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IONIZATION PROCESSES IN THE HELIOSPHERE – RATES AND METHODS OF THEIR DETERMINATION

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Abstract. The rates of the most important ionization processes acting in interplanetary space on interstellar H, He, C, O, Ne and Ar atoms are critically reviewed in the paper. Their long-term modulations in the period 1974 – 1994 are reexamined using updated information on relevant cross-sections as well as direct or indirect data on variations of the solar wind/solar EUV fluxes based on IMP 8 measurements and monitoring of the solar 10.7 cm radio emission. It is shown that solar cycle related variations are pronounced (factor of ~ 3 between maximum and minimum) especially for species such as He, Ne, C for which photoionization is the dominant loss process. Species sensitive primarily to the charge-exchange (as H) show only moderate fluctuations $\sim 20\%$ around average. It is also demonstrated that new techniques that make use of simultaneous observations of neutral He atoms on direct and indirect orbits, or simultaneous measurements of He^{+} and He^{++} pickup ions and solar wind particles can be useful tools for narrowing the uncertainties of the He photoionization rate caused by insufficient knowledge of the solar EUV flux and its variations.

1. Introduction

Interstellar neutral atoms penetrating the heliosphere are subjected to several ionization processes that reflect their interaction with the solar wind plasma and solar EUV radiation. These processes are commonly recognized to play a dual role. Firstly, they are responsible for the shaping of the local distribution of neutrals inside the Solar System. Secondly, they lead to the creation and determine the amount of the new, secondary components, as for example pickup ions. These ions while convected outwards with the solar wind may be preaccelerated at the travelling interplanetary shocks (Gloeckler et al., 1994) and later accelerated at the termination shock and thus are thought to be the source of the anomalous cosmic ray (ACR) component. To determine the properties of the gas in the Very Local Interstellar Medium (VLISM), or at least in the outer heliosphere, various experimental techniques based on the observations of the original neutral gas or the secondary products inside the Solar System are used. They include observations of the backscattered

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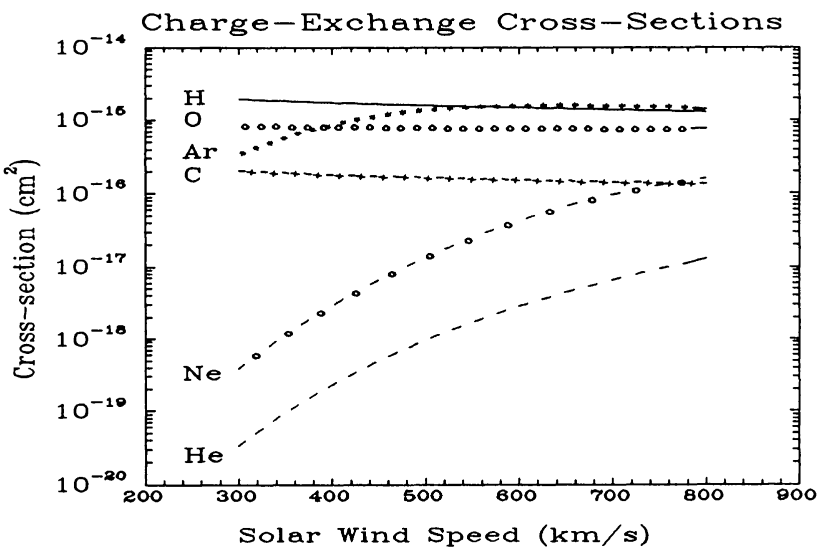

Figure 1. The dependence of the charge-exchange cross-section on the solar wind speed for H, He, C, O, Ne, and Ar.

solar EUV radiation (see e.g. Lallement et al., 1991; Quèmerais et al. 1994 and references therein), the most recent direct He gas measurements (Witte et al., 1993), pickup ion measurements (see e.g. Möbius et al., 1985, 1995; Gloeckler et al., 1993; Geiss et al., 1994), and observations of the ACR (Cummings and Stone, 1988, 1990, 1996). The reliability of the quantitative conclusions inferred from these studies is to large extent dependent on the accuracy of our knowledge of the ionization rates. Thus, the goal of this paper is to reexamine the efficiency of ionization processes for several interstellar species (H, He, C, O, Ne, Ar) that have been identified in the heliosphere. This includes in particular the variability of the ionization rates over the solar cycle. Though the study is mainly focused on photoionization and charge-exchange – the most important processes – we also refer briefly to other reactions of local importance, such as electron impact ionization, and double charge exchange with solar wind alpha particles which only recently could be traced to observable effects.

