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Deuterium and Helium-3 in the Protosolar Cloud

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Abstract. New measurements of the isotopic composition of helium in the solar wind obtained from the Solar Wind Ion Composition Spectrometer (SWICS) on Ulysses are presented and compared with earlier SWICS results and previous mass spectrometric determinations of this ratio with the Apollo Solar Wind Composition (SWC) experiment and the Ion Composition Instrument (ICI) on the International Sun Earth Explorer 3 (ISEE 3). The new SWICS data from both the fast and slow solar wind are extrapolated to the photosphere to obtain a representative value of the present-day ratio of ^{3}He/^{4}He = $(3.75 \pm 0.27) \times 10^{-4}$ in the Outer Convective Zone (OCZ) of the Sun. After corrections of this ratio for secular changes caused by diffusion, mixing and ^{3}He production by incomplete H-burning (Vauclair 1998), we obtain (D + ^{3}He)/H = $(3.6 \pm 0.38) \times 10^{-5}$ for the Protosolar Cloud (PSC). Adopting the Jovian ^{3}He/^{4}He ratio = $(1.66 \pm 0.05) \times 10^{-4}$ measured by the Galileo Probe mass spectrometer (Mahaffy et al. 1998) as representative for the PSC, we obtain $(\mathrm{D/H})_{\mathrm{protosolar}} = (1.94 \pm 0.39) \times 10^{-5}$. Using results of galactic evolution studies (Tosi 1998, 2000) and the D and ^{3}He abundances in the Protosolar Cloud and the Local Interstellar Cloud (Linsky 1998; Gloeckler & Geiss 1998), we estimate $(\mathrm{D/H})_{\mathrm{primordial}} = (2.4 - 4.2) \times 10^{-5}$. This range corresponds to a universal baryon/photon ratio of $(5.9 - 4.2) \times 10^{-10}$.

1. Introduction

At present, primordial abundances of deuterium and helium-3 are deduced from observations and measurements in three samples of cosmic material. (1) The present-day galaxy, (2) the Protosolar Cloud (PSC), and (3) clouds with very low contamination from stellar nucleosynthesis, using metallicity as an indicator. Here, we present estimates for the abundances of D and ^{3}He in the Protosolar Cloud that represents a sample of galactic material with a nucleosynthetic age of approximately 4.6 Gyr. Since D was converted into ^{3}He in the early Sun, the abundance of ^{3}He in the Outer Convective Zone (OCZ) of the Sun corresponds approximately to the abundance of D + ^{3}He in the PSC. We summarize and

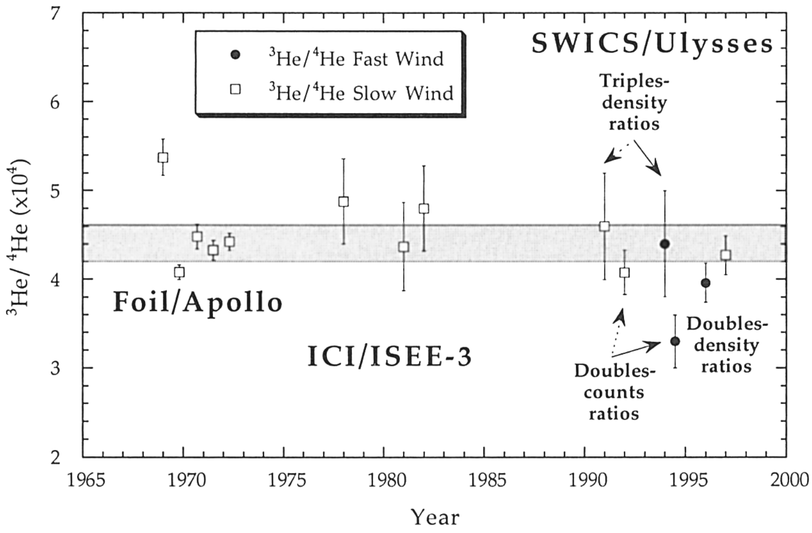

Figure 1. Plot of the average ^{3}He/^{4}He ratio measured with space-borne mass spectrometers (Apollo: Geiss et al. 1970, 1972; ISEE-3: Ogilvie et al. 1980, Coplan et al. 1984, Bochsler 1984; Triples — density ratios: Bodmer et al. 1995; Doubles — counts ratios: Gloeckler & Geiss 1998; Doubles — density ratios: present work) as a function of the approximate time when the measurements were made. Except for some of the recent Ulysses measurements, all observations were made in the in-ecliptic, slow solar wind. The errors bars shown are the result of statistical uncertainties and the real variability of the solar wind ratio during the averaging period.

