Light Elements in the Universe
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Abundances of hydrogen and helium isotopes in the Protosolar Cloud

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Abstract. For our understanding of the origin and evolution of baryonic matter in the Universe, the Protosolar Cloud (PSC) is of unique importance in two ways: 1) Up to now, many of the naturally occurring nuclides have only been detected in the solar system. 2) Since the time of solar system formation, the Sun and planets have been virtually isolated from the galactic nuclear evolution, and thus the PSC is a galactic sample with a degree of evolution intermediate between the Big Bang and the present.

The abundances of the isotopes of hydrogen and helium in the Protosolar Cloud are primarily derived from composition measurements in the solar wind, the Jovian atmosphere and "planetary noble gases" in meteorites, and also from observations of density profiles inside the Sun. After applying the changes in isotopic and elemental composition resulting from processes in the solar wind, the Sun and Jupiter, PSC abundances of the four lightest stable nuclides are given.

Keywords. Sun: solar wind, corona, abundances

1. Introduction

Our concepts of nucleosynthesis were originally derived from solar system abundances, and even to this day, our knowledge of the production of most stable and long-lived nuclei is based on elemental and isotopic composition measurements in solar system material. Without isotopic abundances in meteorites and terrestrial samples, could we clearly distinguish the s- and r-processes, recognize the p-nuclei or establish a nuclear chronology for the Galaxy? For most nuclear species, Galactic evolution models are really models for the evolution of the matter that made up the PSC some 4.6 Gyr ago. Extensions to the present for most nuclei would be mere extrapolations, if we had not reliable Galactic *and* solar system data for several elements and a few isotopic ratios. Among these are, most importantly, the isotopes of hydrogen and helium. Composition measurements in the solar wind, the Jovian atmosphere and to a lesser extend - the "planetary gas" in meteorites provide the main evidence from which the protosolar abundances of these nuclides are derived (Table 1).

2. Protosolar (D+^{3}He)/H derived from ^{3}He/^{4}He in the solar wind

In the early Sun, deuterium was converted into ^{3}He by the reaction

$$D + H = {}^3He + \gamma. \tag{2.1}$$

The short D-burning phase, involving the whole Sun, preceded the H-burning epoch (Ezer & Cameron, 1965; Mazzitelli & Moretti, 1980). In the material of the Outer Convective Zone (OCZ) of the present Sun, ^{3}He has not been further processed, as can be surmised

Table 1. Measurements primarily used in this paper for deriving Solar and Protosolar Abundances.

SOLAR WIND $^3He/^4He$ measurements with SWICS/Ulysses, SWC/Apollo, old solar wind in lunar material → Extrapolation to $^3He/^4He$ in the OCZ (Outer Convective Zone of the Sun) →Protosolar (D + ^3He)/H → Protosolar D/H
METEORITES $^3He/^4He$ measurement in the "Planetary Gas" Component of Meteorites → Protosolar $^3He/^4He$
SUN Density Profile from SOHO Seismology → Protosolar He/H
JUPITER $^3He/^4He$, He/H measurement with Galileo Entry-Probe D/H measurement with ISO → Protosolar D/H, $^3He/^4He$, (D + ^3He)/H

from the abundance there of beryllium (Geiss & Reeves, 1972). At any temperature ^9Be is destroyed much faster by thermonuclear reactions than ^3He (Figure 1). Thus, ^3He in the OCZ represents not only protosolar ^3He, but the sum of protosolar D and ^3He (see Geiss, Eberhardt & Signer, 1966).

Systematic investigations of $^3He/^4He$ in the solar wind have been carried out using various space experiments: SWC/Apollo, ICI/ISEE-3, SWICS/Ulysses, SWICS/ACE and recently Genesis. The results have revealed significant variations in solar wind composition. Theoretical studies have shown that the variations are caused by separation

