Coordinated observation of local interstellar helium in the Heliosphere

Kinetic parameters of interstellar neutral helium

Review of results obtained during one solar cycle with the Ulysses/GAS-instrument

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Abstract. The GAS-instrument onboard the space probe Ulysses is designed to measure the local angular distribution of the flow of interstellar neutral He-atoms within ≈ 3 AU distance from the sun. It allows to infer the kinetic parameters (velocity vector, temperature and density) of these particles outside the heliosphere (“at infinity”). During three observational periods, 1990/1991, shortly after launch and during the two fast latitude scans of Ulysses, from 9/1994 to 8/1996 and from 9/2000 to 8/2002, more than 300 measurements of the distributions were obtained and analyzed in detail. Known issues that relate to the pointing accuracy of the detector and to the efficiency calibration along with their impact on the results are addressed in this paper. The average values, derived from these observations and their refined analysis, are the bulk speed ($v_{\text{He}\infty} = 26.3 \pm 0.4 \text{ km s}^{-1}$), the flow direction (ecliptic longitude $\lambda_{\infty} = 74.7^\circ \pm 0.5^\circ$, ecliptic latitude $\beta_{\infty} = -5.2^\circ \pm 0.2^\circ$) and temperature ($T_{\text{He}\infty} = 6300 \text{ K} \pm 340 \text{ K}$). From 1990 to 2002, covering a complete solar cycle, no significant temporal variations of these parameters were observed, nor variations with solar latitude. In contrast, in the density $n_{\text{He}\infty}$, derived from the series of local observations along the Ulysses-orbit, substantial apparent variations were seen. After a first attempt to explain these by an inadequate energy calibration of the efficiency they are now interpreted as variations in the loss processes (predominantly photo-ionization), which the neutral gas experiences along its trajectory to the observer. While the temporal variations of the ionization rate were taken into account using the measured solar EUV irradiance (from CELIAS/SEM on SOHO), the residual latitudinal variation has been attributed to a dependence of the solar irradiance on latitude, which thus far has not been accessible to direct observations. As a result of a simple model that includes these effects a density $n_{\text{He}\infty} = 0.015 \pm 0.003 \text{ cm}^{-3}$ has been deduced, which is in good agreement with an independent result from pickup ion observations.

Key words. interplanetary medium – ISM: atoms – ISM: kinematics and dynamics – instrumentation: detectors – methods: observational – plasmas

1. Introduction

Of the constituents in the local interstellar cloud (LIC), besides high energy cosmic rays, only neutral particles, such as H, He, and O atoms, can penetrate into the inner solar system and are accessible to in situ measurements. The determination of their kinetic parameters (velocity vector $v_{\text{He}\infty}$, density $n_{\text{He}\infty}$, and temperature $T_{\text{He}\infty}$) provides clues about the physical state of the LIC, surrounding our solar system. Out of these species He enters the heliosphere unimpeded, while H and O, are significantly decelerated and depleted by charge exchange at the heliospheric boundary (Fahr 1991; Izmodenov et al. 1999; Müller et al. 2000). Therefore, observations of He in the inner heliosphere can provide an unbiased view of the conditions in the LIC. Similar observations of H and O not only hold clues on the parameters of these species, but also provide constraints on the processes at the heliospheric boundary.

Over the past decades continued effort has been invested, to obtain such data, in particular for H and He, since the first observations of UV-backscattering at interstellar H (Bertaux & Blamont 1971) and at He (Weller & Meier 1974). An additional, fertile source is the observation of pickup ions (Möbius et al. 1985; Gloeckler et al. 1993), providing accurate density measurements with He^{2+} (Gloeckler et al. 1997), and LIC parameters from He-cone observations (Möbius et al. 1995). A further, very powerful method became available through the in situ detection of low energy He-atoms by means of sputtering secondary charged particles from a surface coated with pure lithium fluoride (LiF). Proposed by Rosenbauer & Fahr (1977) this method was realized in space for the first time with the GAS-instrument on board the space probe Ulysses.

These three methods focus on the observation of neutral interstellar particles which enter the inner solar system. So far, He is the only species of the interstellar medium for which

all three of them have been employed. After varying and even contradicting results from these methods in the past, the main parameters appear to converge now (Gloeckler & Geiss 2003; Lallement et al. 2003; Witte et al. 2004; Lallement et al. 2004b) and to agree with measurements of the LIC parameters from UV absorption measurements over the line-of-sight to nearby stars (Lallement & Bertin 1992; Linsky et al. 1993).

