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RECENT RESULTS ON THE PARAMETERS OF THE INTERSTELLAR HELIUM FROM THE ULYSSES/GAS EXPERIMENT

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Abstract. Velocity and direction of the flow of the interstellar helium and its temperature and density have been determined from the measurements of the ULYSSES/GAS experiment for two different epochs: during the in-ecliptic path of ULYSSES, representing solar maximum conditions, and during the south to the north pole transition (11/94-6/95), close to the solar minimum conditions. Within the improved error bars the values are consistent with results published earlier.

The determination of the density n_∞ of the interstellar helium at the heliospheric boundary from observations in the inner solar system requires knowledge about the loss processes experienced by the particles on their way to the observer. The simultaneous observation of the helium particles arriving on "direct" and "indirect" orbits at the observer provides a tool to directly determine the effects of the loss processes assumed to be predominantly photoionization and – for particles travelling close to the Sun – electron impact ionization by high-energy solar wind electrons.

Such observations were obtained with the ULYSSES/GAS instrument in February 1995, before the spaceprobe passed its perihelion. From these measurements values for the loss rates and the interstellar density could be derived. Assuming photoionization to be the only loss process reasonable fits to the observations were obtained for an ionization rate $\beta = 1.1 \cdot 10^{-7}$ s^{-1} and a density $n_\infty \approx 1.7 \cdot 10^{-2}$ cm^{-3}. Including, in addition, electron impact ionization, a photoionization $\beta = 0.6 \cdot 10^{-7}$ s^{-1} was sufficient to fit both observations, resulting in a density $n_\infty \approx 1.4 \cdot 10^{-2}$ cm^{-3}.

1. Introduction

Since more than twenty years the interstellar neutral particles as representatives of the local interstellar medium have been of particular interest. Except for high energy galactic cosmic rays these particles are the only ones which are available in the inner solar system for in-situ measurements or short-range remote observations. From the determination of the local parameters (flow velocity and direction, temperature and density) it should be possible to infer the values of these parameters outside the heliosphere ("at infinity").

In the past, first results were obtained from the measurement of the intensity distribution of solar UV-light resonantly backscattered from the local density distribution of interstellar hydrogen and helium atoms (e.g. Bertaux and Blamont, 1971; Thomas and Krassa, 1971; Chassefière et al., 1986, 1988; Dalaudier et al., 1984).

In addition to these ongoing observations (e.g. Bertaux et al., 1995, Pryor et al., 1995) other techniques and methods more recently provided improved results: The observation of pick-up ions (e.g. Möbius et al., 1985, 1995) revealed an independent source for the parameters of, in particular, the interstellar helium distribution. With the ULYSSES/SWICS instrument it was possible for the first time to measure their

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full phase space distribution and derive in a self-consistent way the local loss and production rates of the pick-up ions (Gloeckler et al., 1996).

Also, with new data from the Hubble Space Telescope, the analysis of the dopplershift in the absorption lines in the light of near-by stars provided independent new information about the velocity v_∞ of the motion of the solar system through the local interstellar medium (Lallement et al., 1996).

A completely different approach in the determination of the parameters of the interstellar helium has been performed for the first time with the ULYSSES/GAS-instrument, which detects individual helium atoms. In this paper we shall describe in detail the observations and analysis of the data obtained around the perihelion of ULYSSES, when it was possible for the first time to observe simultaneously particles on “direct” and “indirect” orbits.

In this unique case it was possible to infer the rate of the losses, the helium particles experience on their way to the observer and to determine the density n_∞ of the helium particles outside the heliosphere. Finally, we shall summarize the results obtained so far for the velocity v_∞ and temperature T_∞.