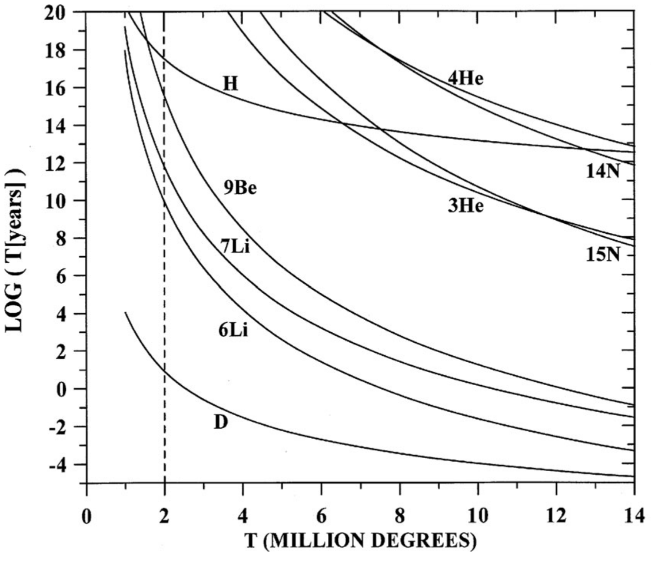

Figure 1. Life-time of light nuclides as a function of temperature. Given are the life-times due to thermonuclear reactions with density and composition normalized to the present conditions at the bottom of the Outer Convective Zone (OCZ) of the Sun. The dashed line marks the present temperature at the bottom of the OCZ. Note: D-burning proceeds well before H-burning commences due to the temperature difference at which the two hydrogen isotopes are fusing (Ezer & Cameron,1965; Mazzitelli & Moretti, 1980). ^9Be is destroyed much faster than ^3He at all temperatures that could have occurred during the life of the Sun. Thus the presence of Beryllium (^9Be) in the OCZ at protosolar abundance precludes the loss there of ^3He by nuclear reactions (Geiss & Reeves, 1972).

Table 2. **Protosolar (D+^{3}He)/^{4}He from ^{3}He/^{4}He in the solar wind.**

Solar Wind (SWICS/Ulysses)	^{3}He/^{4}He	Figure 1
Solar Wind (SWC/Apollo)	^{3}He/^{4}He	Figure 1
Sun, Outer Convective Zone	^{3}He/^{4}He	$(3.83 \pm 0.25) \times 10^{-4}$
Protosolar Cloud	**(D + ^{3}He)/^{4}He**	$\mathbf{(3.68 \pm 0.25) \times 10^{-4}}$

processes in the corona (Geiss, Hirt & Leutwyler, 1970; Bürgi & Geiss, 1986; Isenberg & Hollweg, 1983) as well as ion-neutral separation processes in or near the chromosphere (Geiss, 1982; von Steiger & Geiss, 1989). Several physical processes were identified that cause or control charging, separation and transport of major and minor ion species from the chromosphere to the corona and into the supersonic solar wind. Their varying influence produces the observed variations in space and time. Theory alone cannot exactly predict the changes in composition caused by different solar and solar wind conditions, but theory can predict which pairs of ion species should causally correlate and could be used to obtain OCZ abundances from solar wind data by extrapolation.

So far empirical extrapolations from abundances in the slow solar wind and the high-speed streams coming out of the polar coronal holes give the best results. We follow here the method introduced by Gloeckler & Geiss (2000). Figures 2a and 2b show, respectively, the correlations of ^{3}He/^{4}He with Si/O and with H/He measured by SWICS/Ulysses in several periods each of in-ecliptic solar wind and high speed streams. Extrapolating by linear regression to Si/O observed in the photosphere and to H/He = 11.9 determined for the OCZ (Pérez Hernández & Christensen-Dalsgaard, 1994) gives $(^3\text{He}/^4\text{He})_{\text{OCZ}} = (3.78 \pm 0.18) \times 10^{-4}$ and $(^3\text{He}/^4\text{He})_{\text{OCZ}} = (3.88 \pm 0.14) \times 10^{-4}$ respectively (Figure 2). The 1-σ errors include statistical uncertainties as well as the spread due to solar wind variability. The systematic instrumental uncertainties are estimated to be 0.2×10^{-4} (Gloeckler & Geiss, 2000). The two extrapolation methods give essentially the same result, leading to an average of $(^3\text{He}/^4\text{He})_{\text{OCZ}} = (3.83 \pm 0.25) \times 10^{-4}$ (Table 2), which is in remarkable agreement with earlier values of $(^3\text{He}/^4\text{He})_{\text{OCZ}}$ obtained by other methods (see Geiss & Gloeckler, 1998).

