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Interstellar atom and pick-up ion fluxes along the Ulysses flight-path

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Abstract. Neutral atom and pick-up ion flux computations using a hot model for hydrogen, helium, oxygen and neon along the trajectory of the *Ulysses* spacecraft, including predictions for the *Extended Mission* are reported and discussed. The feasibility of using absolute pick-up ion fluxes and pick-up ion flux ratios to derive the orientation of the heliospheric upwind-downwind axis is investigated. Finally, the ratio of pick-up ion and neutral fluxes for helium and oxygen expected to be seen by the Ulysses spacecraft are presented and their relevance for a determination of the long- and short-term averages of the total ionization frequencies of neutrals is discussed.

Key words: interplanetary medium – ISM: general – solar neighborhood

1. Introduction

The interstellar matter contains a sizable fraction of the mass of our universe. A knowledge of its physical parameters is of uttermost interest for a variety of reasons ranging from theories of star formation over transport processes of cosmic rays to the formation and dynamics of the heliosphere. For recent reviews on the nearby interstellar matter and the heliosphere, see e.g. Frisch (1995) and Suess (1990), respectively.

Due to the motion of the solar system relative to the local interstellar medium (LISM), the solar system is exposed to a wind of neutral and ionized local interstellar matter that sweeps through and around the heliosphere, respectively. Since the neutrals are coupled to the plasma flow only by charge exchange reactions, they can penetrate into the heliosphere to become subject to the net gravitational force and ionization processes. As a consequence, a circumsolar structure with a pronounced *upwind-downwind asymmetry* is formed.

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In the past, most information on the distant interstellar medium has originated from radio observations and interstellar absorption lines towards nearby stars (Lallement et al. 1990). UV scattering methods measuring the intensity of solar EUV-lines resonantly back-scattered from neutral particles have been used to shed light on the spatial distribution of hydrogen and helium in the heliosphere, thus allowing a determination of the number density, speed and direction of the LISM flow (Bertaux & Blamont 1971; Thomas & Krassa 1971; Weller & Meier 1974; Chassefière et al. 1986, Ajello et al. 1993, Quemerais et al. 1994).

Due to the ionization processes, so-called secondary ions are produced which are not part of the primary solar wind ion flow. The electromagnetic forces connected with the frozen-in magnetic fields of the solar wind pick up these newly created ions and convect them outwards as suprathermal ions not completely assimilating to the primary solar wind ion population, thus forming an energetic ion population with a distinct non-Maxwellian distribution function.

The advent of the Ulysses mission with its unique flight path and new generation of instrumentation allows us to study the interstellar medium via different processes. The SWICS (Gloeckler et al. 1992) and GAS (Witte et al. 1992) experiments on board Ulysses measuring the pick-up ions and the neutral interstellar atoms are now in a position to deliver new complementary information, thus providing new constraints for the basic parameters of the LISM using a different approach with different systematic errors. The purpose of this paper is (i) to stimulate comparisons between theory and experiment thereby showing which parts of the Ulysses flight-path are well-suited for inferring LISM parameters and (ii) to point out the relevance of combining measurements of neutral atom and pick-up ion fluxes from instrumentation on board the same spacecraft.

So far, only very short intervals of the Ulysses trajectory have been used to compare theory with observation (Geiss et al. 1994a,b; Gloeckler et al. 1993, 1994, 1995). To the best of our knowledge, neither a comparison of Ulysses observations with theory for the out-of-ecliptic part of the mission nor a detailed prediction of what should be expected along this part of the spacecraft's flight-path and the period of the *Extended Mission*, beginning with Ulysses' second circumnavigation of the Sun, have been published to date. We have therefore undertaken the task of calculating the directly experimentally observable neutral- and pick-up ion-fluxes for hydrogen, helium, oxygen and neon along the actual Ulysses trajectory. This should help to provide an improved basis for deriving information about the LISM.

2. Neutral and pick-up ion fluxes: theory

2.1. Neutral fluxes

The inflow of cold interstellar gas into the heliosphere has been predicted by Fahr (1968), Blum & Fahr (1970). The corresponding model was later modified to include the temperature effects of the LISM (Fahr 1971, Thomas 1978, Wu & Judge 1979). The flow direction of interstellar matter relative to the Sun was found to represent a symmetry axis for the distribution of the neutrals. Therefore, the neutral density depends upon two geometrical coordinates: the distance r from the Sun as well as the angle θ between the symmetry axis (hereafter referred to as the upwind-downwind axis) and the direction from the Sun to the point in space at which the density is described. In general, the heliospheric density distribution $N_i(r,\theta)$ of a neutral gas in the heliosphere depends on the density, temperature and velocity of the neutral interstellar gas in the vicinity of the solar system. Furtheron, on the cross-sections of the interaction processes of the neutral gases with the solar wind and the solar radiation (charge exchange reactions with solar wind ions, electron impact ionization, and EUV-ionization), the intensity and angular distribution of both solar EUV- and corpuscular radiation as well as possible heating effects of the neutral gas as it approaches the Sun. $N_i(r,\theta)$ can be computed from the so-called *cold* or *hot model*, either neglecting or taking into account the finite temperature of the interstellar gas, respectively. Using the latter, one finds:

