MEASUREMENT OF THE ABUNDANCE OF HELIUM-3 IN THE SUN AND IN THE LOCAL INTERSTELLAR CLOUD WITH SWICS ON ULYSSES

GEORGE GLOECKLER
Department of Physics and IPST, University of Maryland, College Park, MD 20742, USA,
and
Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, Ann Arbor, MI 48109, USA.

JOHANNES GEISS
International Space Science Institute, Hallerstrasse 6, CH–3012 Bern, Switzerland.

Abstract. The abundance of ^{3}He in the present day local interstellar cloud (LIC) and in the sun has important implications for the study of galactic evolution and for estimating the production of light nuclei in the early universe. Data from the Solar Wind Ion Composition Spectrometer (SWICS) on Ulysses is used to measure the isotopic ratio of helium ($^3\mathrm{He}/^4\mathrm{He} = \Gamma$) both in the solar wind and the local interstellar cloud. For the solar wind, the unique high-latitude orbit of Ulysses allows us to study this ratio in the slow and highly dynamic wind in the ecliptic plane as well as the steady high-latitude wind of the polar coronal holes. The $^3\mathrm{He}^+/^4\mathrm{He}^+$ ratio in the local cloud is derived from the isotopic ratio of pickup helium measured in the high-speed solar wind. In the LIC the ratio is found to be $(2.48^{+0.68}_{-0.62}) \times 10^{-4}$ with the 1-σ uncertainty resulting almost entirely from statistical error. In the solar wind, Γ is determined with great statistical accuracy but shows systematic differences between fast and slow solar wind streams. The slow wind ratio is variable. Its weighted average value $(4.08 \pm 0.25) \times 10^{-4}$ is, within uncertainties, in agreement with the Apollo SWC results. The high wind ratio is less variable but smaller. The average Γ in the fast wind is $(3.3 \pm 0.3) \times 10^{-4}$.

1. Introduction

Knowledge of the isotopic ratio of helium in the local interstellar cloud (LIC) and in the outer convective zone (OCZ) of the sun has importance for cosmology and stellar evolution (e.g. Geiss and Gloeckler, 1998). We obtain the present day ^{3}He abundance from the isotopic analysis of pickup helium, using a longer averaging period than in our previous work (Gloeckler and Geiss, 1996). The helium isotopic ratio in the solar wind, $\Gamma_{\mathrm{SW}} = {^3\mathrm{He}^{++}}/{^4\mathrm{He}^{++}}$, provides a good and reliable sample of (^{3}He + ^{2}H) in the protosolar cloud some 4.6 Gy ago (Geiss and Gloeckler, 1998). Here we determine Γ_{SW} for various solar wind flow conditions both in the fast, high-latitude, and in the slow, in-ecliptic wind using SWICS/Ulysses data from 1991 to mid-1997. Previous studies (Geiss *et al.*, 1970; Geiss *et al.*, 1972; Coplan *et al.,* 1984; Bochsler, 1984) were based on data taken in the slow solar wind during several years of relatively high solar activity. Using the 6.5 years of SWICS data we determine the dependence of Γ_{SW} on solar activity and solar wind characteristics such as its speed, and FIP strength based on the Fe/O ratio. From this analysis we find the base-line value of the solar wind $^3\mathrm{He}^{++}/^4\mathrm{He}^{++}$ ratio with good precision.

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2. The ^{3}He/^{4}He Ratio in the Local Interstellar Cloud

The orbit of Ulysses and the low background capabilities of the SWICS instrument (Gloeckler *et al.*, 1992) made it possible to discover and study many of the interstellar pickup ions (Gloeckler *et al.*, 1993; Geiss *et al.*, 1994). Interstellar pickup ions are created deep inside the heliosphere through ionization of interstellar atoms (e.g. Gloeckler *et al.*, 1997a; Gloeckler and Geiss, 1998), and provide new information on the elemental and isotopic abundance in the local interstellar cloud.