During the in-ecliptic periods, steady low-speed solar wind prevailed, free of CME events. Winds related to CMEs would compromise the correlation between ^{3}He/^{4}He and H/He, because they combine low H/He ratios with relatively high ^{3}He/^{4}He ratios, i.e. opposite to the correlation in Figure 2b.

We have plotted in Figure 2 also the average ^{3}He/^{4}He ratio of the SWC/Apollo experiments that collected the solar wind during five periods in 1969-1972 (Geiss et al., 2004, see also Geiss *et al.* 1970). These were slow wind periods (320-510 km/s), and there are no indications of a CME influence. The H/He and Si/O ratios for the SWC exposure periods are estimates. Solar wind composition data were rudimentary during the Apollo epoch (1969-1972). Thus the corresponding estimates of H/He and Si/O are crude by necessity.

Recently Heber *et al.* (2009) published precise isotopic abundances of noble gases including the ^{3}He/^{4}He ratio obtained from the DOS Genesis target. The Genesis value is 9 % higher then the SWC/Apollo average i.e. well within the known variability of in-ecliptic ^{3}He/^{4}He ratios. The collection period of the DOS target lasted 2.3 years and included slow solar wind, high speed streams and some CME events. Therefore, their results are not directly applicable to our extrapolation method.

The ^{3}He/^{4}He value derived from the extrapolations shown in Figure 2 refers to the present-day OCZ. Two processes, however, could have changed this ratio during the life of the Sun.

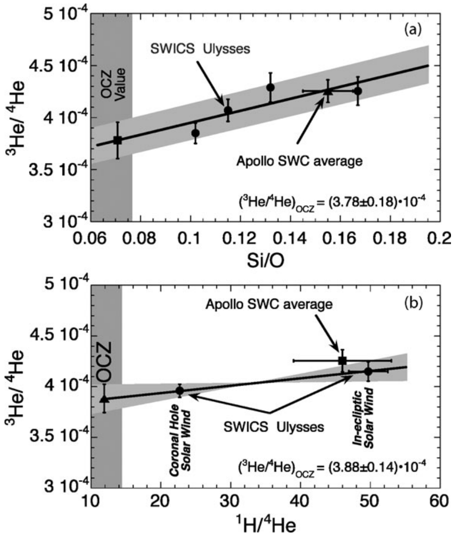

Figure 2. ^{3}He/^{4}He versus Si/O (2a) and ^{1}H/^{4}He (2b)) measured in the Solar Wind with SWICS/Ulysses and extrapolated to the corresponding values in the Outer Convective Zone (OCZ) of the Sun (adapted from Gloeckler & Geiss, 2000). The OCZ value for H/He was given by Pérez Hernández & Christensen-Dalsgaard (1994), the Si/O value by Grevesse & Sauval (1998). Combining these methods of extrapolation gives ^{3}He/^{4}He $= (3.83 \pm 0.25) \times 10^{-4}$ for the OCZ (Table 2). The ^{3}He/^{4}He ratio measured in 1969-1972 with Apollo SWC is identical to the "in-ecliptic" ^{3}He/^{4}He ratio measured with SWICS/Ulysses during quiet slow solar wind conditions.

Solar models show that He/H in the OCZ is 16% lower than it was in the PSC (e.g. Bahcall, Pinsonneault & Wasserburg, 1995). The difference is interpreted as being due to settling of helium out of the OCZ into deeper layers of the Sun. ^{3}He settles more slowly than ^{4}He, resulting in an increase in the present-day $(^3\mathrm{He}/^4\mathrm{He})_{\mathrm{OCZ}}$ ratio of 2 to 3% (Gautier & Morel, 1997).

The second possible change of $(^3\mathrm{He}/^4\mathrm{He})_{\mathrm{OCZ}}$ over solar history is due to solar mixing. During the lifetime of the Sun, the pp-reaction produces additional ^{3}He outside the solar core at intermediate depth in the Sun (Figure 3). H-burning at low temperature is controlled by the weak interaction reaction

$$^1\mathrm{H} + {}^1\mathrm{H} \rightarrow {}^2\mathrm{H} + e^+ + \nu. \tag{2.2}$$

Deuterium (D or ^{2}H) is immediately converted into ^{3}He (Eq. 2.1). Further fusion of ^{3}He becomes effective only at substantially higher temperature (see Figure 1).