In this paper, we shall summarize all results of neutral He observations, obtained with the Ulysses/Gas instrument since launch of Ulysses in October 1990 and its analysis with respect to the flow vector and the temperature. In addition, we present the progress made in the determination of the density $n_{\text{He}\infty}$, since time-resolved, instantaneous observations of the ionization rates ν_{iPh} , became available through measurements with the CELIAS/SEM instrument on board SOHO (Judge et al. 1998; McMullin et al. 2002). This review is part of a coordinated effort to obtain the LIC parameters for He through simultaneous observations of neutral He, pickup ions, and backscattering of solar UV at the local interstellar gas distribution. A description of the coordinated campaigns and a synopsis of this effort is given by Möbius et al. (2004).

2. Observations and data evaluation

The GAS-instrument observes the local, angular distribution of the flux of incoming interstellar He atoms. The detector acts like a pinhole camera, which by means of an instrument-provided stepping platform and the space craft spin can scan the entire celestial sphere or selected subsections (see Witte et al. 1992). From the measured angular distribution, the kinetic parameters of the interstellar He atoms outside the heliosphere are derived, with an assumed Maxwellian distribution in $v_{\text{He}\infty}$, $n_{\text{He}\infty}$, $T_{\text{He}\infty}$ at infinity. Through “forward modelling” by comparing the observations with model distributions, best-fit values of the parameters are determined in a multidimensional fitting process (for details, see Banaszkiewicz et al. 1990, 1996).

The sputtering process on a clean LiF-surface, used to convert impacting neutral particles into more easily detectable ions, shows a distinct cut-off in the efficiency at energies below 30 eV (Witte et al. 1992, 1999). Therefore, it requires a favourable combination of the spacecraft velocity vector and the local flow vector of the particles to achieve a relative energy of the particles in the instrument frame of reference, which exceeds this detection threshold (Fig. 1, lower panel). This is the case only during parts of the Ulysses orbit, when the S/C-velocity is high, resulting in three distinct periods of observations: after launch from Nov. 1990 to Feb. 1991 and during the fast latitude scans around perihelion from Sep. 1994 to Aug. 1996 and from Sep. 2000 to Aug. 2002 (indicated by boxes in Fig. 1). Further data can be obtained around the next fast latitude scan starting in 2007, again during solar minimum conditions, because meanwhile (February 2004) ESA has approved an extension of the mission until March 2008.

3. Flow vector $v_{\text{He}\infty}$ and temperature $T_{\text{He}\infty}$

The results of the forward modelling and fitting process, obtained for each individual observation, are shown in Fig. 2.

Fig. 1. Summary of relevant parameters over the Ulysses-mission: *Upper panel:* as indicators for the solar conditions the smoothed solar sunspot number (observed and predicted) and He-ionization rate ν_{iPh} as derived from MgII-indices and CELIAS/SEM-observations (McMullin et al. 2002). *Lower panel:* the inclination of the particles' orbital plain (green) and the relative energy of He-particles on direct (red) and indirect (blue) orbits, which needs to exceed a detection threshold of about 30 eV to allow observation of the particles. The resulting observation times for direct particles (and potential times in 2007/08) are indicated by boxes (the first period had to be terminated in January 1991 for administrative reasons).

The entire set of interstellar parameters, including the He density with the applicable ionization rates (which will be discussed below) is summarized in Table 1 for the different measurement periods. Also shown in Table 1 are the values derived from our previous analysis (Witte et al. 1996) and the refined mean values for the entire data set.

The refinements and the reduction of the uncertainties have become possible through a re-analysis of the data that is based mostly on in-flight calibration efforts for the pointing, using the sensitivity of the sensor to UV stars, which will be discussed in the next section. The local, apparent arrival direction of the particles is the one and only independent observable that can be obtained during the observations. The detection method (sputtering from a LiF-surface) does not provide information about the mass or energy of the primary particles, so that, e.g., the speed and thus the energy of the particles has to be derived from the amount of their gravitational deflection from their direction “at infinity” to their local arrival direction, which in the case of the GAS-observations ranges from about 5 to 22°.

3.1. Pointing accuracy and velocity determination

In a special analysis effort an “end-to-end” test of the pointing accuracy was performed. By means of some hundred measurements of well known star positions with the GAS instrument a systematic error in the original over-all pointing calibration was found, including both the orientation of instrument-provided stepping platform and the spacecraft attitude determination. This amounted to an offset of about 0.5°, which translated into

Fig. 2. a), b), c): Summary of the components of the flow vector ($v_{\text{He}\infty}$, λ_{∞} , β_{∞}) and the temperature $T_{\text{He}\infty}$ for the three observation periods. Average values are indicated in the panels and are summarized in Table 1.

Table 1. Interstellar He – parameter.