$$N_i(r,\theta) = \int\int\int f_\infty(\boldsymbol{v}_\infty(r,\theta,\boldsymbol{v})) \; exp\left(-\int_\infty^{s(r,\theta)} \beta_{loss}(r',\theta',\boldsymbol{v}')\frac{ds'}{v'}\right) d\boldsymbol{v} \qquad (1)$$

where f_∞ denotes the LISM velocity distribution function of interstellar atoms entering the solar system with velocity $\boldsymbol{v}_\infty(r,\theta,\boldsymbol{v})$ such that they reach the space point (r,θ) with a velocity $\boldsymbol{v}$. The exponential function describes the total losses of such atoms along their trajectories. These losses can be treated conveniently by using a total loss frequency β_{loss}. A more detailed account on the model is given in Rucinski et al. (1993). For further refinements (see e.g. Fahr 1990) one includes the ionization fraction ξ_i of an element i, its relative cosmic abundance α_i relative to hydrogen, and the probability T_i with which neutrals of species i are transmitted through the heliospheric plasma interface.

The neutral atom-flux $F_{N_i}(r,\theta)$ of element i at a point (r,θ) inside the heliosphere is then given by:

$$F_{N_i}(r,\theta) = V_{rel}\ \alpha_i\ (1-\xi_i)\ T_i\ N_i(r,\theta) \qquad (2)$$

where V_{rel} denotes the speed of the LISM relative to the spacecraft. As has recently been shown by Rucinski & Bzowski (1995b), the *hot model* has to be used in the parameter range (r,θ) sampled by Ulysses in order to compute the hydrogen fluxes correctly, whereas the *cold model* is sufficient to deliver the fluxes of heavy ions without too much loss of accuracy. We computed all fluxes in the present paper using the *hot model*.

2.2. Pick-up ion fluxes

The flux $F_{P_i}(r,\theta)$ of pick-up ions is found by integrating the production rate $\beta_{prod}\cdot N_i(r,\theta)$ as was first done by Vasyliunas & Siscoe (1976). In the present study the production frequency β_{prod} is taken to be equal to the loss frequency β_{loss} introduced above. Using the notation of Eq. (2), the pick-up ion fluxes are given by:

$$F_{P_i}(r,\theta) = \alpha_i\ (1-\xi_i)\ T_i\ \frac{a^2}{r^2\tau_{a,i}} \int_{r_\odot}^{r} \beta_{prod} N_i(r',\theta)dr' \qquad (3)$$

where $r_\odot$ denotes the Sun's radius.

$\tau_{a,i}$ can be considered as the average lifetime of a neutral of species i at a heliocentric distance $a = 1\ AU$ and is usually taken to be constant. Strictly speaking, $\tau_{a,i}$ is not constant since the ionization processes by the solar EUV flux and charge exchange reactions between solar wind protons and neutral atoms show both a temporal (see Rucinski & Bzowski 1995a) and possible latitudinal variation leading to corresponding changes of the density distribution in the heliosphere. Due to the long time span required by the interstellar wind atoms to move through the solar system (about 2.5 month per AU), longitudinal anisotropies are smoothed out by the 25-day solar rotation period so that long-term averages for the neutral atom loss rate, $<\beta_{loss}>$, may indeed be appropriate. For the locally produced pick-up ions however, due to their high velocities, short-term averages of the production rate, must be used. Therefore, pick-up production rates, $<\beta_{prod}>$, which can be extracted from measured pick-up phase space distributions, may be different from $<\beta_{loss}>$ for neutrals (Gloeckler et al. 1993, 1994, 1995).

2.3. LISM density values and interface parameters

The two most recently published values of the neutral hydrogen density in the LISM, derived using two different measuring techniques, i.e. mass spectrometric (Gloeckler et al. 1993) and UV (Quemerais et al. 1994) measurements, differ by a factor of two. This discrepancy has not yet been resolved. Since the interstellar hydrogen density, enters into Eq. (2) and (3) simply as a factor, this discrepancy does not change the principle shape of the computed flux curves.

Table 1. Parameters for the computation of the neutral and pick-up ion fluxes according to Eq. (2) and (3).

ion	$1/\tau_a \cdot 10^{-7} s^{-1}$	α	$1-\xi$	T
H	5.00	1.00	0.54	0.33
He	0.68	0.07	1.00	1.00
O	5.00	$6.76 \cdot 10^{-4}$	0.68	0.35
Ne	1.10	$1.08 \cdot 10^{-4}$	1.00	0.90
N	3.50	$1.18 \cdot 10^{-4}$	0.75	0.15
C	40.00	$3.71 \cdot 10^{-4}$	0.01	1.00

The value for the neutral hydrogen density assumed in our computations is close to that found with recent observations with the ALAE Lyman alpha spectrometer flown on the ATLAS 1 mission aboard the space shuttle Atlantis (Quemerais et al. 1994), namely $n_H = 0.14\ cm^{-3}$. In addition, we used the parameters shown in Table 1 compiled from Fahr (1990) and Rucinski et al. (1993).

Following the strategy of Rucinski et al. (1993), we have not explicitly included the filtering effect of the interstellar part of the plasma interface in the computation of the fluxes because the actual transmissivities, in particular for hydrogen, are uncertain. However, this effect can be taken into account *a posteriori* by multiplying the fluxes with an appropriate T_i.