A significant increase of ^{3}He in the OCZ could have been caused by mixing of pp-produced ^{3}He into the OCZ. Theoretical studies show this increase to be small, dependent on solar models and solar rotation (Vauclair, 1998; Turck-Chièze *et al.*, 2001). Recent changes in solar abundances imply changes in opacity. Whether this has a significant effect on solar mixing is under investigation.

Addition of pp-produced ^{3}He to the OCZ has also been investigated by comparing solar wind helium trapped in very old and more recent lunar surface material. Using this method, Wieler & Heber (2003) concluded, that the increase of ^{3}He/^{4}He in the OCZ by solar mixing is at most 5%. Combining the two effects, settling of helium out of the OCZ

Table 3. Protosolar ^{3}He/^{4}He from ^{3}He/^{4}He in Jupiter and the Meteoritic "Planetary Gas".

	^{3}He/^{4}He $\times 10^{-4}$
Planetary Component in Meteorites[1,2]	$\sim 1.5 \pm 0.2$
Q-Phase of Carbonaceous Chrondite Isna[3]	1.23 ± 0.02
Jupiter Entry-Probe[4]	1.66 ± 0.06
Protosolar Cloud[5]	$\mathbf{1.66^{+0.06}_{-0.10}}$

Notes: [1] Eberhardt (1974); [2] Frick & Moniot (1977); [3] Busemann, Baur & Wieler (2000); [4] Mahaffy *et al.* (1998); [5] see text.

and solar mixing, we thus adopt a correction of $-(4 \pm 2)\%$ for $(^3\mathrm{He}/^4\mathrm{He})_{\mathrm{OCZ}}$ and obtain $[(\mathrm{D} + ^3\mathrm{He})/^4\mathrm{He}]_{\mathrm{PSC}} = (3.68 \pm 0.25) \times 10^{-4}$ (Table 2).

3. Protosolar ^{3}He/^{4}He

Before data of the Galileo Entry Probe were available, the ^{3}He/^{4}He ratio in the "planetary gas" of meteorites (e.g. Eberhardt, 1974; Frick and Moniot, 1977) served as a proxy for the isotopic abundance of helium in the PSC. More recently, it was realized that this planetary component is a mixture of components differing somewhat in composition. In Table 3 we have included the ^{3}He/^{4}He ratio in the "Q-phase" of the carbonaceous chondrite Isna (e.g., Busemann *et al.*, 2000). The situation changed when the ^{3}He/^{4}He ratio in the Jovian atmosphere was measured by the Galileo Probe Mass Spectrometer (GPMS), (see Niemann *et al.*, 1996). The ratio of $(1.66 \pm 0.06) \times 10^{-4}$ obtained by Mahaffy *et al.* (1998) given in Table 3 is presently considered to be the best value for estimating the protosolar value.

In the atmosphere of Jupiter helium is depleted by $\sim$ 18% relative to the protosolar cloud (von Zahn, Hunten & Lehmacher, 1998). The degree, of helium depletion in the OCZ of the Sun is similar, but the causes could be quite different: diffusive separation in the case of the Sun, and probably descent of helium-rich droplets in the case of Jupiter (Stevenson & Salpeter, 1976; von Zahn, Hunten & Lehmacher, 1998). If the droplet hypothesis is correct, the Jovian process should fractionate isotopes much less than the solar process, and ^{3}He/^{4}He fractionation in the Jovian atmosphere would be less than the $\sim$2% fractionation that has occurred in the OCZ of the Sun (Gautier & Morel, 1997; Vauclair, 1998). Thus, we adopt here the Jovian ^{3}He/^{4}He ratio obtained by Mahaffy *et al.* (1998) as the protosolar value, giving it, however, an asymmetric error.

The ^{3}He/^{4}He ratios in the "planetary gas" of meteorites are typically lower by (10-20)% than the Jovian ratio (Table 3). If ^{3}He/^{4}He in the Jovian atmosphere is identical to the OCZ value, a depletion of ^{3}He/^{4}He by (10-20)% in the planetary component in meteorites is certainly not high, considering the large mass difference of the two helium isotopes (cf. Geiss & Gloeckler, 2003).