	Witte et al. (1996)	1994/1996	2000/2002	best values
Velocity $V_{\text{He}\infty}$ [km s^{-1}]	25.0 ± 0.6	26.3 ± 0.4	26.3 ± 0.4	26.3 ± 0.4
Ecliptic longitude λ_{∞} [°]	74.4 ± 0.9	74.7 ± 0.4	74.7 ± 0.5	74.7 ± 0.5
Ecliptic latitude β_{∞} [°]	-5.1 ± 0.5	-5.2 ± 0.2	-5.2 ± 0.2	-5.2 ± 0.2
Temperature $T_{\text{He}\infty}$ [K]	6600 ± 600	6300 ± 340	6466 ± 400	6300 ± 340
Density $n_{\text{He}\infty}$ [10^{-2} cm^{-3}]	1.4–1.7	1.61 ²	1.48 ²	(1.5 $\pm$ 0.3)
@ Photo ionization rate ν_{iPh} [10^{-8} s^{-1}]	6–11	(7–11) ¹	(13–16) ¹	n/a
Number of observations	20	103	181	

¹ Distance-weighted (r^{-2}), time-averaged photo ionization rates were derived from SEM/SOHO measurements, and from MgII-index for pre-SOHO times (see text).

² Depending on the model assumption about the latitudinal variation of the ionization rate ($\nu_{\text{iPh}}(Q)$), the quoted density-values $n_{\text{He}\infty}$ are for $Q = 0.5$ (for the discussion of the density determination see Sect. 4).

potential errors in the determination of the instantaneous sensor pointing (for details see e.g., Witte et al. 2004). – After updating the pointing calibration, the star positions could be reproduced with a small residual mean deviation of $-0.07^\circ \pm 0.12^\circ$ in cone angle and $0.05^\circ \pm 0.47^\circ$ in spin angle, a precision which hardly can be improved given the width of the intrinsic fields of view (FOV) of 2.4° and 4.7° , respectively. These numbers reflect the precision which can be achieved in the transformation of directions determined in the space craft coordinate system into the inertial, ecliptic coordinate system. Subsequently, all data have been reprocessed with the corrected pointing calibration. Early results from the first two observation periods have been presented in Witte et al. (1993, 1996) and are shown for comparison with the new results in Table 1. From the obvious significant change it becomes immediately clear that knowledge of the pointing to an accuracy of the order of 0.1° or even better is required, which includes both spacecraft attitude knowledge and stability.

The accuracy of the velocity vector depends on the pointing accuracy and the counting statistics in the observed directional distribution of the neutrals. The uncertainty ranges given in Table 1 reflect the statistical variations of the neutral distributions and of the star positions during the respective observation periods. Potential additional systematic errors should be largely removed because the independent overall pointing calibration was performed through the same instrument as the neutral gas observations. The astronomical star positions that were used as reference are known with a very high precision.

3.2. Temperature

The information about the temperature $T_{\text{He}\infty}$ is obtained from the angular width of the local He distribution, which is typically of the order of about 12° FWHM. In Dec. 1990, a nutation-like motion of the spacecraft spin axis with up to 4° in cone angle developed as a result of thermal bending of the axial

boom heated by solar radiation. As the direction of this bending varies with the spin of the spacecraft (spin period = 12 s) it forced the spacecraft into a nutation-like motion, which decreased with distance from the Sun and with the amount of shadowing of the boom by the spacecraft body. As the effect of this motion could not be removed from the measurements because of long integration times (1–2 h), the observed angular distributions were artificially broadened, suggesting temperatures that were too high. Therefore, the values of the temperature $T_{\text{He}\infty}$ obtained in the 1990/91 period should be disregarded. A closer inspection of this effect shows that one degree of nutation (half cone) increases the temperature value by about 800 K. Accordingly, the values of the velocity components obtained during this early time period are less reliable and have larger uncertainties. During the two perihelion passages, the nutation could be kept below 0.2° by active nutation damping using the S/C-attitude control system. During the period 1995/96 longer periods with close to zero nutation could be maintained compared with the 2000/2002 period. Therefore, the lower temperature value obtained during this period is assumed to be the more appropriate result (see Table 1).

4. Determination of the density $n_{\text{He}\infty}$

From the observed neutral atom count rates the interstellar density $n_{\text{He}\infty}$ of He can be inferred only with sufficient knowledge about the instrument detection efficiency and the losses these particles experience on their way to the observer. They occur mainly through ionization, in case of He, predominantly through photo-ionization ν_{IPh} by solar EUV-light, but also by charge exchange ν_{ISW} with solar wind ions, and through collisions with fast electrons ν_{IEl} , existing in the high-energy tail of the solar wind electron distribution ($\sim\text{keV}$) close to the sun and in hot plasma driving interplanetary shocks (e.g., Rucinski et al. 1996). Considerable progress was made in recent years in modelling the relative and absolute contribution of these processes (McMullin et al. 2004). However, their verification through actual measurements is still an open issue as they vary considerably with solar (activity-) conditions and with latitude.

In essence, the determination of the absolute density of the interstellar He-particles from the local fluxes observed in the inner solar system depends mainly on two issues:

1. on instrumental effects, in particular the over-all detection efficiency; and
2. the loss of particles on their way from interstellar space to the observer by ionization.