The local interstellar cloud ^{3}He/^{4}He ratio, Γ_{LIC}, is derived from the measured velocity distributions of interstellar pickup helium isotopes (Gloeckler and Geiss, 1996) as illustrated in Fig. 1. Because virtually all physical and instrument parameters that are used to determine the pickup ion distributions for ^{3}He$^+$ are the same as for ^{4}He$^+$, Γ_{LIC} reduces to the ratio of counts divided by the ratio of probabilities of detecting the two helium isotopes respectively. The only possible other systematic correction comes from the ratio of the anisotropy factors. However, because the distribution function anisotropy of pickup ^{4}He^{++} was found to be the same (within errors) as that of ^{4}He$^+$ (Gloeckler and Geiss, 1998) it is reasonable to assume that the ^{3}He$^+$ anisotropy (which has a rigidity between that of ^{4}He^{++} and ^{4}He$^+$) is also equal to that of ^{4}He$^+$.

Because pickup ^{3}He$^+$ has very low abundance, long accumulation times and the most stringent coincidence conditions were necessary to positively identify these ions. The mass/charge (m/q) histogram of ions of masses between 2 and 6 amu and W (ion speed/solar wind speed) from 1.6 to 2 is shown in the top panel of Fig. 2. Since singly-charged helium ions are absent in the solar wind, especially in this speed range, the identification of these ions as pickup ions is virtually certain. These triple coincidence data were accumulated during a 40 month period in the high speed solar wind ($>$700 km/s) in order to increase counting efficiency of ^{3}He$^+$. Despite the low count rate the peak at m/q of about 3 (due to ^{3}He$^+$) is well separated from the two neighboring peaks (pickup ^{4}He^{++} and ^{4}He$^+$) and well above the residual small background of less than one count in three years.

The distribution function of ^{3}He$^+$ (divided by 2.4×10^{-4}) is compared to that of ^{4}He$^+$ in the bottom panel of Fig. 2. These spectra were averaged during all times when Ulysses was in the high-speed solar wind of both the south and north polar coronal holes. Within the statistical errors the five point ^{3}He$^+$ is the same as the ^{4}He$^+$ distribution (solid curve) averaged over the same time period reinforcing the case for the correct identification of interstellar ^{3}He$^+$. The interstellar ^{3}He$^+$/^{4}He$^+$ ratio obtained by least-squares (χ^2) fit from the ratio of the two speed distributions is 2.48×10^{-4}. The 1-σ statistical uncertainties ($\chi^2_{\text{min}} + 1$) are $+0.63 \times 10^{-4}$ and -0.57×10^{-4} and systematic errors are estimated to be $\pm 0.25 \times 10^{-4}$. Our present value, derived from a more extended data set than was used in Gloeckler and Geiss (1996), is slightly higher than our previous ratio (Gloeckler and Geiss, 1996), but well within the statistical errors of both measurements.

Interstellar number density of atoms with mass m, ρ_m

- $\rho_m = F_{m/q}(W, R, \Theta) \Big/ \int_{\Omega_{\text{inst}}} d\Omega\, f_{m/q}(w, \theta, \phi)$

$W =$ ion speed / solar wind speed V_{SW}
R, Θ are spacecraft position coordinates; $\Theta = 0°$ is along motion of solar system
Integration over instrument view angles

Measured velocity distribution of pickup ions with mass per charge m/q

- $F_{m/q}(W, R, \Theta) = C_{\text{inst}}\{r_{m/q}(R, \Theta)/\eta_{m/q}(W)\}W^{-4}$

$C_{\text{inst}} =$ instrument factor
$r_{m/q} =$ count rate of pickup ion
$\eta_{m/q} =$ count efficiency of pickup ion

Velocity distribution of pickup ions in the solar wind frame as a function of $\mathbf{w} = \mathbf{W} - \mathbf{V}_{\text{SW}}/|V_{\text{SW}}|$

- $$f_{m/q}(w, \theta, \phi) = (3/8\pi)w^{-3/2}\{(\beta_{m/q,\text{prod}})(R_0^2/R)\} \times \{N(w, R, \Theta, \beta_{m,\text{loss}}/V_0)\}\{G(\lambda_{m/q}, \theta, \phi)\}$$