4. Protosolar deuterium abundance

The deuterium abundance in the PSC has been derived in two ways: One method is based on a direct deuterium abundance measurement in Jupiter, either by remote spectroscopy (e.g. Beer & Taylor, 1973; Drossart *et al.*, 1982; Encrenaz *et al.*, 1996; Lellouch *et al.*, 2001) or by in-situ mass spectrometry (Niemann *et al.*, 1996; Mahaffy *et al.*, 1998). The values obtained by infrared spectroscopy have been given lower errors than those obtained by the Galileo Probe Mass Spectrometer (cf. Table 4). Lellouch

Table 4. Protosolar D/H from D/H in the Jovian Atmosphere.

	D/H $\times 10^{-5}$
Galileo Probe 1	2.6 ± 0.7
ISO 2	
H2	2.4 ± 0.4
CH4	2.2 ± 0.7
H2, CH4 Combined	2.25 ± 0.35
Corrected for D-Excess in Ice-Phase	2.1 ± 0.4
Protosolar D/H from Jovian D/H Data	$\mathbf{2.1 \pm 0.4}$

et al. (2001) measured D/H = $(2.40 \pm 0.4) \times 10^{-5}$ in molecular hydrogen and D/H = $(2.2 \pm 0.7) \times 10^{-5}$ in methane. Recently, Bézard (2002) obtained a D/H ratio in the methane below $< 2 \times 10^{-5}$. We adopt here the results of Lellouch *et al.* (2001) who combined their two determinations and obtained D/H = $(2.25 \pm 0.35) \times 10^{-5}$ as representative for Jupiter.

For the other method, the relation

$$(\mathrm{D/H})_{\mathrm{Protosolar}} = \{[(\mathrm{D} + {}^3\mathrm{He})/{}^4\mathrm{He}]_{\mathrm{Protosolar}} - ({}^3\mathrm{He}/{}^4\mathrm{He})_{\mathrm{Protosolar}}\} \times (\mathrm{He/H})_{\mathrm{Protosolar}} \tag{4.1}$$

is used. With protosolar $(\mathrm{D} + {}^3\mathrm{He})/{}^4\mathrm{He} = (3.68 \pm 0.25) \times 10^{-5}$, protosolar ${}^3\mathrm{He}/{}^4\mathrm{He} = (1.66^{+0.06}_{-0.10}) \times 10^{-4}$ (cf. Table 3) and protosolar H/He = 10.28 (Bahcall, Pinsonneault & Wasserburg (1995)) we obtain $(\mathrm{D/H})_{\mathrm{Protosolar}} = (1.97 \pm 0.3) \times 10^{-5}$ (Table 5).

Jupiters D/H ratio is probably enriched above the protosolar value by the admixture of deuterium-rich ices to the nebular gas during the planets formation (cf. Owen, 2003). According to Guillot (1999) the enrichment is about (5-10)%. Lellouch *et al.* (2001) have corrected their ISO value for this effect and obtain $(\mathrm{D/H})_{\mathrm{Protosolar}} = (2.1 \pm 0.4) \times 10^{-5}$. The agreement between the D/H ratio determined using the solar wind value and that based on Jupiter measurements is excellent. We adopt $(2.0 \pm 0.3) \times 10^{-5}$ as the protosolar D/H ratio (Table 5).

5. Remarks and Conclusions

The protosolar abundances of hydrogen and helium isotopes are summarized in Table 5. We give "recommended abundances" whenever there are two independent values for the same abundance ratio. Our results are not very different from those in our earlier publications (Gloeckler & Geiss, 2000; Geiss & Gloeckler, 2003).

Deriving OCZ abundances from solar wind measurements could be improved, if data from experiments with different capabilities can be sensibly combined. Using Figure 2b, we present here an example. The SWC/Apollo ${}^3\mathrm{He}/{}^4\mathrm{He}$ ratio is 2.9% above the SWICS/Ulysses correlation line. There are two extremes we could consider: (1) Assuming that the 2.9% difference is due to a systematic error of the ${}^3\mathrm{He}/{}^4\mathrm{He}$ ratios determined with SWICS Ulysses and the difference of 2.9% was the same for all solar wind conditions covered in Figure 2b, the Apollo data would extrapolate to $({}^3\mathrm{He}/{}^4\mathrm{He})_{\mathrm{OCZ}} = 3.99 \times 10^{-4}$. This value lies well within the systematic error limit assumed for the $({}^3\mathrm{He}/{}^4\mathrm{He})_{\mathrm{OCZ}}$ ratio in Table 2. (2) As Figure 2a suggests, we assume that there are no systematic deviations between the ${}^3\mathrm{He}/{}^4\mathrm{He}$ values measured by the two instruments. In this case we correlate the SWC/Apollo slow wind data point with the high speed data point measured by SWICS/Ulysses and obtain $({}^3\mathrm{He}/{}^4\mathrm{He})_{\mathrm{OCZ}} = 3.83 \times 10^{-4}$, about 1.3 % below the value given in Table 2. These examples demonstrate the potential of combining the composition data of two experiments.