review the various ^{3}He/^{4}He abundance measurements in the solar wind. Then we obtain an estimate of the ^{3}He/^{4}He ratio in the present-day OCZ by extrapolating our new long-time averages of the ^{3}He/^{4}He ratio in both the slow and fast stream solar wind using a new method. After a discussion of the processes that have changed the He/H and ^{3}He/^{4}He ratios in the OCZ over the lifetime of the Sun, we give our best estimate for (D + ^{3}He)/H in the PSC. The protosolar D/H ratio is then obtained by combining the solar wind ^{3}He/^{4}He data with the recently determined ^{3}He/^{4}He ratio in Jupiter (Mahaffy et al. 1998). Finally, by comparing the D and ^{3}He abundances in the PSC and in the Local Interstellar Cloud (LIC) we discuss constraints on the evolution of these two nuclei in the galaxy and on their primordial abundances.

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

The ^{3}He/^{4}He ratio in the solar wind has been measured by several space-borne instruments. Since the results clearly show that this ratio is not constant, a comprehensive database and at least some understanding of the causes for the changes in ^{3}He/^{4}He is needed for obtaining the best estimate for the ^{3}He/^{4}He ratio in the present-day OCZ. Comprehensive results have been obtained from three investigations: (1) the Apollo Solar Wind Composition (SWC) experiments, using solar wind collection in foils with subsequent analysis by laboratory mass spectrometry, (2) the Ion Composition Instrument (ICI) on the International Sun Earth Explorer 3 (ISEE 3) using an electromagnetic mass spectrometer allowing unambiguous measurement of the mass/charge ratio of the ions, and (3) the Solar Wind Composition Spectrometer (SWICS) on Ulysses, a time-of-flight system giving the mass/charge ratio as well as the mass of the ions. The results obtained with these three techniques are shown in Figure 1.

True variations in the ^{3}He/^{4}He ratio were found by all three experiments. However, for comparable solar wind flows (cf. the averages in the slow wind) the agreement between the results obtained over 25 years by these three completely different techniques is very remarkable. Prior to the Ulysses mission, all ^{3}He/^{4}He data were taken in the ecliptic plane, where the low speed solar wind dominates, although some data were obtained in fast streams and during CME events. The SWC-Apollo foils collected solar wind particles mainly during slow wind conditions. Because of the polar orbit of Ulysses and the large energy range of the SWICS instrument, it became possible for the first time to investigate systematically the helium isotopes in the high speed streams coming out of large coronal holes. Below we present the latest SWICS results based on measurements of the phase-space density distributions of ^{3}He and ^{4}He using the double coincidence technique (see Gloeckler and Geiss 1998). The final results of this analysis for the fast and slow wind are shown in Figure 1 as the two respective ratios labeled 'Doubles-Density Ratios'. It is evident that ^{3}He/^{4}He is lower in the fast streams than it is in the average slow solar wind (shaded region of Figure 1). This is consistent with previous results based on other methods of analysis of the SWICS data.