$\beta_{m/q,\text{prod}} =$ rate of pickup ion production by photoionization and charge exchange of atom of mass m
$\beta_{m,\text{loss}} =$ ionization loss rate of interstellar atoms of mass m
$R_0^2 = (1\ \text{AU})^2 = (1.5 \times 10^{13}\ \text{cm})^2$
$N =$ normalized ($N = 1$ in LIC) spatial distribution of interstellar atoms in heliosphere
$V_0 =$ relative speed of the interstellar cloud and the Sun
$G =$ anisotropy function of the pickup ion velocity distribution
$\lambda_{m/q} =$ pitch-angle scattering mean free path

Interstellar ^{3}He/^{4}He density ratio $= \Gamma_{\text{LIC}} \approx$

- $F_{^3\text{He}^+}(W)/F_{^4\text{He}^+}(W) \approx \{r_3(W)/r_4(W)\}\{\eta_4(W)/\eta_3(W)\}\{G(\lambda_4)/G(\lambda_3)\}$

Figure 1. Computational steps relating the number density ratio of helium isotopes in the local interstellar cloud to the phase space density ratio of the corresponding helium pickup ion in the heliosphere. Because the distribution functions of $^4\text{He}^+$ (especially $^3\text{He}^+$) can only be measured in a limited portion of phase space, model velocity distributions in the solar wind frame, $f(w, \theta, \phi)$, are used to fill in the missing portions of phase space.

