A&A 426, 897–907 (2004)
DOI: 10.1051/0004-6361:20035834

Astronomy
&
Astrophysics

Coordinated observation of local interstellar helium in the Heliosphere

Synopsis of the interstellar He parameters from combined neutral gas, pickup ion and UV scattering observations and related consequences

E. Möbius[1], M. Bzowski[2], S. Chalov[3], H.-J. Fahr[4], G. Gloeckler[5,6], V. Izmodenov[7], R. Kallenbach[8], R. Lallement[9], D. McMullin[10], H. Noda[11], M. Oka[12], A. Pauluhn[8], J. Raymond[13], D. Ruciński[2,⋆], R. Skoug[14], T. Terasawa[12], W. Thompson[15], J. Vallerga[16], R. von Steiger[8], and M. Witte[17]

[1] Dept. of Physics and Space Science Center, University of New Hampshire, Durham, NH 03824, USA
e-mail: `Eberhard.Moebius@unh.edu`
[2] Space Research Centre, Polish Academy of Sciences, Bratycka 18 A, 00-716 Warsaw, Poland
[3] Institute for Problems in Mechanics, Russian Academy of Sciences, Prospect Vernadskogo 101-1, Moscow 117526, Russia
[4] Institut für Astronomie und Extraterrestrische Forschung, Universität Bonn, Auf dem Hügel 71, 53121 Bonn, Germany
[5] Dept. of Physics and IPST, University of Maryland, College Park, MD 20742, USA
[6] Dept. of Atmospheric, Oceanic and Space Sciences, University of Michigan, Ann Arbor, MI 48109, USA
[7] Department of Mechanics and Mathematics, Lomonosov Moscow State University, Moscow 119899, Russia
[8] International Space Science Institute (ISSI), Hallerstr. 6, 3012 Bern, Switzerland
[9] Service d'Aéronomie du CNRS, BP 3, 91371 Verrières-le-Buisson, France
[10] Space Science Center, University of Southern California, Los Angeles, CA 90089, USA
Now at: Naval Research Laboratory/Praxis, Inc., Space Science Division, Code 7660, 4555 Overlook Ave. SW, Washington DC 20375, USA
[11] National Astronomical Observatory of Japan, Hoshi-ga-oka 2-12, Mizusawa Iwate, Japan
[12] Department of Earth and Planetary Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113, Japan
[13] Harvard Smithsonian Center for Astrophysics, 60 Garden St., MS-15, Cambridge, MA 02138, USA
[14] Los Alamos National Laboratory, MS D466, Los Alamos, NM 87545, USA
[15] Goddard Space Flight Center, Code 682.3, Greenbelt, MD 20771, USA
[16] Space Sciences Laboratory, University of California Berkeley, Berkeley, CA 94720, USA
[17] Max Planck Institut for Solar System Research, Max-Planck-Str. 2, 37191 Katlenburg-Lindau 3, Germany

Received 9 December 2003 / Accepted 29 March 2004

Abstract. A coordinated effort to combine all three methods that are used to determine the physical parameters of interstellar gas in the heliosphere has been undertaken. In order to arrive at a consistent parameter set that agrees with the observations of neutral gas, pickup ions and UV backscattering we have combined data sets from coordinated observation campaigns over three years from 1998 through 2000. The key observations include pickup ions with ACE and Ulysses SWICS, neutral atoms with Ulysses GAS, as well as UV backscattering at the He focusing cone close to the Sun with SOHO UVCS and at 1 AU with EUVE. For the first time also the solar EUV irradiance that is responsible for photo ionization was monitored with SOHO CELIAS SEM, and the He I 58.4 nm line that illuminates He was observed simultaneously with SOHO SUMER. The solar wind conditions were monitored with SOHO, ACE, and WIND. Based on these data the modeling of the interstellar gas and its secondary products in the heliosphere has resulted in a consistent set of interstellar He parameters with much reduced uncertainties, which satisfy all observations, even extended to earlier data sets. It was also established that a substantial ionization in addition to photo ionization, most likely electron impact, is required, with increasing relative importance closer to the Sun. Furthermore, the total combined ionization rate varies significantly with solar latitude, requiring a fully three dimensional and time dependent treatment of the problem.

Key words. interplanetary medium – ISM: general – ISM: atoms – methods: observational – plasmas

1. Introduction and historical context

The local galactic environment of the Sun consists of a warm relatively dilute partially ionized interstellar gas cloud, which is quite structured (e.g., reviews by Cox & Reynolds 1987; Frisch 1995). Apparently, the Sun finds itself close to a cloud boundary, possibly with a significant gradient in the ionization fraction of He (e.g., Cheng & Bruhweiler 1990; Slavin & Frisch 2002). While the environment and structure of the

---

[⋆] Deceased.

local interstellar cloud (LIC), including integral densities and relative speeds, has been studied on scales of several parsec through UV line absorption by the surrounding medium in the light of nearby stars (e.g., McClintock et al. 1978; Frisch 1981; Crutcher 1982; Lallement & Bertin 1992; Linsky et al. 1993), the conditions at the location of the Sun may be different. However, it is these very local conditions that determine the size and shape of the heliosphere as well as the processes that control its boundary regions. Beyond that the influence of the interstellar gas reaches much deeper into the heliosphere, for example, with the generation of pickup ions (e.g., Möbius et al. 1985; Gloeckler & Geiss 1998) and of anomalous cosmic rays (e.g., Klecker 1995; Jokipii 1998) as well as a slow down of the solar wind (Richardson et al. 1995). The basic understanding of the heliosphere and its interaction with the interstellar medium has been summarized in early reviews (Axford 1972; Fahr 1974; Holzer 1977; Thomas 1978). Since then substantial progress has been made in the global modeling (Baranov & Malama 1993; Linde et al. 1998; Fahr et al. 2000; Zank & Müller 2003; Zank 1999, and references therein), but fixing the parameters in these models requires detailed knowledge of the very local boundary conditions. It should also be noted that this is the only place in the universe where a local measurement is possible, thus providing an important benchmark for interstellar medium studies.