2. Efficiency of the ionization processes

2.1. Charge-exchange with solar wind protons

Revisiting charge-exchange between the solar wind protons and aforementioned neutral interstellar species, we adopt in our analysis the most recent data on the relevant cross-sections. The updated relations between the cross-sections and the solar wind speed based on studies by Barnett et al. (1990) for H and He; Ehrhardt and Langer (1987) for C; Stebbings et al. (1964) for O; and Nakai et al. (1987) for Ne and Ar, are shown in Fig.1 for the range 300 – 800 km/s. The experimental data can be represented either by simple analytical formulae or by fitted Chebyshev polynomials. While for H the modern values of Barnett et al. (1990) remain in good

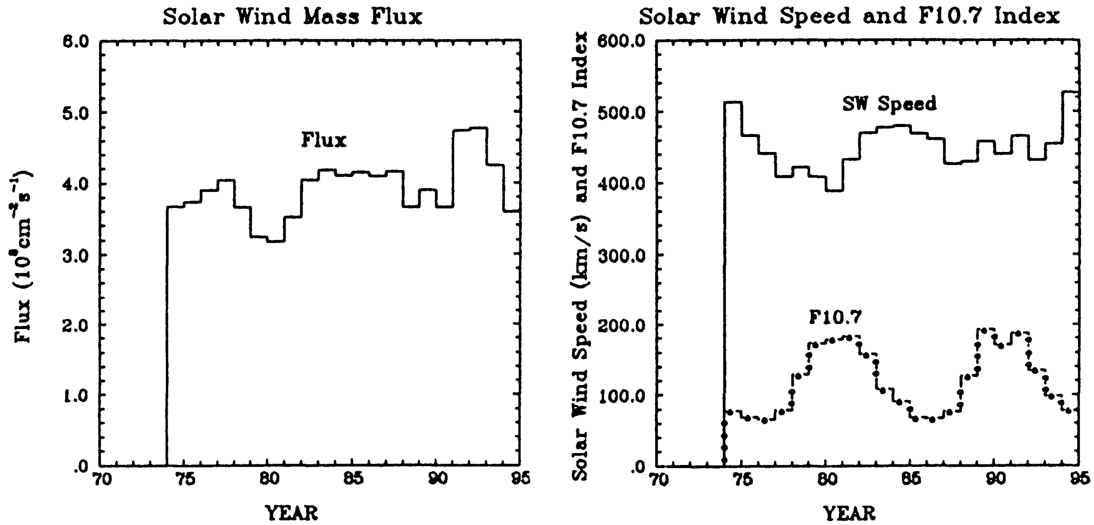

Figure 2. Yearly averages during 1974 – 1994 of the solar wind mass flux (left panel), solar wind speed (solid curve, right panel) from IMP 8 measurements and the yearly averages of the absolute 10.7 cm radio flux (in $10^{-22} Wm^{-2} Hz^{-1}$) (dash-circled curve, right panel).

agreement ($\sim$ 10 %) with the classical formula of Maher and Tinsley (1977), recent studies of Nakai et al. (1987) indicate much lower cross-sections for noble gases (mainly He and Ne), than reported earlier (Afrosimov et al., 1967; Tawara, 1978). To evaluate the charge-exchange rate (at 1 AU) for these species and to demonstrate their long-term variations, we use a comprehensive data set of yearly averages of the solar wind speed and mass flux from the IMP 8 measurements for the period 1974 – 1994. They are shown in Fig.2 together with the absolute F10.7 cm radio flux as an indicator for the solar cycle variation. The resulting charge-exchange rates are displayed in Fig.3. The temporal variation of the H rate is relatively low and its amplitude does not exceed $\sim$ 20% , what is consistent with observations from Helios (Schwenn, 1983). Similar behavior is found also for O and C. In contrast to that, the charge-exchange rates for Ne and He (see Fig.3, lower panel) may vary strongly (even by factor of $\sim$ 5) mainly due to the high sensitivity of the relevant cross-sections to the changes of the solar wind velocity. However, these drastic variations do not cause any practical consequences, since their contribution to the total ionization does not exceed $\sim$ 3% for Ne and is below 1% for He. In essence charge-exchange is much less effective for He and Ne than previously thought (Axford, 1970; Holzer, 1977).