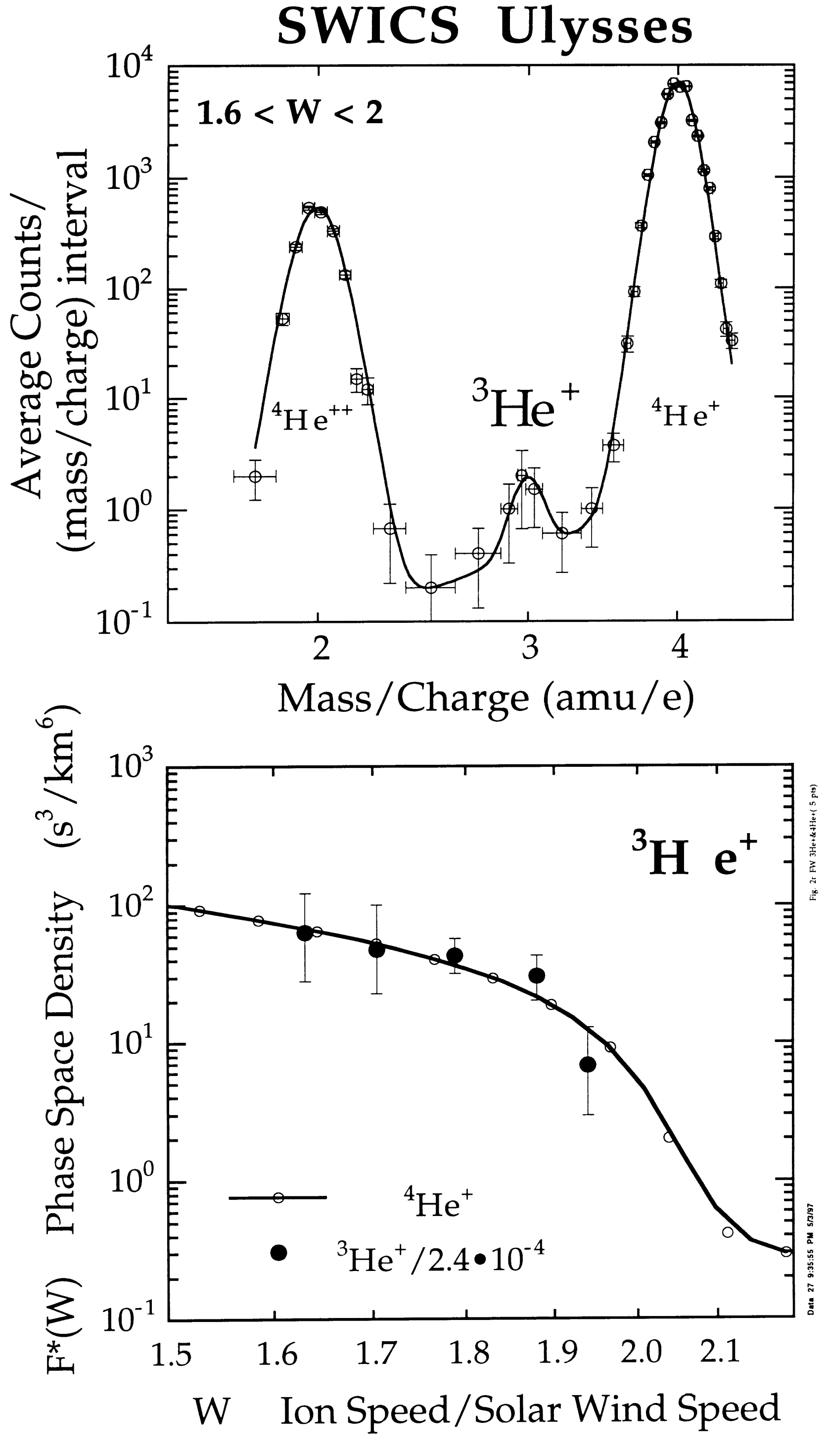

Figure 2. Top: Average triple-coincidence count rate density of ions selected to have masses between 2 and 6 amu and speeds W between 1.6 and 2 versus mass/charge (m/q). The ^{3}He$^+$ peak at $m/q = 3$ is well separated from the two adjacent much larger peaks at $m/q = 2$ and 4 from pickup ^{4}He^{++} and ^{4}He$^+$ respectively. Triple coincidence is required to measure both mass and mass/charge of the ion (Gloeckler *et al.*, 1992) and to reduce background sufficiently to see the ^{3}He$^+$ peak.
Bottom: Phase space density, scaled by $(438/V_{\mathrm{SW}})^4$, of ^{4}He$^+$ (open circles) and ^{3}He$^+$ divided by 2.4 × 10^{-4}, (filled circles) versus W. The similarity of the two spectra is evident despite the large statistical errors for ^{3}He$^+$. Below $W = 1.6$ the triple coincidence efficiency for ^{3}He$^+$ becomes extremely small, and above $W = 2$ no ^{3}He$^+$ was detected, consistent with the sharp cutoff of pickup ion spectra at $W = 2$ (e.g. Gloeckler and Geiss, 1998).

3. The ^{3}He/^{4}He Ratios in the Solar Wind

Unlike pickup ion distributions which are broad and have a cutoff at $W = 2$ (e.g. Gloeckler and Geiss, 1998), the solar wind velocity distribution is narrow and well represented by a kappa function in the solar wind frame.

$$f(w) = f_0[1 + (w/\theta)^2/\kappa]^{-(\kappa+1)} \tag{1}$$

$$V_{\rm th} = (1 - 1.5/\kappa)^{-1/2}\theta \tag{2}$$

$$w = |(\mathbf{V}_{\rm ion} - \mathbf{V}_{\rm SW})|/|\mathbf{V}_{\rm SW}| \tag{3}$$

The isotopic helium density ratio in the solar wind, $\Gamma_{\rm SW} = {}^3{\rm He}^{++}/{}^4{\rm He}^{++}$ is derived from the respective integrated phase space densities of these isotopes as indicated in Fig. 1. However, because the full distribution functions are measured (unlike for pickup ions), knowledge of the shape of the distribution functions is not required and $\Gamma_{\rm SW}$ is simply equal to $(N_{^3{\rm He}^{++}}/N_{^4{\rm He}^{++}}) \times \langle(\eta_{^4{\rm He}^{++}}/\eta_{^3{\rm He}^{++}})\rangle$. Here $N_{^3{\rm He}^{++}}$ and $N_{^4{\rm He}^{++}}$ are the total counts in a given time period of the two isotopes respectively and $\langle(\eta_{^4{\rm He}^{++}}/\eta_{^3{\rm He}^{++}})\rangle$ is the average ratio of efficiencies for these ions at the average measured solar wind speed for that period.