2.4. The flight-path of Ulysses

We show the flight-path of the Ulysses spacecraft, launched on Oct. 6, 1990, in heliocentric coordinates in Fig. 1a illustrating the geometrical variables. The angle θ, counted from the upwind direction is shown as a function of days since launch in Fig. 1b and as a function of heliocentric distance in Fig. 1c. The projection of the path onto the ecliptic is given in Fig. 1d. We have also included in Fig. 1b the kinetic energy per nucleon of neutral atoms encountering the spacecraft since this variable is important for detection efficiency reasons. As can be seen from Fig. 1a, Ulysses probed the region near the downwind axis only at the beginning of its flight and later on remains in a narrow θ-range between approximately $85-95$ degrees. Despite the fact that the spacecraft stays in this narrow angular range, the change in radial distance from 1.3 AU to 5.4 AU during this flight period leads to a pronounced variation in the measured pick-up ion fluxes. We want to point out that an extension of the Ulysses Mission will be particularly interesting since the spacecraft will probe the same (r, θ) values during its second circumnavigation of the Sun and thereby will allow us to investigate the influence of a changing solar cycle (see e.g. Rucinski & Bzowski 1995a). We therefore have the computed observables also for the *Extended Mission* using projected trajectory information. Since in the present study we use a time-independent model to compute the observable quantities, the resulting variations solely reflect the fact that Ulysses probes different regions in the (r, θ) space.

3. Neutral and pick-up ions fluxes: predictions

3.1. Neutral fluxes

Fig. 2 displays the computed neutral atom fluxes F_{N_i} of hydrogen, helium, oxygen and neon as defined in Eq. (2), i.e. as observed by Ulysses. Since the velocity of the spacecraft and the neutral atom velocities are comparable, the displayed fluxes are different from those seen by an observer in the rest frame of the solar system. To be discussed in more detail in the following section, all flux curves can be divided into a non-periodic part before Ulysses' encounter with Jupiter, and a periodic part afterwards, when the spacecraft was put into its final elliptical orbit around the Sun. Here, due to the comparable velocities between the neutrals and the spacecraft, these two sections of the curves are separated by a strong step-like decrease in the flux levels near day 450. This decrease is a consequence of the change in the spacecraft's velocity at Jupiter. In order to put Ulysses into the desired off-ecliptic orbit around the Sun, the spacecraft was strongly accelerated during a gravitational assist maneuver at the planet. Since that time Ulysses had a velocity component pointing to the upwind direction (see Fig. 1). Its relative velocity with respect to the neutrals was considerably decreased, resulting in a sharp flux decrease. All later variations during the flight of Ulysses along the periodic part of its trajectory are a superposition of two effects. One effect arises from the spacecraft's changing spatial position, mainly characterized by a change in heliocentric distance. The other, the change in off-upwind axis angle θ, is important for a change in the relative velocity between the spacecraft and neutral particles.

3.2. Pick-up ion fluxes

Fig. 3 shows the computed pick-up ion fluxes F_{P_i} of hydrogen, helium, oxygen and neon along the Ulysses flight-path as a function of the numbers of days since its launch. We discuss the earliest phase of the trajectory in section 3.3 below. Here, beginning with day 50, one can distinguish two classes, one represented by hydrogen and oxygen, and the other by helium and neon. For the former, the flux during day 50 to 400 is sharply increasing from a rather low-level at the beginning of the mission to a plateau-like level exhibiting pronounced minima around day 1600 and day 3860. The latter show an opposite behavior, with a strong flux decrease during day 50 to 400 to a low-level with moderate flux increases around day 1600 and day 3860. The flux variation is periodic after day 440 of the mission. These curves can readily be understood.

Their separation into a non-periodic and a periodic part reflects the fact that the Ulysses spacecraft reached its desired elliptic off-ecliptic orbit around day 440 after launch, after its gravitational assist maneuver at Jupiter. The plane of this orbit is approximately perpendicular to the upwind-downwind axis (see Fig. 1d) and, therefore, almost coincides with the plane separating the upwind and the downwind heliosphere, so that the spacecraft never probes distinct upwind or downwind conditions. This was different for the first part of the trajectory when Ulysses was on its way from the Earth' to Jupiter's or-