Interstellar neutral gas penetrates into the inner heliosphere as a neutral wind due to the relative motion between the Sun and the local interstellar medium. Through the interplay between this wind, the ionization of the neutrals upon their approach to the Sun, and the Sun's gravitational field (distinctly modified by radiation pressure for H), a characteristic flow pattern and density structure is formed with a cavity close to the Sun and gravitational focusing on the downwind side (for all species except H). Starting with the analysis of backscattered solar Lyman α intensity sky maps (Bertaux & Blamont 1971; Thomas & Krassa 1971) the parameters of H became accessible to measurements. Based on early modeling using a cold interstellar gas flow (e.g., Blum & Fahr 1970; Holzer & Axford 1971; Axford 1972; Fahr 1974) the general flow direction and an order of magnitude estimate for the density could be deduced. Through the Doppler effect high-resolution profiles of backscattered Ly α from Copernicus provided a first reasonable value for the H bulk speed ($\approx$22 km s^{-1}) and constraints for the temperature (Adams & Frisch 1977). Substantial progress towards the kinetic parameters was made with the use of hydrogen absorption cells (Bertaux et al. 1985) yielding $v_{\rm H}$ = 20 km s^{-1} and $T_{\rm H}$ = 8000 K. First rocket-borne (Paresce et al. 1974) and satellite-borne (Weller & Meier 1974) observations of interstellar He in the solar He I 58.4 nm line followed a few years after the detection of H. Through the gravitational focusing of the interstellar He flow on the downwind side of the Sun the direction of the interstellar wind was immediately constrained much better (Weller & Meier 1974) than by the H maps. Density, bulk flow speed, and temperature of He could also be deduced from the total intensity of the glow, relative intensity and width of the cone, provided this structure is modeled with a hot gas distribution (e.g., Fahr et al. 1978; Wu & Judge 1979). Based on multiple He cone scans in Venus' orbit with Mariner 10 (Ajello 1978; Broadfoot & Kumar 1978) and in Earth's orbit with Solrad 11 (Weller & Meier 1981) and Prognoz 6 (Dalaudier et al. 1984) sets of dynamic parameters were derived in a multi-parameter fit, including solar line width and ionization rates, which gravitated around $T_{\rm He}$ = 11 000–16 000 K with $v_{\rm He}$ = 22–28 km s^{-1} and around $T_{\rm He}$ = 6000–8000 K with about half the speed. Chassefière et al. (1986) compiled a critical evaluation of all interstellar density measurements, with values for $n_{\rm H}$ from 0.02 to 0.068 cm^{-3}, including their latest value of 0.065 ± 0.01, and $n_{\rm He}$ from 0.0035 to 0.032 cm^{-3}, including theirs of 0.01 ± 0.0045. The counterintuitive difference between H and He in temperature, or depending on the choice of parameters in speed, persisted. Further progress was made with the He UV observations when the low Earth orbit of EUVE provided the opportunity to use the exosphere as a natural gas absorption cell. After modeling the not well known spectral distribution of the geocorona, Flynn et al. (1998) derived $v_{\rm He}$ = 26.4 km s^{-1} and $T_{\rm He}$ = 6500 K, suggesting that the previous high temperature or low speed results may have been artifacts. Meanwhile the discovery of interstellar He pickup ions at 1 AU (Möbius et al. 1985) introduced a first in situ method to probe interstellar particles. This enabled an independent determination of the interstellar He flow parameters (Möbius et al. 1995), but the method was hampered in its accuracy by strong variations in pickup ion fluxes (Möbius et al. 1998) and the discontinuous data set of an Earth orbiting spacecraft. Continuous coverage in interplanetary space up to 4.5 AU and access to H^{+} and He^{2+} pickup ions with Ulysses SWICS provided a more precise account of the H (0.11 cm^{-3}) and He (0.015 cm^{-3}) densities (Gloeckler et al. 1997), and a more direct evaluation of the abundance of minor species, such as N, O and Ne, (Gloeckler & Geiss 2001a) than is provided by anomalous cosmic rays (Cummings et al. 2002). Finally, direct observations of the neutral gas velocity distribution (Witte et al. 1996) have become available for He, with the most complete information about this key species in the LIC yet.

As can be seen from this brief account, the parameters obtained from various observations, using the same method or comparing different methods, have varied greatly in the past (Chassefière et al. 1986; Möbius 1993), and the uncertainties quoted for the analysis have been substantial. Two major contributors to these variations in the results can be identified. Firstly, neither of the three observation methods provides us with first hand information on the physical parameters in the LIC, and various levels of modeling are necessary to connect the observations in the inner heliosphere with the LIC. Because of the complexity and incomplete information a number of approximations and simplifications have been made. Secondly, in order to account for the depletion of LIC material on its way to the Sun and for the observable spatial and velocity distribution information on ionization and solar illumination of the interstellar gas is needed. In the past simultaneous availability of these parameters has been incomplete and spotty at best. Therefore, key input parameters for the modeling, such as ionization rates and photon pressure, intensities and line profiles of illuminating solar radiation, as well as their spatial and temporal variations, had to be inferred and were adapted during the modeling. Since each of the three observation methods is affected by a different combination of these parameters, a careful comparison of the results from all three methods can provide valuable insight into the root causes for the reported differences in the LIC parameters. If this comparison is combined with state-of-the-art modeling and can rely on improved availability of ancillary parameters, such a coordinated effort should lead to the determination of a benchmark set of physical parameters for the LIC.

It turns out that He is the first interstellar species that can be studied simultaneously with all three local observation methods, partly because it penetrates closest to the Sun to well inside 1 AU with its high ionization potential. More importantly, He provides us with almost completely unbiased information about the physical parameters of the LIC, i.e. its bulk flow velocity v_{He}, longitude λ and latitude β of the inflow direction, temperature T_{He} and density n_{He}, as it enters the heliosphere unimpeded. Conversely, the abundance of H and O, along with other species, is significantly depleted, their speed decreased, and their temperature increased, through charge exchange in the heliospheric interface (Fahr 1991; Ruciński et al. 1993; Izmodenov et al. 1999; Müller et al. 2000; Izmodenov et al. 2004). Thus He can provide a solid basis for the study of the filtration effects at the heliospheric boundary through comparison with H and O, a prerequisite for the determination of the LIC composition from observations inside the heliosphere. Consequently, we have seized the opportunity to mount a coordinated observation and analysis effort towards a benchmark set for the physical parameters of interstellar He, which has presented itself through simultaneous UV scattering, pickup ion and neutral atom observations on He with EUVE, SOHO, ACE, NOZOMI, and Ulysses. Because these spacecraft also provide simultaneous monitoring of the relevant ionization rates and solar illumination, it is possible to constrain these effects, to capture the related solar activity variations, and thus to determine, which problems and physical processes have made the resulting interstellar parameters so variable in the past. Finally, these refined methods may then be used to attempt long term monitoring of solar and interstellar variations, including reevaluation of past observations.

As conclusion of a special section in this volume of Astronomy & Astrophysics, this paper provides a synoptic view of the combined results from our coordinated observation and analysis effort together with implications for our knowledge of the LIC and related interaction processes within the heliosphere. In the first paper of the sequence Witte (2004) presents the derivation of the LIC velocity vector, temperature and density for He from the combined Ulysses GAS observations over the time periods 1994−1996 and 2000−2002, together with implications on the 3D structure of the ionization rate in the heliosphere. Then Gloeckler et al. (2004) present an updated evaluation of the He density from He^{2+} pickup ion observations with Ulysses SWICS and their modeling of the He cone observations from 1998 through 2002 with ACE SWICS. The UV scattering observations of the He cone with the EUVE spacecraft at 1 AU from 1998 through 2001 are discussed next by Vallerga et al. (2004). Lallement et al. (2004a) present the strong dependence of the He cone very close to the Sun on solar activity, which has been observed with SOHO UVCS from 1996 through 2002. This discussion is followed by a reevaluation of the Prognoz 6 observations of the He cone Lallement et al. (2004b), which were originally analyzed by Dalaudier et al. (1984) with the surprising result of a higher He temperature than found for H. Finally, McMullin et al. (2004) present the combined observations of the relevant ionization rates and of the illuminating solar He I 58.4 nm line profile and intensities, together with a discussion of their influence on the interstellar He observations, crucial information that could only be inferred in the past. In this paper we will first describe the coordinated observation campaigns, compare the strengths and weaknesses of the different observation techniques, i.e. how they complement each other and where they rely on additional observations and modeling, and then compile and combine the resulting LIC parameters in light of their relative uncertainties. We will close with a brief discussion of the implications, including the future prospects of and requirements for a long term monitoring of the locally obtained LIC parameters and their relation to astronomical studies of the interstellar medium.

This series of papers is dedicated to our long time friend and collaborator Daniel Ruciński, who passed away prematurely and unexpectedly in February 2002, while this collaborative analysis was still in full swing. Daniel had and even after his passing still has a very profound role in our study, with many important leads and ideas that forced us to look at the emerging results from all possible angles. After all he was the one who pointed out first that electron impact ionization has a substantial effect on the spatial distribution of neutral interstellar gas in the inner heliosphere, with increasing importance closer to the Sun (Ruciński & Fahr 1989). From the report of the first pickup ion observations he repeatedly stressed that this new method should reveal electron ionization. Indeed the combination of observations of the He distribution inside 1 AU that forms the basis of this coordinated study provides the first window into electron ionization close to the Sun. One of the study's important findings is that this ionization channel has even a more profound impact than thought before and that it varies significantly stronger with solar activity than EUV ionization. In a way, the completion of our study of the interstellar He distribution in the inner heliosphere is a capstone for Daniel Ruciński's scientific work. Its findings provide the long sought for validation of his prediction and excellent corroboration for his modeling.