We shall summarize past and current work and discuss sources of uncertainties in the absolute density determination.

4.1. Instrument issues

In order to detect low-energy interstellar He-particles, sputtering on a surface coated with a thin layer of lithium fluoride (LiF) was used for the first time ever. At the beginning of the development the absolute efficiencies of the material for the generation of sputtered ions as a function of energy was not

well known, nor its long-term stability. Therefore, a careful calibration of the energy dependence of the sputtering efficiency was performed in laboratory experiments (see Fig. 4 in Witte et al. 1992). A complete description may be found elsewhere (Witte et al. 1999). In order to provide the means to improve and test long term stability during flight, an onboard surface regeneration system was installed in the instrument and observations under varying kinematic conditions were monitored.

4.1.1. Absolute efficiency

The absolute efficiency calibration curves presented in Witte et al. (1999) were obtained in an instrumental configuration identical to the flight instrument. That means, secondary effects, such as the transmissivity of grids in the particle path or the efficiency of collecting secondary particles in the channeltrons, are included in the “overall”-efficiency determination. The most delicate task in the calibration effort was to generate a beam of neutral He with well defined properties, such as particle energy, intensity, and beam geometry. Witte et al. (1999) described the facility and the complete calibration effort for the GAS instrument before flight. Because it is not known whether and how the instrument efficiency might change after launch and during the mission in-flight monitoring is highly desirable.

In fact, there is a way of checking the energy calibration in using in-flight data. Given the highly inclined ($i = 80^\circ$), almost polar, orbit of Ulysses around the sun with a perihelion close to the ecliptic plane, the true anomaly of the position along the Ulysses orbit (angular distance from perihelion) and its position in solar latitude are almost identical (i.e. within a few degrees, at least during the relevant periods of the Fast Latitude Scans). While the latitude of Ulysses increases, the velocity of the spacecraft decreases, and so does the relative energy of the He-particles in the instrument frame of reference (see Fig. 1). As a result of its energy dependence the detection efficiency also decreases. A comparison of the modelled spatial distribution of interstellar He with the observed variation along the orbit can then be used for an in-flight check of the energy dependence of the efficiency. It should be noted that this effect has a similar latitude dependence as a reduction in the ionization rate with increasing solar latitude as is postulated later. Based on our observations, both lead to a decrease of the count rates with increasing angular distance from perihelion.

After the first fast latitude scan a surprising and unexplained apparent variation of the observed He density with latitude was therefore interpreted in terms of inaccuracies in the energy dependence of the efficiency calibration in the early stages of the data analysis. Under the (reasonable) assumption, that the interstellar He density does not vary significantly on time scales of months or even a few years, one would expect that the measurements result in more or less constant density values. However, results from the data obtained during the first fast latitude scan in 1995/1996 still showed a systematic temporal variation that correlated with relative energy. With the limited knowledge of the actual ionization rates and thus assuming a constant rate, these variations were attributed to an inadequate calibration of the efficiency at low energies (<30 eV). In order

to achieve constant density values, Witte et al. (1999) proposed a correction, which would increase the detection efficiency below 30 eV by up to 20%.

However, this conclusion needed to be revised later, as even with this “modified” efficiency curve it was still impossible to compensate for a similar, but much more pronounced variation in the density that was observed during the 2000/2002 fast latitude scan. Together with the now available actual data on the photo-ionization rate, it can be shown that the *original* energy calibration leads to satisfying results for both periods. As an additional assumption a latitudinal dependence of the ionization rate has to be introduced (Figs. 4a and b in Witte et al. 2004, see also Sect. 4.2.3). Therefore, we have gone back to the original calibration curve of Witte et al. (1992) in our most recent data analysis.

4.1.2. Long term stability

As LiF was used for the first time in space, little was known about the long-term stability of the detection efficiency for the sputtering of ions induced by He particles, in particular at low energy (0–100 eV). Experience from Lab-experiments (e.g., Witte et al. 1992) seemed to indicate that the efficiency could drop by up to a factor of 2 by degradation and/or contamination of the LiF-surface, e.g. by water vapour, as LiF is slightly hygroscopic.

To avoid pre-launch contamination, the instrument was launched with maiden conversion surfaces. In 1990, shortly after launch and after 10 days of outgassing the sensor, new layers of LiF were deposited in several steps by evaporation from a supply of high-purity LiF. The deposition was monitored through the frequency change of a quartz crystal, while it is exposed simultaneously to the same vapour plume as the detection surfaces. An accumulation of 2–3 nm was achieved during each step. Between the steps the gradual build-up of the efficiency was verified through the step-by-step increase in the signal from He particles. After a total thickness of about 11 nm was reached the signal became constant, indicating that a sufficiently thick LiF layer was accumulated. Its long-term stability was tested in 1995 and 2001 when further layers, 4–5 nm each, were deposited. These times are marked in Figs. 4a and b. While in 1995 the LiF-deposition coincides with a short increase of the derived density values by about 12%, potential variations in 2001 cannot be resolved from other variations in the data. In view of the short duration of the increase in 1995, the frequent occurrence of variations with almost the same amplitude, and the absence of a similar effect after the deposition in 2001, it is reasonable to assume that the earlier increase may be a coincidence. For example, variations of the order of 10% may well be produced by variations in the electron ionization rate as the persistent solar wind stream structure during solar minimum may imprint spatial inhomogeneities on the neutral gas distribution. As discussed in the paper by McMullin et al. (2004), the electron ionization rate may vary locally by up to one order of magnitude. In conclusion, for over 11 years in space and even after passing the harsh Jupiter environment, any