3. SWICS measurements of the ^{3}He/^{4}He Ratio in the Slow and Fast Solar Wind

For the present analysis we have chosen four 300-day long time periods, the same time periods during which von Steiger et al. (2000) computed average solar wind elemental abundances. In two of the periods we sampled the in-ecliptic, slow wind and in the other two the high-speed wind. The solar wind ^{3}He^{++}/^{4}He^{++} ratios were derived from the phase-space densities of ^{3}He^{++} and ^{4}He^{++}. The ^{3}He^{++} spectra were computed from the SWICS pulse-height (PHA), double-coincidence (i.e. time-of-flight) data (see Gloeckler & Geiss 1998 and Gloeckler et al. 1992 for details). A background correction amounting to less than 6% of the peak ^{3}He^{++} density was made to eliminate the spill-over (mostly at $W <$ ~0.9 and $W > 1.1$) from the many orders of magnitude more abundant solar wind protons and ^{4}He^{++}. The ^{4}He^{++} distributions were derived from the unsaturated triple-coincidence rate MR1 which was then multiplied by the ratio of double-coincidence to triple-coincidence PHA counts selected for ^{4}He^{++}. The spectral shapes of ^{3}He^{++} and ^{4}He^{++} were found to be identical within experimental uncertainties, and the ^{3}He/^{4}He ratio in the fast solar wind (3.83×10^{-4}) was lower than in the slow solar wind (4.34×10^{-4}).

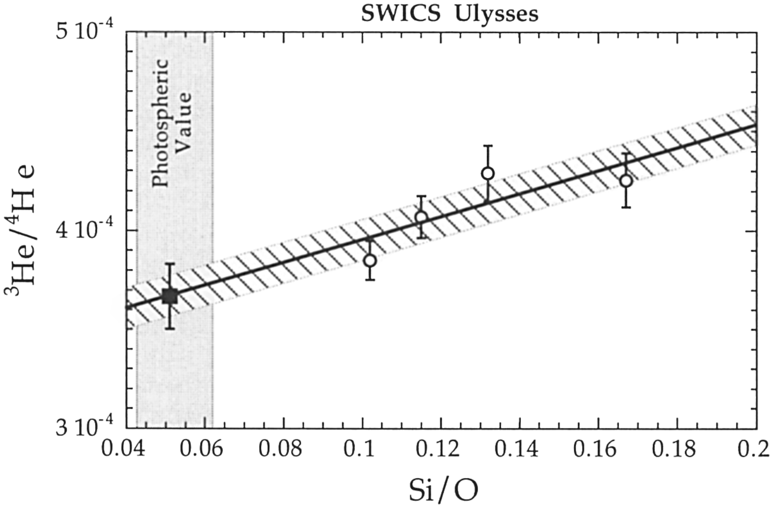

Figure 2. Correlation of the 300-day average ^{3}He/^{4}He and the Si/O ratios measured in the two fast wind and the two slow wind intervals. The Si/O ratios are taken from von Steiger et al. (2000). Using linear regression (solid line) and the photospheric abundance of Si/O (Grevesse & Sauval 1998) we estimate the ^{3}He/^{4}He ratio (solid square) in the OCZ.

4. Derivation of the Present-day ^{3}He/^{4}He Ratio in the Outer Convective Zone

It is now well established that the abundance of elements with low First Ionization Potential (FIP) is higher in the solar wind than in the photosphere of the Sun (e.g. Geiss 1982). This so called 'FIP bias' is found to be smaller in the fast solar wind than in the slow wind (e.g. von Steiger et al. 2000). Furthermore, the solar wind H^+/He^{++} ratio is lower in the fast wind than the slow wind. We use the FIP-dependent compositional bias measured for Si/O, H/He and ^{3}He/^{4}He in the slow and fast solar wind to derive the ^{3}He/^{4}He abundance ratio in the present-day Outer Convective Zone (OCZ) of the Sun. Figure 2 shows the dependence of the average solar wind ^{3}He/^{4}He on the Si/O ratios for the four 300-day intervals. We notice that the two ratios are correlated, and using linear regression and the photospheric value of Si/O we estimate the ^{3}He/^{4}He ratio in the OCZ to be $(3.67 \pm 0.17[\text{stat.} + \text{var.}] \pm 0.20[\text{sys.}]) \times 10^{-4}$. The 1-$\sigma$ errors include statistical and systematic instrumental uncertainties as well as the spread due to solar wind variability.