2.2. Photoionization

Another important process of the interaction of neutral gases in interplanetary space is photoionization. The relevant dependencies of the cross-sections on wavelength taken from Allen (1973) for H; Marr and West (1976) for He, Ne and Ar; and from a compilation of M. Allen (1995, private communication) for C and O are shown in Fig.4. In contrast to the solar wind flux and velocity, for which continuous monitoring is available from several spacecraft (even over two decades), there are only very few direct measurements of the solar EUV flux, not even over any extended

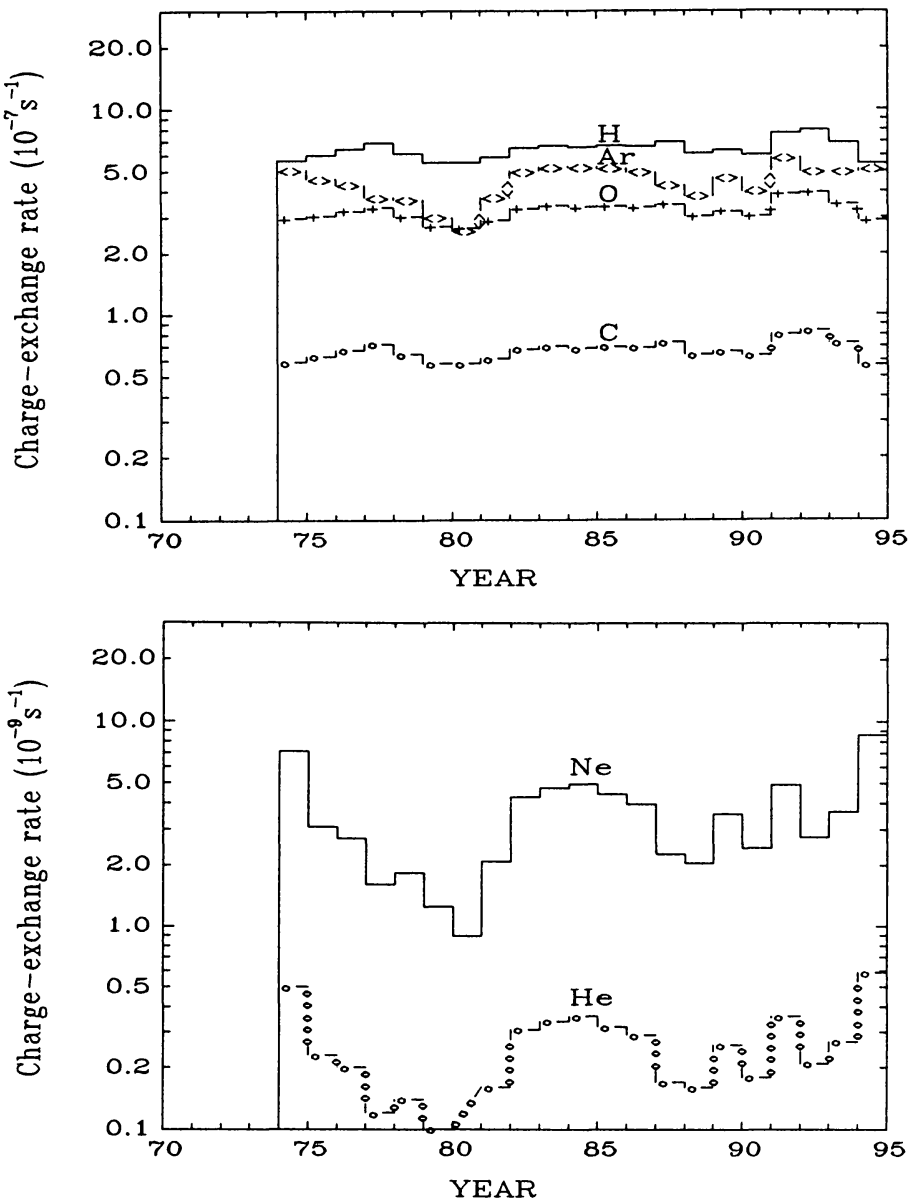

Figure 3. Histograms of the variations of the yearly average charge-exchange rates at 1 AU in the period 1974 – 1994. Corresponding curves in the upper panel: H (solid), Ar (diamonds), O (crosses), C (dash-circled); in the lower panel: He (dash-circled), Ne (solid). Note the difference in units on vertical axis by two orders of magnitude between the upper panel (10^{-7} s^{-1}) and the lower panel (10^{-9} s^{-1}).