2. Instrument Description

The GAS-instrument on the ULYSSES spaceprobe, which acts like a pinhole camera, is capable to detect individual interstellar helium particles and allows to determine their local flow direction (Witte et al., 1992). From these local angular distributions the parameters of the interstellar particles outside the heliosphere (“at infinity”), the velocity magnitude and direction v_∞ and the temperature T_∞, can be determined in a straight forward manner (Witte et al., 1993) as one can assume that the particles move on hyperbolic orbits around the Sun because radiation pressure and interactions at the heliospheric interface are negligible. The details of mathematical methods involved in the detailed analysis (tomography problem) and their limitations have been extensively described by Banaszkiewicz et al. (1996).

3. Observations

In principle, interstellar helium particles having the same velocity v_∞ at infinity can arrive at a given point in space (observer) only on two hyperbolic orbits named “direct” and indirect”, lying in a common plane which is uniquely determined by the focal point (the Sun), the position of the observer and the vector v_∞ (Fig. 1).

As the kinetic energy of these particles is only of the order of a few 10 eV which is close to the detection threshold of the instrument it requires a favorable combination of the velocity vectors of the spaceprobe and the particles to get a sufficiently large relative energy in the instrument’s frame of reference (Fig. 2). In the course of the ULYSSES-mission, this is the case for the direct particles during the in-ecliptic

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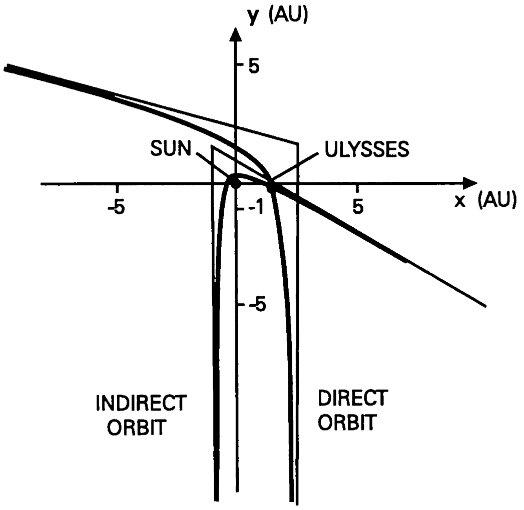

Figure 1. The "direct" and "indirect" hyperbolic orbits of helium particles, that arrive at the position of the spaceprobe at 1.3 AU in February 1995, during the perihelion of ULYSSES. Particles on indirect orbits have had their closest distance to the Sun at 0.2 AU and are ionized much more (~98%)than the particles on the direct orbit. The simultaneous observation of both particle intensities allows the determination of the rate of the photoionization, the pre-dominant loss process.

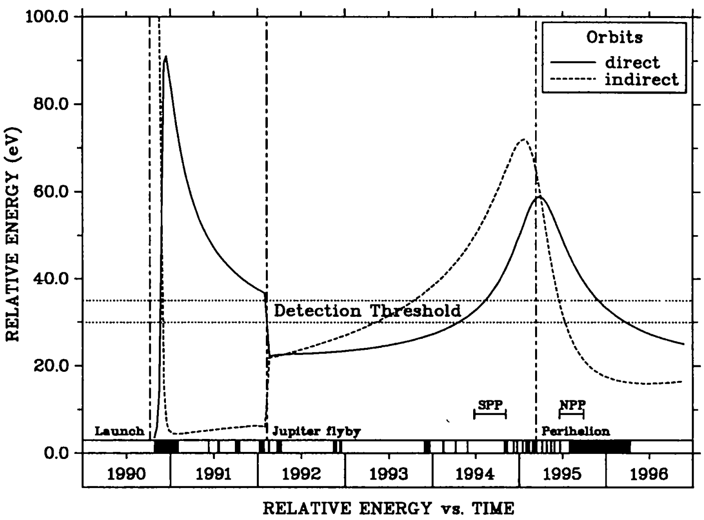

Figure 2. The relative energy of interstellar helium particles on direct and indirect orbits in the instrument's frame of reference. Mainly, this energy is determined by the velocity and flight direction of the spaceprobe with respect to the local flow of the particles (~ 43 km/s). Due to the high velocity after launch (~ 40 km/s) and around perihelion (~ 32 km/s), there are two periods, 1990-1992 and 1994-1996, when the particle energy exceeds the detection threshold of about 35 eV. (Periods, when the instrument was active, are indicated on the abscissa.)

