag{5}$$

The combined loss rate at 1 AU is equal to $\sim 1.1 \cdot 10^{-7}\,{\rm s}^{-1}$, according to the values listed in Table 1. In the case of newly-born He^+ ions (either of pickup or 'solar' type) main contributions to their losses come also from photoionization and electron impact effects. Using the approximate formula for the photoionization cross-section of He^+ given by Verner et al. (1996):

$$\begin{aligned} &\sigma(E) = \sigma_0 F(y), \quad y = \frac{E}{E_0}, \\ &F(y) = (y-1)^2 \, y^{0.5P-5.5} \left(1 + \sqrt{y/y_a}\right)^{-P}, \end{aligned} \tag{6}$$

where E is the photon energy in eV and $\sigma_0 = 1.369 \cdot 10^{-14}\ \mathrm{cm}^2$, $E_0 = 1.720$ eV, $y_a = 3.288 \cdot 10^1$, $P = 2.963$ are the fit parameters tabulated by Verner et al. (1996) in their Table 1, one can compute the expected photoionization rate $\beta_{\mathrm{phot}}^{\mathrm{He}^+}$. In typical conditions its value at 1 AU is about $9.0 \cdot 10^{-9}\ \mathrm{s}^{-1}$. Similarly to the case of neutral helium, one can compute the electron impact rate for He^+ ions. Now, using the cross-section formula from Lotz (1967), one can apply the general form of the solution by Ruciński and Fahr (1989) given by Eq. (1) with the values from Table 2 corresponding to the He^+ case.

The calculated electron impact rate $\beta_{\mathrm{el}}^{\mathrm{He}^+}$ for He^+ at 1 AU for the assumed solar wind conditions is about $5.7 \cdot 10^{-10}\ \mathrm{s}^{-1}$, i.e. about 6.5% of the photoionization rate for this species.

The probability of survival of He^+ ions can be given by the following formula:

$$P^{\mathrm{He}^+} = \exp\left[-\int_r^R \frac{\beta_{\mathrm{phot}}^{\mathrm{He}^+}(r') + \beta_{\mathrm{el}}^{\mathrm{He}^+}(r')}{V_{\mathrm{SW}}} \mathrm{d}r'\right]. \tag{7}$$

As it results from a straightforward comparison of the relevant total loss rates for neutral He and He^+ ions, the latter one is smaller from the former by about one order of magnitude. Thus, only a very small fraction of the newly-born He^+ ions can be lost due to the ionization from the place of their birth to the observer located in the inner heliosphere. It has also to be pointed out that He^+ ions may also be lost due to recombination processes. As discussed by Burgess (1962), the dielectronic recombination dominates over the radiative recombination for this species. One can prove, however, that for the recombination coefficient of the order of $10^{-12}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$ (Burgess, 1962), relevant for the range of electron temperatures 10^5–10^6 K, typical for the properties of the solar wind electrons inside 1 AU, this mechanism is significantly less efficient than the photoionization and electron impact. Therefore we ignore it in our considerations of the He^+ losses.

The newly created He^{++} (pickup) ions cannot be further ionized. They can only be destroyed in single or double charge-exchange processes with neutrals or due to recombination. Because the density and flux of newly-born He^{++} ions are much smaller than the density and flux of original solar wind α particles (typically by 4–5 orders of magnitude at 1 AU), the combined rate for all these processes is extremely low, not exceeding $10^{-13}\ \mathrm{s}^{-1}$ at 1 AU. In this context, because the travel time throughout the whole heliosphere is of the order of ~ 1 year ($\sim 3 \cdot 10^7$ s), one can safely assume that practically 100% of newly created He^{++} ions will reach any observational point inside the Solar System.

Therefore, for the purpose of the present study we just assume that the probability of survival of the newly-created He^{++} ions is following:

$$P^{\mathrm{He}^{++}} = 1. \tag{8}$$

The probabilities that an He atom, He^+ ion, and He^{++} ion, born at a distance r from the Sun, will reach the observer at 1 AU are shown in Fig. 2. It is evident that He^{++} and He^+ do not suffer any significant losses (more than 95% of He^+ ions born at 0.1 AU can reach 1.0 AU). Somewhat higher losses are expected in the case of newly-created energetic neutral He atoms, but also in this case a vast majority of atoms ($\sim 65\%$ of those born at 0.1 AU and more than 90% of those born at 0.3 AU and outwards) withstands ionization before reaching 1.0 AU.

3. Helium pickup ions

Amongst all minor $^4\mathrm{He}$ populations in the solar wind, the most abundant and the best known is the population of helium pickup ions, originating due to the ionization of the neutral interstellar helium gas. Predictions that such a mechanism supplies He^+ ions to the solar wind (see e.g. Holzer and Axford, 1971; Vasyliunas and Siscoe, 1976) were confirmed by the first direct detection of the He^+ pickup ions in the solar wind by SULEICA measurements onboard AMPTE/IRM spacecraft (Möbius et al., 1985, 1988), as well as by recent SWICS observations on Ulysses (Gloeckler et al., 1993; Gloeckler, 1996). As recently shown by Möbius et al. (1995,1996) and Möbius (1996), the interpretation of a continuous monitoring of He^+ pickup ion data, covering the region of the helium gravitational cone and its flanks, with the use of appropriate theoretical models may be a useful tool for the determination of several interstellar helium parameters. The Ulysses SWICS measurements led also to the detection of a minor He^{++} pickup component in the solar wind (see e.g. Gloeckler, 1996; Gloeckler et al., 1997), confirming, in general, earlier theoretical predictions of the non-negligible amount of such species by Ratkiewicz et al. (1990). Since the extensive theoretical modeling of the He^+ pickup fluxes, including several subtle effects, have been performed in recent time (see e.g. Fahr and Ruciński, 1989; Ruciński and Fahr 1991; Ruciński et al., 1993), we present here only a concise summary of the expected He^+ pickup characteristics and abundances, providing more quantitative estimates on the less known He^{++} pickup ion population.

The He^+ pickup population originates mainly due to the photoionization and electron impact (important inside $\sim$ 1–2 AU) of interstellar helium, i.e. from the following reactions:

(R1) He + photon → He^+ + e (with ionization rate $\beta_{\mathrm{phot}}^{\mathrm{He}}$ from Table 1)

(R2) He + e → He^+ + 2e (with ionization rate $\beta_{\mathrm{el}}^{\mathrm{He}}$ as in Table 1 and discussed in Sect. 2.1)

The production channel of He^{++} pickup ions is basically the reaction of double charge-exchange between the neutral He atoms and the solar wind α-particles which follows:

(R3) He + α → He^{++} + He

The approximate cross section's dependence on the relative velocity v in the range from 300 to 850 km/s, fitted to the data from Barnett et al. (1990), can be represented by the following formula: $\sigma_3(v) = 5.25357 \cdot 10^{-16} + 3.89461 \cdot 10^{-18} \ln v - 8.20517 \cdot 10^{-18} (\ln v)^2$, where the cross section is given in cm^2 and the velocity in km s^{-1}.

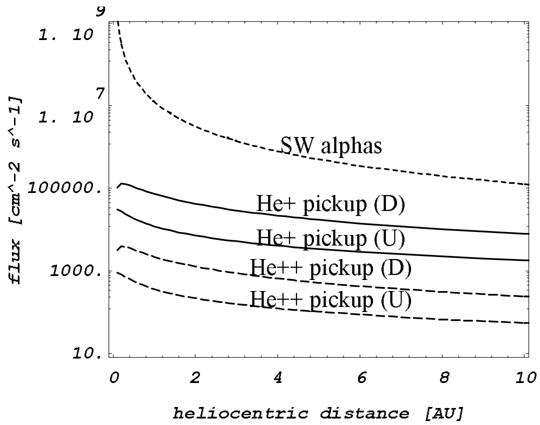

Fig. 3. Comparison of the expected absolute fluxes of the original solar wind α-particles, He^+ pickup ions, and He^{++} pickup ions. The flux of the solar wind α-particles is assumed to be isotropic, the fluxes of the latter two species are presented for the upwind (U) and downwind (D) directions.

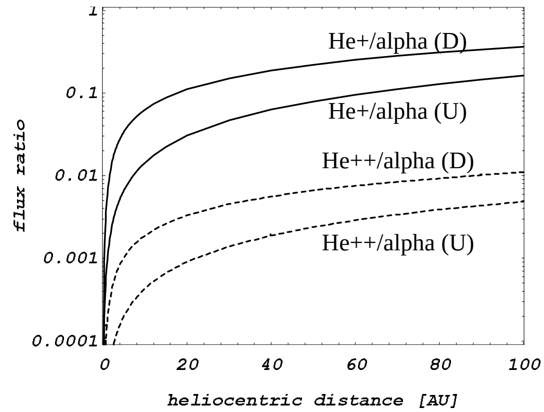

Fig. 4. Ratios of the fluxes of He^+(pickup)/α(sw) and He^{++}/α(sw), as a function of the heliocentric distance r for the downwind (D) and upwind (U) axes.

For the solar wind conditions assumed ($n_\alpha\,(1\ \mathrm{AU}) = 0.24\ \mathrm{cm}^{-3}$, i.e. 4% of the proton density; $V_{\mathrm{SW}} = 450$ km/s), multiplying the resulting solar wind α-flux at 1 AU of $1.08 \cdot 10^7\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ with the value of the appropriate cross-section of about $2.45 \cdot 10^{-16}\ \mathrm{cm}^2$ (Barnett et al., 1990), one obtains the production rate of He^{++} pickup ion component $\beta^{\mathrm{He}}_{\mathrm{dcx}}\,(1\ \mathrm{AU}) = 2.65 \cdot 10^{-9}\,\mathrm{s}^{-1}$. While the process (R3) contributes only less than 3% to the total loss rate of helium (see Table 1), and thus in terms of the destructive efficiency of neutrals can be practically neglected in comparison to photoionization and electron impact, it remains still the basic source of the He^{++} pickup ion component.

As it is evident from the comparison of the formulae for the expected fluxes of He^+ and He^{++} pickup ions, given below:

$$F^{\mathrm{He}^+}_{\mathrm{pup}}\,(R,\theta) \;=\; \int_{R_\odot}^{R} n^{\mathrm{He}}\,(r,\theta)\,\big[\beta^{\mathrm{He}}_{\mathrm{phot}}\,(r) \;+\; \beta^{\mathrm{He}}_{\mathrm{el}}\,(r)\big]\left(\frac{r}{R}\right)^2 P^{\mathrm{He}^+}\,(r)\ \mathrm{d}r, \qquad (9)$$

$$F^{\mathrm{He}^{++}}_{\mathrm{pup}}\,(R,\theta) = \int_{R_\odot}^{R} n^{\mathrm{He}}(r,\theta)\ \beta^{\mathrm{He}}_{\mathrm{dcx}}(r)\left(\frac{r}{R}\right)^2 P^{\mathrm{He}^{++}}(r)\ \mathrm{d}r \qquad (10)$$

where P^{He^+} and $P^{\mathrm{He}^{++}}$ are the relevant survival probabilities of these newly created species as defined in Eqs. (7) and (8), if one neglects minor differences in survival probabilities P^{He^+} and $P^{\mathrm{He}^{++}}$ (see Fig. 2), the He^+/He^{++} pickup flux ratio is closely related to the ratio of the relevant production rates, "averaged" over the integration path, which for the conditions assumed is ~ 40. Since both pickup species are created from the same neutral (He) background, all characteristic spatial features of their expected fluxes are similar. As shown in Fig. 3, the expected fluxes of He^+ at 1 AU varies from $\sim 10^4\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at the upwind side to $\sim 10^5\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ in the downwind direction, and correspondingly from $3.5 \cdot 10^2\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ to $2.2 \cdot 10^3\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for the He^{++} pickup component. The maximum of the expected flux is located well inside 1 AU, typically around ~ 0.1–0.2 AU. The spectacular downwind/upwind flux anisotropy (reaching factor of ~ 6 at 1 AU) results from the strong gravitational focusing of interstellar helium. It slowly diminishes with the heliocentric distance, but remains still clearly pronounced even far away from the Sun (factor of ~ 4.5 at 10 AU and ~ 2 at 100 AU).