period of time. The lack of continuous data requires the use in the current analysis of an indirect method that is based on the correlation between the solar EUV flux and the F10.7 cm radio flux. The existence of such a correlation has been pointed out for example by Feng et al. (1989), and Ogawa et al. (1990), who compiled results from various rocket/spacecraft measurements of the EUV flux. Recently, it was frequently used in more refined modeling of the solar EUV output (see e.g. Tobiska, 1993). Adopting the aforementioned cross-sections (see Fig.4) and using

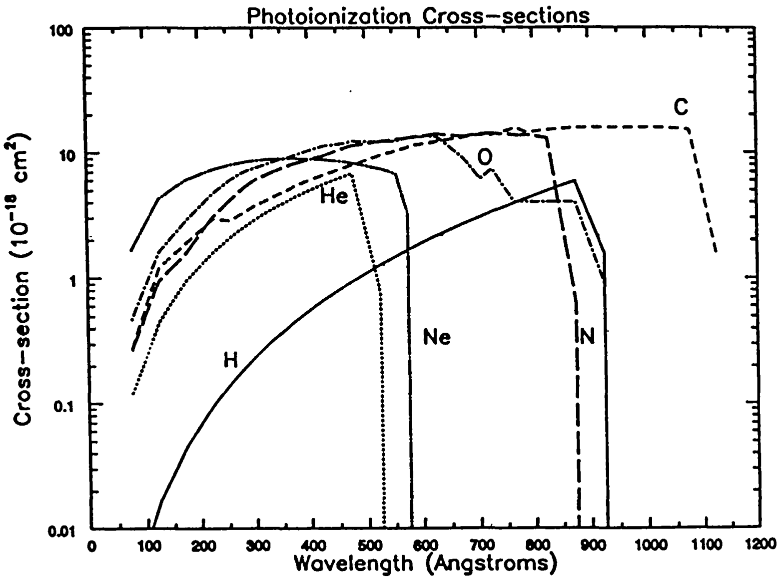

Figure 4. The dependence of the photoionization cross-section on wavelength for H, He, C, O, Ne and Ar.

the Atmospheric Explorer and rocket measurements of the solar EUV flux (Torr et al., 1979), with doubling of the flux below 250 Å, as suggested by Richards et al. (1994), we have calculated the photoionization rates of various species for two dates in April 1974 and February 1979 (74DOY113 and 79DOY050, respectively), which represent extreme (low and high) conditions of solar activity. Assuming a linear relation between the photoionization rate and the F10.7 cm flux which is in good agreement with the compilation of the experimental results by Ogawa et al. (1993), we have estimated the yearly averages of all rates for the period 1974 – 1994. Histograms of the photoionization rates calculated in this way are shown in Fig.5. As a consequence of the correlation of the photoionization rates with the F10.7 cm flux, they vary with the level of the solar activity. Relatively strong changes (typically by factor of ~ 3) between the solar minimum and maximum are expected. However, we should stress here that our estimates are not based on direct absolute solar EUV flux measurements, but employ an indirect method. Therefore, the results may still contain significant uncertainties. Another reason for relatively large uncertainty are serious discrepancies between existing measurements as well as differences between the most commonly used EUV flux models, pronounced especially at wavelengths below 250 Å (Richards and Torr, 1984; Ogawa and Judge, 1986; Richards et al., 1994). Since the total photon flux in this interval may be comparable to the flux at 304 Å, dominating the solar EUV spectrum, a possible uncertainty in its determination by a factor of ~ 2 may cause an error in the determination of the photoionisation rate of $\sim 10 - 15\%$ for species with the high ionization potential, such as He and Ne. Comparing results shown in Fig.3 and in Fig.5 one can conclude that the photoionization is the absolutely dominant loss process for He, Ne, and C. It is comparable with charge-exchange for O and Ar. Only in the case of hydrogen charge-exchange is dominant with photoionization contributing only $\sim 10 - 20\%$ to the total rate. These rates and the range of their variability in the period 1974 – 1994 are compiled in Table 1.