3.1. ANALYSIS

The solar wind $\Gamma_{\rm SW}$ may be obtained from the SWICS data in a number of different ways (Gloeckler *et al.*, 1992; Bodmer, 1996). However, each method used requires knowledge of the corresponding efficiency ratio at the appropriate speed for these helium isotopes. Unfortunately, preflight calibration with ^{3}He^{++} could not be obtained and thus ^{3}He^{++} efficiencies for the SWICS/Ulysses instrument were not determined. In this analysis we have therefore used a method that is least sensitive to our lack of measured ^{3}He^{++} efficiencies. We use data requiring only double coincidence efficiencies which (a) vary little with solar wind speed, (b) can be determined (for ^{4}He^{++}) from flight data, and (c) are nearly equal for ^{3}He^{++} and ^{4}He^{++} at the same speed (as indicated by measurements with the SWICS spare instrument as well as model predictions).

The ^{3}He^{++} counts (averaged over a given time interval) are obtained directly from the SWICS pulse-height (PHA) data corresponding to double-coincidence (i.e. time-of-flight) selected to have m/q between 1.42 and 1.60 amu/e and mass (m) less than 5 amu. When plotted against $W_{^3{\rm He}^{++}}$, the speed of ^{3}He^{++} divided by the solar wind speed, a distinct peak is always seen in the counts spectrum at $W_{^3{\rm He}^{++}} = 1$, indicating measurements of solar wind ^{3}He^{++}. Because the maximum count rate corresponding to ^{3}He^{++} was always low, no corrections for PHA event saturation were required. That is, all ^{3}He^{++} detected were registered as pulse-height events. However, a background correction resulting from spill-over from the five orders of magnitude more abundant solar wind protons was necessary. This correction reduced ^{3}He^{++} counts primarily below $W_{^3{\rm He}^{++}} \sim 0.95$. The total reduction in the integrated counts, however, was smaller than 10% in all cases.

A selection similar to that used for ^{3}He^{++} could not be used for ^{4}He^{++} because its high count rate resulted in substantial pulse-height saturation. To correct for this, we used the unsaturated triple-coincidence ^{4}He^{++} rate MR1 (Gloeckler *et al.*, 1992) counts and multiplied these by the ratio of double-coincidence to triple-coincidence PHA counts selected for ^{4}He^{++}. The PHA selection used for double-coincidence events was: m/q between 1.76 and 2.53 amu/e, and m between 2.6 and 5.6 amu as well as mass-0 (no energy) events. The triple-coincidence PHA data had the same m/q and m selection applied to it as rate MR1 $(1.571 < m/q < 2.521$ and $3.56 < m < 5.13)$.

3.2. RESULTS

Using the method described above we have analyzed twelve time periods varying in length from 1.5 days to 310 days both in the slow in-ecliptic as well as the fast coronal hole solar wind. The count rate densities of ^{3}He^{++} and ^{4}He^{++} for two such periods are given in Fig. 3. In the top panel the long-term average in the steady, fast (779 km/s) solar wind of the north polar coronal hole shows identical shapes for the count density distributions of the two helium isotopes. The average solar wind $\Gamma_{\rm SW}$ for this high-speed period, computed from the ratio of the integrated counts from the kappa fits (eq. 1) to the distributions, was $(2.88 \pm 0.03) \times 10^{-4}$, the lowest value observed in the twelve periods analyzed. Essentially the same result $(\Gamma_{\rm SW} = (2.85 \pm 0.04) \times 10^{-4})$ was obtained from the ratio of the sum of counts in the four W bins (0.95 to 1.05) with the highest counts.

The bottom panel of Fig. 3 is a plot of the count rate density distributions of the solar wind helium isotopes during a relatively unperturbed period in the slow solar wind (437 km/s) near the ecliptic. The distributions of both isotopes in the slow wind are narrower than in the fast wind and the ^{4}He^{++} spectrum is slightly broader than that of ^{3}He^{++}. The isotopic ratio computed from the kappa fits (same value of kappa is used for both distributions) is $\Gamma_{\rm SW} = (3.92 \pm 0.07) \times 10^{-4}$. In addition to the statistical errors a systematic error (estimated to be $\pm 6\%$) due to a combination of uncertainties in the ratio of efficiencies, $\langle(\eta_{^4{\rm He}^{++}}/\eta_{^3{\rm He}^{++}})\rangle$, and background correction (for ^{3}He^{++}) is assumed for all solar wind helium isotopic ratios given here.