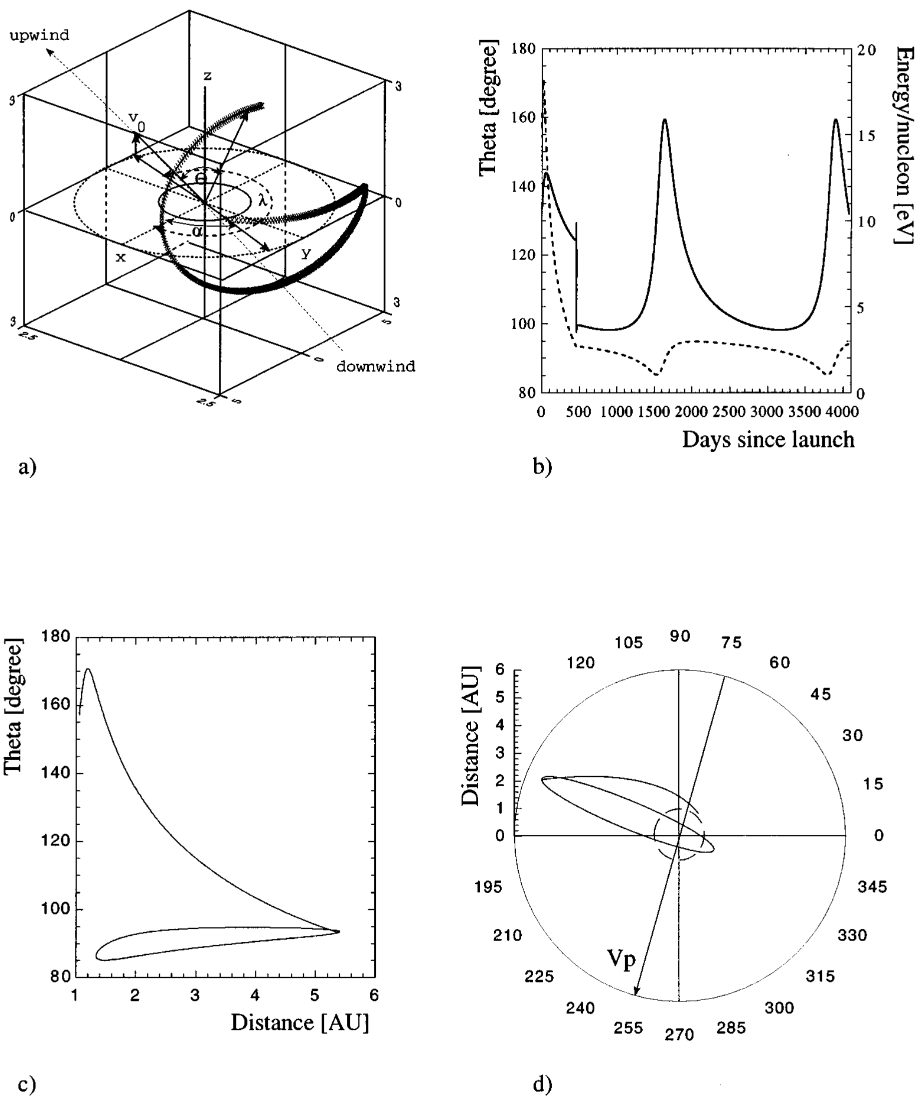

Fig. 1. **a** Ulysses trajectory in heliocentric coordinates; **b** spacecraft's off-upwind axis position (dashed line) and kinetic energy per nucleon of neutral atoms (solid line) as function of mission days; **c** spacecraft position relative to upwind-downwind direction as function of distance from the Sun; **d** projection of spacecraft trajectory onto the ecliptic plane shown together with a vector v_p indicating the upwind direction projected onto the ecliptic.

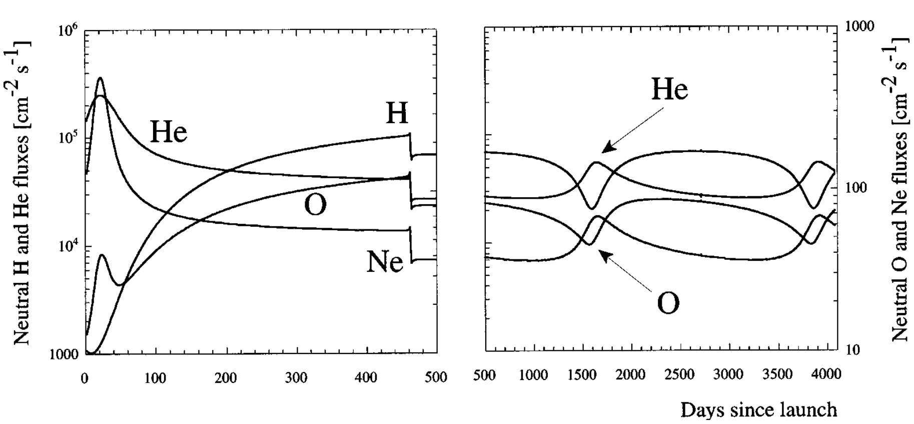

Fig. 2. Neutral atom fluxes along the Ulysses flight-path as seen by the spacecraft.

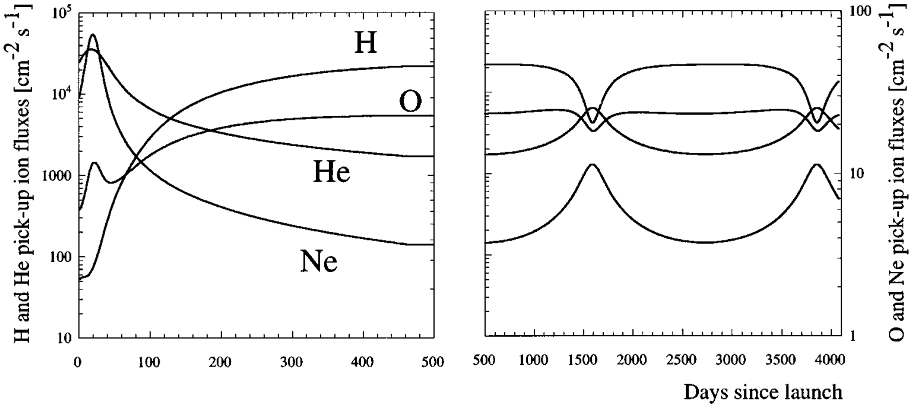

Fig. 3. Pick-up ion fluxes for H^+, He^+, Ne^+, and O^+ along the Ulysses-flight path.