Table 1a

Modulation of basic ionization rates at 1 AU over the period 1974 – 1994

	Charge Exchange [$10^{-7}s^{-1}$]			Photoionization [$10^{-7}s^{-1}$]			Ch- ex + photoionization* [$10^{-7}s^{-1}$]		
	Min.	Max.	Average**	Min.	Max.	Average**	Min.	Max	Average**
H	5.5	8.0	6.4±0.14	0.6	1.7	1.04±0.09	6.2	9.3	7.44±0.16
He	0.001	0.006	0.0025 ±0.0003	0.5	1.8	1.07±0.12	0.5	1.8	1.08±0.11
C	0.57	0.83	0.67±0.015	5.6	15.3	9.68±0.78	6.2	16.0	10.35±0.79
O	2.65	3.93	3.21±0.07	2.3	7.5	4.54±0.41	5.5	11.2	7.75±0.42
Ne	0.02	0.09	0.035 ±0.004	1.7	5.9	3.49±0.33	1.7	5.9	3.52±0.34
Ar	2.5	5.8	4.46±0.18	3.2	9.7	5.97±0.51	7.6	15.3	10.44±0.48
N***				2.3	7.2	4.38±0.38			

*Note that due to the time shift between the minimum and maximum of the two effects the total rate may not reproduce a simple sum of the min./max. rates of both processes.
**Uncertainty of averages represents the standard deviation of the mean value. The standard deviation for the sample of the 21 yearly averages is higher by factor $\sqrt{21}$.
***No charge exchange data found for nitrogen.

Table 1b

Variations of yearly averages of other quantities at 1 AU during 1974 – 1994

	Minimum	Maximum	Average
Solar wind flux [10^8 cm^{-2} s^{-1}]	3.18	4.77	3.92±0.09
Solar wind speed [km s^{-1}]	389	527	451±7
10.7 cm radio flux [10^{-22} W m^{-1} Hz^{-1}]	66.0	192.1	119.4±10

2.3. Other ionization processes

Although charge-exchange and photoionization are the most significant reactions for the ionization of interstellar atoms, a few minor processes can be locally important. The studies of Askew and Kunc (1984) and Ruciński and Fahr (1989, 1991) showed that electron impact ionization plays a non-negligible role for H and He inside ~ 3 AU from the Sun, with a relatively strong increase of its rates at smaller distances. To calculate the characteristic rates for the process, we adopt analytical relations for the energy dependence of the cross-sections as given by Lotz (1967). The variations of the "core" and "halo" solar wind electron populations with the heliocentric distance are taken from the recent determinations of Scime et al. (1994) from Ulysses observations at $\sim 1-5$ AU: $T_c = 1.3 \cdot 10^5 R^{-0.85}$ [K], and $T_h = 9.2 \cdot 10^5 R^{-0.38}$ [K]. The relevant rates (at 1 AU) calculated for the solar wind density of 9 cm^{-3} (96% "core" + 4% "halo") are shown in Table 2. The characteristic contribution of the process to the total rate (at 1 AU) is of the order of $\sim$ 10% or even more. The process was recently recognized by Isenberg and Feldman (1995) as an important loss process for H and He at interplanetary shocks.

The significance of the effect near the Sun was also quite convincingly confirmed during recent direct measurements of the neutral helium gas on Ulysses (Witte et. al., 1996). It was demonstrated that to fit the observed signals referring separately to the He atoms on the 'direct' and 'indirect' orbits (i.e. those which swept out angle less or greater than 180° along their trajectory, respectively), one may either include the electron impact and adopt relatively low $(6.0 \cdot 10^{-8}\ \mathrm{s}^{-1})$ photoionization rate, adequate for the period of observation (March 1995), or if treating the photoionization as the only important effect – its rate must be much higher $(\approx 1.1 \cdot 10^{-7}\ \mathrm{s}^{-1})$ and thus irrelevant for that time. Another minor effect of obser-

Table 2
Typical electron impact ionization rate at 1 AU

Element	H	He	O	Ne	Ar
Electron impact ionization rate [$10^{-7}\ \mathrm{s}^{-1}$]	0.64	0.16	1.30	0.88	2.20

vational importance is the double-charge exchange between neutral He and solar wind α-particles ($\sigma = 2.4 \cdot 10^{-16}\ \mathrm{cm}^2$ for $V_{SW} = 500$ km/s, see Gruntman (1994)). As discussed by Ratkiewicz et al. (1990), the process should lead to the creation of a non-negligible population of the He^{++} pickup ions. This was recently confirmed by Ulysses measurements (Gloeckler and Geiss, 1994). However, no independent information on the related charge-exchange rate is available from this result. In order to derive the interstellar He density from the simultaneously measured pickup ion and solar wind flux a charge-exchange cross section has to be adopted from published values. It should be noted that this is probably the largest uncertainty in this method, because the ratio of pickup and solar wind flux is measured with the same instrument and therefore no absolute calibration factors influence the result.