orbit towards Jupiter (October 1990 to February 1992) and around perihelion (end 1994 to early 1996) for particles on both orbits. The angular distributions, which have been measured in February 1995 shortly before the perihelion of ULYSSES, are shown in Fig. 3 (uppermost panels) for particles on direct (left h.s.) and indirect (right h.s.) orbits. They are represented in the instrument's coordinate system of elevation angle (i.e. cone angle with respect to the spacecraft's spin axis) and azimuth angle (the rotation angle) as measured in steps of 2° × 2.8°, respectively. The instrument's coordinate system can be directly converted into an inertial coordinate system (e.g. solar ecliptic system) using the available orbit and attitude data of the spacecraft.

While there is a clear signal of the direct particles (~ 8 cts/s), the signal of the indirect particles (~ 0.2 cts/s) hardly exceeds the background, immediately showing the high degree of losses for these particles due to ionization. (To reduce the statistical fluctuations and improve the image a sliding-3 × 3-box averaging has been applied to the data.)

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4. Density Determination

If one wants to infer the density of the interstellar neutral particles at the boundary of the solar system from remote or in-situ measurements in the inner solar system, knowledge about the effectiveness and also about the time dependence of various loss processes acting on the neutral particles on their way into the inner solar system is a prerequisite. In general, it is difficult to obtain quantitative figures because of the various processes involved (e.g. Rucinski et al., 1996). With the observations described above it was possible, however, to estimate the actual, global loss rates valid for the time of the measurement.

In the first step of this analysis, we have assumed that photoionization is the pre-dominant loss process for the interstellar helium particles. In our model (Witte et al., 1993, Banaszkiewicz et al., 1996) used to simulate the observations processes with a $1/r^2$-dependence have been taken into account and are characterized by the ionization rate β_{ion} at 1 AU distance. However, the ionization rate is a free input-parameter to the model and can, in general, not be derived from one measurement of the local density alone.

This problem can be overcome when particles can be observed simultaneously arriving at the position of the observer on “direct” and “indirect” orbits.

In the case of the observation, reported here, particles on “indirect” orbits had their closest distance to the Sun during their perihelion at 0.2 AU while particles on “direct” orbits, still inbound, have their closest distance from the Sun during the arrival at the observer at 1.3 AU (Fig. 1).

Therefore, both groups of particles experience a completely different history with respect to their exposure to the solar UV radiation field, responsible for their photoionization. As the travel time of the indirect particles is only about a month longer as compared to the direct particles, temporal variations of the radiation may be neglected and the same ionization rate can be used for the simulation of both observations eliminating this degree of freedom in the model.

The results of the simulation of the direct particles are shown in the l.h.s. of Fig. 3. While the values of the velocity $(v_\infty, \beta_\infty, \lambda_\infty)$ and temperature T_∞ are a result of a fitting process, for the ionization rate reasonable values have been chosen. As a result the model yields densities n_∞ which increase with increasing loss rates to reproduce the observed local densities as one would expect. It is obvious that the simulated distributions match the observed distribution of direct particles equally well, it is not possible to determine a unique pair of ionization rate β_{ion}/density n_∞ from a single measurement. Quantitatively, the extinction factor (ratio of the density at the point of observation to the density at infinity) ranges from 0.73 to 0.54 for $\beta_{ion} = 0.8 \cdot 10^{-7}\ \mathrm{s}^{-1}$ to $0.16 \cdot 10^{-7}\ \mathrm{s}^{-1}$, respectively and is 0.68 for $\beta_{ion} = 1.0 \cdot 10^{-7}\ \mathrm{s}^{-1}$.