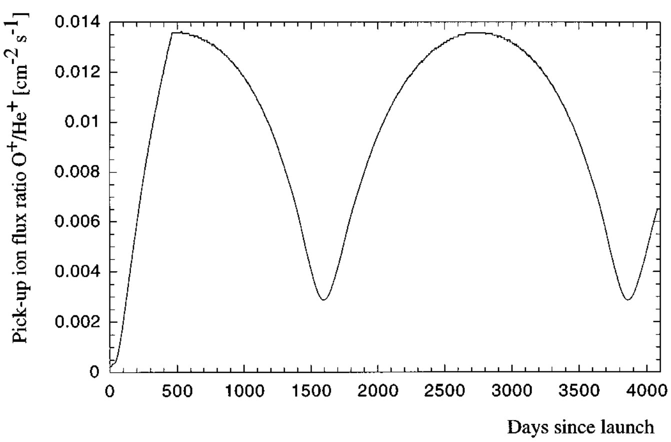

Fig. 4. Pick-up ion flux ratio O^+/He^+ along the Ulysses flight-path.

bit. As illustrated in Fig. 1, during the first part of the Mission, Ulysses spent some time close to the downwind direction before it went to larger heliocentric distances, gradually moving towards the upwind heliosphere. Combining these trajectory properties with our knowledge about the pick-up ion distributions, we can straightforwardly interpret the other characteristics of the flux curves.

The evident separation of the pick-up ion species into two groups arises from the different ionization probability of the corresponding neutrals. The ionization frequencies for hydrogen and oxygen atoms in the heliosphere are of the order of $5.0 \cdot 10^{-7} s^{-1}$, those for helium and neon $6.8 \cdot 10^{-8} s^{-1}$ and $1.1 \cdot 10^{-7} s^{-1}$, respectively (see e.g. Rucinski et al. 1993). In other words, in contrast to helium and neon, hydrogen and oxygen are strongly depleted due to ionization in the upwind hemisphere. This different behavior manifests itself in a characteristic flux variation with heliocentric distance as was demonstrated by Rucinski et al. (1993). In the inner heliosphere, in particular for the distance range of the Ulysses trajectory, the fluxes of hydrogen and oxygen increase with increasing heliocentric distance, whereas for helium and neon, the opposite is true. This explains the flux increase (decrease during day 50 to 400 of the mission and the minima (maxima) occurring along the periodic off-ecliptic orbit for hydrogen and oxygen (helium and neon). These variations are simply due to the changing heliocentric distance of the spacecraft. The fact that the flux variations during the first non-periodic part of the trajectory are stronger than those during its periodic part, is a consequence of the motion of the spacecraft from its initial position close to the downwind direction towards the upwind hemisphere, i.e. a consequence of a pronounced θ-variation which is absent for the periodic orbit.

Having discussed the principal features of the fluxes of individual pick-up ion species as seen along the Ulysses flight path, we now turn our focus to observable ratios of pick-up ion fluxes.

3.3. Pick-up ion flux ratios

Pick-up ion flux ratios have been studied so far primarily for two reasons. First, from an experimental point of view, instrument characteristics cancel out and, second, conclusions about abundance ratios can be drawn even for the cases where only low statistics are available. The fact that pick-up He^+ turns out to be one of the elements which is not affected by filtration effects when crossing the interface region is a particularly fortunate circumstance. This allows the conversion of relative abundance ratios (heavy elements to helium) into absolute fluxes once the He^+-flux is determined. Geiss et al. (1994a,b) have reported such ratios for the first part of the spacecraft's trajectory. As illustrated with Fig. 4, Ulysses as it leaves the Jupiter system, should detect a periodic variation of the flux ratio beginning with a rather moderate decrease. Due to the anticorrelation of the O^+- and the He^+-fluxes, the resulting variation of the combined fluxes is larger than that of the individual fluxes. The first non-periodic part corresponds to Fig. 6 in Geiss et al. (1994a) and Fig. 3 in Geiss et al. (1994b). The shape of the curve is understandable. Since the O^+-flux increases and the He^+ flux decreases during day 50 to 400 of the mission, the corresponding ratio strongly increases. Analyzing a short data interval from 1992, Fahr et al. (1995) have shown that agreement between theory and observation (Geiss et al. 1994a,b) may be achieved by correctly taking into account the filtration of oxygen in the heliospheric interface.

From a theoretical point of view, pick-up ion flux ratios add another interesting aspect to the discussion of filtration effects.