It is beyond the scope of the present study to investigate thoroughly the expected time-variability due to the solar cycle effects. Nevertheless, because of a relatively weak influence of the change of the loss rate on neutral helium distribution in the upwind hemisphere, one may expect that at ~ 2 AU and beyond, the He^+ pickup flux, determined mainly by the efficiency of photoionization, will be correlated with the solar activity and should vary somewhat weaker than the typical variations of the photoionization rate for helium, that typically reach factor of ~ 3 from minimum to maximum (see e.g. Ruciński et al., 1996). On the other hand, the higher depletion of neutral helium during solar maximum (due to higher photoionization), when combined with somewhat lower solar wind α-flux (Schwenn, 1983), may result in the opposite behaviour of the He^{++} temporal variability. While the production of He^+ pickups, determined mainly by photoionization, is only marginally dependent on the type of the solar wind (Ruciński and Fahr, 1991), such dependence for the He^{++} constituent may be more clearly visible. As it results from the Helios data, supported also by recent Ulysses out-of-ecliptic observations (Schwenn, 1990; Marsden, 1996; Barraclough et al., 1996), the decrease by $\sim 30\%$ of the proton flux at high speed (~ 750 km/s) solar wind regime in comparison to the slow (~ 450 km/s) solar wind case may be approximately compensated by the higher relative abundance of alpha particles in the similar amount. However, since in the same time the relevant cross-section for the double charge-exchange reactions decreases by $\sim 30\%$ (Barnett et al., 1990) (see also Fig. 8), the absolute production of the He^{++} pickup ions may be somewhat lower in the high speed solar wind conditions. The ratio of the fluxes of newly created He^{++} pickup ions to the original solar wind α-particles is practically independent on the value of the flux of alphas but it still remains a function of the value of the solar wind velocity, which moderately influences the value of the double charge-exchange cross section, as mentioned above.

While moving outwards to the larger heliocentric distances, one can expect a systematic, substantial increase of the relevant He^{+}(pickup)/α(sw) and He^{++}(pickup)/α(sw) ratios. As shown in Fig. 4, the relative abundance of the He^{+} pickups in comparison to the original alpha particles exceeds 1% already at ~ 10 AU, and finally may reach even $\sim$ 15–35% at ~ 100 AU, depending on the angular distance from the upwind direction. At the same large distances the He^{++} (pickup)-to-solar wind alpha abundance ratio is around 0.5–1%. Another interesting point, related to the He^{++} pickup constituent, is the fact that it seems to be the only relatively abundant multiply charged population of pickup ions. Its expected flux in the outer heliosphere ($R \sim 100$ AU), being in the range of 5–10 $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, although much smaller than the fluxes of He^{+} and H^{+} pickup ions, may be still comparable to the one of O^{+} pickup ions (Ruciński et al., 1993). The latter ones were detected for the first time by SWICS instrument on Ulysses operating inside ~ 5 AU (Geiss et al., 1994) and shown to be the most abundant amongst heavy pickup ion species. Since the pickup ions are commonly considered to be a "seed" population for the Anomalous Cosmic Ray (ACR) component, our study indicates that one may expect a non-negligible ACR He^{++} population. Such fact may be especially true if the acceleration of the He^{++} at the shock works more efficiently than for He^{+} .

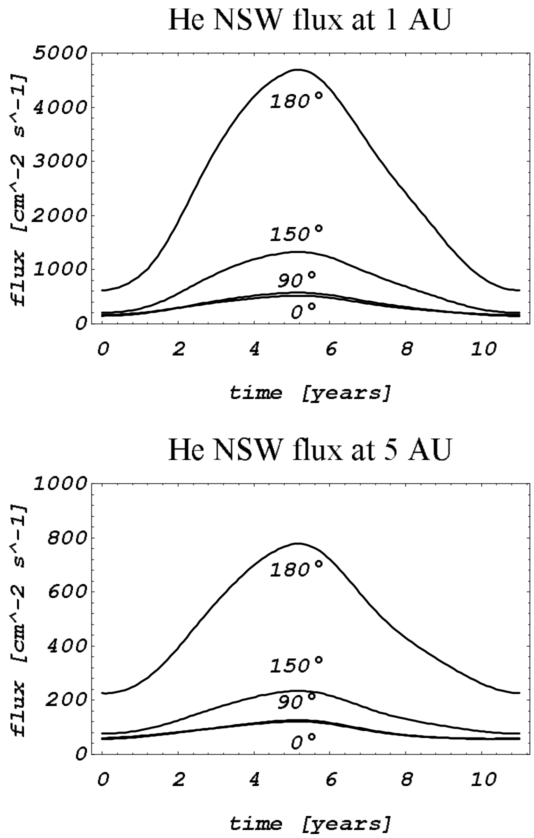

Fig. 5. Expected evolution of the NSW He flux at 1 AU (upper panel) and at 5 AU (lower panel) during the 11-year solar cycle for the upwind (0°), sidewind (90°), 150° from upwind, and downwind (180°) directions. Time = 0 corresponds to the solar maximum phase.

4. Neutral helium component of the solar wind

The Neutral Solar Wind (NSW) originating due to the charge-exchange between interstellar neutrals and solar wind ions is most often identified as a population of energetic (~ 1 keV) hydrogen atoms convected outwards with the solar wind flow (see e.g. Błeszyński et al., 1992). The hydrogen component is by far the dominant one globally in the NSW, and eventually in the vicinity of the termination shock it may constitute even ~ 10% of the solar wind composition (Grzędzielski and Ruciński, 1990). However locally, up to few AU, as already briefly pointed out by Gruntman (1994) and Bzowski and Ruciński (1996), the NSW may contain a noticeable amount of energetic He atoms. In view of the characteristics of the differential charge-exchange cross section, it is commonly accepted that the distribution function of the NSW species should generally reflect the properties of the solar wind ions (protons or α-particles) from which the considered NSW components (NSW H or NSW He, respectively) originated. This means a relatively narrow, "thermal" distribution centered at the velocity of the solar wind, with a sharp directional decrease of its value with the offset angle from the direction of the solar wind flow. Although up-to-now no measurements of the ~ 1 keV NSW components in interplanetary space have been available, so the postulated predictions still require experimental verification, the general concepts of their direct detection was elaborated many years ago (for details see Gruntman et al. (1990) and references therein). The detectability of this minor component seems to be essentially feasible by the fact that the dominant charged solar wind particles can be deflected by a magnetic device and thus do not reach the detector. Moreover, the combination of the special baffle device suppressing the contamination by the direct solar UV photons, and the coincidence technique enabling separation of the potential signals induced by the background UV and by the NSW atom provide favourable conditions for the NSW detection.

Since our study is devoted to various minor helium species, in the present section we examine the expected supply of the energetic neutral He component to the solar wind.

The production of neutral He component is determined by the same mechanism as the creation of He^{++} pickup ions, namely the double charge-exchange between interstellar helium atoms and solar wind alpha particles (reaction R3), and all contributions from other processes (such as recombination of He^{+}) can be neglected. Thus, the expected flux distributions of NSW He atoms and He^{++} pickup ions should be almost identical. The only difference is the fact that while newly born He^{++} pickup ions are practically not affected by the interactions with neutral species on their way from the place of birth to the observer (i.e. the probability of their survival is about 100%, as demonstrated

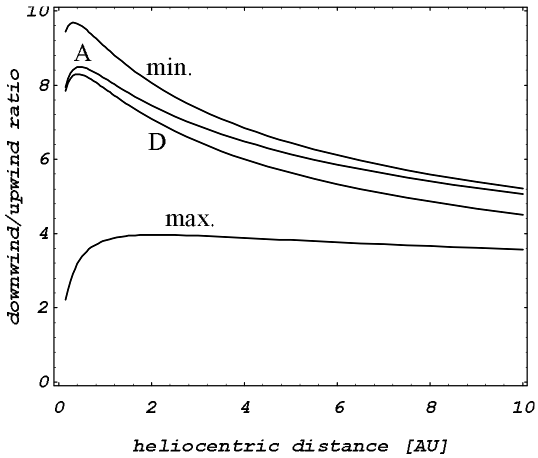

Fig. 6. Variations of the downwind/upwind NSW He flux ratio for four phases of the solar cycle: solar minimum, solar maximum and two intermediate phases. Phase D corresponds to the middle of the descending period between maximum and minimum, phase A - to the middle of the ascending interval between solar minimum and maximum.

in Fig. 2), some small fraction of the energetic neutral He atoms may be lost due to the photoionization and electron impact.

Therefore, to compute the expected NSW He flux in the inner Solar System, we employ Eq. (10) with one modification in the integrand, namely the probability of survival of He^{++} pickup ions $P^{He^{++}}$, set equal to 1, is now replaced with the probability of survival of energetic He atoms described by P^{He} defined by Eq. (5):

$$F_{\mathrm{NSW}}^{\mathrm{He}}\left(R,\theta\right)=\int_{R_{\odot}}^{R} n^{\mathrm{He}}(r,\theta)\;\beta_{\mathrm{dcx}}^{\mathrm{He}}(r)\left(\frac{r}{R}\right)^{2}P^{\mathrm{He}}(r)\;\mathrm{d}r. \quad (11)$$

This minor change does not change the general conclusion that the behaviour of the pickup He^{++} and NSW He fluxes is very similar. For the "average" stationary situation with the interstellar wind and solar wind parameters assumed, the expected flux at 1 AU varies from $\sim 350\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ in the upwind hemisphere and along crosswind direction to $\sim 2100\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ on the downwind axis, indicating a strong downwind–upwind anisotropy that reaches a factor of ~ 6. When moving outwards, the total NSW He flux and the degree of anisotropy are systematically decreasing. Nevertheless, the anisotropic structure remains noticeable even at large heliocentric distances ($R = 80$–100 AU), where the expected downwind/upwind flux ratio is still about 2. Similarly as in the He^{++} pickup ion case, the relative abundance of NSW He component in the solar wind slowly increases with the distance from the Sun, and at the regions of the expected termination shock, the He(NSW)/α(sw) ratio varies from about 0.4 to 1.0% at the upwind and downwind directions, respectively. An interesting question is the variability of the expected NSW He fluxes during the solar cycle. On one hand, it results mainly from the large temporal variations of the photoionization rate, typically by a factor of 3 from minimum to maximum (Ruciński et al., 1996), what affects the neutral He distribution in the inner heliosphere. On the other hand, it depends also to some extent on the variability of the content of the solar wind alpha flux in the solar wind (Schwenn, 1983), and on the cross-section dependence on the solar wind speed, affecting the NSW He production rate. Using the time-dependent model of helium density distribution developed by Fahr et al. (1987) for the case of realistic range of variabilities of the helium ionization rate between solar maximum and minimum and adopting temporal variabilities of the alpha abundance and solar wind flux from Helios measurements (Schwenn, 1983), we calculated the expected evolution of the NSW He flux in the inner heliosphere during the 11-year solar cycle.