degradation of the He detection efficiency appears to be limited to 5–10%, not exceeding other residual variations in the data.

4.1.3. Potential contribution from other species

As mentioned earlier, the method of particle detection used here (sputtering from a LiF-surface) does not provide information about the mass of the impacting particles. Therefore, potential contribution of particles other than He are taken into account in the following way:

1. Interstellar H: although much more abundant in the interstellar medium than He, H is depleted to the density of He or even less in the inner solar system, due to strong ionization by charge exchange with solar wind protons and due to solar radiation pressure. Secondly, with the same bulk velocity as He, the energy of H is just a quarter of the energy of He particles. During the fast latitude scans (see Fig. 1) the maximum relative energy of He was about 60 eV, leading to a maximum for H of 15 eV. As the sputtering efficiency has a distinct cut-off in energy at 30 eV, the detection probability for H becomes less than 10^{-4} . For these reasons a contribution of H to the measured distributions has been neglected.
2. Heavier particles (O, Ne): contributions of these species have been included in the forward modelling, assuming cosmic abundances in the LIC (8×10^{-5} and $2 \times 10^{-5} \text{ cm}^{-3}$, respectively), average ionization rates (9×10^{-7} and $2 \times 10^{-7} \text{ s}^{-2}$, respectively), and reasonable detection efficiencies. Their maximum total contribution to the count rates per angular bin was calculated to be of the order of 5%, i.e. smaller than the statistical uncertainty of the counts rates. Because of this small total contribution, constant fractions were included in the modelling, but temporal variations, e.g., due to varying ionization rates, have been neglected.

4.2. Analysis of the neutral particle loss processes

In order to derive the neutral gas density in the LIC from local observations of the neutral gas fluxes in the inner heliosphere the depletion of the density due to an adequate combination of ionization processes has to enter the model. Of the three relevant ionization processes charge exchange with solar wind ions contributes typically only less than 5% to the total effect (Rucinski et al. 1996) and thus can be neglected here. This leaves us with photo- and electron-impact ionization as the two important players. In the past no simultaneous observations of these important parameters were available. However, more recently independent information has become available.

4.2.1. Total ionization rate and electron impact ionization

There is one possibility to assess the total ionization, i.e. the combined effect of electron-impact and photo-ionization, self-consistently from observations with the Ulysses GAS instrument. The idea is to compare at the location of the observer the intensities of particles, which arrive at the same time on direct

Fig. 3. The solar meridional plane (ecliptic coordinate system), containing the He-particle velocity at infinity $v_{\text{He}\infty}$ and both solar poles, is crossed by Ulysses at the locations and times marked by asterisks. For these locations the direct and indirect orbits are shown, demonstrating that at certain times the observed particles spend considerable time at high solar latitudes where they are ionized from the UV irradiance originating from the polar hemisphere.

orbits (on the shortest path from the LIC to the spacecraft) with those on indirect orbits (after they have already passed their perihelion on the path from the LIC) (Fig. 3). Assuming that both are essentially exposed to the same solar EUV radiation field (decreasing with r^{-2}), the particles on indirect orbits are affected more strongly by electron-impact ionization as they move much closer around the sun, where this ionization process becomes increasingly important. The Ulysses GAS instrument is ideally suited to perform such measurements. However, most of the time, the apparent arrival direction of indirect particles is too close to the Sun. In this case they cannot be observed without risking the health of the sensors by overexposure to sunlight.

Only at one occasion during the Ulysses mission, around perihelion in 1995, it was possible to observe both species simultaneously. At that time, the velocity of the spacecraft was essentially perpendicular to the local velocity of the particles. Due to the aberration the apparent arrival direction of the indirect particles was sufficiently offset from the solar direction to allow their observation. At this instance, the closest approach to the Sun for direct particles was ≈ 1.3 AU (the position of Ulysses) and ≈ 0.2 AU for indirect particles (their perihelion). As expected, the intensities of indirect particles were significantly depleted, in this particular case to $\approx 1\%$, compared to direct particles, hardly exceeding the omni-directional background. Witte et al. (1996) have modelled this observation under two assumptions:

1. the only acting loss process is photo-ionization. Then the observations were best fitted with a rate $\nu_{\text{IPh}} \approx 1.1 \times 10^{-7} \text{ s}^{-1}$ at 1 AU as reference distance, requiring a density $n_{\text{He}\infty} \approx 0.017 \text{ cm}^{-3}$;
2. in addition to photo-ionization, ν_{IPh} , electron-impact ionization ν_{IEI} was included, modelled according to

Rucinski & Fahr (1989). As a result, a photo-ionization rate $\nu_{\text{IPh}} \approx 0.6 \times 10^{-7} \text{ s}^{-1}$ and density $n_{\text{He}\infty} \approx 0.014 \text{ cm}^{-3}$ provided the best agreement between modeling and observations.