2. Coordinated observation campaigns

During the late 1990's a unique opportunity had been created with instrumentation capable to support all three known interstellar gas observation methods on a variety of operating solar, heliospheric and astronomical spacecraft. At the same time also continuous monitoring of crucial interplanetary parameters, such as ionization rates and solar line profiles, had become available for the first time or had been greatly improved. Therefore, several observation campaigns for near Earth spacecraft were initiated during the Earth's crossing of the He focusing cone over consecutive years, which were combined

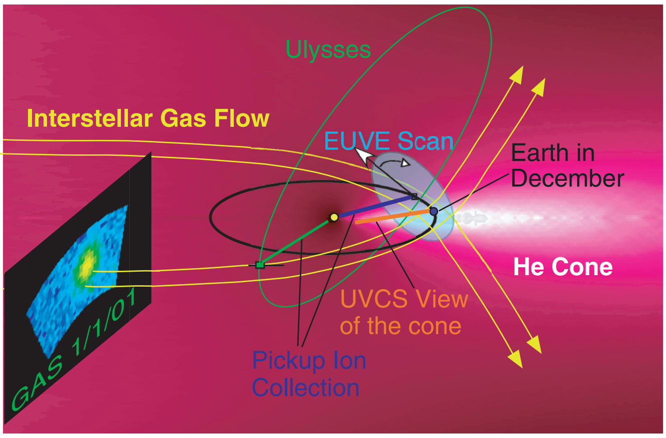

Fig. 1. Perspective view of the inner heliosphere with the interstellar He flow and the resulting focusing cone, as modeled by J. Raymond (Michels et al. 2002; Lallement et al. 2004a), based on a hot model of the interstellar gas. A line-of-sight through the near-Sun cone, as obtained with SOHO UVCS in December, is indicated in orange. Also shown is a scan across the focusing cone in the He I 58.4 nm line glow from a February location with EUVE, as an example for the determination of the He parameters from the cone shape (Vallerga et al. 2004). A typical location of Ulysses during the neutral He observations is shown together with a sample of a sky image of the inflowing He distribution, from which the physical parameters were derived (Witte 2004). Finally, the dark blue line that extends from the Earth to the Sun indicates a sample accumulation of He^{+} pickup ion spectra in the ecliptic plane with ACE SWICS, and the green line shows the corresponding accumulation with Ulysses SWICS (Gloeckler et al. 2004).

with ongoing observations by the Ulysses spacecraft. Figure 1 presents a pictorial overview on where and how the observations were made that contributed to this coordinated effort. With SOHO JOP 129 a series of UVCS observations of the He cone close to the Sun was scheduled during the cone crossing of the Earth for 1998, 1999, and 2000, together with full solar disk scans by CDS of all important lines between 30 and 60 nm. SOHO SEM was monitoring the solar EUV irradiation continuously. For these years also He cone observations were scheduled at 1 AU with EUVE.

During the December cone crossings SOHO UVCS observed the He cone at a radial distance of $\approx$0.2 AU or 1.75° from the center of the Sun. At the same time EUVE looked along the cone just outside 1 AU. Two months before and after the cone crossing a full 360° scan across the cone was scheduled. In this way the intensity of the cone could be measured as a function of distance from the Sun, which is very sensitive to ionization of the interstellar gas. A cross-section of the cone could be obtained simultaneously.

From early 1998 on ACE SWICS was fully operational and took He^{+} pickup ion observations continuously, except for short intervals during spacecraft maneuvers or during the passage of the Leonid meteor shower in November 1998. Up to the completion of our analysis the data set comprises five consecutive cone crossings from close to solar minimum to just after solar maximum. In 2000 the NOZOMI spacecraft also passed the cone at 1.01 to 1.2 AU on its way to Mars and provided pickup ion observations with the plasma instrument. These pickup ion observations complement the UV measurements with information on the azimuthal and radial cone structure inside 1 AU. In addition, Ulysses SWICS data were available almost continuously during the entire time, which contribute He^{2+} pickup ion data. Direct He neutral gas observations with Ulysses GAS require a minimum relative velocity between interstellar gas flow and spacecraft motion (Witte 2004), which after the original observations in 1992 and 1994–96 was met again starting October 2000, i.e. for the last coordinated cone observation. Both instruments on Ulysses provide interstellar gas observations at distances from the Sun where not much reduction in the density over the interstellar value has occurred yet. In particular the density obtained with Ulysses SWICS at up to 5 AU is least affected by the modeling of the flow of the LIC gas through the heliosphere and thus closest to model independent.

3. Comparison of the observation methods

Figure 2 provides a flow chart with all the different observations and the modeling involved in our analysis towards the interstellar gas parameters. We have used the strengths of each observation towards maximum advantage, which is reflected in our choice of the methods to derive certain parameters and in the direction of the analysis flow for each observation method. For none of the methods are the results completely model independent. However, in each case the knowledge of a different set of environmental parameters is needed, and the needed levels of modeling vary depending on the observable used. In our flowchart we have color-coded the key observations and their analysis path, blue for pickup ions, red for neutral atoms and yellow for UV scattering. Rectangles represent input of observables, rounded rectangles indicate the various layers of modeling, and ellipses contain the results and their implications.

Clearly, as we are looking for the density, bulk flow vector, and temperature of interstellar He, the observation of the distribution function of neutral He provides the most direct insight into the LIC conditions. That is why each of these parameters can be directly derived from the neutral gas observations, as indicated by the colored underlining. Yet the He distributions observed with Ulysses GAS between 1.3 and 2.5 AU from the Sun have been altered by the influence of solar gravitation and ionization on the way from the interstellar medium into the inner heliosphere. Because the amount of ionization loss depends on the time spent under its influence, the original velocity distribution will become asymmetric, with the slowest atoms affected the most. Although this affects the derivation of all parameters, it can be corrected in the modeling, as neutral atom fluxes represent the most direct observable. However, the requirement of Ulysses GAS to observe near perihelion of the orbit in order to satisfy the minimum energy condition and an involved absolute calibration of the count rate (Banaszkiewicz et al. 1993) leave a significant uncertainty for the density.

Pickup ion measurements start from a secondary product of interstellar gas that emerges through ionization and thus involves the independent knowledge of ionization rates and additional modeling of the observed velocity distribution of pickup ions. However, the observations of He^{2+} pickup ions