As presented in Fig. 5, one can expect a significant modulation of the NSW He flux at 1 AU, especially pronounced for the downwind region, where the flux reaches maximum value. Higher fluxes (up to $\sim 5000\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ in the downwind region and $\sim 500\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ on the upwind side) are expected during solar minimum conditions, whereas at solar maximum, when neutral interstellar helium is more effectively ionized, the NSW He fluxes attain their minimum values ($\sim 600\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and $\sim 150\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, correspondingly). As a consequence, the degree of downwind–upwind anisotropy shown in Fig. 6 for distances $R < 10$ AU may significantly vary during the solar cycle, being anticorrelated with the solar activity. Nevertheless, at any considered conditions the downwind–upwind anisotropy is clearly pronounced, always exceeding a factor of ~ 3 at 10 AU. Comparing the NSW He fluxes for solar minimum, solar maximum and intermediate epochs with the expected fluxes of the NSW hydrogen atoms obtained in time-dependent approach by Bzowski and Ruciński (1996), one can estimate the relative contribution of the NSW He component to the total NSW flux. As shown in Fig. 7, the region where energetic helium component dominates expands with the increase of the offset angle from the upwind direction. Along the upwind axis helium is the dominant constituent of the NSW only inside ~ 0.4–0.6 AU, depending on the phase of the solar cycle, but its contribution drops below 10% already at 1 AU. In the sidewind direction ($90°$ from the apex) the NSW H and NSW He fluxes become comparable at 1 AU during solar maximum epoch. In the downwind region the dominance of helium in the content of the NSW is evident for all distances smaller than 2–4 AU, depending on the activity phase. This behaviour and the characteristics of a detector proposed by Gruntman et al. (1990), which would be able to register ~ 3 keV atoms (for instance slow NSW He) with the efficiency one order of magnitude higher than ~ 600 eV atoms (slow NSW H), determine the contribution of NSW He to the expected NSW signal. In these conditions, comparable signals from the more numerous NSW H atoms and from the more-readily detected NSW He atoms would be registered in the upwind hemisphere by the detector aboard an Earth-bound satellite. When moving the detector towards the downwind region, the contribution of the helium component to the expected signal systematically increases. Finally, in December, when the Earth crosses the downwind axis, the registered NSW signal would be very strongly dominated by the helium component owing to a) much higher value of the absolute NSW He flux

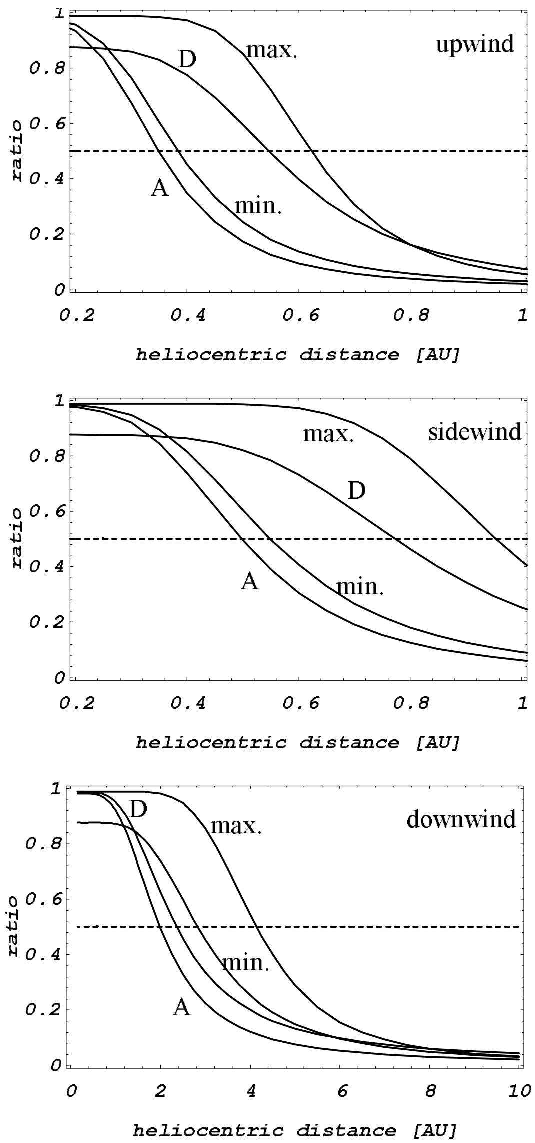

Fig. 7. Relative contribution of the NSW He component to the total flux of the Neutral Solar Wind at four phases of the solar cycle (the same as in Fig. 6) as a function of the heliocentric distance. The upper panel corresponds to the situation along the upwind direction, the middle one – along the sidewind direction, and the lower one – along the downwind axis. The horizontal dashed level corresponds to the exact balance between NSW He and NSW H fluxes.

than of the NSW H flux, and b) significantly higher efficiency of the detection. Therefore these orbital conditions seem to be optimum for the successful detection and clear identification of the NSW He.

5. Mechanisms of production of the 'solar' $^4\mathrm{He}^+$ ions

The He^+ pickup ions discussed in Sec. 3 are generally the most abundant population amongst all secondary components of $^4\mathrm{He}$ in the solar wind. This component of interstellar origin, distinguishable from the original solar wind He^+ ions by its characteristic distribution with the cut-off at energies corresponding to $2V_{\mathrm{SW}}$, does not represent the only form of $^4\mathrm{He}^+$ ions in the solar wind. According to the equilibrium models of the expanding $\sim 1.0 \cdot 10^6$ K solar corona, one may expect an original remnant solar $^4\mathrm{He}^+$ component with the typical ratio He^+ / He^{++} of $\lesssim 10^{-5}$ for the normal solar wind conditions (Tucker and Gould, 1966; Kozlovsky, 1968; Arnaud and Rothenflug, 1985). An extensive search to identify this species and to determine its relative abundance was initiated in 1970's on the basis of the solar wind observations from IMP-7, IMP-8, ISEE-1, ISEE-3, and Helios-1 spacecraft (Schwenn et al., 1980; Gosling et al., 1980; Zwickl et al., 1982). This search led, however, only to the identification of few occasional events of unusually high $^4\mathrm{He}^+$/$^4\mathrm{He}^{++}$ ratio in the range of 10^{-3} – 0.3. It was recognized that these sporadic events were associated with the eruptive prominences or other solar transients, when a parcel of chromospheric plasma might escape being only partially ionized during its convection through the corona. Since such spectacular events associated with coronal ejections were rare, the high ratios derived did not represent the typical value of the solar He^+ relative abundance in the quiet solar wind. The only estimate from that epoch for the steady state solar wind was given by Feldman et al. (1974) basing on the Vela-5 and Vela-6 measurements performed at 1 AU on June 23, 1969; May, 27, 1970; September 27 1970; and September 11, 1971. The upper limit for the $^4\mathrm{He}^+$ / $^1\mathrm{H}^+$ ratio, derived from these observations, was found to be $2.5 \cdot 10^{-6}$, what for the typical 4% abundance of the solar wind alpha particles can be translated to the $^4\mathrm{He}^+$/ $^4\mathrm{He}^{++}$ ratio of about $6.2 \cdot 10^{-5}$ at 1 AU. The value derived, somewhat higher than the values predicted by coronal equilibrium theories, could have been taken as indicative of possible enhancement of the solar He^+ abundance. Since this determination referring to the quiet solar wind was put under question (Holzer, 1977), the early observations of He^+ ought to be classified as rather inconclusive and it became obvious that more sophisticated ion mass spectrometers were required for a reliable determination of the typical solar He^+ content.

The most recent search for the 'solar' $^4\mathrm{He}^+$ was undertaken during the Ulysses mission on the basis of the solar wind observations performed by the SWICS instrument. The determination of the abundance of the He^+ ions of the solar wind characteristics is intrinsically difficult because the distribution function of these ions cannot be separated in a straightforward way from the contriburtions to the data from other ions with the mass to charge ratio $M/Q = 4$. Essentially, it is swamped by the contributions from $^4\mathrm{He}^+$ pickup ions, and heavy solar wind ions with $M/Q = 4$, like $^{28}\mathrm{Si}^{7+}$, $^{24}\mathrm{Mg}^{6+}$, $^{56}\mathrm{Fe}^{+14}$ (see Mall et al., 1997). The enhanced mass resolving capabilities of the SWICS instrument (Gloeckler et al., 1992), which uses a time-of-flight (TOF) unit and a solid state detector system, allow, however, to disentangle to a large extent the contributions of the heavy solar ions. This is due to the fact that a portion of all heavy ion species is directly detected as a triple coincidence events. Since from ground and in-flight calibrations the fraction of the double to triple coincidence events for heavy ions is known, it is possible to estimate the amount of heavy ions which are detected as double coincidence events and to correct the double coin-

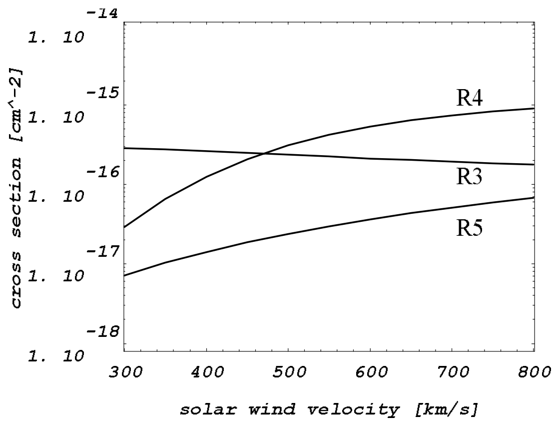

Fig. 8. The cross-section dependence as a function of the solar wind velocity. The curves correspond to the double charge-exchange between α-particles and He atoms (reaction R3), to the charge-exchange between α-particles and neutral H atoms (reaction R4), and to the charge-exchange between α-particles and neutral He atoms (reaction R5), as marked at the figure.

cidence events in the M/Q range around 4 by the appropriate count numbers. By doing so, one can come up with an estimate of an upper limit for the signal produced by $^4\mathrm{He}^+$ ions. An additional constraint on this contribution may be also extracted from the observed abundances of various charge states of the relevant heavy ions and their comparison with the theory (U. Mall – private communication, 1997). What concerns the $^4\mathrm{He}^+$ pickup ion contribution to the considered signal, it can be inferred from their observed characteristic velocity distribution. Basing on the direct measurements of the He^+ pickup spectra available for $w < 0.8$ and $w > 1.2$, where $w = v_{\mathrm{ion}}/v_{\mathrm{SW}}$, analyzing their shape one can estimate by interpolation also the amount of the He^+ pickup ions being in the range $0.8 < w < 1.2$, typical for the original, thermal 'solar' He^+ component. Combining the measured and the estimated contributions, one can finally infer the total contribution of the $^4\mathrm{He}^+$ pickup component to the apparent $^4\mathrm{He}^+$ signal. This methodology, allowing to assess reasonably well the contamination by the heavy solar wind ions with $M/Q = 4$ and by the He^+ pickup ions, when applied to the analysis of the SWICS solar wind data, provided more favorable opportunities to search for 'solar' He^+ component in comparison to the old instrument used in the past. One has, however, still to keep in mind that the procedure of removing all contaminations is very difficult and the results partially depend on the estimations involved. Therefore the uncertainty of the determination of the 'solar' He^+ abundance still seems to be quite large. The preliminary estimate by Geiss et al. (1992) from a 6-day observational period by Ulysses, has recently been supported by a more advanced study by Mall et al. (1997) based on long-term Ulysses observations covering an extended period 1991–1993. The new estimate of the upper limit of the $^4\mathrm{He}^+/^4\mathrm{He}^{++}$ ratio, averaged over the whole abovementioned period, was equal to: $(2.4 \pm 2.1) \cdot 10^{-4}$.