Now, in the r.h.s. column, the distributions are shown, which are the predictions of the model for the indirect particles, using the same sets of parameters as for the distributions of direct particles. As one can see, only for ionization rates around

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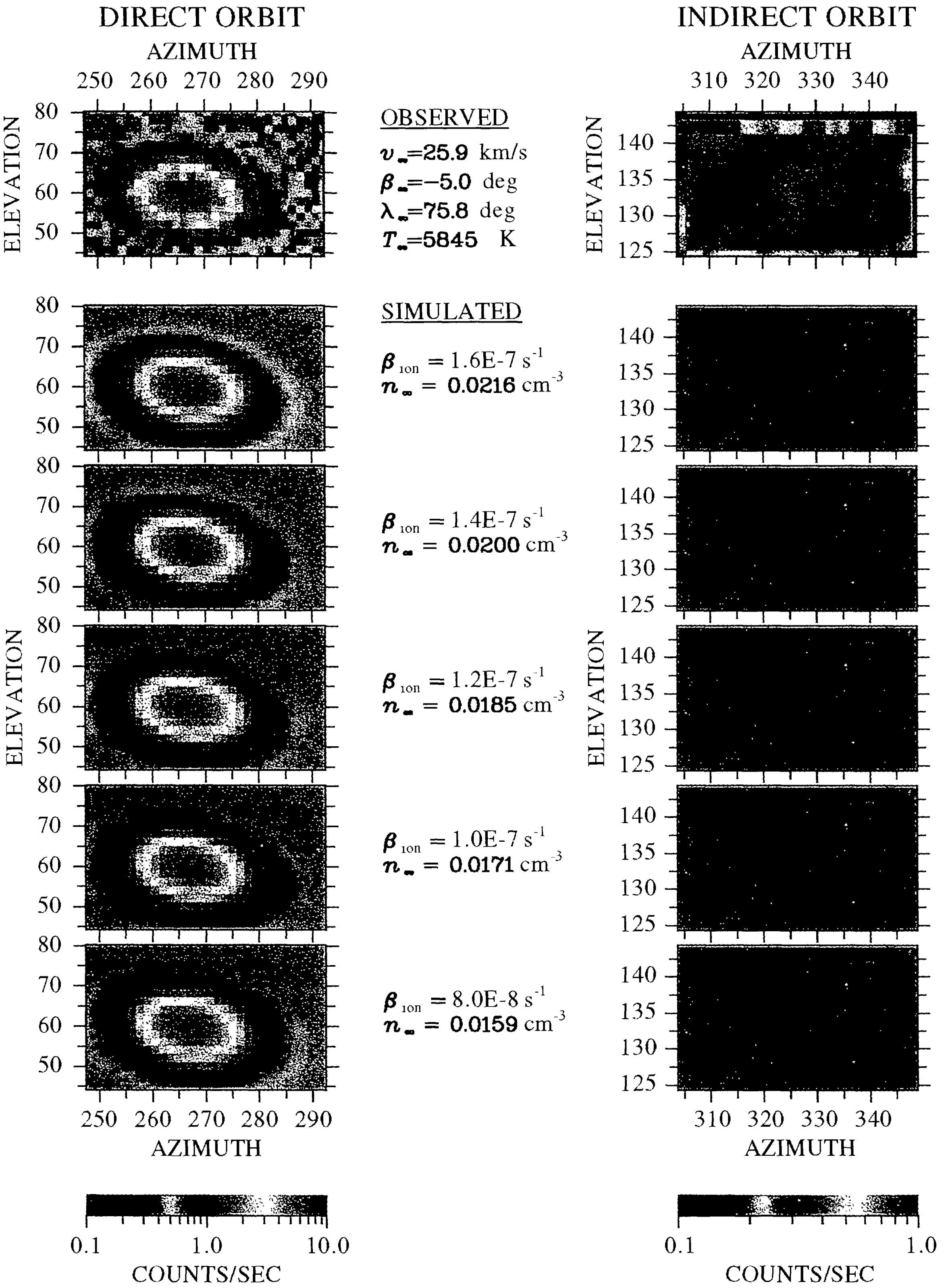