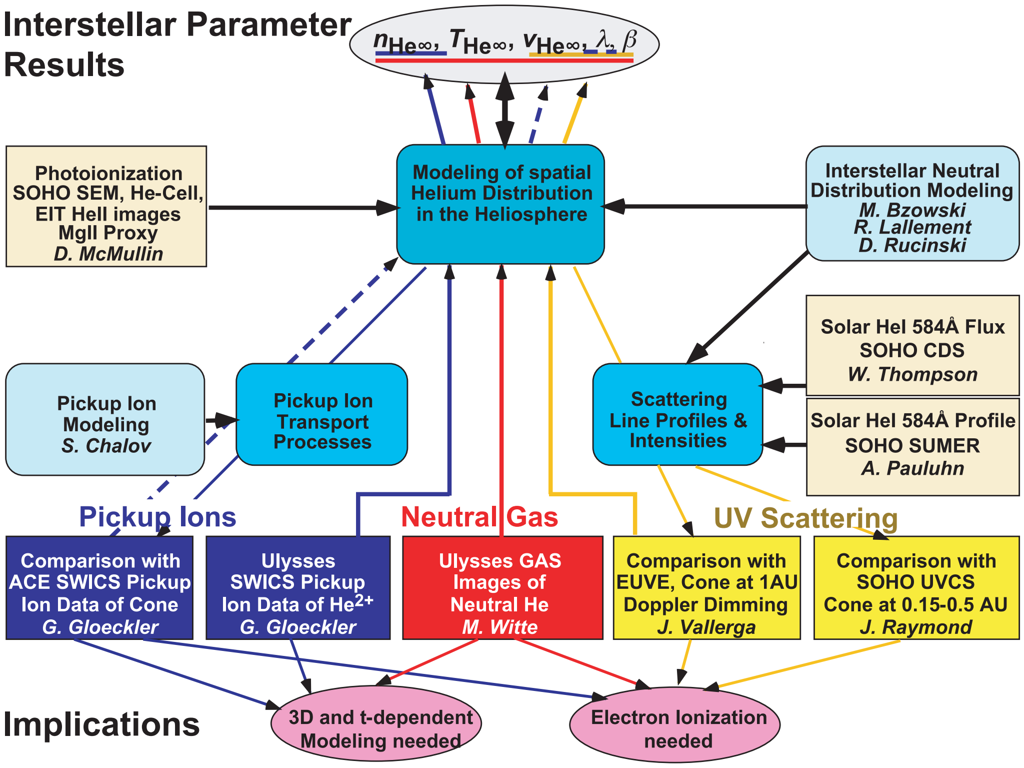

Fig. 2. Flowchart of the different observations and modeling involved in the coordinated analysis effort towards the interstellar He parameters. Rectangular boxes indicate observations that were used, the rounded boxes indicate modeling used to either derive parameters or to reproduce observations. The arrows indicate the flow in the analysis, either from observation to derived parameter or from parameter used to additional implications. The oval boxes contain the main results, i.e. the He parameters (*top*) with a color-coding that indicates the primary method, from which the values were derived, and implications that need future attention (*bottom*), as deduced from this analysis.

with Ulysses SWICS at distances from the Sun of up to 5 AU come from an almost completely unchanged density (Gloeckler et al. 1997; Gloeckler & Geiss 2001b). Equally important is the fact that this observation does not require any absolute calibration, because He^{2+} is to more than 90% produced by solar wind alpha particles, whose flux is observed with the same instrument that measures the pickup ions. Therefore, the analysis relies on a ratio of these two measurements with the same instrument, and the main uncertainty is reduced to the knowledge of the cross-section for double charge exchange of He into He^{2+}. Therefore, the He^{2+} observations have the potential to give the most accurate density value (indicated by the blue underlining of the He density in Fig. 2), and the direct comparison of the two complementary particle observations, neutral gas and pickup ions, is a powerful tool to check the consistency of the results.

All He UV backscattering observations have been performed close to or inside 1 AU and therefore are influenced even stronger by the variability of the ionization than the neutral gas observations outside 1.3 AU. This is particularly true for the new near-Sun cone observations with UVCS (Lallement et al. 2004a). Conversely, this strong dependence on the ionization can also be a strength, as it can be used to derive reliably the total ionization rate for helium and its variation with solar conditions. Like pickup ion observations the UV scattering method relies on a secondary product to derive the He distribution, i.e. photons scattered off the interstellar gas in the inner heliosphere. Clearly, the intensity and the line profile of the illuminating solar UV line (He I 58.4 nm) is needed to extract the He distribution from the UV scattering observations, but good independent measurements of these parameters are scarce at best. Therefore, past analysis has relied on multi-parameter fits of the observations with all gas parameters and the ionization rate as variables. In addition, the solar illumination was adapted for best consistency. However, the Doppler effect can be used to derive the He velocity vector separately and almost as directly as through neutral atom measurements. In the past the flow vector has been determined for interstellar H using absorption gas cells (Bertaux et al. 1985; Quémerais et al. 1999), but no such measurement has been carried out completely successfully for He thus far. Although introducing the penalty of an additional exospheric background, the near Earth orbit of EUVE has created the opportunity for a large-scale exospheric gas absorption cell experiment (Flynn et al. 1998; Vallerga et al. 2004) and has led to the first determination of the He velocity vector using the observed Doppler shift. The yellow underlining of the flow vector variables in Fig. 2 reflects this independent analysis with EUVE, which allows for another cross-check within our coordinated analysis effort.

As has been shown in the past (e.g., Fahr 1974) the gravitational focusing cone of interstellar He is a good independent measure of the interstellar inflow pattern and thus of the full

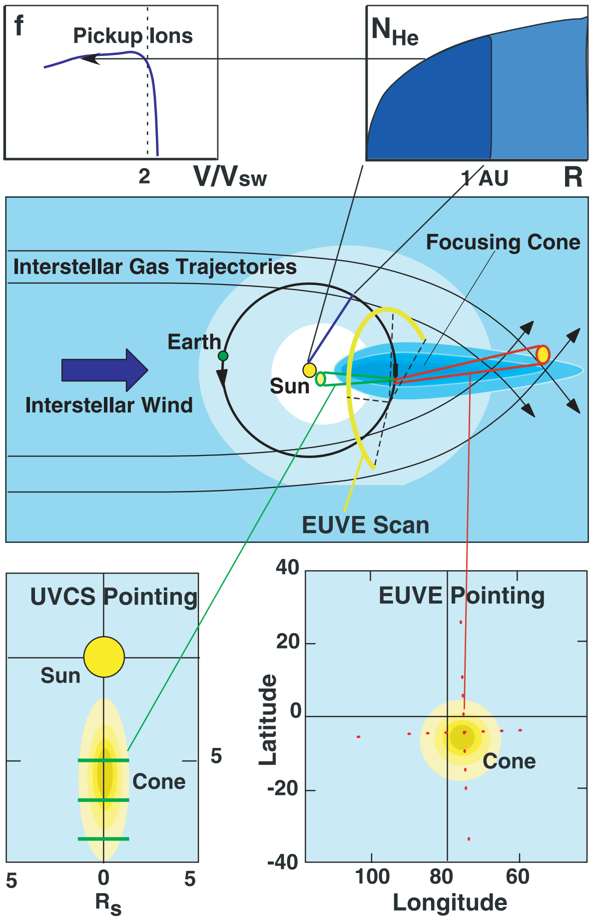

Fig. 3. Schematic view of the He cone in the ecliptic plane and its observation through pickup ions and UV scattering. The pickup ion phase space density as a function of $v/v_{\rm SW}$ obtained with ACE SWICS represents the radial density profile inside the Earth's orbit (*top*). With SOHO UVCS a line-of-sight integral through the near Sun cone is taken at 5, 7, and 9 $R_{\rm s}$ below the Sun, i.e. it cuts through the cone at 0.15−0.24 AU in December and 0.2−0.5 AU in June (*lower left*). EUVE provides a line-of-sight integral through the cone that is most sensitive just outside 1 AU (*lower right*). In addition, EUVE obtained 360° latitudinal scans of the cone in October and February (center).

set of interstellar parameters, although heavily influenced by ionization. This structure has been exploited using UV scattering observations (e.g., Ajello 1978; Weller & Meier 1981; Dalaudier et al. 1984) and pickup ion observations (Möbius et al. 1995). Because admittedly this is a more indirect method and the interstellar parameters can solely be determined by inference, we have started with the set of interstellar parameters, as derived from neutral atom observations and cross-checked with Ulysses pickup ion and EUVE backscattering observations. The cone structure was then modeled using two independent hot models of the He inflow. All the UV scattering observations were simulated as described by Michels et al. (2002), with a model that goes back to Dalaudier et al. (1984). For the pickup ion observations a model by Ruciński & Fahr (1989) was used that goes back to Wu & Judge (1979). The results of both models have been compared against each other for several parameter sets. Given a fixed set of parameters for interstellar He outside the heliosphere, the remaining variables in these models are the absolute value of the total ionization rate as well as its spatial and temporal variation. It should be pointed out here, that the rate for the most important ionization process, i.e. photo ionization, is being monitored since the launch of SOHO through the continuous measurement of the solar EUV flux (Judge et al. 1998). However, the information on another strong contributor, electron impact ionization, which gains increasing importance close to the Sun, is far from complete (McMullin et al. 2004). A schematic representation of the cone observations with their key observation regions is shown in Fig. 3. Given a fixed input for the interstellar He parameters, the combination of the cone observations just outside 1 AU with EUVE (Vallerga et al. 2004), inside 1 AU with ACE SWICS (Gloeckler et al. 2004), and very close to the Sun with SOHO UVCS (Lallement et al. 2004a) provides strong quantitative constraints for the absolute value of the total ionization rate and its variation with distance from the Sun. As we will see, the combined observations even require a distinct variation with latitude. Making use of the independently measured photo ionization rate, the required amount of electron impact ionization can be inferred and thus can be compared with available electron distribution functions at 1 AU and on Ulysses.