The fact that this value, being averaged over the period when the Ulysses heliocentric distance from the Sun was within the range of ~ 1.5–5.4 AU is significantly higher than the results expected from equilibrium calculations for a 10^6 K-corona (approximately by one order of magnitude) and also higher than the upper limit determined from Vela observations carried out at 1 AU (Feldman et al., 1974) stimulated us to perform a theoretical study of various physical mechanisms which either locally or in a more global scale may supply ions with such characteristics to the solar wind and thus may potentially contribute to the possible enhancement of the abundance the solar $^4\mathrm{He}^+$. Up to now neither the value obtained by Mall et al. (1997) nor the earlier estimate by Feldman et al. (1974), giving only upper limits of the solar He^+ abundance, do permit a clear, definite answer whether this systematic enrichment is present or not. However, we feel that such a hypothesis seems plausible and it merits careful consideration in the interpretation of the future data related to the solar He^+ abundance. We want to emphasize that in the present section we analyze only the processes producing the He^+ ions with the solar wind characteristics, and not just singly-charged helium pickup ions considered previously. The quantitative study of this problem was rather scarce and essentially limited only to the analysis of one possible mechanism, namely the charge-exchange between solar wind alphas and neutral H atoms (Hundhausen et al., 1968; Gruntman, 1992). Therefore, we revisit this question in a more extended way. In the subsequent subsections we will discuss the expected contribution to the enrichment of the solar wind in He^+ component from various processes such as: the charge-exchange between the solar wind alpha particles and neutral interstellar H and He atoms (Sec. 5.1), similar transcharge on dust-originated neutral H and H_2 inside the Earth's orbit (Sec. 5.2), ionization of the NSW He atoms (Sec. 5.3), and finally due to radiative recombination of the solar wind alpha particles (Sec. 5.4).

5.1. Solar He^+ ions as a result of charge-exchange between interstellar H and He neutral atoms and solar wind alpha particles

Here we discuss the expected production of the solar He^+ ions from the interactions of the solar wind alpha particles with the interstellar neutral gas inflowing into the Solar System. While the He^+ and H^+ pickup ions are created mainly due to the photoionization of He atoms and the charge-exchange between interstellar H atoms and the solar wind protons, respectively, both processes being the main loss processes destroying these species and affecting the local distribution of He and H, the solar wind He^+ ions can originate from the following two reactions, rarely taken into account in the studies related to the interstellar gas, namely:

(R4) $\mathrm{He}^{++} + \mathrm{H} \rightarrow \mathrm{He}^+ + \mathrm{H}^+$,

(R5) $\mathrm{He}^{++} + \mathrm{He} \rightarrow \mathrm{He}^+ + \mathrm{He}^+$.

The approximate formulae for the cross-sections' dependences on the relative velocity v in the range from 300 to 850 km/s, fitted to the data from Barnett et al. (1990), can be expressed in the general form of a modified power law as follows: $\sigma(v) = 10^{B_0 + B_1 v + B_2 v^2 + B_3 v^3 + B_4 \ln v}$. The values of coeffi-

Table 3. Coefficients of the formulae for charge exchange cross-sections of α particles with H and He atoms

	B_0	B_1	B_2	B_3	B_4
Reaction (R4)	-40.4341	$7.99583 \cdot 10^{-3}$	$1.82801 \cdot 10^{-6}$	0.0	4.5802
Reaction (R5)	-21.5441	$3.55675 \cdot 10^{-3}$	$-4.28137 \cdot 10^{-6}$	$1.61638 \cdot 10^{-9}$	0.651666

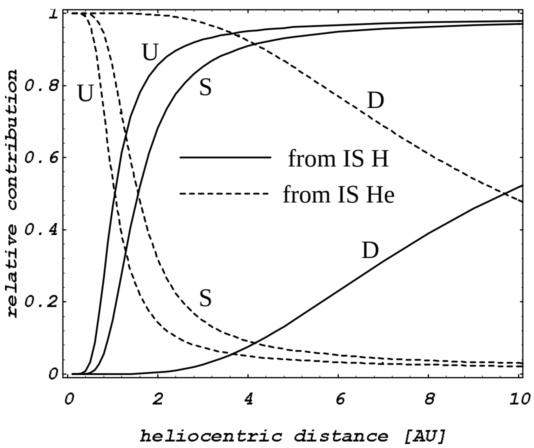

Fig. 9. The relative contributions of the reactions R4 (solid curves) and R5 (dashed curves) to the total production of solar He^+ ions due to charge-exchange between solar wind α-particles and neutral interstellar H and He atoms as a function of the heliocentric distance for the upwind (U), sidewind (S), and downwind (D) directions.

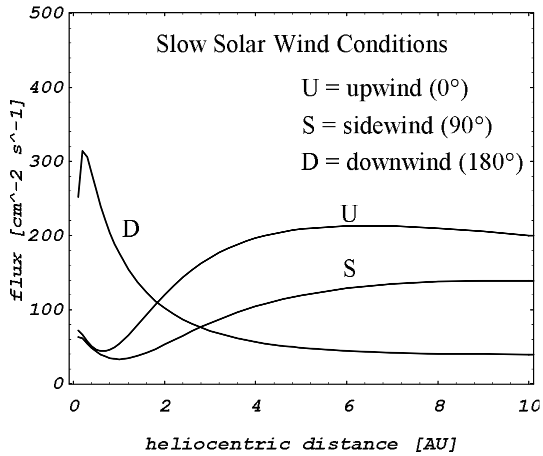

Fig. 10. Total expected fluxes of solar He^+ ions resulting from charge-exchange of solar wind α-particles and interstellar H and He atoms (reactions R4 and R5) along upwind (U), sidewind (S) and downwind (D) directions as a function of heliocentric distance.

cients B_i relevant for the reactions (R4) and (R5) are listed in Table 3, and the dependences considered are displayed in Fig. 8.

This fit returns values of the relevant cross-sections in cm^2 for the velocities specified in km/s with the accuracy better than 10%.

As a result of these charge-exchange reactions the original solar wind alpha particles are converted to He^+ ions. In particular, the first process (reaction R4), involving interstellar hydrogen, was firstly considered by Hundhausen et al. (1968), but their estimate of the resulting abundance of He^+ was affected by unrealistic assumptions on the density of interstellar hydrogen atoms and led to substantial overestimation of the resulting He^+ abundance. Later, this problem was revisited by Gruntman (1992), who provided more accurate estimates of the efficiency of prodution via channel R4. Actually, we extend this analysis by including also the transcharge of He atoms (reaction R5), discussing in more detail whether and where these mechanisms can potentially lead to a non-negligible increase of the solar He^+ ion abundance and comparing its predicted range with the values of the upper level of He^+ / He^{++} ratio reported from the aforementioned Vela and Ulysses observations. For the adopted solar wind conditions (see Sec.2), typical for the initial in-ecliptic phase of the Ulysses mission, the relevant production rates of He^+ ions, both varying like $1/r^2$, are the following:
$\beta_4\,(1\mathrm{AU}) = 2.2 \cdot 10^{-9}\,\mathrm{s}^{-1}$ for reaction (R4), and
$\beta_5\,(1\mathrm{AU}) = 2.0 \cdot 10^{-10}\,\mathrm{s}^{-1}$ for reaction (R5), respectively.

Applying the distributions of neutral hydrogen and helium calculated with the use of the "hot" model modified by the inclusion of the electron impact effect (Ruciński and Fahr, 1989) one can express the expected fluxes of the newly-created He^+ from the two reactions as follows:

$$F_{\mathrm{R4}}^{\mathrm{He}^+} = \int_{R_\odot}^{R} n^{\mathrm{H}}\,(r',\theta)\;\beta_4\,(r')\left(\frac{r'}{R}\right)^2 P^{\mathrm{He}^+}\,\mathrm{d}r', \qquad (12)$$

$$F_{\mathrm{R5}}^{\mathrm{He}^+} = \int_{R_\odot}^{R} n^{\mathrm{He}}\,(r',\theta)\;\beta_5\,(r')\left(\frac{r'}{R}\right)^2 P^{\mathrm{He}^+}\,\mathrm{d}r'. \qquad (13)$$

Our calculations show that at small heliocentric distances ($\sim$ 1 AU) the reaction with helium (R5) is responsible for the production of a major (or comparable to resulting from reaction R4) fraction of the solar He^+ ions. In the downwind region, because of the pronounced enhancement of helium density owing to the gravitational focusing combined with the strong depletion of hydrogen density, the charge exchange of alphas with helium may dominate the similar reaction with hydrogen even to significantly larger distances of ~ 9 AU. The relative contributions of the two reactions are shown in Fig. 9.