3. In-situ methods to determine ionization rates

Direct measurements of interstellar gas and its ionization products also provide a new handle on ionization rates. This carries the promise to substantially improve the accuracy of these rates in the near future in a cross-calibration between complementary techniques. As can be easily seen in the following discussion, the new in-situ

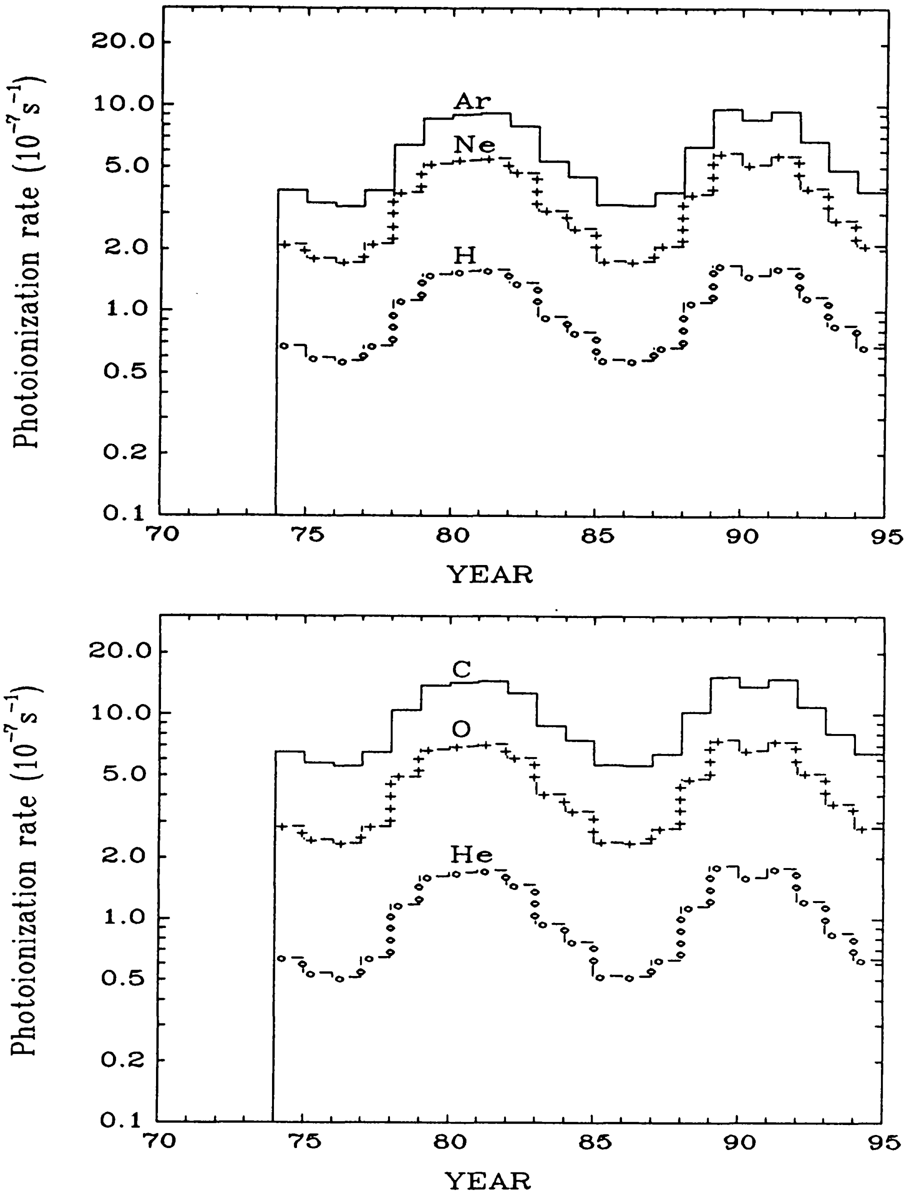

Figure 5. Histograms of the variations of the yearly average photoionization rates at 1 AU (in 10^{-7} s^{-1}) in the period 1974 – 1994. Corresponding curves in the upper panel: H (dash-circled), Ar (solid), Ne (crosses); in the lower panel: He (dash-circled), O (crosses), C (solid).

measurements are sensitive to the total ionization rate, i.e. an integral determination of all ionization processes combined is made. A compilation of current results from in-situ measurements in comparison with the contribution from most important ionization processes is shown in Table 3. Due to the adiabatic cooling of the pickup ion distribution during the outward convection with the radially expanding solar wind the velocity distribution is a direct image of the neutral gas distribution along the Sun-spacecraft line upstream of the observer. Therefore, it is possible to derive radial density gradient from the energy spectra of pickup ions taken in the