4. Compilation and comparison of the interstellar He results

In the following we will combine the individual results obtained with the different methods for each of the He parameters, discuss how they compare with each other in light of their uncertainties, and relate them to previous observations of some of these parameters inside and outside the heliosphere. To facilitate this discussion all values as presented in the papers of this special section are compiled in Table 1 along with observations of LIC parameters integrated over the line-of-sight to nearby stars (Lallement & Bertin 1992; Linsky et al. 1993). Also shown are the weighted mean values and uncertainties for the independent observations inside the heliosphere. To find the weighting factor the uncertainties of the results have been treated as equivalent to a purely statistical uncertainty. Then the relative weighting factors are proportional to the inverse of the squared uncertainty values. Naturally this weighting brings the resulting mean values close to those obtained with the smallest uncertainties.

Figure 4 presents an illustrated two-panel comparison of the interstellar flow parameters as they were independently derived from the direct neutral gas observations with Ulysses GAS and from UV scattering observations with EUVE and Prognoz 6 along with the weighted means. In addition, they are compared with other relevant observations where available. As can be seen in the figure, the three components of the interstellar gas flow vector and the LIC temperature of He have been derived from the Ulysses GAS observations overall with the smallest uncertainties. The upper panel shows two angles of the flow vector, while the lower panel contains the bulk speed and the temperature. As discussed in detail by Witte (2004), an

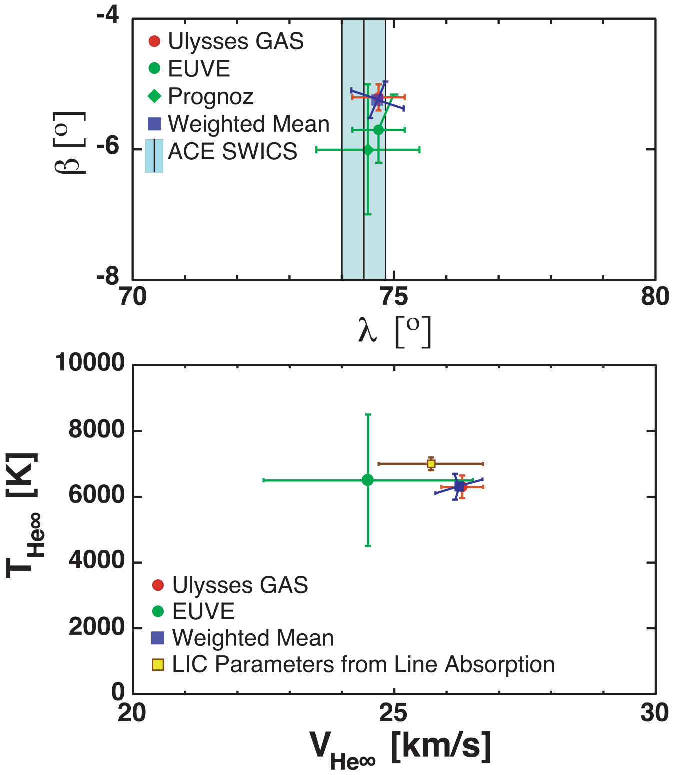

Fig. 4. Compilation and comparison of the independently obtained results for the interstellar He parameters. *Top*: latitude β versus longitude λ of the interstellar gas flow vector from Ulysses GAS observations (Witte 2004) and from UV backscattering observations of the cone with EUVE (Vallerga et al. 2004) and Prognoz 6 (Dalaudier et al. 1984; Lallement et al. 2004b) along with a weighted mean of the two results. Also shown is the determination of λ from the averaged pickup ion observations of the cone (Gloeckler et al. 2004). *Bottom*: He temperature $T_{He\infty}$ versus inflow speed $v_{He\infty}$ from Ulysses GAS and EUVE observations along with the weighted mean. For comparison the LIC parameters obtained from absorption lines in nearby spectra is shown (Lallement & Bertin 1992; Linsky et al. 1993).

ecliptic longitude $\lambda = 74.7 \pm 0.5^\circ$ and latitude $\beta = -5.2 \pm 0.2^\circ$ as well as a bulk speed $v_{He} = 26.3 \pm 0.4$ km s^{-1} of the flow vector and a temperature $T_{He} = 6300 \pm 340$ K was derived from the combined observations during the entire Ulysses mission to date. Completely independently from these kinetic observations of the gas distribution the direction for the inflow vector has been derived from the position of the focusing cone using EUVE observations. The mean values of the ecliptic longitude and elevation have been determined to $\lambda = 74.7 \pm 0.5^\circ$ and $\beta = -5.7 \pm 0.5^\circ$ and are given in the upper panel of Fig. 4. The Prognoz 6 results (Dalaudier et al. 1984), which were derived with the same method as used for EUVE, are included. The direction ($\lambda = 74.5 \pm 1^\circ$ and $\beta = -6 \pm 1^\circ$) is close to the new results, but with larger uncertainties. It should be pointed out that the bulk flow velocity vector is obtained with two almost completely independent methods, through direct observations of the neutral gas velocity distribution and through scans of the cone structure. The former has the advantage of a direct determination of the kinetic properties of the flow, while the latter employs gravitational focusing and Doppler dimming, both making use of the Sun as a gravitational lens. Finally, the longitude found from averaging pickup ion observations over five cone crossings of ACE ($\lambda = 74.43 \pm 0.33^\circ$, Gloeckler et al. 2004) is shown with a vertical bar, as no latitude can be determined independently from pickup ions. The excellent agreement of the pickup ion result with the longitude determination of the other two methods has an important consequence. Apparently, spatial diffusion of the pickup ions and their convection with the spirally oriented interplanetary magnetic field do not substantially alter the cone observations obtained with pickup ions, as had been suggested by Möbius (1996), at least not for the average spatial structure. Because of the use of the pickup ion observation to constrain the pickup ion transport in interplanetary space this result appears below the weighted mean values in Table 1 and has not been included in the determination of the mean. According to the excellent agreement obtained here any such effect on the cone observation must be much smaller than 1°.

By employing the Earth's exosphere as a He absorption cell EUVE has determined the bulk flow velocity independently to $v_{He\infty} = 24.5 \pm 2.0$ km s^{-1} and the temperature to $T_{He\infty} = 6500 \pm 2000$ K (Vallerga et al. 2004). Within the given uncertainties, these results are in reasonably good agreement with the values derived from Ulysses GAS observations. Both results are shown in the lower panel of Fig. 4 together with their weighted mean. As far as the absolute value of the bulk flow speed and the temperature are concerned the direct neutral gas observations appear to have the greater potential towards the most accurate determination right now, as the accuracy of the Doppler dimming measurement is compromised by uncertainties about the spectral shape of the exospheric glow and its variations. Using a more detailed modeling of the exospheric glow, Vallerga et al. (2004) obtained a somewhat lower value for the bulk speed from their more extensive dataset than Flynn et al. (1998) with $v_{He\infty} = 26.4 \pm 1.6$ km s^{-1}. This dependence on modeling also leads to a much larger systematic uncertainty compared with the direct neutral measurements. The situation may be improved with a direct gas absorption cell observation as has been used successfully for hydrogen (Bertaux et al. 1985; Lallement et al. 1985). Also shown in the figure are the relative flow velocity and temperature of the LIC, as obtained from CaII (Lallement & Bertin 1992) and D, H, CaII and FeII (Linsky et al. 1993) absorption lines in the spectra of nearby stars. The relative velocity obtained over the line of sight to nearby stars falls within the uncertainty of the values obtained at the location of the Sun, but the temperature found for the LIC appears slightly higher than the values obtained inside the heliosphere, although the values are not significantly different in light of the combined uncertainties. In addition, it should be pointed out that the LIC value represents an integral over a long line of sight and thus includes any variations in the LIC.