The expected solar He^+ fluxes at 1 AU from the two processes considered vary from $\sim 60\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at the upwind axis to $\sim 40\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ sidewind, and increase to $\sim 180\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ in the downwind direction (see Fig. 10), indicating a strong anisotropy, reflected by the downwind/upwind ratio of ~ 3. When moving outwards, the flux observed at the upwind and sidewind directions systematically increases, reaching its maximum levels of $\sim 200\ \mathrm{cm^{-2}\,s^{-1}}$ and $\sim 140\ \mathrm{cm^{-2}\,s^{-1}}$, and a broad plateau at distances of ~ 5–10 AU. Contrary to that, the downwind flux drops down, below the upwind and sidewind values already beyond ~ 3 AU. This indicates that the channel of the He^{+} production by transcharge of alphas on helium is generally important only at small heliocentric distances, while further away the production is controlled mainly by the reaction with the interstellar hydrogen. This explains why already beyond a few AU the upwind flux noticeably exceeds the downwind one. Excluding regions closest to the Sun ($R < 3$ AU) this creates anisotropy, present up to large heliocentric distances, which is generally opposite to the anisotropy of helium pickup ions discussed in Sec.3. Having calculated the total solar He^{+} fluxes from both channels, one can easily express the He^{+} / He^{++} ratio, just by dividing them by the solar alpha flux at the considered position (assumed to vary like $1/r^2$ with the distance from the Sun). Although the absolute value of the He^{+} flux depends on actual value of the solar wind alpha flux, the aforementioned ratio is independent of it because both production rates β_4 and β_5 vary in tact of the changes of the alpha flux. It remains, however, a function of density of neutral species and of the relevant neutral atom–alpha particle charge-exchange cross-sections σ_4 and σ_5. As shown in Fig. 11, the corresponding ratio systematically increases with the heliocentric distance, more steeply for the upwind and sidewind directions than along the downwind one. While at 1 AU it is still relatively low (less or around 10^{-5}) and reaches generally the same level as the original coronal abundance, already around 4–5 AU it is about one order of magnitude higher (i.e. $\sim 10^{-4}$). Such behaviour encouraged us to compare it with the Ulysses estimates of its upper limit reported by Mall et al. (1997) and based on the solar He^{+} observations over the extended period of time: 1991–1993.

At the beginning of 1991 Ulysses was about 1.5 AU from the Sun, but starting from September 1991 till the end of the period discussed (i.e. for about 75% of the whole time), it was close or outside 4 AU. Except for the first few months of 1991, Ulysses remained steadily at the offset angles of 90-110°, which can be considered as the sidewind direction. Moreover, starting from 1992 its trajectory led towards higher latitudes. In particular during the last year (1993) its latitude increased sharply from $23°$ to $48°$, and the solar wind speed observed was systematically increasing from ~ 450 km/s in the near ecliptic regions to ~ 750 km/s at high latitudes.

It is evident from Fig. 11 that for the slow solar wind case, relevant for the in-ecliptic phase of the Ulysses mission, the resulting He^{+} / He^{++} ratio varies from ~ 1.0 to $3.0 \cdot 10^{-4}$ for the Ulysses heliocentric distance larger than 4.0 AU (i.e. starting from September 1991). As it was shown in Fig. 8, the relevant cross-sections for the charge-exchange reactions between the solar wind alphas and H or He neutral atoms strongly increase with the increase of the solar wind velocity. Typically, for the solar wind speed of ~ 750 km/s, the cross-section for reaction R4 increases approximately by a factor of 4, and for reaction R5

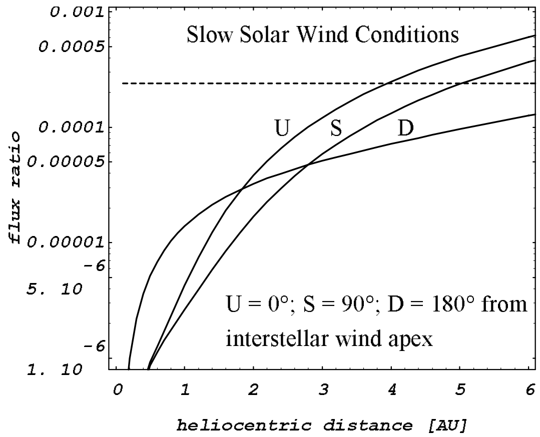

Fig. 11. The expected ratios of the fluxes displayed in Fig. 10 to the flux of the solar wind alphas as a function of heliocentric distance for slow solar wind conditions. The dashed horizontal curve corresponds to the level of the upper limit of the value of the solar He^{+}/He^{++} ratio, determined by Mall et al. (1997) from the Ulysses SWICS observations performed from 1991 till 1993.

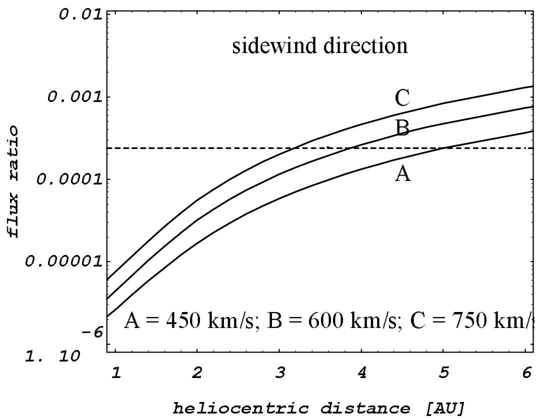

Fig. 12. The dependence of the ratio from Fig. 11 for the sidewind direction for different solar wind velocities. Curve A corresponds to slow solar wind with $V_{\mathrm{sw}} = 450$ km/s, curve B to $V_{\mathrm{sw}} = 600$ km/s and curve C refers to the high speed solar wind with $V_{\mathrm{sw}} = 750$ km/s. The horizontal dashed curve has the same meaning as in Fig. 11.

by a factor of 3 in comparison to the considered slow solar wind case ($V_{\mathrm{SW}} = 450$ km/s). This means that in high speed solar wind conditions (i.e. at high latitudes) the production of solar He^{+} ions becomes much more efficient than for the case of the slow solar wind discussed here up-to-now. In Fig. 12 we present the expected ratios for the slow solar wind of 450 km/s (typical for the in-ecliptic phase), 600 km/s (corresponding to the mean value of the highly variable behaviour at latitudes of $\sim 25°$), and 750 km/s (characteristic at latitudes higher than $\sim 40°$). It confirms that during almost whole period 1991–1993 (excluding only the first few months, when Ulysses was still closer to the Sun), the theoretically predicted ratio varied between 10^{-4} and $5 \cdot 10^{-4}$, i.e. just around the upper level of the He^{+} / He^{++} ratio inferred by Mall et al. (1997).

The agreement between the above-mentioned predictions and observations suggests that the considered mechanisms of

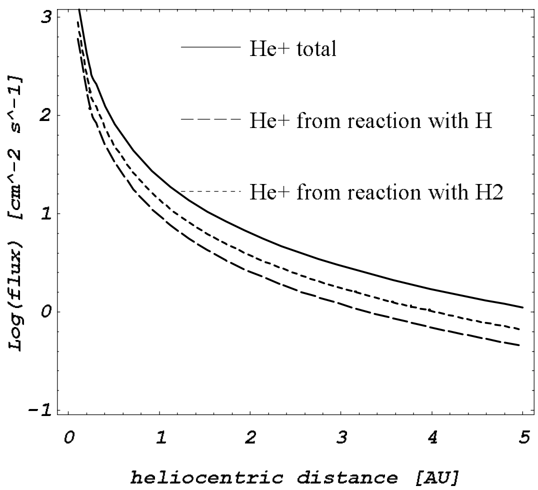

Fig. 13. The expected (isotropic) solar He^+ ion fluxes resulting from the charge-exchange of the solar wind α-particles on dust-desorbed neutral H atoms and H_2 molecules as a function of heliocentric distance. The solid curve represents the total sum of He^+ flux produced from interactions with the dust-desorbed H atoms and H_2 molecules.

the charge-exchange of solar wind alphas with the interstellar H (and He) atoms could potentially explain the possible enrichment of the solar He^+ content at distances around and beyond 4 AU, up to the range of the upper limit determined from the Ulysses observations. However, at small heliocentric distances, typically of 1 AU, this source is not sufficiently efficient to increase the solar He^+ ion abundance well above the expected coronal values, especially in slow solar wind conditions.

In the next subsections, we will consider several other mechanisms that can be of importance, especially concerning possible local enrichment of the He^+ content at small heliocentric distances (inside a few AU).

5.2. Production of solar He^+ ions due to charge-exchange of solar wind alpha particles with dust-desorbed neutral atoms and molecules

Although the interstellar H and He gases are the largest global source of neutral atoms in the interplanetary space, non-negligible amounts of neutral atoms and molecules may be produced close to the Sun (mainly inside 1 AU) by outgassing of the interplanetary dust grains (Banks, 1971).

The plasma-dust interactions in the interplanetary space and their possible observational consequences were theoretically considered by several authors (e.g. Fahr et al., 1981; Gruntman, 1996). Recent Ulysses observations of the C^+ pickup ions that originate most probably from dust grains (Geiss et al., 1995a) are an illustrative example of a non-negligible role of the dust as a source of interplanetary plasma components.

The amount of neutrals produced from dust has been a matter of long debates and is still poorly known because estimates of the geometrical factor Γ (the inverse of the mean free path against adsorption), being a crucial factor determining the dust deionization, vary over a very wide range of $10^{-21}\ \mathrm{cm}^{-1} \leq \Gamma \leq 10^{-17}\ \mathrm{cm}^{-1}$ (see e.g. Gruntman, 1996). For the purposes of this study, we adopt the value often assumed by different authors, $\Gamma = 2 \cdot 10^{-19}\ \mathrm{cm}^{-1}$, for which several useful formulae describing densities of dust-originated particles were derived (Holzer, 1977; Fahr et al., 1981; Gruntman, 1994, 1996).

The quantitative estimates of the production of dust-desorbed species by Fahr et al. (1981) and Gruntman (1994) for this value of Γ indicate that the density of H atoms from dust may exceed or be approximately equal to the density of interstellar H atoms inside 0.4 AU. Moreover, as shown by Gruntman (1994,1996), the expected density of dust-desorbed H_2 molecules is similar to the dust-desorbed H atoms. According to the studies by Fahr et al. (1981) and Gruntman (1994), the density of dust-desorbed He atoms is generally much smaller than the local density of interstellar He atoms. The dust-desorbed He atoms may be the dominant neutral He component only in the closest vicinity of the Sun (typically at $R < 0.05$ AU), but already beyond 0.2 AU its density becomes smaller by at least two orders of magnitudes than the density of interstellar He atoms. That is why we disregard here the contribution from similar process for He, which is negligibly small at the considered distances of ~ 1 AU, and we limit our considerations of possible production of solar He^+ ions only to the charge-exchange reactions between the solar wind alphas and dust-originated H and H_2.

While the neutral dust-originated H contributes to the production of solar He^+ via charge-exchange reaction with the solar wind alphas (same as R4):
(R6) $He^{++} + H \rightarrow He^+ + H^+$ single electron capture;
the dust-originated H_2 molecules may contribute through the following three channels (the corresponding cross-sections at slow solar wind conditions are taken from Gruntman (1996)):
(R7A) $He^{++} + H_2 \rightarrow He^+ + H_2^+$ single electron capture; $\sigma_{7\mathrm{A}} \simeq 5 \cdot 10^{-17}\ \mathrm{cm}^{-2}$,
(R7B) $He^{++} + H_2 \rightarrow He^+ + H^+ + H$ dissociative electron capture; $\sigma_{7\mathrm{B}} \simeq 1 \cdot 10^{-16}\ \mathrm{cm}^{-2}$,
(R7C) $He^{++} + H_2 \rightarrow He^+ + H^+ + H^+ + e$ electron capture with ionization; $\sigma_{7\mathrm{C}} \simeq 1.3 \cdot 10^{-16}\ \mathrm{cm}^{-2}$.
Thus, for the considered solar wind parameters at 1 AU, namely: $n_\mathrm{p} = 6\ \mathrm{cm}^{-3}$; $V_\mathrm{SW} = 450$ km/s; $n_\alpha = 0.04\, n_\mathrm{p}$, one obtains that for the solar wind α flux at 1 AU of $1.08 \cdot 10^7\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ the resulting rates (at 1 AU) of the charge-exchange between alphas and dust-originated H atoms (reaction R6) and H_2 molecules (combined effect of reactions R7A, R7B and R7C) are the following:
$\beta_6\,(1\mathrm{AU}) = 2.2 \cdot 10^{-9}\ \mathrm{s}^{-1}$, and $\beta_7\,(1\mathrm{AU}) = 3.0 \cdot 10^{-9}\ \mathrm{s}^{-1}$.