In Figure 3 we plot the average ^{3}He/^{4}He ratios in the polar coronal hole solar wind (average of the two high-speed wind periods) and the in-ecliptic solar wind (average of the two low-speed wind periods) against the ^{1}H/^{4}He ratios for the corresponding periods. Using a linear extrapolation and the value of 11.9 (Pérez Hernández & Christensen-Dalsgaard 1994) for the OCZ H/He, we obtain an OCZ ^{3}He/^{4}He ratio of $(3.82 \pm 0.14[\text{stat.} + \text{var.}] \pm 0.20[\text{sys.}]) \times 10^{-4}$. The two extrapolation methods give essentially the same result. The average of the two

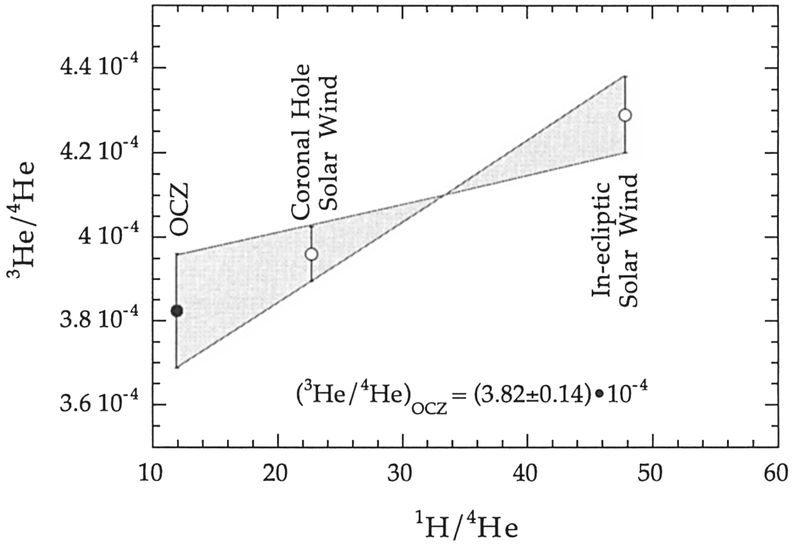

Figure 3. Correlation of the average $^3He/^4He$ and the $^1H/^4He$ ratios measured in the coronal hole wind and the in-ecliptic wind, respectively. The H/He ratios are measured by the SWOOPS instruments on Ulysses (Bame et al. 1992).

values gives $(^3He/^4He)_{OCZ} = (3.75 \pm 0.11[\text{stat.} + \text{var.}] \pm 0.20[\text{sys.}]) \times 10^{-4}$, which is in remarkable agreement with the value $(3.8 \pm 0.5) \times 10^{-4}$ obtained by Geiss & Gloeckler (1998).

5. (D+^{3}He)/H, D/H and ^{3}He/H in the Protosolar Cloud

When material from an interstellar cloud collapsed to form the solar system 4.6 Gy ago, the Sun was largely formed by direct infall (Tscharnuter 1987) implying that the material going into the Sun was representative of the Protosolar Cloud (PSC). In the early Sun, D was converted into ^3He which has not been further processed in the OCZ, as can be surmised from the existence there of beryllium (Geiss & Reeves 1972). Thus, the $^3He/^4He$ ratio in the OCZ basically represents the protosolar $(D + {^3He})/H$ ratio. There are, however, two processes that could have changed the $^3He/^4He$ ratio in the OCZ during the lifetime of the Sun.

Solar seismic data and solar models show that He/H in the OCZ is 16% lower than it was in the PSC (e.g. Bahcall & Pinsonneault 1995). The difference is interpreted as being due to settling of helium out of the OCZ into deeper layers of the Sun. ^3He settles more slowly than ^4He resulting in an increase in the present-day OCZ $^3He/^4He$ ratio of a few percent (Gautier & Morel 1997).

The second possible change of $(^3He/^4He)_{OCZ}$ over solar history is due to solar mixing. Using mixing models to various solar depths, Vauclair (1998) has shown that in order to deplete lithium by two orders of magnitude, as is required, some p-p-produced ^{3}He will be added to the OCZ, possibly increasing ^{3}He /^{4}He there by several percent.