Figure 3. Comparison of observed (uppermost panels) and simulated distributions of particles on direct (left hand column) and indirect orbits. While for the direct particles various sets of density n_∞ and photoionization rate β_{ion} can be found which fit equally well to the observed distribution, the observed distribution of indirect particles can be fitted reasonably only by $\beta_{ion} \approx 0.9 - 1.1 \cdot 10^{-7}$ s^{-1} and a density around $n_\infty \approx 1.7 \cdot 10^{-2}$ cm^{-3}. (Note the change in the countrate scale by a factor of 10.)

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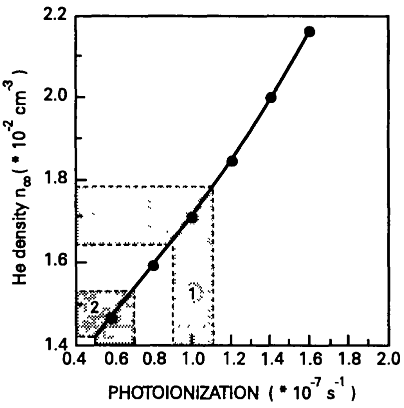

Figure 4. Relation between the photoionization and the helium density (solid line) as derived from the model fits to the observed distributions of particles on direct orbits (Fig. 3, left column) and the ranges of photoionization rate, required to reproduce the observations of indirect particles, assuming photoionization to be the only loss process (1) or including electron-impact ionization (2). (Note, that this relation is valid only for the particular position of ULYSSES close to perihelion (~ 1 February 1995, R = 1.3 AU).

$\beta_{ion} \approx 1.0 \cdot 10^{-7}$ s^{-1} the count rates from the simulation agree with the observed ones (in the uppermost panel). From a more detailed comparison of the observed data and the simulated ones, we get a likely range for the ionization rate of 0.9 – 1.1 $\cdot$ 10^{-7} s^{-1}, which is partly due to uncertainties in the determination of the background. As a result, a density range $n_\infty \approx$ 1.64 – 1.78 $\cdot$ 10^{-2} cm^{-3} would be required to fit simultaneously the observed local fluxes of direct and indirect particles (Fig. 4, shaded area (1)).

As mentioned already, in this model so far we have assumed photoionization due to a stationary UV-radiation field to be the only noticeable loss process for the interstellar helium particles. However, Rucinski and Fahr (1989) pointed out that in regions close to the Sun an additional ionization process might be important which results from collisions of hot solar wind electrons with the helium atoms (see also Rucinski et al., 1996). As the electrons rapidly cool down in the expanding solar wind, this effect is estimated to have decreased to the order of 20% of the photoionization at 1 AU only. Therefore, this effect is assumed to be negligible for the particles on direct orbits but not for particles on indirect orbits which have a perihelion distance of 0.2 AU only.

In an improved version of the model this loss process has been included, using the same average solar wind conditions as in Rucinski and Fahr (1989). The effect has then been calculated from numerical integration along the particle trajectory.

Applying the same procedure as before, the best fits between the observation and simulation of the direct particles were obtained with the same set of parameters (v_∞, T_∞), as before. Also, the relation between ionization and density remained essentially the same as before (Fig. 4, solid line), verifying that the electron impact ionization has little effect on particles outside 1.3 AU. For the indirect particles the results were significantly different. As part of their losses now are due to the electron impact ionization only a smaller photoionization rate $\beta_{ion} \approx 0.6 \cdot 10^{-7}$ s^{-1} is required to account for the total losses observed. (In this case, the total extinction factor of 0.024 is the product of the extinction factors for photoionization of 0.11 (at $\beta_{ion} = 0.6 \cdot 10^{-7}$ s^{-1}) and 0.22 for electron impact ionization.) As indicated in Fig. 4, region (2), a density in the range $n_\infty \approx 1.4 - 1.5 \cdot 10^{-2}$ cm^{-3} is required to simultaneously fit the observations of the local fluxes on direct and indirect orbits.