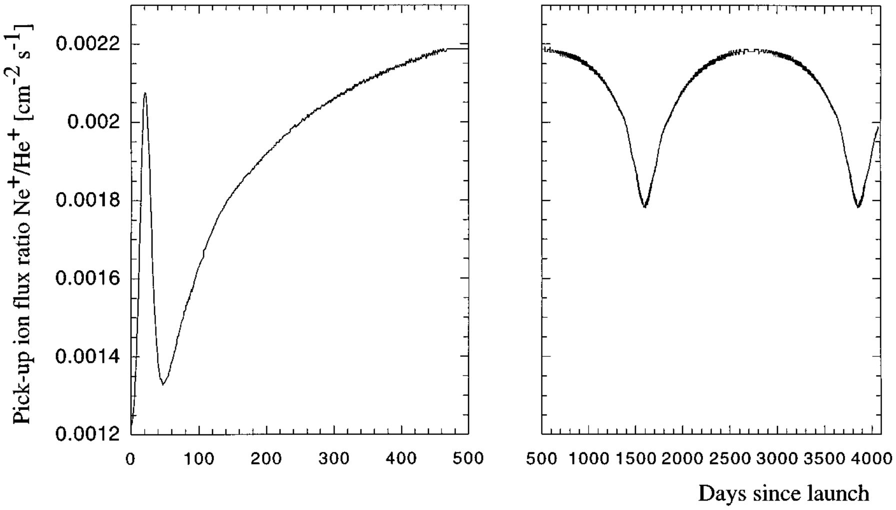

Fig. 5. Pick-up flux ratio Ne^{+}/He^{+} along the Ulysses flight-path.

Whereas the helium and oxygen interact differently in the interface region, pick-up ion flux ratio measurements of elements with similar cross sections should be less sensitive to the specific characteristics of the interface. Based on the similarity of the charge exchange cross sections (Siscoe & Mukherjee 1972), and the fact that the plasma temperature in the interface region is of the order of 10^4 to 10^6 K, the elements helium, neon and carbon should be able to penetrate the interface region with minimal interaction (see the corresponding transmissivities T_i in Table 1. We also show, therefore, the Ne^{+}/He^{+}-ratio in Fig. 5. The disadvantage from the experimental side is that the Ne^{+}/He^{+} ratio only varies by a factor of two over the whole flight path. Of special importance is therefore the use of flux ratios of pick-up ions to neutral atoms for a particular species, as shown in Fig. 7 (see below).

The O^{+}/He^{+}-ratio might be used to check on the possibility to derive the orientation of the upwind-downwind axis. The direction of the LISM inflow into the solar system is an important input for models aiming at a global description of the heliosphere. So far, the orientation of the upwind-downwind axis was determined either from resonant back-scattering of solar EUV radiation (e.g. Bertaux et al. 1985, Chassefière et al. 1988, Lallement et al. 1990) or, most recently, from direct observations of the neutral distributions in the heliosphere with Ulysses (Witte et al. 1993). In principle, due to their symmetry w.r.t. the upwind-downwind axis, the pick-up ion distributions contain the same information. We compute, therefore, the flux ratio along the Ulysses trajectory for two axis orientations. The first, *LISM A*, was derived by Bertaux et al. (1985) with an ecliptic longitude of $\lambda = 71.0^o$ and an ecliptic latitude of $\beta = -7.5^o$. The second, *LISM B*, obtained by Witte et al. (1993) from Ulysses' neutral measurements, is given by $\lambda = 72.0^o$ and $\beta = -2.5^o$. Fig. 6 shows the corresponding fluxes. Although the flux levels for the two orientations of the upwind-downwind axis are not the same, the difference between the two cases is rather small. It is not sufficiently pronounced to discriminate between different orientations on the basis of the available data having a rather high degree of uncertainty (see e.g. Geiss et al. 1994a,b).

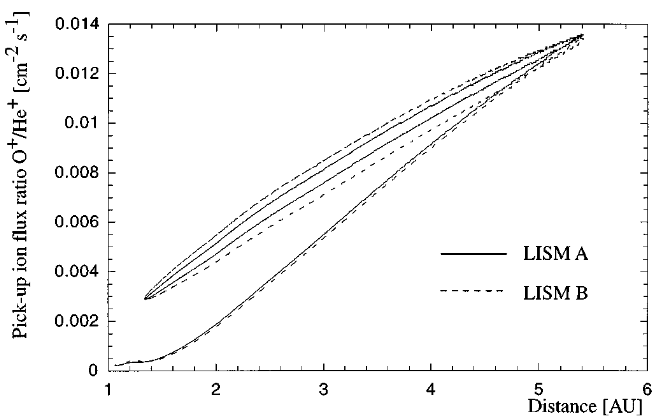

Fig. 6. Pick-up ion flux ratio O^{+}/He^{+} along the Ulysses flight-path for two different LISM inflow directions (see Sect. 3.3).

Considering in addition that the value $\beta = -2.5^o$ is a rather extreme case and, most likely, has to be corrected to $\beta = -5.0^o$ (Witte et al. 1995), we arrive at the conclusion that the periodic part of Ulysses' trajectory is not well-suited to extract information about the inflow direction of the LISM from pick-up ion data. This is mainly due to the fact that in the plane separating the upwind and the downwind heliosphere, the pick-up ion flux distributions do not have large spatial gradients. Sufficiently large gradients of the pick-up ion distributions occur in the downwind hemisphere close to the upwind-downwind axis where several pick-up ion species exhibit pronounced cone structures resulting from a focussing by the Sun's gravitation (see e.g. Fig. 9 in Rucinski et al. (1993) or Fig. 1 in Fichtner et al. (1994)). The very first part of the mission (day 1 to 50), where the spacecraft traversed these downwind cones, would have been particularly interesting if the instruments would have been fully operational. Instrumentation on the GEOTAIL, the WIND (see e.g. Acuna et al. 1995) or the CASSINI spacecraft (e.g. Matson 1992) spending longer time in the downwind heliosphere close to the upwind-downwind axis should be in a