A record of solar wind irradiation on the lunar surface goes back to about 4 Gy. While in most lunar materials, the ^{3}He/^{4}He ratio of the old solar wind samples has been affected by strong diffusive losses of helium, the loss is least severe in ilmenite. Using an on-line etching technique applied to this mineral, Wieler et al. (1992) have deduced that the change in the solar wind ^{3}He/^{4}He ratio over the last 3 Gy was less than 10 percent. Since the peak of ^{3}He increases over solar history and moves slowly outward, we expect a large fraction of the contamination of the OCZ with ^{3}He from incomplete H-burning to have occurred during the last 3 billion years of solar history. Thus settling of helium out of the OCZ and solar mixing could not have increased the ^{3}He/^{4}He ratio in the OCZ by much more than 10%. We thus adopt a correction of $-(4 \pm 2)\%$ and apply this to the ^{3}He/^{4}He ratio in the present-day OCZ to obtain $[(\mathrm{D} + {}^3\mathrm{He})/\mathrm{H}]_{\mathrm{PSC}} = (3.6 \pm 0.38) \times 10^{-4}$.

The solar wind data give only the protosolar abundance of the sum of D and ^{3}He. We use the Jovian value of $^3\mathrm{He}/^4\mathrm{He} = (1.66 \pm 0.05) \times 10^{-4}$, determined by the mass spectrometer on the Galileo Probe (Mahaffy et al. 1998), and $(\mathrm{He/H})_{\mathrm{PSC}} = 0.10$ (Bahcall & Pinsonneault 1995) to obtain the Protosolar value of $(\mathrm{D/H})_{\mathrm{PSC}} = (1.94 \pm 0.39) \times 10^{-5}$. The error limits are 1-σ uncertainties. They include statistical and systematic (instrumental) errors, broadening due to solar wind variability, uncertainties in the correction for chromospheric and coronal effects on the solar wind composition, and the uncertainty resulting from helium settling and admixture of p-p produced ^{3}He to the OCZ. We have not included an error for a possible difference between the ^{3}He/^{4}He ratio in Jupiter's atmosphere and in the PSC. We note, however, that a small decrease (probably less than 10%) in ^{3}He/^{4}He by gravitational escape from the protoplanetary disc or the Jovian sub-nebula cannot be excluded.

The method of deriving the protosolar D abundance from the ^{3}He/^{4}He ratio in the solar wind has been used for over 25 years (Geiss & Reeves 1972: $(\mathrm{D/H})_{\mathrm{PSC}} = (2.5 \pm 1.0) \times 10^{-5}$; Reeves et al. 1973: $(2.6 \pm 1.0) \times 10^{-5}$). As additional solar wind data, new estimates of He/H in the OCZ and PSC, better data for the protosolar ^{3}He/^{4}He ratio, and revised assumptions or model results on solar mixing and fractionation processes in the solar atmosphere became available, several authors have used this method as well as remote and in situ measurements of the Jovian atmosphere (e.g. see Mahaffy et al. (1998) for a summary of in situ and spectroscopic measurement techniques) for deriving $(\mathrm{D/H})_{\mathrm{PSC}}$. The more recent results (since 1985) are summarized in Figure 4 along with the present determination of $(\mathrm{D/H})_{\mathrm{PSC}}$. The average of the four data points after 1997 gives $(\mathrm{D/H})_{\mathrm{PSC}} = (2.11 \pm 0.18) \times 10^{-5}$. The errors are standard errors of the average values. It is interesting to note that both averages, lie within the error bars given in 1972 and 1993, indicating the robustness of the solar wind method to derive the protosolar D/H ratio.

6. Implications for Galactic Evolution and Cosmology

With the Protosolar Cloud and the Local Interstellar Cloud (LIC) we have two galactic samples, differing in nucleosynthetic age by 4.6 Gy, for which we have