For further calculations, we adopted the following density distributions of these "dusty" H and H_2 species inside 1 AU:

$$n_\mathrm{H}^\mathrm{d}\,(R) = 4.3 \cdot 10^{-5}\, R^{-1.15}\ \mathrm{cm}^{-3}, \tag{14}$$

(Gruntman, 1994)

$$n_{\mathrm{H}_2}^\mathrm{d}\,(R) = 4.0 \cdot 10^{-5}\, R^{-1.15}\ \mathrm{cm}^{-3} \tag{15}$$

(adapted Equ.(23) from Gruntman (1996) for the case of $V_\mathrm{SW} = 450$ km/s).

To calculate the fluxes of solar He^+ ions originated from charge-exchange between alphas and dust-desorbed H and H_2, one can modify the formulae in Eqs. (12, 13) by inserting the appropriate densities and production rates to the form:

$$F_{\mathrm{R6}}^{\mathrm{He}^+}(R,\theta) = \int_{R_\odot}^{R} n_{\mathrm{H}}^{\mathrm{d}}(r,\theta)\ \beta_6(r) \left(\frac{r}{R}\right)^2 P^{\mathrm{He}^+}(r)\ \mathrm{d}r, \quad (16)$$

$$F_{\mathrm{R7}}^{\mathrm{He}^+}(R,\theta) = \int_{R_\odot}^{R} n_{\mathrm{H}_2}^{\mathrm{d}}(r,\theta)\ \beta_7(r) \left(\frac{r}{R}\right)^2 P^{\mathrm{He}^+}(r)\ \mathrm{d}r. \quad (17)$$

From the adopted density distribution and production rates it comes out straightforwardly that both "dusty" components contribute comparably to the conversion of the solar wind alpha particles to the He^+ ions, with a slight ($\sim 25\%$) preference for the contribution from the channels involving H_2 molecules. As it is shown in Fig. 13, at 1 AU the expected isotropic fluxes of He^+ born from reactions R6 and R7A+R7B+R7C are equal to about 14 $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ and 18 $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, respectively. The total flux at 1 AU, of about 30 $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, is only slightly lower than the relevant fluxes in the upwind hemisphere and sidewind direction, which result from the charge-exchange reactions with neutral interstellar H and He atoms, discussed in Sec. 5.1. It is, however, smaller by a factor of 5 from the aforementioned downwind flux, enhanced due to the focusing of interstellar helium in the downwind region. Nevertheless, since the contribution from dust increases with the decrease of the heliocentric distance and exceeds the flux produced by transcharge of interstellar neutrals, this source should not be totally ignored at small heliocentric distances ($R < 1$ AU) as a mechanism contributing noticeably to the production of solar He^+. We have to stress that because of the poor knowledge of the dust geometrical factor Γ our estimate has still a large uncertainty. However, one should take into account that for higher values of Γ the contribution from the interplanetary dust may be a quite substantial factor, responsible for systematic enhancement of the solar He^+ content on the way from the solar corona to the regions near the Earth's orbit.

5.3. *Solar He^+ from the ionization of the helium component of the Neutral Solar Wind*

Another process contributing locally (inside 1–2 AU) to the production of the solar He^+ ions is the ionization of the NSW helium. As discussed in Sec. 4, this component is born due to the double charge-exchange between the solar wind alpha particles and neutral interstellar He atoms. In this reaction, alpha particles are converted into neutral He atoms which inherit the solar wind velocity. The important difference in the ionization of this and the original (slow, ~ 25 km/s) interstellar He component is such that while the ionization of the energetic He atoms leads to the creation of solar He^+ ions inheriting the properties of the solar alpha particles, the ionization of original interstellar He atoms forms a new, distinct population, namely the He^+ pickup ions,

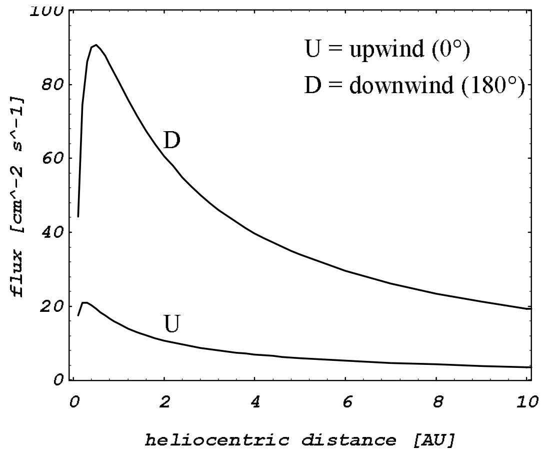

Fig. 14. The expected fluxes along upwind and downwind directions of the 'solar' He^+ ions originating due to the ionization of the NSW He component.

already discussed in Sec.3. Thus, the currently discussed mechanism can be treated as a two-step process, converting the solar wind alphas to the solar wind He^+ ions through the intermediate stage of energetic He atoms, which can be reionized during their outward flow with the solar wind. Although the density of energetic He atoms inside 1 AU is significantly lower than the density of original interstellar He atoms (approximately by two or three orders of magnitude), the production rate (per sec) of the He^+ solar ions from the energetic He atoms, determined by photoionization and electron impact, exceeds by a comparable factor the charge exchange rate between the original neutral interstellar He and the solar wind alphas.

The calculation of the expected flux of the solar wind He^+ ions, produced due to this mechanism, can be performed in a straightforward way, by applying only a slightly modified form of Eq. (11). Now, the term P^{He} in the integrand, describing the probability that a newly created energetic He atom is not ionized underway from the place of its birth to the considered point of observation, should be just replaced by $1 - P^{\mathrm{He}}$, expressing the probability that such an atom becomes ionized between the place of its birth and the observer. We tacitly assume here that all neutral He atoms belonging to the NSW population, which are lost due to the ionization processes while moving outwards, become singly charged He^+ ions. This assumption is acceptable for the purposes of our analysis, since when considering in Sec.2 the ionization (loss) mechanisms acting on neutral He, we already decided to take into account only the two most efficient processes, namely: the photoionization and the electron impact, both creating the He^+ population. The neglect in this consideration of the double charge-exchange process, discussed in Sec.3, does not have any significance, since it contributes by less than 3% to the total loss rate of helium. Thus, this simplification does not affect our main conclusions. Similarly, since currently the solar He ions should be considered as a minor component, originating from another minor helium component (i.e. energetic He atoms), and having in mind that for the ions created beyond 0.1 AU the probability to reach 1 AU is greater than 95% (see Fig. 2), we neglect here the potential losses of He ions on their way from the place of birth to the observer, as a “third order effect”. All that allows us to use in our computation the modified form of Eq. (11).

Our calculations indicate that for the adopted case one can expect fluxes of $\sim$ 20–100 cm^{-2} s^{-1} at 1 AU (see Fig. 14), with significant upwind-downwind asymmetry. Typically, the expected downwind flux can be larger by a factor 5 compared to that on the upwind side. As one can infer from the discussion in Sec.4, the fluxes expected at small heliocentric distances ($\sim$ 1 AU) should be higher at solar minimum conditions than during solar maximum epoch. We thus conclude that this source of production of the solar H^+ ions gives comparable contribution to the formerly discussed mechanisms of the transcharge of alphas on the interstellar and dust-originated neutrals, being of importance especially well inside 1 AU. Its significance systematically decreases with the increase of the heliocentric distance and beyond ~ 3 AU it can be safely neglected (even for the downwind side) in comparison with the main source of He^+ ions, namely the charge-exchange of interstellar H atoms with the solar wind alphas.

5.4. *Radiative recombination of the solar wind alpha particles as a source of solar He$^+$ ions*

Analyzing various local mechanisms (inside a few AU) that produce solar He^+ ions and lead to the increase of their original abundance in the solar wind, one should also consider the role of recombination processes. In the present section we provide a general estimate of the expected contribution from the radiative recombination of the solar wind alpha population due to the reaction with electrons:

(R8) He^{++} + e $\rightarrow$ He^+ + photon

The recombination processes operate especially efficiently in the regions close to the Sun ($R \leq 0.1$ AU), where the electron density is still sufficiently high and the temperature has already fallen down. The precise and consistent calculation of the contribution from the region above the solar corona at $R < 5R_\odot$ (including also later losses of the newly-born He^+ ions) requires, however, extended modeling of the solar wind outflow, treated in a broad context, including tracing of variations of the electron density and temperature, changes of the relative abundance of alpha particles, increase of the solar wind speed, etc. Since such detailed study of the phenomena in the closest vicinity of the Sun is beyond the scope of this paper, we decide to give only a rough but illustrative estimate of the efficiency of the radiative recombination, taking into account only the contribution from the regions outside $5R_\odot$, where the solar wind flow (velocity) can be considered as at least to some extent established. Because of the neglect of some possible contribution from the innermost region, our estimate can be treated as a conservative limit of the effect.