Table 1 also contains a comparison of three different determinations of the He density. The interstellar He gas density can be determined very accurately using He^{2+} pickup ions from Ulysses SWICS observations, even without the need of absolute calibration: $n_{He} = 0.0151 \pm 0.0015$ cm^{-3} (Gloeckler et al. 1997; Gloeckler & Geiss 2001b; Gloeckler et al. 2004). Pickup ions and solar wind He^{2+}, the main producer of these

Table 1. Compilation of the interstellar helium parameters as obtained with different methods and comparison with the velocity and temperature in the LIC.

v_{He} [km s^{-1}]	λ [°]	β [°]	T_{He} [K]	N_{He} [cm^{-3}]	**Method** Instrument	Reference
					Neutral gas	
26.3 ± 0.4	74.7 ± 0.5	−5.2 ± 0.2	6300 ± 340	0.015 ± 0.003	Ulysses GAS	Witte (2004)
					Pickup ions	
				0.0151 ± 0.0015	Ulysses SWICS	Gloeckler et al. (2004)
					UV backscatter	
24.5 ± 2	74.7 ± 0.5	−5.7 ± 0.5	6500 ± 2000	0.013 ± 0.003	EUVE	Vallerga et al. (2004)
	74.5 ± 1	−6 ± 1			Prognoz 6	Lallement et al. (2004)
26.24 ± 0.45	74.68 ± 0.56	−5.31 ± 0.28	6306 ± 390	0.0148 ± 0.0020	**Weighted mean**	
					Pickup ions	
	74.43 ± 0.33				ACE SWICS	Gloeckler et al. (2004)
					Absorption	
*25.7 ± 1			*7000 ± 1000		Haute-provence	Lallement & Bertin (1992)
					Absorption	
			*7000 ± 200		Hubble ST	Linsky et al. (1993)

* LIC bulk parameters.

pickups ions, are observed with the same instrument. In addition, these observations are taken at distances typically >3 AU so that the effect of depletion of neutral He by ionization is insignificant. Therefore, the current knowledge of the cross section for charge exchange between solar wind He^{2+} and interstellar neutral He constitutes the main potential source of uncertainty. As a consequence, the pickup ion observations return a value with an uncertainty of 10%. As discussed by Witte (2004) the determination of the He density with Ulysses GAS at ≈1.3−2 AU is affected by the assumptions about the total ionization rate and its variation over time before the actual measurement was taken, as neutral He is depleted along its trajectories through the inner heliosphere. These observations are also sensitive to variations of the ionization rate with latitude. Assuming an isotropic ionization rate in the heliosphere leads to apparent variations in the derived He density that correlate with the latitude of the Ulysses observations. As no latitude information on the ionization and no fully three-dimensional model of the interstellar gas distribution are available to date, Witte (2004) has used an ionization rate with a sinusoidal variation over latitude. Adapting its amplitude has minimized the apparent density variations and has led to a He density from the Ulysses GAS observations of $n_{\mathrm{He}} = 0.015 \pm 0.03$ cm^{-3}, which agrees perfectly with the pickup ion result. This density value holds also for the observation of He on indirect orbits, i.e. neutrals that have already passed their perihelion on their way to the sensor, if electron ionization according to Ruciński & Fahr (1989) is added to the observed photo ionization. The uncertainty quoted for the absolute density value contains both statistical fluctuations and systematic contributions. The latter include the confidence in the absolute flux calibration of the GAS instrument (Witte et al. 1999) and remaining uncertainties of the ionization rates that fold into the derived value through the modeling of the neutral gas in the inner heliosphere. The fact that the two observation methods independently produce the same values for the density provides a strong justification to adopt this result as a benchmark value. In view of the fact that the pickup ion result is independent of an absolute calibration and that loss due to ionization is insignificant at the location of the observations the pickup ion result should be given a slightly higher weight. It should be noted that the Long Wavelength Spectrometer data from EUVE also return a density of 0.013 ± 0.003 cm^{-3} for He in good agreement with the other two observations, while the Scanner data on the same spacecraft appear to be consistent with a significantly lower value (Vallerga et al. 2004), a discrepancy, which could not be resolved within the given calibrations of the instruments. In light of the fact that three independent observations agree on a density value close to $n_{\mathrm{He}} = 0.015$ cm^{-3} we adopt this value as the benchmark for all further deliberations. In summary, this combination of neutral gas, UV scattering, and pickup ion observations provides a complete, consistent, and accurate account of the LIC parameters of He, as observed inside the heliosphere. It should be emphasized that short of sending a probe into the interstellar medium proper, taking these observations inside the heliosphere, is the only way to derive a local value of LIC parameters. Any remote sensing observations, such as absorption measurements employing the light of nearby stars, can only provide line-of-sight integrals over a region. In light of this fact it becomes an important realization that the physical parameters, as found with all three local methods, are consistent with the flow parameters and temperature derived for the average local interstellar medium from UV line absorption in nearby star spectra (Lallement & Bertin 1992; Bertin et al. 1993; Linsky et al. 1993).

Using these parameters the spatial structure of the He focusing cone has been computed for a direct comparison with the cone observations using pickup ions with ACE SWICS inside 1 AU (Gloeckler et al. 2004) as well as UV scattering with EUVE (Vallerga et al. 2004) just outside 1 AU and with UVCS at 0.15 to 0.5 AU (Lallement et al. 2004a). While the shape of the cone as observed with these methods can be reproduced within the observational uncertainties, the peak height or the absolute scattering intensity of the cone appears to be consistently overestimated, when only the observed photo ionization rates are used to compute the local He neutral density. While the SOHO UVCS observations of the cone at solar minimum can be modeled with the observed photo ionization rates (McMullin et al. 2004) and a contribution from electron impact ionization according to Ruciński & Fahr (1989), the amount of electron impact ionization has to be increased by a factor of 3.5 for solar maximum observations, when photo ionization only increases by a factor of about 2 (Michels et al. 2002; Lallement et al. 2004a). After including an electron ionization rate that is adapted to the solar maximum observations and varies linearly with solar activity according to the observed solar EUV flux, Lallement et al. (2004a) have modeled the near Sun cone observations with the same set of interstellar He parameters over the entire observation period that spans almost from solar minimum to solar maximum. Thus the near-Sun observations, for the first time, provide experimental constraints on the unknown electron impact ionization rates close to the Sun. However, using these increased rates together with the radial dependence adopted by Ruciński & Fahr (1989) would lead to a substantially higher electron ionization rate at 1 AU than that deduced from simultaneous pickup ion observations (Gloeckler et al. 2004). As a consequence the combination of the observations at different distances from the Sun can be used to deduce the so far unknown and probably variable radial dependence of this ionization process (Ruciński et al. 1996; McMullin et al. 2004). Yet these observations can only be used to determine the electron ionization rate and its spatial variations quantitatively and accurately, if the correct latitudinal and temporal behavior is built into the interstellar gas modeling, as the cone is composed of neutral atoms that have passed the Sun over the entire range of latitude. Indeed there is a substantial latitudinal variation of the ionization rate, as has become evident from the neutral gas observations (Witte 2004). For now these variations can only be inferred.

Nevertheless, using the same He parameters and similarly increased ionization rates, Lallement et al. (2004b) were able to reproduce even the observations of the He cone with the UV instrument on Prognoz 6, after realizing that an unaccounted for background in the instrument may have been the reason for the substantially different interpretation of the same data by Dalaudier et al. (1984). In order to recreate the environmental parameters for the observation period of Prognoz 6 the Mg II index of the Sun, which has been available since the early 1970's, was used as a reliable proxy for the solar EUV irradiance (Viereck et al. 2001) and for solar the He I 58.4 nm line that illuminates the He distribution (McMullin et al. 2004).