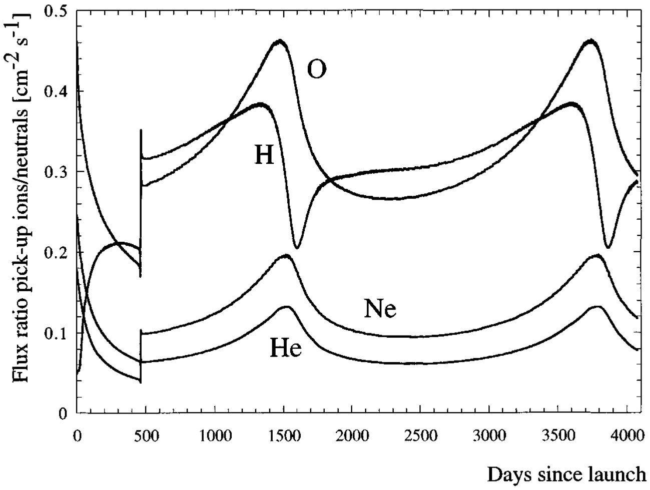

Fig. 7. Ratio of pick-up ion flux to neutral atom flux for H^+, He^+, O^+ and Ne^+ along the Ulysses flight-path.

better position to discriminate between different axis orientations (Mall et al. 1996).

3.4. Pick-up ion to neutral flux ratios

As mentioned in the introduction, the Ulysses spacecraft offers the unique opportunity to combine in-situ measurements of neutrals and pick-up ions. As discussed above, the extraction of LISM parameters from pick-up ions measurements relies on a knowledge of the actual ionization rates. So far, information on the local production rate was obtained by fitting velocity distribution functions to the measured pick-up ion distributions (Gloeckler et al. 1995). Due to the many parameters involved, such a procedure suffers from all the standard problems of multi-parameter fitting. To get a handle on the pick-up production and neutral atom loss rates, we suggest to consider the flux ratio of pick-up ions to neutral atoms F_{P_i}/F_{N_i}, since in such a ratio, all constant factors (i.e. the total elemental densities in the LISM, the fractional ionization and the filtration in the heliospheric interface) would cancel out (compare Eq. (2) and (3)). We assume here that the filtration effect can be treated via a simple transmission factor as done in Rucinski et al. (1993) and above (Sects. 2.1 and 2.2). Stated differently, using pick-up ions to neutral atoms ratios would have the advantage that there are significantly less parameters available to adjust the theoretical result to the data since it depends only upon the loss and production rate. The corresponding flux ratios are shown in Fig. 7.

As can be seen from the figure, the Ulysses Mission is directly destined for such an approach since the inflow velocity of the neutrals into the heliosphere is of the same order as the spacecraft velocity, and thereby becomes sensitive to changes in the spacecraft velocity. Since Ulysses undergoes both an acceleration and a change of direction during the Jupiter fly-by, the ratios shown in Fig. 7 have a step-like structure around day 440. This effect was discussed in Sect. 3.1. Although the sputtering processes used by the GAS experiment in its method of neutral gas detection create a threshold for the detection of neutral atoms lighter than helium, we have included in this plot all the elements investigated in this study. Among the possible choices, the most interesting case is oxygen, since hydrogen and neon neutrals are not observed, and helium does not experience any filtration.

Due to the independence of the mentioned interface and LISM properties, the F_{P_i}/F_{N_i}-ratio shown should be the same for all corresponding models. We are well aware of the fact that such an approach from the experimental side is not easy since (i) instrumental effects have to be controlled to high degree since data from two very different experiments have to be combined and (ii) the instruments will not be able to deliver the same quality of data for a particular solar wind condition. However, such an approach could offer an independent check on the determination of the parameters involved.

4. Summary and conclusions

Employing the so-called hot model to derive the time-independent heliospheric distributions of interstellar neutrals and the corresponding pick-up ions, we have studied the fluxes of four neutral and pick-up ion species to be expected along the Ulysses flight-path.

We have investigated three representations of these fluxes, namely (i) the neutral and pick-up ion flux curves for hydrogen, helium, oxygen and neon, (ii) the flux ratios O^+/He^+ and Ne^+/He^+, as well as (iii) the pick-up ion to neutral flux ratios for all four species. The first representation allows us to distinguish between species with high (hydrogen, oxygen) or low (helium, neon) ionization probability. The variations of the corresponding fluxes are anticorrelated. The second representation, the pick-up ion flux ratios, are of interest because they can be obtained easily as the ratio of count rates (see Geiss et al. 1994a) and because the variations are larger than those of the fluxes of individual species. Using the O^+/He^+ ratio, we have explored the possibility of deriving information about the orientation of the upwind-downwind axis of the heliosphere. The result demonstrates that the Ulysses spacecraft is not well-suited for this purpose, because its final orbit is almost perpendicular to the upwind-downwind axis. Due to the fact that the pick-up ion distributions do not have strong spatial gradients in the plane and distance range of Ulysses' orbit, they are rather insensitive to changes in the axis orientation. In order to extract such information directly from pick-up ion data, a spacecraft located in the downwind heliosphere close to the downwind direction would be required. Hence, performing an analogous analysis for the GEOTAIL, WIND or CASSINI spacecraft would probably yield much better results. As a final representation we have considered the pick-up ion to neutral flux ratios which have the advantage of being independent of the total elemental LISM densities, the fractional ionizations of the species, and the filtration effect, if the latter is treated using a transmission factor. These ratios only depend on the loss rates of the neutrals and the production rates of the pick-up ions, i.e. the long- and short-term averages of the total ionization frequencies, thus allowing their determination from a comparison of theory and observation without having the need to assume further parameters.