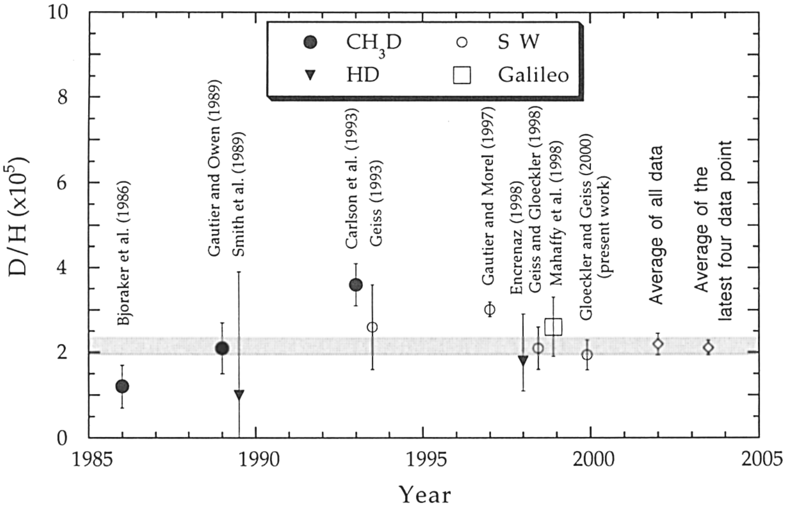

Figure 4. Measurements or estimates of the protosolar D/H ratio as a function of the approximate time when the measurements were made or reported. D/H ratios based on solar wind ${}^3He/{}^4He$ are indicated by open circles. The in situ mass spectrometric measurement with the Galileo Probe (Mahaffy et al. 1998) is shown as the open square. Spectroscopic determinations of D/H derived from CH_3D and HD measurements in Jupiter's atmosphere are shown as solid circles and solid triangles respectively.

reliable data on the isotopic abundances of both hydrogen and helium. D/H in the LIC (Linsky 1998) is lower than it was in the PSC while ${}^3He/{}^4He$ in the LIC (Gloeckler & Geiss 1998) is higher than it was in the PSC. The direction of these changes is as expected. Because D is destroyed but not produced by stars, the D/H ratio in the galactic interstellar medium ought to decrease continuously with time. ${}^3He$, on the other hand, is both destroyed and produced by stars. The observed increase in ${}^3He$ from the PSC to the LIC value is mainly due to p-p production in small stars (cf. Tosi 1998) that began to leave the main sequence and to lose material only relatively late in galactic history.

The LIC is of course not a direct descendent of the PSC. However, since (a) we have good D and ${}^3He$ abundance data for both, (b) they evolved at roughly the same distance from the galactic center and (c) their age difference is not small, but $>$ 30% of the age of the universe, a comparison of the two clouds provides us with unique information on galactic evolution. The PSC is the sample with the best defined nucleosynthetic status. Our knowledge on elemental and isotopic abundances in the LIC is still scarce, but will be growing, thanks to refined spectroscopic methods, and to direct measurements on interstellar grains and gas components that pass through the heliosphere. At the present time, the data do not allow a determination of the difference in the He/H ratio or in metallicity between LIC and PSC.

In Figure 5 we plot the abundance ratios as a function of nucleosynthetic age, with the age of the universe taken as ~14 Gy. (cf. Tammann 1998). The