5. Conclusions and future perspectives

In summary, a consistent set of physical parameters has been derived for local interstellar He through a coordinated analysis of interstellar He data obtained simultaneously through three observation techniques in the inner heliosphere, along with the photo ionization rates and the solar illumination. For the first time the same parameter set reproduces the results from backscattering of solar UV, pickup ion and direct neutral gas diagnostics. The flow vector and temperature (v_{He}, λ, β and T_{He}) are determined most accurately from direct neutral gas observations (Witte 2004), but are independently validated by UV scattering observations with EUVE (Vallerga et al. 2004; Lallement et al. 2004b). The density n_{He} is derived most precisely from He^{2+} pickup ions as these do not require an absolute calibration (Gloeckler et al. 2004) and is supported by both neutral gas and UV observations. This consolidation essentially removes major differences and uncertainties in the results that were prevalent in the interstellar gas observations in the past (e.g., Chassefière et al. 1986; Möbius 1993). Previous differences and uncertainties could be traced to uncertainties in the instrumental calibration and to insufficient knowledge of environmental conditions that influence these observables, such as ionization and solar illumination, including their spatial and temporal variations.

Besides providing a first benchmark set of interstellar He parameters, our analysis strongly implies that significant additional ionization – with a stronger solar activity variation than photo ionization – is at work inside 1 AU, most likely electron impact ionization. All observations used in this coordinated analysis consistently require such additional ionization, and in combination provide the means to deduce its unknown radial dependence. In addition, a careful analysis of all neutral gas observations with Ulysses GAS reveals that the ionization rate must be lower over the solar poles than in the ecliptic (Witte et al. 2004; Witte 2004). These anisotropies have their root in the fundamentally three-dimensional structure of the Sun's atmosphere, and a true three-dimensional monitoring of its radiation is required for a complete understanding of the Sun's environment.

The results of our coordinated analysis of the interstellar He in the inner heliosphere provide us with a consolidated and rather accurate physical parameter set that reflects the undisturbed dynamic and kinetic conditions of the LIC, because He is unaffected by the heliospheric interface. The improved knowledge of the environmental conditions that shape the interstellar populations inside the heliosphere has been instrumental for this achievement. Because ionization rates and solar illumination can even be connected to proxies that are available on a longer time scale (McMullin et al. 2004), this newly gained understanding may now also be used to retroactively improve the analysis of previous interstellar gas observations.

The achieved precision gives rise to the hope that potential variations of the LIC parameters may be traced with good enough accuracy so that the question can be decided, whether there are spatial fluctuations in the interstellar medium on a micro-scale, as discussed in a review by Dickey (2004). Apparently, VLBI studies of 21-cm absorption variations in quasar spectra, time variations in the absorption spectra of pulsars, variations in interstellar absorption lines against close binary stars (Heiles 1997; Faison et al. 1998) seem to consistently suggest spatial variations on scales as small as ≈25 AU. Such small-scale variations are reasonable for electrons as they are confined by the interstellar magnetic field and possibly for relatively high density clouds. However, around the Sun the mean free path length for neutral H is of the order of a few 100 AU, so that neutral gas variations should probably be at least on scales larger than these distances. Alternative interpretations of these phenomena that would not require the assumption of such small-scale spatial variations are also under debate (Faison & Goss 2001). At the measured relative velocity of 26.3 $\mathrm{km\,s^{-1}}$ the Sun traverses 25 AU in approximately 5 years, and thus potential variations in the parameters on that scale should become apparent on a time scale of 5 to 10 years, if they exist. Of course, this requires precision observations of the interstellar density and velocity, preferably with uncertainties better than 10−15% over sufficiently long time intervals. As pointed out in this series of publications, neutral gas and pickup ion observations are capable of providing the necessary precision for the density, while neutral gas and UV scattering observations provide accurate values for the velocity vector. In both cases simultaneous monitoring of the solar UV radiation is crucial. Therefore, the ongoing monitoring of the LIC parameters with the inner heliospheric observation methods can provide crucial information towards closure of this important question relevant to the interstellar medium structure.

Finally, our results can be used as a stepping-stone for the more complex analysis of H and O in the LIC, both of which, in contrast to He, are decelerated, heated, and depleted by charge exchange processes at the heliospheric boundary. Therefore, differences between the observed He parameters and those of O and H will set very tight constraints on the physical processes in the heliospheric interface region that lead to filtration of most of the LIC species, except for He, when they enter the heliosphere (Izmodenov et al. 1999; Müller et al. 2000). Having established the amount of filtration, the observation of elemental abundances of several LIC species, such as He, H and O, inside the heliosphere together with detailed modeling can be used to deduce a LIC abundance pattern for the neutral gas component (Izmodenov et al. 1999; Müller et al. 2000; Izmodenov et al. 2004). Such results can then be compared with quantitative predictions made for the ionization state of the LIC based on modeling of the radiation environment of our galactic neighborhood (Frisch & Slavin 1996; Slavin & Frisch 2002). Therefore, similar concerted efforts to observe interstellar H and O are extremely important tasks for the near future (Möbius 2003). Because direct neutral gas observations provide the most comprehensive view of the kinetic state of the gas a strong effort should be made to include this method for H and O. The prospects to extend the successful determination of interstellar gas parameters of He from neutral gas observations to these species are promising as instruments with such capabilities are under development (Wurz et al. 1995; Livi et al. 2003). Similar coordinated observation and analysis campaigns will then constrain quantitatively the physical processes in the heliospheric interface layers and the local radiation environment of our solar system, which is tightly coupled to the ionization state of the LIC.

Combining all this information these results will also narrow the predictions for the highly anticipated encounter of Voyager 1 with the termination shock (Izmodenov et al. 2003). Recent unusual activity in the energetic particles has sparked the discussion, whether an encounter has already occurred or is at least very close (Krimigis et al. 2003; McDonald et al. 2003; Burlaga et al. 2003). A confirmed crossing of the termination shock will soon add an independent value for the total interstellar ram pressure on the heliosphere, within the bounds of its variation with solar activity (e.g., Stone & Cummings 2003; Whang et al. 2004). In combination with these constraints on the total pressure, an accurate set of benchmark values for the physical parameters of several species in the neutral component of the inflowing interstellar gas will provide an observational handle on our local galactic plasma and magnetic field environment and on its interaction with the only astrosphere that can be studied with in situ methods.

Acknowledgements. This work was initiated and partly carried out with support from the International Space Science Institute (ISSI) in the framework of an International Team entitled "Physical parameters of the LISM through coordinated observations of the gravitational focusing cone at 1 AU". The authors are indebted to ISSI and its staff in Bern, Switzerland, for the support of this activity, the stimulating atmosphere, and the great hospitality, without which this coordinated analysis and its results would not have been possible. The combined effort of the participating group of scientists was supported in part under NASA SEC GI grant NAG5-10890, NASA/Caltech grant NAG 5-6912, NASA/JPL contract 955460, NASA grant NAG5-11420, NASA grant NAG5-5333, NASA contract NAS5-29298, NSF grant ATM-9800781, by DLR under grant 50 0N 91035. V.I. was supported by INTAS grant 2001-0270 and RFBR grants 03-02-04020, 04-01-00594. M.B. and D.R. were supported by the Polish State Committee for Scientific Research under Grant 2P 03C 005 19, M.O. and T.T. were supported by Grant-in-Aids for Scientific Research (No. 13874055, 15-10936) from the MEXT, Japan.