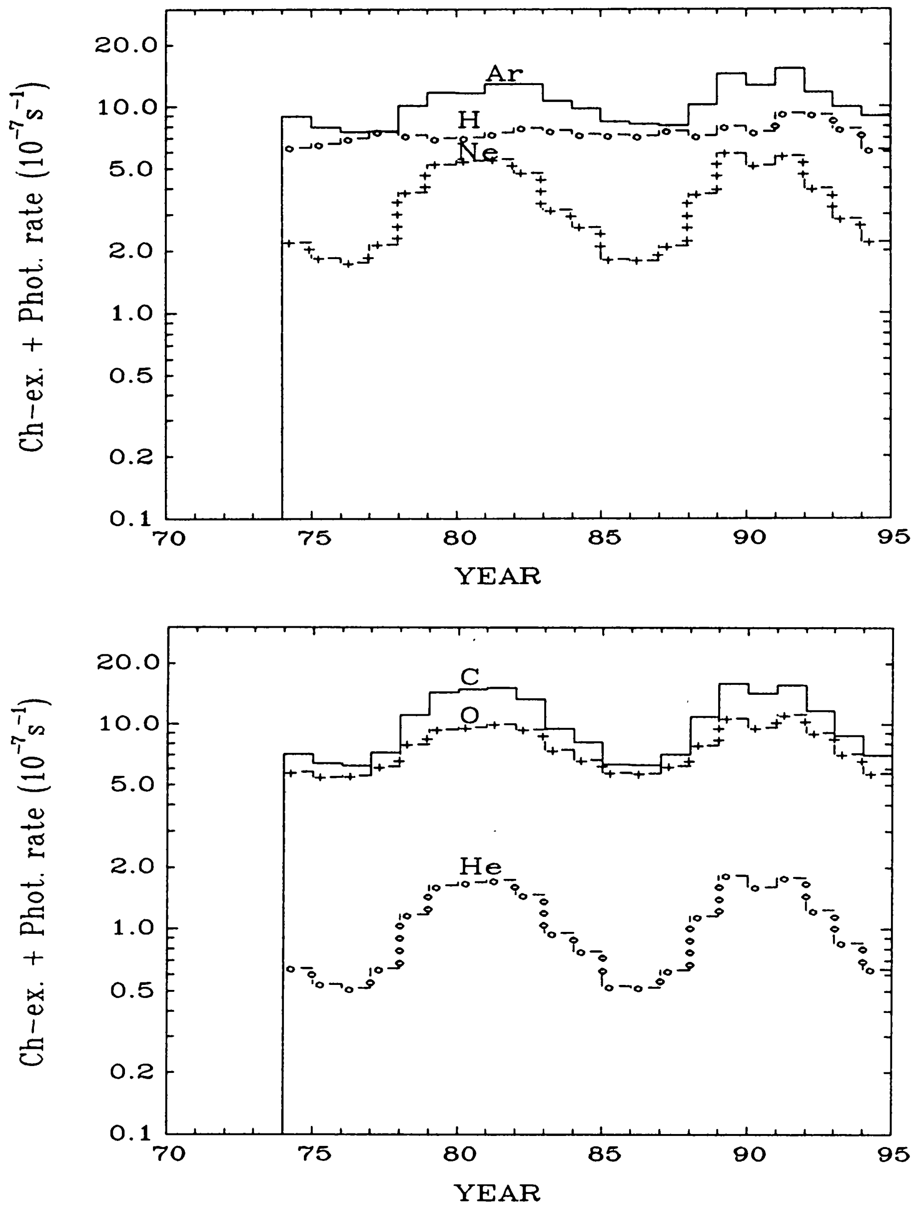

Figure 6. Histograms of the variations of the total (i.e. charge-exchange + photoionization) rates at 1 AU (in 10^{-7} s^{-1}) in the period 1974 – 1994. The curves in upper panel correspond to: H (dash-circled), Ne (crosses), Ar (solid); whereas in lower panel to: He (dash-circled), O (crosses) and C (solid).

solar wind direction and compare this with model distributions of the interstellar gas in the inner Solar System (e.g. Möbius et al., 1988). The radial gradient is a sensitive indicator of the total destruction rate of neutral gas, as long as the observations are made within the typical penetration distance of the species from the Sun (≤ 1 AU for He and ≤ 5 AU for H, Gloeckler et al. (1994)). The resulting energy spectra have led to constraints on the ionization rates which are compatible with other observations. It should be noted that the resulting ionization rate represents