4. Discussion and Conclusions

Our measurements of the solar wind helium isotopic ratio, $\Gamma_{\rm SW}$, during eleven of the twelve time periods analyzed here are summarized in Fig. 4. During the 5-day interval of the twelfth period (days 168 to 173 of 1992) $\Gamma_{\rm SW} = (1.11 \pm 0.26) \times 10^{-3}$ was more than a factor of two higher than the slow-wind average, possibly because the solar wind ^{4}He^{++} (and proton) densities were unusually low (30 times below the ambient values). During the in-ecliptic portion of Ulysses' trajectory (days 145

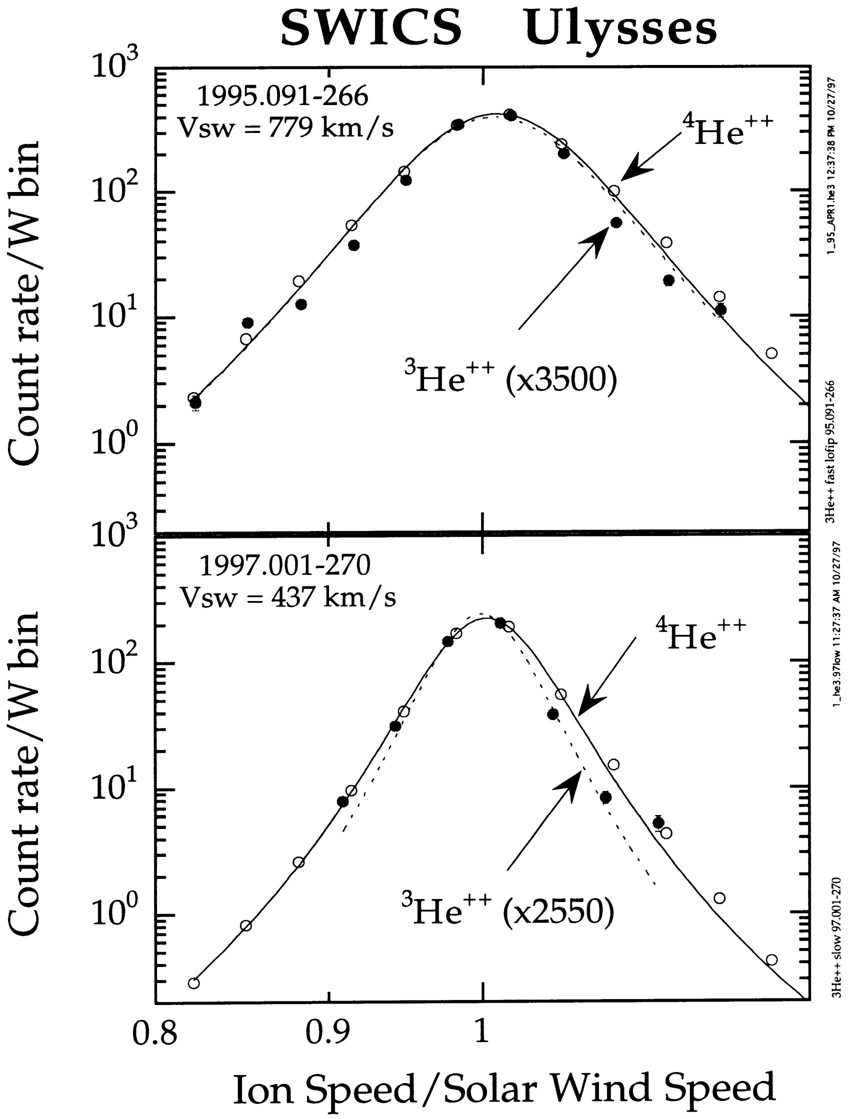

Figure 3. Average count rate density versus ion speed divided by solar wind speed (W) for $^4\mathrm{He}^{++}$ and $^3\mathrm{He}^{++}$ (multiplied by the factor in parentheses) in a high-speed (779 km/s) solar wind from the north coronal hole (top panel) and a low-speed wind (437 km/s) in the ecliptic plane. $\Gamma_{\mathrm{SW}} = {}^3\mathrm{He}^{++}/{}^4\mathrm{He}^{++}$ is computed directly from the ratio of total counts obtained by integrating the kappa function fits to the respective distributions. Γ_{SW} measured in the coronal hole wind is lower than in the slow in-ecliptic wind.