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Table I

EPOCH			INECLIPTIC 12/90 – 1/92	SOUTH/NORTH 11/94 – 6/95
Velocity	V_∞	(km/s)	25.3 ± 0.4	24.6 ± 1.1
Ecl. longitude	L_∞	(°)	73.9 ± 0.8	74.7 ± 1.3
Ecl. latitude	B_∞	(°)	-5.6 ± 0.4	-4.6 ± 0.7
Temperature	T_∞	(K)	7000 ± 600	5800 ± 700
Density	n_∞	$(10^{-2}\ \mathrm{cm}^{-3})$	1.7 ± 0.2	1.4 1.7
@ Photoionization	β_{Ion}	$(10^{-7}\ \mathrm{s}^{-1})$	1.4	0.6* 1.1
No. of distributions			36	10

(* plus electron impact ionization)

5. Discussion and Conclusions

We have extended the analysis of the measurements of the Interstellar Neutral Gas Experiment (Witte et al., 1993) to a period in 1994/1995 when ULYSSES performed its rapid latitudinal transition from the south pole to the north pole of the Sun. The results obtained so far for the velocity vector $\boldsymbol{v}_\infty$ and temperature T_∞ are summarized in Table I.

Within the error bars these results do not significantly deviate from the values obtained in the first epoch in 1990/1992 during the in-ecliptic trajectory of ULYSSES towards Jupiter. Compared to the results, published earlier (Witte et al., 1993) the error bars could be substantially reduced because of the larger data base available and the statistical error analysis applied (Banaszkiewicz et al., 1996). It should be noted that the first epoch was characterized by solar maximum conditions while the measurements in the second epoch took place close to solar minimum.

The determination of the density n_∞ of the interstellar helium outside the heliosphere from measurements in the inner solar system requires knowledge of the loss processes the particles are exposed to during their travel to the observer, e.g. charge exchange, photoionization, electron impact ionization. This is yet regarded the most uncertain aspect in the determination of the interstellar density. (Updates of this topic may be found also in the papers by Cummings et al., 1996; Rucinski et al., 1996; and Geiss and Witte, 1996).

For the analysis of the measurements in the first epoch we had to assume (in accordance to literature) that a photoionization $\beta_{ion} \approx 1.4 \cdot 10^{-7}\ \mathrm{s}^{-1}$ is an appropriate value for the solar maximum conditions, resulting in an interstellar density $n_\infty \approx 1.7 \cdot 10^{-2}\ \mathrm{cm}^{-3}$ (Table I).

Contrary to this, in the second epoch there was direct observational evidence about the acting loss processes, for the first time. The simultaneous observation of particles on direct and indirect orbits, which experience a completely different history with respect to their loss processes, allows to determine the actual loss rates.

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Within the limitations of the data due to the weak signal of the indirect particles and problems related with the background determination, a range of most likely photoionization rates could be obtained (Fig. 4). An additional uncertainty comes from the inclusion of the electron impact ionization because of the assumptions which have to be made about this loss process, e.g. the actual electron distributions. However, in this particular case studied, the total effect (with or without electron impact ionization) leads to a variation of the density of the order of 25% only and, as a consequence, attempts to refine the (solar wind-) parameters used to describe this effect would have even smaller effects. It is interesting to note that the results of the density n_∞ and ionization rates obtained from pick-up ion measurements, with the SWICS-instrument on ULYSSES (Gloeckler et al., 1996; Geiss and Witte, 1996) perfectly agree with the results presented here, which are almost a factor of two larger than most previously published values.

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