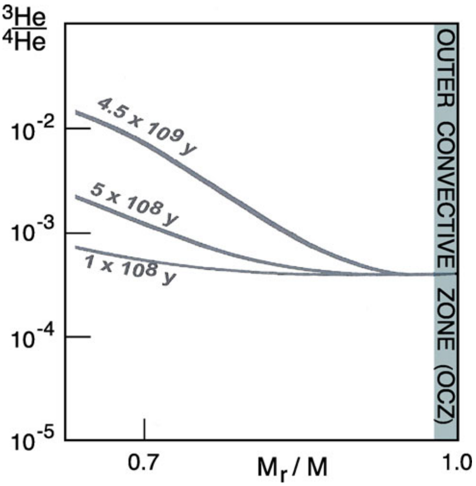

Figure 3. The secular buildup of ^{3}He at intermediate depth in the Sun as a function of M_r, (where M_r is the mass radius), calculated for a non-mixing Sun (Bochsler & Geiss, 1973) The buildup does not get close to the OCZ, but thorough experimental and theoretical investigations are needed to exclude contamination by ^{3}He produced at intermediate depth of the Sun.

Table 5. Protosolar Abundances.

From Solar Wind (SW) Data	$[(D+^3He)/H]_{Protosolar}$	$(3.58 \pm 0.25) \times 10^{-5}$
From Jupiter Data	$[(D+^3He)/H]_{Protosolar}$	$(3.72 \pm 0.42) \times 10^{-5}$
Recommended	$\mathbf{[(D+^3He)/H]_{Protosolar}}$	$\mathbf{(3.65 \pm 0.30) \times 10^{-5}}$
From Jupiter Data	$\mathbf{[^3He/H]_{Protosolar}}$	$\mathbf{(1.66^{+0.06}_{-0.10}) \times 10^{-4}}$
From Jupiter D/H	$[D/H]_{Protosolar}$	$(2.1 \pm 0.4) \times 10^{-5}$
From $(^3He/^4He)_{SW}$ and $(^3He/^4He)_{Jup}$	$[D/H]_{Protosolar}$	$(1.97 \pm 0.3) \times 10^{-5}$
Recommended	$\mathbf{[D/H]_{Protosolar}}$	$\mathbf{(2.0 \pm 0.3) \times 10^{-5}}$

Presently, the uncertainties in the protosolar abundances are not so much due to measurement errors, but they result mainly from uncertainties in the transformation of solar wind or Jupiter data to protosolar values.

The systematic difference in H/He between OCZ and high-speed streams is caused mainly by ion-atom separation in or near the chromosphere (Geiss, 1982). Therefore, models applicable to corona ion fractionation cannot be applied to extend the (^{3}He/^{4}He) versus H/He correlation from the high-speed wind data to the OCZ abundance. Theories for ion-atom separation depending on photo-ionization time predict only very minor fractionation for ^{3}He/^{4}He (von Steiger & Geiss, 1989). Since the difference between ^{3}He/^{4}He in the High-Speed Streams and the OCZ is only 2% (see Figure 2), the error introduced by the extrapolation ought to be small.

The contamination of the OCZ with pp-produced ^{3}He from below is one of the more serious uncertainties, but what could be done about this problem? The ^{9}Be abundance gives us a solid argument against loss of ^{3}He in the OCZ due to nuclear reactions. There is no comparable argument against a raise of ^{3}He/^{4}He in the OCZ by admixture of pp-produced ^{3}He. It is the other way around: a raise in time of ^{3}He in the OCZ or the solar wind is the most sensitive indicator for admixture of material to the OCZ from below, as was recognized long ago (Schatzman, Maeder, Angrand & Glowinski, 1981). Only by further theoretical studies and analyses of solar wind particles trapped in ancient dust and breccias could we further reduce the uncertainty of the protosolar (D+^{3}He)/H ratio.