To calculate the flux of the solar He^+ ions born due to the radiative recombination, we adopt the formula for the recombination coefficient given by Verner and Ferland (1996), valid for a wide range of temperatures (3 K – 10^{10K}), in the following

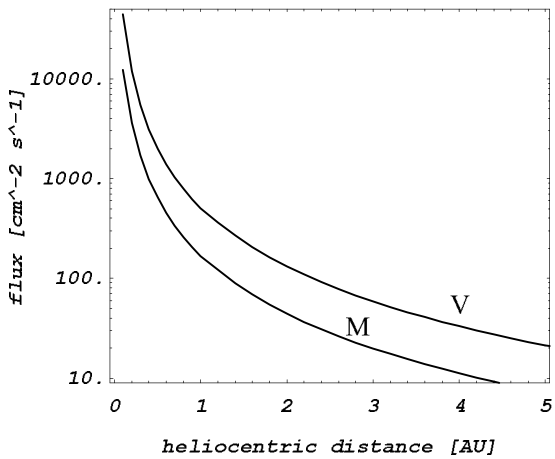

Fig. 15. Expected isotropic fluxes of He^+ ions originating from the radiative recombination of the solar wind alpha particles as a function of heliocentric distance, presented for the electron density profiles following the dependencies determined from Viking (curve V) and Mariner (curve M) observations.

form:

$$\alpha_r(T) = a\left[\sqrt{T/T_0}\left(1+\sqrt{T/T_0}\right)^{1-b} \times \times \left(1+\sqrt{T/T_1}\right)^{1+b}\right]^{-1} \quad (18)$$

where for the case considered the parameters a, b, T_0, and T_1 (taken from Table 1 of Verner and Ferland (1996)) are as follows:

$$a = 1.891 \cdot 10^{-10},\ b = 0.7524,\ T_0 = 9.370\ \mathrm{K}, \mathrm{and} \quad T_1 = 2.774 \cdot 10^6\ \mathrm{K}. \quad (19)$$

The variation of electron temperature with the heliocentric distance is the same as assumed in Sec.2 for the purposes of calculation of the electron impact rate. Since the recombination effects are especially efficient in the closest neighbourhood of the Sun, we should take into account in the present considerations the fact that the electron density in this region does not vary according to the $1/r^2$ law, generally valid at larger distances. It is well known that the electron density profiles as a function of the heliocentric distance demonstrate pronounced differences depending on the observed region/structure near the Sun such as: streamers, equatorial regions, polar regions, coronal holes, etc., which may reach even orders of magnitude (see e.g. Newkirk, 1967; Koutchmy, 1994). Since we do not pretend to analyze all these different cases in detail, but intend rather to give a simple illustrative estimate, just reflecting the typical expected range of the contribution from radiative recombination, we decided to take (as two alternatives) the functional dependencies derived from Viking (Muhleman and Anderson, 1981) and Mariner 6 (Muhleman et al., 1977) observations, relevant for the considered regions $R > 5R_\odot$. We used the original formulae for the case of the solar equatorial region scaled by the multiplicative factors: $\xi_V = 1.282$ and $\xi_M = 0.672$ for the Viking and Mariner cases, respectively, in order to reach the

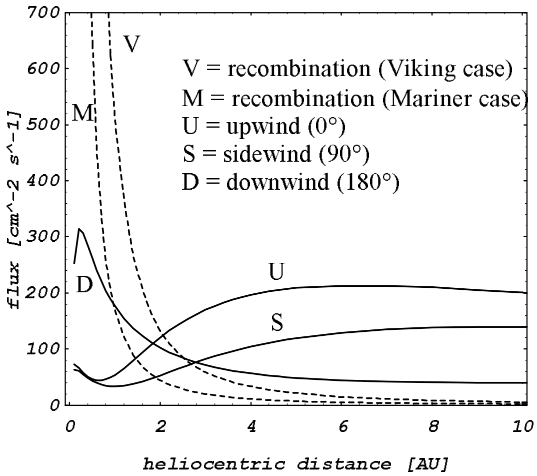

Fig. 16. Same as Fig. 10, but including also the solar He^+ flux originating from the radiative recombination of solar wind alpha particles (dashed curves) for the cases of the electron density profiles as determined from Viking (branch V) and Mariner (branch M) observations.

same electron density of 6.0 cm^{-3} at 1 AU as assumed in our study:

$$n_e(r) = \left[1.32 \cdot 10^6\, r^{-2.7} + 2.3 \cdot 10^5\, r^{-2.04}\right] \xi_V \tag{20}$$

for the Viking dependence, and

$$n_e(r) = \left[0.69 \cdot 10^8\, r^{-6} + 0.54 \cdot 10^6\, r^{-2.05}\right] \xi_M \tag{21}$$

for the Mariner 6 dependence, where r is expressed in solar radii and the density is given in cm^{-3}.

Then one can calculate the expected flux of solar He^+ ions created from the recombination of the solar wind alpha particles as the sum of contributions from the "core" $n_e^c(r')$ (96% of n_e) and the "halo" $n_e^h(r')$ (4% of n_e) electron populations, according to the formula:

$$F_{rec}^{He^+}(r) = \int_{r^\star}^{R} \left[n_e^c(r')\, \alpha^c(r') + n_e^h(r')\, \alpha^h(r')\right] \times \times\; n_{He^{++}}(r') \left(\frac{r'}{R}\right)^2 P^{He^+}(r')\, dr' \tag{22}$$

where the lower integration limit adopted $r^\star = 5\,R_\odot$. As it is shown in Fig. 15, this recombination process is a quite efficient source of new He^+ ions at small heliocentric distances ($R \leq 3$ AU), and the resulting fluxes at 1 AU vary in both considered cases (with Mariner and Viking types of dependencies of the assumed electron density profiles) from ~ 180 cm^{-2} s^{-1} to ~ 500 cm^{-2} s^{-1}. It means that even in our conservative estimate, they may be already a few times higher than the typical fluxes from other processes, considered earlier in this section (see Fig. 16). Comparing them with the direct interstellar source of such ions one can conclude that the radiative recombination mechanism may be the dominant one up to distances of 2–3 AU, as shown in Fig. 17. This fact suggests that near the Sun the anisotropic features of the distribution of the He^+ ions produced due to decharging of solar wind alphas on interstellar neutrals discussed in Sec.5.1 may not be visible, being suppressed by the isotropic contribution from radiative recombination. Only at larger distances, where the recombination becomes negligible (similarly to the other 'local' sources considered in Sec. 5.2 and 5.3) and the charge-exchange process between neutral interstellar hydrogen and alpha particles discussed by Gruntman (1992) becomes the dominant global source of these ions, the upwind–downwind anisotropic features may clearly manifest. It has to be pointed out that in the present section we limit our analysis to the radiative recombination and do not consider the dielectronic recombination as a source of the 'solar' He^+ ions. This process, which can be of significance, should be carefully considered in a separate study. Despite this simplification, when adding up the contributions to the production of the 'solar' He^+ ions from all mechanisms discussed in Sec. 5.1–5.4, the expected range of the resulting flux at 1 AU is ~ 300–750 cm^{-2} s^{-1}. For the assumed (slow) solar wind conditions, and the α-particle flux at 1 AU equal to $1.08 \cdot 10^7$ cm^{-2} s^{-1}, this translates to the He^+ / He^{++} ratio of ~ 3–$7 \cdot 10^{-5}$. Similarly as in the case of the Ulysses observations discussed above, we can conclude that also this value of the ratio remains in good agreement with the early determination of its upper limit from the Vela 5 and 6 solar wind measurements at 1 AU (Feldman et al., 1974).

6. Summary and outlook

In the paper we examine various physical processes leading to the extra-coronal production of several sorts of secondary helium species. In particular, we consider products of photo- and electron impact ionization, of charge-exchange reactions between neutral helium and hydrogen atoms and dust-desorbed H_2 molecules with the solar wind alpha particles, and from the recombination processes in the solar wind. It is shown that the ionization of the interstellar H and He gas is in the global scale the most efficient mechanism supplying neutral and ion helium components to the solar wind. The expected fluxes of the He^+ pickup ions, being the most abundant secondary population, remain in good agreement with the data registered by SWICS instrument onboard Ulysses at distances beyond 4 AU as reported by Gloeckler et al. (1993). The comparison of this flux with the flux of original solar wind alpha particles indicates that their ratio continuously increases with the heliocentric distance and in the distant heliosphere it may reach value of ~ 0.15–0.35. Also the fluxes of other minor constituents, such as He^{++} pick-up ions or helium component of the Neutral Solar Wind, though significantly lower than the flux of He^+ pickups (with maximum abundance in the outer heliosphere up to 1% of the SW alpha abundance), can reach detectable level. We consider also various mechanisms of the possible increase of the 'solar' He^+ ion abundance above their original coronal content. We demonstrate that charge-exchange processes between the neutral interstellar H (and He) atoms and the solar wind alpha particles, leading to the conversion of the latter ones to He^+, can be an efficient source of these ions, responsible for the substantial global increase of the 'solar' He^+ abundance above its typical coronal value. Since the cross sections for these reactions

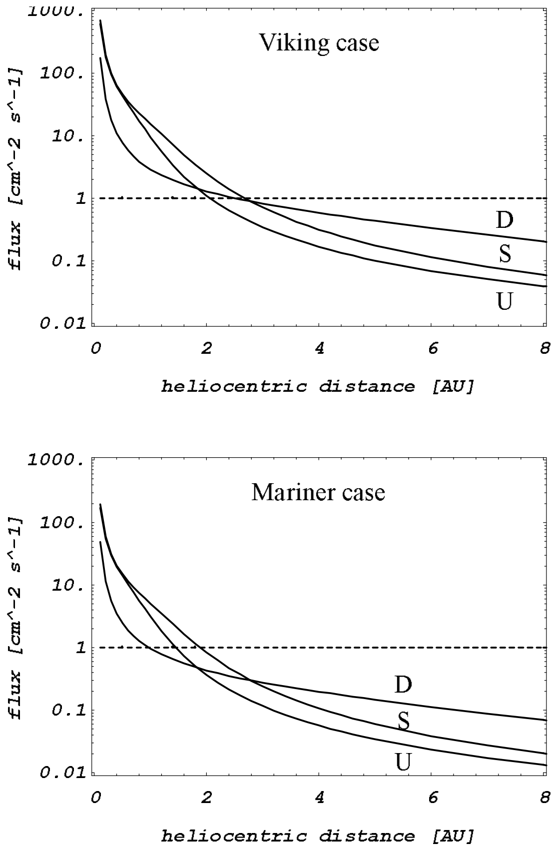

Fig. 17. The ratio of the fluxes of solar He^+ ions produced from the radiative recombination of solar wind α-particles to those created in the charge-exchange processes between the solar wind α-particles and neutral interstellar H and He atoms, expected along the upwind (U), sidewind (S) and downwind (D) directions. The level equal to 1 (dashed line) corresponds to the exact balance between these two sources of solar He^+ ions.

are strongly energy- or relative velocity-dependent, it turns out that under the fast solar wind conditions one can expect higher relative ratios of newly created He^+ ions to the original solar He^{++}. This would support expectations that at higher ecliptic latitudes, where high speed solar wind is dominant, correspondingly higher He^+ / He^{++} abundances may prevail unless it is found in theoretical calculations that already the original solar wind plasma, expanding from the high latitude corona, is characterized by ion abundances significantly different from those present in the low latitude coronal plasma. We also show that the postulated enrichment of the 'solar' He^+ abundance owing to the decharge of alphas on interstellar hydrogen atoms remains in good quantitative agreement with recent determination of the upper limit of the He^+ / He^{++} ratio from Ulysses observations (Mall et al., 1997). It is worth mentioning that beyond $\sim$ 2–3 AU, the spatial anisotropy of the newly created He^+ flux is expected to be opposite to the anisotropy of helium pickup components or helium NSW. As a consequence, the 'solar' He^+ flux in the outer regions of the upwind hemisphere may be only ~ 5 times lower than the He^+ pickup flux, while in the distant downwind region this discrepancy is significantly higher, by about one order of magnitude.

Locally, in the close vicinity of the Sun ($R \leq$ 2–3 AU) several other mechanisms discussed in the paper can noticeably contribute to the production of the 'solar' He^+ component, and in particular the recombination of solar wind alpha particles becomes the major source of such ions. We argue that even in our very simplified estimate of the recombination yield (neglect of the channel of dielectronic ionization, neglect of the contribution from the regions closest to the solar corona), the amount of newly created He^+ ions of the solar wind characteristics, observed at 1 AU (and created mainly due to recombination, as demonstrated in Figs. 16 and 17) is consistent with the determination of the upper limit of He^+ / He^{++} ratio from the early observations from Vela 5 and Vela 6 (Feldman et al., 1974).