Later, when the MgII-index was identified to provide a good proxy for the solar EUV-radiation (Viereck et al. 2001) responsible for the He photo-ionization, an ionization rate $\nu_{\text{IPh}} \approx 0.7 \times 10^{-7} \text{ s}^{-1}$ was derived for this particular period (see Fig. 4a). Within the limitations of this investigation (with regard to the model assumptions and poor statistical accuracy in the observations) the good agreement of the photo-ionization rates derived in case b) and independently from the MgII-index provides strong support for the suggestion that electron-impact ionization should be regarded a significant ionization process at closer solar distances (< 1 AU).

Unfortunately, it was not possible to repeat this investigation during the second perihelion passage of Ulysses in 2001. Due to proximity to solar activity maximum, the photo-ionization rate had increased by almost a factor of 2 ($\nu_{\text{IPh}} \approx 1.2 \times 10^{-7} \text{ s}^{-1}$, see Fig. 1). As a consequence, the signal from particles on indirect orbits was depleted below the omni-directional background and could not be analyzed.

In all our further work, only particles were analyzed which were still inbound on their direct orbits and never came closer to the sun than the applicable position of Ulysses (mostly > 1.3 AU). For these distances from the Sun the relative effect of electron-impact ionization does not exceed a few percent of photo-ionization and thus, along with charge exchange, can be neglected for the evaluation of the He density (cf. McMullin et al. 2004).

4.2.2. Photo-ionization

In the task to determine the LIC density $n_{\text{He}\infty}$ from the locally observed fluxes great progress could be made, when sufficiently precise, time-resolved measurements of integral solar irradiances became available. The CELIAS/SEM instrument on SOHO provides full-disk absolute solar flux measurements of the HeII (30.4 nm)-line as well as the absolute integral flux between 17 and 70 nm (Hovestadt et al. 1995; Judge et al. 1998). From these data the applicable ionization rates ν_{IPh} have been derived (McMullin et al. 2002) and cross-calibrated with direct observations of the ionization rate with He gas absorption cells (McMullin et al. 2002b). Furthermore, Viereck et al. (2001) showed that the solar MgII-index as observed from the earth since the 1970's, is a reliable proxy for the solar EUV-irradiance, thus providing data for the pre-SOHO era. From these datasets, daily averages of the He-ionization rate were derived (McMullin et al. 2002) for the entire time of the Ulysses mission. This information allowed us for the first time (Witte et al. 2004) to apply actual ionization rates to the neutral He distributions, as observed with the GAS-instrument (Figs. 4a and b, upper panel).

4.2.3. Latitudinal dependence of ionization

As a result of the stimulating discussions during the second ISSI workshop in 2002, a further improvement of the

Fig. 4. a), b): Summary of the parameters contributing to the density determination for the two fast latitude scans of Ulysses: *Upper panel:* ionization rates for He-particles derived from the irradiances observed by CELIAS/SEM (solid black line), resulting time-averaged, distance-weighted ionization rate for isotropic distribution derived from the irradiance in the ecliptic ($Q = 0$, blue) or after including effects of a latitudinal dependence partially ($Q = 0.5$, red) and with full impact ($Q = 1$, green). *Middle panel:* latitude β of Ulysses and the inclination (i) of the particles' orbital plane relative to the ecliptic plane. *Lower panel:* He densities, obtained with a latitudinal dependence of the ionization rate for ratios $Q = 0, 0.5$ and 1 . The long-term variations in the density are smallest for ratios around $Q \approx 0.5$, indicating that a reasonable result can be obtained under the assumption that $\approx 50\%$ of the total ionization rate is latitude dependent. Dates are indicated when new layers of LiF were deposited.

analysis was introduced: As shown in Fig. 3, the travel time of the particles from about 10 AU to the observer, the region where most of the photo-ionization takes place, is of the order of about 600 days. In order to determine an average ionization rate $\langle I \rangle$ (normalized to 1 AU) a time-averaged and distance weighted mean value was calculated along the particles' orbits (see Fig. 3) from daily average values of the rates, assuming that the EUV radiation (hence the ionization probability) decreases with r^{-2} :

$$\langle I \rangle = \frac{\sum_{t=0}^{r(t_0-t) < 10 \text{ AU}} I(t_0 - t) (r(t_0 - t))^{-2}}{\sum_{t=0}^{r(t_0-t) < 10 \text{ AU}} (r(t_0 - t))^{-2}}. \quad (1)$$