to 545 since 1991) SWICS sampled the highly turbulent slow wind over radial distances from 3.2 to 5.4 AU. The means of the ratios in this slow wind are variable but tend to cluster around 4.15×10^{-4}, a value close to the average ratio (indicated

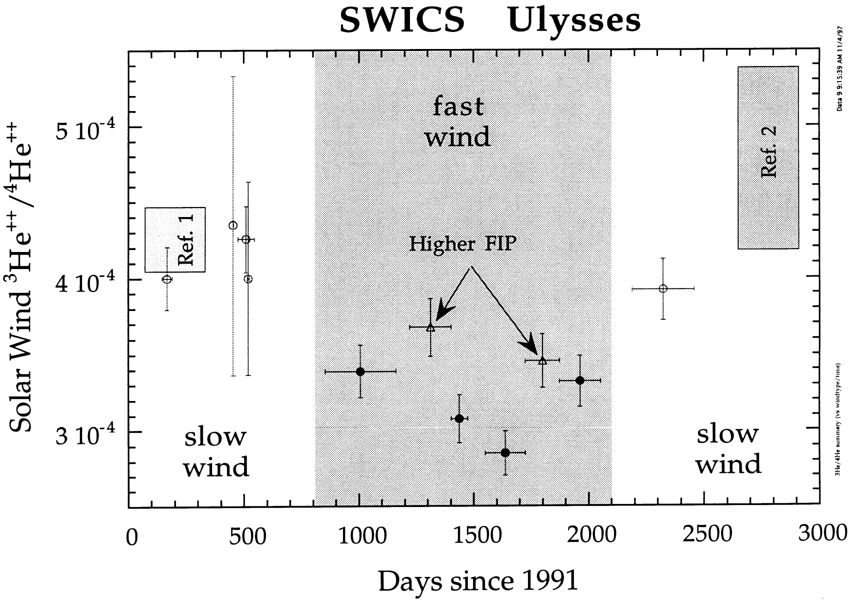

Figure 4. Solar wind isotopic helium ratio, $\Gamma_{SW} = {}^3He^{++}/{}^4He^{++}$, measured during selected time periods with SWICS on Ulysses. In the slow, in-ecliptic wind time periods Γ_{SW} is variable with a weighted slow-wind average of $(4.08\pm0.25)\times10^{-4}$. In the high-latitude fast wind of the polar coronal holes (shaded region) Γ_{SW} has its lowest values. Sorting the coronal hole data by the measured (with SWICS) value of the solar wind Fe/O ratio suggests a dependence of Γ_{SW} on Fe/O. Time periods when Fe/O is at its lowest level (filled circles) have the lowest Γ_{SW}. Except for the shortest time periods, errors shown are due primarily to uncertainties in the ratio of double-coincidence efficiencies of the helium isotopes. Ref. 1 is the $^3He^{++}/^4He^{++}$ value reported by Geiss *et al.* (1970; 1972) and Ref. 2 the average ratio given by Bochsler (1984).

by the box labeled Ref. 1) obtained by Geiss *et al.* (1970; 1972) using foil collection techniques on the moon. Our other slow-wind average ratio was measured during the 270 day period in 1997 near 5 AU when Ulysses was again at low latitudes (see also bottom panel of Fig. 3). The solar wind was relatively quiet at this near-minimum phase of the solar activity cycle. Our value of $\Gamma_{SW} = (3.92\pm0.25)\times10^{-4}$ in the slow wind in 1997 (day $\sim$ 2300 since 1991) is well within the limits of the Geiss *et al.* (1972) average, but outside the error limits of the ratios reported by Bochsler (1984), shown as the box labeled Ref. 2, and especially by Coplan *et al.* (1984), both results obtained with the ICE instrument on ISEE-3. Variability of the $^3He^{++}/^4He^{++}$ ratio in the slow wind has been noted previously (e.g. Geiss *et al.*, 1970; 1972), and recent results (Gloeckler *et al.*, 1997b) indicate unusually high ratios ($\Gamma_{SW} \sim 6\times10^{-3}$) in Coronal Mass Ejections (CMEs) near solar minimum. The time-weighted average of all the slow wind data presented here gives a value for Γ_{SW} of $(4.08\pm0.25)\times10^{-4}$.