References

Adams, T. F., & Frisch, P. C. 1977, ApJ, 212, 300

Ajello, J. M. 1978, ApJ, 222, 1054

Axford, W. I. 1972, in Solar Wind, NASA SP-308, ed. E. P. Sonnett, P. J. Coleman, & J. M. Wilcox, 609

Banaszkiewicz, M., Witte, M., & Rosenbauer, H. 1996, A&AS, 120, 587

Baranov, V. B., & Malama, Yu. G. 1993, J. Geophys. Res., 98, 15157

Bertaux, J. L., & Blamont, J. E. 1971, A&A, 11, 200

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

Bertin, P., Lallement, R., Ferlet, R., Vidal-Madjar, A., & Bertaux, J. L. 1993, J. Geophys. Res., 98, 15193

Blum, P., & Fahr, H.-J. 1970, A&A, 4, 280

Broadfoot, A. L., & Kumar, S. 1978, ApJ, 222, 1054

Burlaga, L. F., Ness, N. F., Stone, E. C., et al. 2003, Geophys. Res. Lett., 30, 9-1

Chassefière, E., Bertaux, J. L., Lallement, R., & Kurt, V. G. 1986, A&A, 160, 229

Cheng, K.-P., & Bruhweiler, F. C. 1990, ApJ, 364, 573

Cox, D. P., & Reynolds, R. J. 1987, ARA&A, 25, 303

Crutcher, R. M. 1982, ApJ, 254, 82

Cummings, A. C., Stone, E. C., & Steenberg, C. 2002, ApJ, 578, 194

Dalaudier, F., Bertaux, J. L., Kurt, V. G., & Mironova, E. N. 1984, A&A, 134, 171

Dickey, J. 2004, Adv. Space Res., 34, 14

Fahr, H. J. 1974, Space Sci. Rev., 15, 483

Fahr, H. J. 1991, A&A, 241, 251

Fahr, H. J., Lay, G., & Wulf-Mathies, C. 1978, COSPAR Space Research, 18, 393

Fahr, H. J., Kausch, T., & Scherer, H. 2000, A&A, 357, 268

Faison, M. D., & Goss, W. M. 2001, ApJ, 121, 2706

Faison, M. D., Goss, W. M., Diamond, P. J., & Taylor, G. B. 1998, ApJ, 116, 2916

Flynn, B., Vallerga, J., Dalaudier, F., & Gladstone, G. R. 1998, J. Geophys. Res., 103, 6483

Frisch, P. C. 1981, Nature, 293, 377

Frisch, P. C. 1995, Space Sci. Rev., 72, 499

Frisch, P. C., & Slavin, J. D. 1996, Space Sci. Rev., 78, 223

Gloeckler, G., & Geiss, J. 1998, Space Sci. Rev., 86, 127

Gloeckler, G., & Geiss, J. 2001a, in Solar and Galactic Composition (Joint SOHO-ACE Workshop), ed. R. Wimmer-Schweingruber, AIP Conf. Proc., 598, 281

Gloeckler, G., & Geiss, J. 2001b, Space Sci. Rev., 97, 169

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

Gloeckler, G., Möbius, E., Geiss, J., et al. 2004, A&A, 426, 845

Heiles, C. 1997, ApJ, 481, 193

Holzer, T. E. 1977, Rev. Geophys. Space Phys., 15, 467

Holzer, T. E., & Axford, I. 1971, J. Geophys. Res., 76, 6965

Izmodenov, V., Geiss, J., Lallement, R., et al. 1999, J. Geophys. Res., 104, 4731

Izmodenov, V., Gloeckler, G., & Malama, Y. 2003, Geophys. Res. Lett., 30, 3

Izmodenoz, V., Malama, Y. G., Gloeckler, G., & Geiss, J. 2004, A&A, in press

Jokipii, J. R. 1998, Space Sci. Rev., 86, 161

Judge, D., McMullin, D. R., Ogawa, H. S., et al. 1998, Sol. Phys., 177, 161

Klecker, B. 1995, Space Sci. Rev., 72, 419

Krimigis, S. M., Decker, R. B., Hill, M. E., et al. 2003, Nature, 426, 45

Lallement, R., & Bertin, P. 1992, A&A, 266, 79

Lallement, R., Bertaux, J.-L., & Dalaudier, F. 1985, A&A, 150, 21

Lallement, R., Raymond, J., Bertaux, J. L., et al. 2004a, A&A, 426, 867

Lallement, R., Raymond, J. C., Vallerga, J., et al. 2004b, A&A, 426, 875

Linde, T. J., Gombosi, T. I., Roe, P. L., Powell, K. G., & DeZeeuw, D. L. 1998, J. Geophys. Res., 103, 1889

Linsky, J. L., Brown, A., Gayley, K., et al. 1993, ApJ, 402, 694

Livi, S., Möbius, E., Haggerty, D., Witte, M., & Wurz, P. 2003, in Solar Wind Ten, AIP Conf. Proc., 679, 850

McClintock, W., Henry, R. C., Linsky, J. L., & Moos, W. H. 1978, ApJ, 225, 465

McDonald, F. B., Stone, E. C., Cummings, A. C., et al. 2003, Nature, 426, 48

McMullin, D., Bzowski, M., Möbius, E., et al. 2004, A&A, 426, 885

Michels, J. G., Raymond, J. C., Bertaux, J. L., et al. 2002, ApJ, 568, 385

Möbius, E. 1993, in Landoldt-Börnstein, Numerical Data and Functional Relationships in Science and Technology, VI/3A Chapter 3.3.5.1, 184

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

Möbius, E. 2003, in Solar Wind Ten, AIP Conf. Proc., 679, 799

Möbius, E., Hovestadt, D., Klecker, B., et al. 1985, Nature, 318, 426

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

Möbius, E., Ruciński, D., Lee, M. A., & Isenberg, P. A. 1998, J. Geophys. Res., 103, 257

Müller, H. R., Zank, G. P., & Lipatov, A. S. 2000, J. Geophys. Res., 105, 27419

Paresce, F., Bowyer, S., & Kumar, S. 1974, ApJ, 187, 633

Quémerais, E., Bertaux, J. L., Lallement, R., et al. 1999, J. Geophys. Res., 104, 12585

Richardson, J. D., Paularena, K. I., Lazarus, A. J., & Belcher, J. W. 1995, Geophys. Res. Lett., 22, 1469

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

Ruciński, D., Fahr, H. J., & Grzedzielski, S. 1993, Planet. Space Sci., 41, 773

Ruciński, D., Cummings, A. C., Gloeckler, G., et al. 1996, Space Sci. Rev., 78, 73

Slavin, J., & Frisch, P. C. 2002, ApJ, 565, 364

Stone, E. C., & Cummings, A. C. 2003, in Solar Wind Ten, AIP Conf. Proc., 679, 47

Thomas, G. E. 1978, Ann. Rev. Earth Planet. Sci., 6, 173

Thomas, G. E., & Krassa, R. F. 1971, A&A, 11, 218

Vallerga, J., Lallement, R., Raymond, J., et al. 2004, A&A, 426, 855

Viereck, R., Puga, L., McMullin, D., et al. 2001, Geophys. Res. Lett., 28, 1343

Weller, C. S., & Meier, R. R. 1974, ApJ, 193, 471

Weller, C. S., & Meier, R. R. 1981, ApJ, 246, 386

Whang, Y. C., Burlaga, L. F., Wang, Y.-M., & Sheeley, N. R., Jr. 2004, Geophys. Res. Lett., 31, L03805

Witte, M. 2004, A&A, 426, 835

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

Witte, M., Bleszynski, S., Banaszkiewicz, M., & Rosenbauer, M. 1999, Rev. Sci. Inst., 70, 4404

Witte, M., Banaszkiewicz, M., Rosenbauer, M., & McMullin, D. 2004, Adv. Space Res., 34, 61

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

Wurz, P., Aellig, M. R., Bochsler, P., et al. 1995, Opt. Eng., 34, 2365

Zank, G. P. 1999, Space Sci. Rev., 89, 413

Zank, G. P., & Müller, H.-R. 2003, J. Geophys. Res., 108, 1240