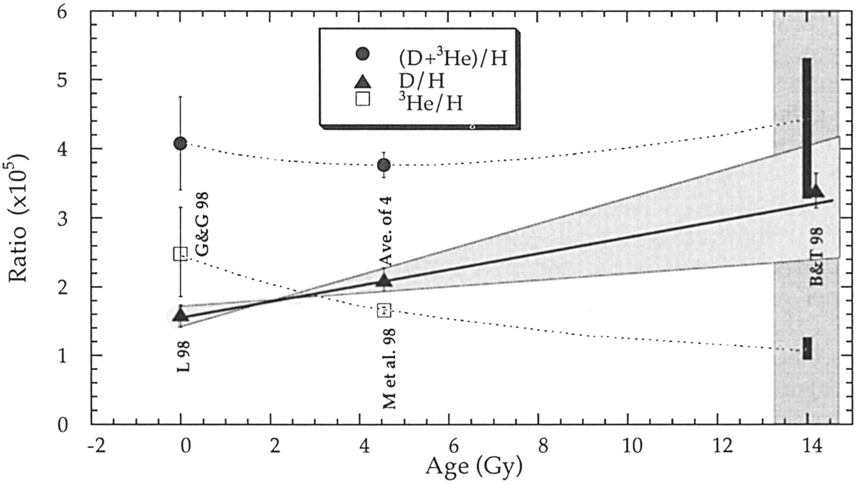

Figure 5. Illustration of the evolution of D and ^{3}He in the "solar ring" of the galaxy. The measured H/D and ^{3}He/^{4}He ratios for the Local Interstellar Cloud (LIC) at age 0 are from Linsky (1998) and Gloeckler & Geiss (1998), those for the Protosolar Cloud (PSC) at age 4.6 Gyr are from this work and from Mahaffy et al. (1998). The shaded region between the lines through the 1-σ limits of the LIC and PSC D/H ratios indicates a range of primordial D/H at 14 Gyr. From the range of primordial deuterium (D/H ~(2.4−4.2) × 10^{-5}) given here, the theory of Standard Big Bang Nucleosynthesis (Walker et al. 1991) allows the determination of the ranges for primordial abundance ratios of (D+^{3}He)/H and ^{3}He/H shown as the vertical solid bars, respectively, from the PSC data. The dotted curves are drawn through the mean values of the (D+^{3}He)/H and ^{3}He/H ratios.

$(D/H)_{LIC}$ is from Linsky (1998) and the $(D/H)_{PSC}$ is the average of the latest four measurements from Figure 4. Since interstellar deuterium is destroyed and not produced by stars and since production of D by cosmic rays is minor, the line going through the lower 1-σ limit of $(D/H)_{PSC}$ and the upper 1-σ limit of $(D/H)_{LIC}$ gives the lower limit of primordial D/H ($\sim 2.3 \times 10^{-5}$). The other line going through the upper 1-σ limit of $(D/H)_{PSC}$ and the lower 1-σ limit of $(D/H)_{LIC}$ gives an approximate upper limit of primordial D/H of $\sim 4 \times 10^{-5}$. Predictions of galactic evolution models (Tosi 1998; Tosi 2000, and references therein) fall well within the range of the two lines (shaded region). We note that the D/H = 3.4 ± 0.25) × 10^{-5} obtained in high-z clouds by Burles and Tytler (1998) is consistent with this range of primordial D/H ratios. Higher values are difficult to reconcile with the D/H and ^{3}He/^{4}He abundance ratios measured in the solar ring of the galaxy.

Galactic evolution models (Tosi 1998) show that the slopes of the D/H and ^{3}He/H curves given in Figure 5 can only be reproduced if an infall into the galactic disc of relatively unprocessed material is postulated. Tosi et al. (1998) give an infall rate for the solar ring of 4×10^{-9} M_{Sun} pc^{-2} yr^{-1}. A radial motion of the Sun by a few kpc during its lifetime would not affect the infall rate very much, as the radial evolution calculations of D/H by Tosi et al. (1998) indicate. Comparison of the infall rate given above with the gas density in the solar ring of the galactic disc of 6 $M_{\rm Sun}$ $\rm pc^{-2}$ lead to a replenishment time of 1.5×10^9 yr. This implies that most of the gas presently in the solar ring of the disc had not yet been accreted into the galaxy at the time of birth of the solar system.

Probably, gas does not fall into the galaxy just as a steady drizzle. Observations of high velocity clouds approaching the galaxy (de Boer & Savage 1983) indicated significant variations of the infall rate in space and time. Accretion of dwarf galaxies into our galaxy may contribute significantly, as the observations of the Sagittarius dwarf galaxy indicate. Thus, spatial variations in D/H and in metallicity are produced by inhomogenous infall as well as inhomogenous nucleosynthesis.

Recent microlensing observations indicate that gravitational wells produced by spiral galaxies have dimensions of up to several hundred kpc (Fischer et al. 2000). If this result is applicable to our galaxy, this would certainly very much influence the dynamics of infall, and it would make a difference whether the gravitational well is mainly produced by dispersed baryonic matter or by non-baryonic matter. Measurement of metallicities and deuterium abundances and their variations could help to understand the dynamics of infall and the evolution of our galaxy.

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