In the fast wind of the polar coronal holes (shaded region) we obtained low Γ_{SW} ratios. In four of the six time periods (filled circles) we measured the lowest solar wind Fe/O (i.e. lowest FIP ratio) of the entire Ulysses observation period. The other two time periods, had a distinctly higher FIP (Fe/O) ratio although not nearly as high as in the slow wind. The average $^3\mathrm{He}^{++}/^4\mathrm{He}^{++}$ ratio of the four lowest FIP periods was $(3.16\pm0.25)\times10^{-4}$ and of the six fast wind periods $(3.3\pm0.3)\times10^{-4}$, in reasonable agreement with the lowest value obtained by Bodmer (1996) using SWICS data in the polar holes. Combining our lowest solar wind value with the (model-dependent) upper limit for the photospheric $^3\mathrm{He}/^1\mathrm{H} = 2.3\times10^{-5}$ deduced from gamma-ray spectroscopy of solar flares (Murphy *et al.*, 1997) we obtain a photospheric $^4\mathrm{He}/^1\mathrm{H} = 0.080 \pm 0.006$. This is in remarkable agreement with the definitive helium to hydrogen ratio of 0.084 obtained from helioseismology.

While it is clear that the high-speed coronal hole wind has a lower Γ_{SW} than the in-ecliptic slow wind, the reason for this difference is not obvious. The solar wind $^3\mathrm{He}^{++}/^4\mathrm{He}^{++}$ may decrease with solar activity (the fast wind periods were near solar minimum of the present cycle). The results shown in Fig. 4 also suggest a correlation with Fe/O which is an indicator of strength of the FIP bias of solar wind elemental abundances. Lower values of Γ_{SW} in the fast solar wind are also observed by Bodmer (1996), although the variation with speed is complicated. It is clearly important to study more thoroughly the variabilities in the solar wind helium isotopic ratio and to find the causes for it.

Based on six years of SWICS/Ulysses data, we have established that the $^3\mathrm{He}^{++}/^4\mathrm{He}^{++}$ ratio in the fast wind is definitely lower than the average slow wind ratio. Such a systematic difference was not found in the earlier work based on ICI/ISEE-3 (Coplan *et al.*, 1984; Bochsler, 1984) and SWICS/Ulysses data (Bodmer, 1996). The difference is not entirely unexpected because of basic differences in the acceleration dynamics of the slow wind and the fast streams (cf. Geiss and Gloeckler, 1998). However, the difference is surprisingly high, and this may be due to unrecognized admixtures into slow wind averages of plasma parcels with anomalously high $^3\mathrm{He}^{++}/^4\mathrm{He}^{++}$ ratio as those found by us during days 168–173 or in CME plasmas. Thus, simple averages of $^3\mathrm{He}^{++}/^4\mathrm{He}^{++}$ ratios in the slow wind have to be corrected for such a bias when deriving the OCZ value.

The OCZ value of $^3\mathrm{He}/^4\mathrm{He}$ of $(3.8\pm0.5)\times10^{-4}$ given by Geiss and Gloeckler (1998) is based on the ratio measured in both the slow wind and the fast streams. If at a later time, an improved theoretical understanding of the dynamics in the solar wind source region confirms that helium isotopes are much less fractionated in the fast streams than in the slow wind, the $^3\mathrm{He}^{++}/^4\mathrm{He}^{++}$ ratio in the OCZ could best be derived from the fast wind data alone, and this would lower the OCZ value. For example, if further study confirms that the fast stream plasma with the lowest Fe/O ratio is the most representative of the OCZ, the $^3\mathrm{He}/^4\mathrm{He}$ ratio of $(3.8\pm0.5)\times10^{-4}$ in the OCZ would be lowered by 10 to 15%.

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