Here $r(t_0 - t)$ is the distance of the particles from the Sun, which for $t = 0$ is the distance (of the spacecraft) at the time t_0 of measurement, t is incremented in 1 day steps until a distance $r(t_0 - t) > 10$ AU is reached, neglecting the small ionization rate beyond this distance. In a first analysis step I equals the instantaneous ionization rate I_e derived from EUV measurements in the ecliptic plane normalized to 1 AU (McMullin et al. 2004). For each measured He distribution the average rate was calculated in this way (plotted in Figs. 4a and b, in the upper panel in blue) and included in the forward modelling of the neutral gas distribution. The resulting density values are shown in the lower panels of Fig. 4 (blue curve).

It is obvious, in particular in the 2000/2002-period (Fig. 4b) that in addition to the scatter of the data, there is still a significant residual variation on a time scale of about half a year, under the assumption of isotropic ionization ($Q = 0$). As it is highly unlikely that the interstellar density $n_{\text{He}\infty}$ varies on such a short time scale, and as temporal variations of the ionization rate have already been taken into account, there must be another heliospheric reason for this distinct variation. In principle, the bulk of the observed particles moves on hyperbolic orbits in a single orbital plane, which is defined by the position of the Sun as gravitational centre, the position of the observer (Ulysses), and the vector of the bulk velocity $v_{\text{He}\infty}$ (Fig. 3). As the orbital plane of Ulysses accidentally is almost perpendicular to the flow direction of He, the inclination of the particles' orbital plane ranges from 0 to 90° relative to the ecliptic plane, when Ulysses performs its latitudinal swing from -80° to $+80^\circ$ solar latitude (Fig. 4, middle panels). When the particles travel over one of the solar poles (Fig. 3) on trajectories in a highly inclined orbital plane, they are illuminated predominantly by the polar regions of the Sun. The irradiance of this region may not be well represented by the irradiances of the equatorial belt, which provides the strongest contribution to the radiation observed by the SEM instrument from 0° latitude. In fact, the apparent variation of the He density appears to follow the latitude variation of the spacecraft position. Thus a latitudinal dependence of the ionization rate may cause the

observed variation. With a simple model we shall test this approach: we assume that the ionization rate ($I(\beta)$) consists of two components, one omni-directional (I_0) and the other one (I_i) modulated according to a cosine in latitude β of the particles: $I(\beta) = I_0 + I_i \cos \beta$. For particles moving in the ecliptic plane ($\beta = 0$) the ionization rate $I(\beta)$ is equivalent to the total ionization rate $I(0) = I_0 + I_i = I_e$. After introducing a parameter $Q = I_i/(I_i + I_0)$, which describes the fraction of the total ionization rate that is modulated with latitude, we get

$$I(\beta) = I_e(1 - Q(1 - \cos(\beta))). \quad (2)$$

Replacing I in Eq. (1) by this expression with the appropriate values of I_e and β for times ($t_0 - t$) provides an average ionization rate $\langle I(\beta) \rangle$ that still contains a dependence on the inclination of the particle orbit and thus the latitude of the Ulysses position.

For three values of Q the resulting ionization rates (I) and densities are shown colour-coded in Fig. 4, calculated for each individual measurement. In particular in Fig. 4b, much of the apparent density variations, seen in the case $Q = 0$ (blue curve), are compensated using $Q = 0.5$ (red curve), while for $Q = 1$ (green curve), the variations are clearly overcompensated. In the period 1994/96 (Fig. 4a), a similar effect can be observed, but much less pronounced. This probably results from the solar minimum conditions, when the total ionization rate is about half that in 2000/02, hence the overall modulation is less pronounced and almost masked by the scatter of the data.

Assuming again, that $n_{\text{He}\infty}$ should have a constant value, a minimum variance analysis was performed for Q (Fig. 5). Flat minima around $Q = 0.5$ for the two time periods suggest that 50% of the total ionization rate is latitude dependent or, in other words, the ionization rate over the poles is 50% lower than at the equator. The average densities $n_{\text{He}\infty}$ resulting from the choice of different values for Q are added in the lower panel. Given the flat minima the difference in the average density values for the two observation periods are not be regarded as significant. It cannot be excluded that part of the apparent latitudinal modulation may still be due to an uncertainty in the knowledge of the energy dependence of the detection efficiency (see Sect. 4.1.1) and the assumption of a simple cosine-law in latitude is certainly an oversimplification. Therefore, the result that approximately 50% of the ionization is latitude dependent contains a relatively large uncertainty. This issue will be one of the topics of a further ISSI-workshop scheduled for 2004: latitudinally resolved EUV-irradiance from the SOHO/EIT-images will be used for a refined analysis of the latitudinal dependence of the ionization rate.