Table 3
Methods of determination of ionization rates applied for helium and hydrogen

Species Method	Photo-ionization [s^{-1}]	Related 10.7 flux [$10^{-22}\cdot$ $Wm^{-2}Hz^{-1}$]	Charge exchange [s^{-1}]	Electron impact [s^{-1}]	Total [s^{-1}]	Uncertainties/ comments
Helium						
Compilation of EUV measurements and literature studies*	**$5.0\cdot10^{-7}$** (min.) **$1.8\cdot10^{-7}$** (max)*	66 (min.) 192 (max)	**$1.0\cdot10^{-10}$** (min.) **$6.0\cdot10^{-10}$** (max.)*		**$5.0\cdot10^{-8}$** (min.) **$1.8\cdot10^{-7}$** (max.)* av. **$1.08\cdot10^{-7}$**	EUV results vary greatly (±25%), EUV flux at $\lambda < 250$ Å poorly known.
Fits to He^+ pickup ion spectra + EUV (*Möbius et al. 1995*)		75	4% of the total rate**	~10% of the total rate	**5.5 – $6.5\cdot10^{-8}$** (1985)	Pickup spectrum varies with transport effects: EUV used as add. constraint
Fits to He^+ pickup ion spectra (*Gloeckler 1996*)		77			**6.5 – $8.5\cdot10^{-8}$** (1994)	Pickup spectrum varies with transport effects
He on direct & indirect orbits (*Witte et al. 1996*)	**$6\cdot10^{-8}$** (1994–95)			rest	**9 – 11 $\cdot10^{-8}$** (1994 – 95)	Large effect from e-impact & elastic collisions at 0.2 AU
He^{++} pickup ions; SW flux+σ_{ch-ex} ** (*Gloeckler 1996*)	$3\cdot10^{-10}$		**1.7 10^{-9}**		**2.0 10^{-9}**	Accuracy of σ_{ch-ex} **
Hydrogen						
Compilation of SW measurements and literature studies	**$6.0\cdot10^{-8}$** (min.) **$1.7\cdot10^{-7}$** (max.)*	66 (min.) 192 (max.)*	**5.5 10^{-7}** (min.) **$8.0\cdot10^{-7}$** (max.)*		**6.2 10^{-7}** (min.) **9.3 10^{-7}** (max.)* av. **7.44 10^{-7}**	Solar wind measurements, accuracy of σ_{ch-ex}, highly variable photo contribution
Fits to H^+ pick-up ion spectra (*Gloeckler 1996*)					**5 – 6 10^{-7}** (1994) high latitude	Anisotropy of pickup spectrum

Values in boldface print have been determined or compiled with appropriate method.
* Compilation over period 1974 – 1994; total rates do not include electron impact.
** Rates refer to the production of He^{++} pickup ions; charge exchange rate denotes here double charge exchange with solar wind alpha particles.

an integral value over several months prior to the measurement, i.e. the travel time of the interstellar neutral gas through the inner Solar System.

Another practical way to determine the total destruction rate of the neutral gas, applied already for the case of He is the comparison of the fluxes of atoms on direct and indirect orbits reaching the neutral gas detector able to differentiate these components (e.g. GAS experiment on Ulysses). As it can be easily seen, the atoms that have passed the point of closest approach (indirect orbits) have been exposed to ionization processes for a longer time. Therefore the flux density on indirect orbits is reduced over that on direct ones. From the difference of the related neutral atom fluxes Witte et al. (1996) have recently computed the combined ionization rate for interstellar helium (see also Section 2.3).

4. Summary

In summary, we can conclude that the contributions of the different ionization processes to the total ionization rate for the most abundant interstellar species are basically known. The ionization of the noble gases He and Ne is almost completely dominated by photoionization, whereas for H charge-exchange with the solar wind is most important. For other species, such as O and Ar, both processes contribute significantly. Electron impact ionization can typically contribute by $\sim 10\%$ to the total rate in the inner Solar System. Because direct measurements of the solar EUV flux are not yet continuously available, the variation of the ionization rate over the solar cycle still contains a relatively large uncertainty. The recent measurements of pickup ion distributions and of the neutral helium gas provide an independent tool to determine the total ionization rate that can be used to cross calibrate with the results obtained for the individual ionization processes.

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