Concluding our analysis we want to stress that our current study, though presenting illustrative estimates of the supply of secondary, newly-originated helium components to the solar wind and assessing the role of particular physical mechanisms, cannot replace a more careful and exact description of the problem, especially in the regions near the Sun. A rigorous calculation of the convective time-dependent changes of the ionization states of ion species, carried out in a rest frame comoving with the expanding solar wind, is needed. In order to draw the relevant conclusions on the latitudinally varying ionization states of the ion species, it is necessary to develop a description of the solar wind outflow from the corona into the interplanetary space which would include modeling of the three-dimensional streamlines together with the monitoring of all thermodynamical properties of the solar wind plasma as a function of the corresponding streamline-element. Such extended analysis of the 3-D evolution of the ionization states related to the 3-D solar wind outflow from the corona, though being well beyond the scope of the present paper, remains the aim of our forthcoming studies.

Acknowledgements. The authors would like to thank U. Mall for several useful discussions, and to the referee of the paper for his constructive comments and valuable suggestions for improvements. The work of D.R. and M.B. was supported by the research grant No.2 P03C 013 11 from the Committee for Scientific Research (Poland). This work was performed in the collaboration between the Space Research Centre of the Polish Academy of Sciences and Institut für Astrophysik und Extraterrestrische Forschung der Universität Bonn as a part of the joint project: "Physics of the outer heliosphere: theory and observations" (DFG 436/POL/ 113/80), carried out in the framework of the cooperation between the Polish Academy of Sciences (PAS) and the Deutsche Forschungsgemeinschaft (DFG). Two of the authors (D.R. and M.B.) are grateful to the staff of the Institut für Astrophysik for the hospitality during their stay in Bonn, where the final part of the work was completed, as well as to the DFG and the PAS for the financial support of this visit.

References

Arnaud, M. and Rothenflug, R.: 1985, A&ASS 60, 425
Banks, P. M.: 1971, J. Geophys. Res. 76, 4341

Barnett, C. F., Hunter, H. T., Kirkpatrick, M. I., Alvarez, I., Cisneros, C., and Phaneuf, R. A.: 1990, Atomic data for fusion. Collisions of H, H_2, He and Li atoms and ions with atoms and molecules, Vol. ORNL-6086/V1, Oak Ridge National Laboratories, Oak Ridge, Tenn.

Barraclough, B. L., Feldman, W. C., Gosling, J. T. et al., 1996, in D. Winterhalter, J. Gosling, S. Habbal, W. Kurth, and M. Neugebauer (eds.), Solar Wind Eight, No. 382 in AIP Conference Proceedings, pp 277–280, American Institute of Physics, Woodbury, New York

Bertaux, J.-L., Lallement, R., Kurt, V. G., and Mironova, E. N.: 1985, A&A 150, 1

Błeszyński, S., Grzędzielski, S., Ruciński, D., and Jakimiec, J.: 1992, Planet. Space Sci. 40, 1525

Bochsler, P.: 1992, in E. Marsch and R. Schwenn (eds.), Solar Wind Seven, COSPAR Colloquia Series Vol. 3, pp 323–332, Pergamon Press, Oxford

Burgess, A.: 1962, ApJ 139, 776

Bzowski, M. and Ruciński, D.: 1996, in D. Winterhalter, J. Gosling, S. Habbal, W. Kurth, and M. Neugebauer (eds.), Solar Wind Eight, No. 382 in AIP Conference Proceedings, pp 650–654, American Institute of Physics, Woodbury, New York

Fahr, H. J.: 1971, A&A 14, 263

Fahr, H. J., Ripken, H. W., and Lay, G.: 1981, A&A 102, 359

Fahr, H. J. and Ruciński, D.: 1989, Planet. Space Sci. 37, 555

Fahr, H. J., Ruciński, D., and Nass, H. U.: 1987, Ann. Geophys. 5, 255

Feldman, W. C., Asbridge, J. R., Bame, S. J., and Kearney, P. D.: 1974, J. Geophys. Res. 79, 1808

Geiss, J., Gloeckler, G., Fisk, L. A., and von Steiger, R.: 1995a, J. Geophys. Res. 100, 23373

Geiss, J., Gloeckler, G., Mall, U., von Steiger, R., Galvin, A. B., and Ogilvie, K. W.: 1994, A&A 282, 924

Geiss, J., Gloeckler, G., and von Steiger, R.: 1995b, Space Sci. Rev. 72, 49

Geiss, J., Ogilvie, K. W., von Steiger, R. et al., 1992, in E. Marsch and R. Schwenn (eds.), Solar Wind Seven, No. 3 in COSPAR Colloquia Series, pp 341–348, Pergamon Press, Oxford

Gloeckler, G.: 1996, Space Sci. Rev. 78, 335

Gloeckler, G., Fisk, L. A., and Geiss, J.: 1997, Nature 386, 374

Gloeckler, G., Geiss, J., Balsiger, H. et al., 1993, Science 261, 70

Gloeckler, G., Geiss, J., Balsiger, H., and L. A. Fisk, e. a.: 1992, A&ASS 2, 267

Gosling, J. T., Asbridge, J. R., Bame, S. J., Feldman, W. C., and Zwickl, R. D.: 1980, J. Geophys. Res. 85, 3431

Gruntman, M. A.: 1992, Geophys. Res. Lett. 19, 1323

Gruntman, M. A.: 1994, J. Geophys. Res. 99, 19213

Gruntman, M. A.: 1996, J. Geophys. Res. 101, 15555

Gruntman, M. A., Grzędzielski, S., and Leonas, V. B.: 1990, in S. Grzędzielski and D. E. Page (eds.), Physics of the outer heliosphere, No. 1 in COSPAR Colloquia Series, pp 355–358, Pergamon Press, Oxford

Grzędzielski, S. and Ruciński, D.: 1990, in S. Grzędzielski and D. Page (eds.), Physics of the outer heliosphere, No. 1 in COSPAR Colloquia Series, pp 367–370, Pergamon Press, Oxford

Holzer, T. E.: 1977, Rev. Geophys. 15, 467

Holzer, T. E. and Axford, W. I.: 1971, J. Geophys. Res. 76, 6965

Hundhausen, A. J., Gilbert, H. E., and Bame, S. J.: 1968, J. Geophys. Res. 73, 5485

Koutchmy, S.: 1994, Adv. Space Res. 14, (4)29

Kozlovsky, B.-Z.: 1968, Sol. Phys. 5, 410

Lotz, W.: 1967, Zeitschrift f. Physik 206, 205

Maksimovic, M., Hoang, S., and Bougeret, J. L.: 1996, in D. Winterhalter, J. T. Gosling, S. R. Habbal, W. S. Kurth, and M. Neugebauer (eds.), Solar Wind Eight, No. 382 in AIP Conference Proceedings, pp 297–300, American Institute of Physics, Woodbury, New York

Mall, U., Gloeckler, G., and Geiss, J.: 1997, Search for $^4\mathrm{He}^+$ with SWICS-Ulysses, submitted to Astron. Astrophys.

Marsch, E., Pilipp, W. G., Thieme, K. M., and Rosenbauer, H.: 1989, J. Geophys. Res. 94, 6893

Marsden, R.: 1996, Space Sci. Rev. 78, 67

Möbius, E.: 1996, Space Sci. Rev. 78, 375

Möbius, E., Hovestadt, Klecker, B., Scholer, M., Gloeckler, G., and Ipavich, F.: 1985, Nature 318, 426

Möbius, E., Klecker, B., Hovestadt, D., and Scholer, M.: 1988, Astrophys. Space. Sci. 144, 487

Möbius, E., Ruciński, D., Hovestadt, D., and Klecker, B.: 1995, A&A 304, 505

Möbius, E., Ruciński, D., Isenberg, P. A., and Lee, M. A.: 1996, Ann. Geophys. 14, 492

Montgomery, M. D., Bame, S. J., and Hundhausen, H. J.: 1968, J. Geophys. Res. 73, 4999

Muhleman, D. O. and Anderson, J. D.: 1981, ApJ 247, 1093

Muhleman, D. O., Esposito, P. B., and Anderson, J. D.: 1977, ApJ 211, 943

Newkirk, G.: 1967, ARA&A 5, 213

Ogilvie, K. W. and Scudder, J. D.: 1978, J. Geophys. Res. 83, 3776

Phillips, J. L., Bame, S. J., Feldman, W. C. et al., 1995, Adv. Space Res. 16, (9)85

Quémerais, E., Bertaux, J.-L., Sandel, B. R., and Lallement, R.: 1994, A&A 290, 941

Ratkiewicz, R., Ruciński, D., and Ip, W.-H.: 1990, A&A 230, 227

Ruciński, D., Cummings, A. C., Gloeckler, G., Lazarus, A. J., Möbius, E., and Witte, M.: 1996, Space Sci. Rev. 78, 73

Ruciński, D. and Fahr, H. J.: 1989, A&A 224, 290

Ruciński, D. and Fahr, H. J.: 1991, Ann. Geophys. 9, 102

Ruciński, D., Fahr, H. J., and Grzędzielski, S.: 1993, Planet. Space Sci. 41, 773

Schwenn, R.: 1983, in M. Neugebauer (ed.), Solar Wind Five, pp 489–507, NASA CP-2280

Schwenn, R.: 1990, Large-scale structure of the interplanetary medium, Vol. 1 of Physics of the inner heliosphere, pp 99–181, Springer Verlag

Schwenn, R., Rosenbauer, H., and Mühlhäuser, K.-H.: 1980, Geophys. Res. Lett. 7, 201

Scime, E. E., Bame, S. J., Feldman, W. C., Gary, S. P., and Phillips, J. L.: 1994, J. Geophys. Res. 99, 23401

Sittler, E. C., Scudder, J. D., and Jessen, J.: 1981, in H. Rosenbauer (ed.), Solar Wind Four, p. 257, Springer Verlag, Berlin, Heidelberg, New York

Tucker, W. H. and Gould, R. J.: 1966, ApJ 144, 244

Vasyliunas, V. and Siscoe, G.: 1976, J. Geophys. Res. 81, 1247

Verner, D. A. and Ferland, G. J.: 1996, A&ASS 103, 467

Verner, D. A., Ferland, G. J., Korista, T. K., and Yakovlev, D. G.: 1996, ApJ 465, 487

von Steiger, R.: 1996, in D. Winterhalter, J. T. Gosling, S. R. Habbal, W. S. Kurth, and M. Neugebauer (eds.), Solar Wind Eight, No. 382 in AIP Conference Proceedings, pp 193–198, American Institute of Physics, Woodbury, New York

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

Wu, F. M. and Judge, D. L.: 1979, ApJ 231, 594

Zwickl, R. D., Asbridge, J. R., Bame, S. J., Feldman, W. C., and Gosling, J. T.: 1982, J. Geophys. Res. 87, 7379