5. Conclusions and discussions

For over 13 years the Ulysses GAS observations have been successfully carried out dedicated to the determination of the kinetic parameters of the interstellar He component.

In this paper we have critically reviewed experimental approaches, summarized the results and their statistical accuracies, and discussed sources contributing to the errors. After

Fig. 5. Minimum variance analysis for the dependence of the density from the latitude-dependence parameter Q . The deviations (variance) of the density values from the assumed constant density are smallest for $Q \approx 0.5$. The corresponding resulting average density values are shown in Figs. 4a and b, respectively.

extensive work with the instrument, the data and their reduction, assessing potential errors and uncertainties still involved, a set of mean values for the physical parameters and their estimated uncertainties has been derived from our observations (see Table 1).

The results for the velocity vector and temperature from the two fast latitude scans of Ulysses in 1994/96 and 2000/02 have been substantially refined in a detailed re-analysis. With a careful end-to-end calibration of the direction determination, using star positions, any uncertainties from potential systematic errors have been minimized and are now smaller than the statistical errors. The effect of the recalibration of the pointing (correction by about 0.5°) can be seen when comparing these data with the early ones (Witte et al. 1996) (Table 1), which show significant deviations from each other: the velocity $v_{\text{He}\infty}$ increased from 25.0 ± 0.6 to 26.3 ± 0.4 km s $^{-1}$, the flow direction changed in ecliptic longitude λ_∞ from $74.4 \pm 0.9^\circ$ to $74.7 \pm 0.5^\circ$ and in ecliptic latitude β_∞ from $-5.1 \pm 0.5^\circ$ to $-5.2 \pm 0.2^\circ$. The temperature value $T_{\text{He}\infty}$ was improved from 6600 ± 600 K to 6300 ± 340 K. This stresses the importance of a precise ($\leq 0.1^\circ$) knowledge of the pointing direction for this particular experimental method. In the last column of Table 1

those values are summarized, which best represent the combined results from all our observations.

Very recently these parameters have been determined again using different approaches: from UV-backscattering observations of the He-cone with the EUVE (Vallerga et al. 2004), a re-examination of the Prognos-data (Lallement et al. 2004a) or from pickup ion observations (Gloeckler et al. 2004). In the coordinated study performed in this ISSI-workshop, a great convergence of the different results to a common data set became obvious (Möbius et al. 2004).

With regard to the ionization rates important issues could be addressed by the GAS-measurements:

1. There is strong evidence from simultaneous measurements of particles on direct and indirect orbits that ionization by electron impact plays an important role for the ionization of He inside 1 AU.
2. There is strong evidence that the total ionization rate and thus the photo-ionization rate decreases with solar latitude, according to the simple model used, by up to 50% from equator to the pole. As a consequence the shape of the “He-cone” would not be symmetrical around the downwind axis rather than the iso-density lines in a cross section would be more like ovals with extensions towards high latitudes.
3. Although a number of temporal and latitudinal variations have been modelled there are still residual variations in the density on a time scale of months. This suggests that not all effects have been included adequately or that additional processes need to be taken into account. For example, the electron-impact ionization shows strong temporal variations with peaks up to the value of photo-ionization on short time scales (McMullin et al. 2004). However, as the particles observed by Ulysses/GAS are on direct orbits, still inbound, these effects must work at larger distances from the sun than the applicable position of Ulysses (>1.3 AU). Here, effects of the energetic (~ 1 keV) “Strahl”-component of the solar wind electron distribution or of strong travelling interplanetary shocks may play a role as they could give rise to variations on the observed time scales.

Although considerable progress has been made recently in the determination of the ionization rates (see e.g., McMullin et al. 2004), their temporal and spatial variations (in particular their variation with solar latitude) provide still the most important source of uncertainty in the determination of the interstellar density $n_{\text{He}\infty}$. Only direct observations of its latitudinal dependence and full 3-dimensional modelling that includes all temporal variations can provide the necessary improvements.

However, with the present state of modelling, an average value of the LIC-density $n_{\text{He}\infty} = 0.015 \text{ cm}^{-3}$ has been obtained. Observed residual temporal deviations from this value rarely exceed a range of $\pm 0.002 \times 10^{-2} \text{ cm}^{-3}$ so that the quoted (Table 1) range of uncertainty of $\pm 0.003 \text{ cm}^{-3}$ is regarded as an upper limit. This is in great agreement with a density value $n_{\text{He}\infty} = 0.0151 \pm 0.0015 \text{ cm}^{-3}$ derived from pickup ion measurements with Ulysses/SWICS (Gloeckler et al. 2004).

Over one solar cycle no significant temporal variations in the kinetic parameters of the interstellar He flow vector have been observed.

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