All fluxes were shown as fluxes seen by the Ulysses spacecraft, i.e. are based on the relative velocity of particles and spacecraft, which is particularly important for the case of the neutrals. This makes any comparison with actual observations straightforward. The computed fluxes should be considered as predictions for the time of the *Extended Mission*, beginning with the second arrival of Ulysses at the Jupiter orbit. Since we used a time-independent model, the fluxes give an average level around which the actual observations do fluctuate. This is due to the solar activity cycle and a possible latitudinal variation of the ionization rates which to date, has not been included in these type of models. Regarding the effect of solar activity, a comparison of the Ulysses Mission with the *Extended Mission* should give insight into the corresponding time variation, since for both Missions, the variation due to the change in spatial location of the spacecraft should be the same.

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References

Acuna, M.H., Ogilvie, K.W., Baker, D.N., Curtis, S.A., Fairfield, D.H., Mish, W.H., 1995, Space Sci. Rev. 71, 5

Ajello, J.M, Pryor, W.R., Barth, C.A., Hord, C.W., Simmons, K.E., 1993, Adv. Space Res. 13(6), 37

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

Blum, P.W., Pfleiderer, J., Wulf-Mathies C., 1975, Planet. Space Sci. 23, 93

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

Chassefière, E., Bertaux, J.L., Lallement, R., Sandel, B.R., Broadfoot, L., 1988, A&A 199, 304

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

Fahr, H.J., Osterbart, R., Rucinski, D., 1995, A&A 294, 587

Fahr, H.J, 1990, *Filtration of the interstellar neutrals at the heliospheric interface and their coupling to the solar wind*, in: Grzedzielski, S., Page D.E. (eds.) Physics of the outer heliosphere, Pergamon, 327

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

Fahr, H.J., 1968, APSS, 2, 474

Fichtner, H., Fahr, H.J., Rucinski, D., Grzedzielski, S., Sreenivasan, S.R., 1994, A&A, 284, 599

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

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

Geiss, J., Gloeckler, G., Mall, U., 1994b, A&A 289, 933

Gloeckler, G., Schwadron, N.A., Fisk, L.A., Geiss, J., 1995, Geophys. Res. Letters 22, 2665

Gloeckler, G., Geiss, J., Roelof, E.C., Fisk, L.A., Ipavich, F.M., Ogilvie, K.W., Lanzerotti, L.J., von Steiger, R., Wilken, B., 1994, J. Geophys. Res. 99, 17637

Gloeckler, G., Geiss, J., Balsiger, H., Fisk, L.A., Galvin, A.B., Ipavich, F.M., Ogilvie,K.W., von Steiger, R., Wilken, B., 1993, Science 261, 70

Gloeckler, G., Geiss, J., Balsiger, H., Bedini, P., Cain, J.C., Fischer, J., Fisk, L.A., Galvin, A.B., Gliem, F., Hamilton, D.C., Hollweg, J.V., Ipavich, F.M., Joos, R., Livi, S., Lundgren, R., Mall, U., McKenzie, J.F., Ogilvie, K.W., Ottens, F., Rieck, W., Tums, E.O., von Steiger, R., Weiss, W., Wilken, B., 1992, A&AS 92, 267

Lallement,. R. Ferlet, Vidal-Madjar, A., Gry, C., 1990, *Velocity structure of the local interstellar medium*, in: Grzedzielski, S., Page D.E., (eds.) Physics of the outer heliosphere. Pergamon, 37

Mall, U., Fichtner, H., Hamilton, D.C., Rucinski, D., 1996, Geophys. Res. Letters 22, 3263

Matson, D.L., 1992, *ESA Symposium on Titan*, SEE N92-3234823-91, 281

Quemerais, E., Bertaux, J.L., Sandel, B.R., Lallement, R., 1994, A&A 290, 941

Rucinski, D., Bzowski, M., 1995a, A&A 296, 248

Rucinski, D., Bzowski, M., 1995b, submitted

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

Siscoe, G.,L., Mukherjee, N.R., 1972, J. Geophys. Res. 77, 6042

Suess, S.T., 1990, Rev. Geophys. 28, 97

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

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

Vasilyliunas, V.M, Siscoe, G.L., 1976, J. Geophys. Res. 81, 7, 1247

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

Witte, M., Banaszkiewicz, M., Keppler, E., Rosenbauer, H., 1995, XXI General Assembly, Boulder, Colorado, July 2-14, Abstracts Week B, B85

Witte, M., Rosenbauer, H., Banaszkiewics, M., Fahr, H., 1993, Adv. Space Res. 13, (6), 121

Witte, M, Rosenbauer, H., Keppler, E., Fahr, H.J., Hemmerich, P., Lauche, H., Loidl, A., Zwick, R., 1992, A&AS 92, 333

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