If we accept ^{3}He/^{4}He $= 1.66 \times 10^{-4}$ as measured in the Jovian atmosphere by Mahaffy *et al.* (1998) as the protosolar value, then ^{3}He/^{4}He in the "planetary gas" of meteorites would have been reduced by 10%. This seems to be a small reduction, considering that in the "planetary gas" ^{20}Ne/^{22}Ne is reduced relative to the solar abundance by (25-30)% (Geiss *et al.* 2004) and ^{36}Ar/^{38}Ar by 2% (Heber *et al.*, 2009).

Considering that the age of the Sun is about 35% of the age of the Galaxy, the chemical evolution during this 35% time interval is small, and for many nuclear species, evolution in time disappears in the noise of local differences. The levelling of evolution is attributed to infall (Tosi, 1998), but there is no consensus on the nature of this infall. Studying the evolution of dwarf galaxies should help to clarify this point.

The principal effect of stellar processing is the conversion of D into ^{3}He with the sum (D + ^{3}He) remaining nearly constant (e.g. Geiss & Gloeckler, 2003). This was recognized when ^{3}He and D were determined in both the Protosolar Cloud and the Local Interstellar Cloud (Gloeckler & Geiss, 1996; Linsky, 1998). At the same time, theoretical studies showed (Charbonnel, 1998; Tosi, 1998) that ^{3}He from incomplete hydrogen burning could not have a large effect on the chemical evolution in the Galaxy. Since then, progress in understanding late Galactic evolution has slowed. Determining abundances of a larger number of nuclides in one and the same Galactic sample could correct this impasse better than further collecting scattered composition data. This could be accomplished with a mission similar to Ulysses but with the primary objective of measuring the composition of the Local Interstellar Cloud by determining abundances of elements and isotopes in the gas and dust that is entering the heliosphere. A study to identify the nuclear species in the Local Interstellar Cloud that could be determined in this way would be most worthwhile. Advanced solar wind composition measurement would be a second objective of such a mission. Moreover, comparing the differing paths of the physical and the chemical evolution of our Galaxy and dwarf galaxies would lead to identifying the nature and origin of the infall into the Milky Way.

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References

Bahcall, J. N., Pinsonneault, M. H., & Wasserburg, G. J. 1995, *Rev. Mod. Phys.*, 67, 781

Beer, R. & Taylor, F. W. 1973, *ApJ*, 179, 309

Bézard, B. 2002, in: *Highlights in Astronomy* (Astron. Soc. Pacific: San Francisco) Vol. 12, pp. 607

Bochsler, P. & Geiss, J. 1973, *Solar Phys.*, 32, 3

Bürgi, A. & Geiss, J. 1986, *Solar Phys.*, 103, 347

Busemann, H., Baur, H., & Wieler, R. 2000, *Meteorites & Planetary Sci.*, 35, 949

Charbonnel, C. 1998, in: *Space Science Series of ISSI*, SSSI-4, and *Space Sci. Rev.*, 84, 199

Drossart, P., Encrenaz, T., Combes, M., Kunde, V., & Hanel, R. 1982, *Icarus*, 49, 416-426

Eberhardt, P. 1974, *Earth Planet. Sci. Lett.*, 24, 182

Encrenaz, Th., de Graauw, Th., Schaeidt, S., Lellouch, E., Feuchtgruber, H., Beintema, D. A., Bézard, B., Drossart, P., Griffin, M., Heras, A., Kessler, M., Leech, K., Morris, P., Roelfsema, P. R., Roos-Serote, M., Salama, A., Vandenbussche, B., Valentijn, E. A., Davis, G. R., & Naylor, D. A. 1996, *A&A*, 315, L397

Ezer, D. & Cameron, A. G. W. 1965, in *Solar Wind Three* (University of California Press: Los Angeles), pp. 58

Frick, U. & Moniot, R. K. 1977, in *Eighth Lunar Science Conference* (Pergamon Press: New York), Vol. 1, pp. 229

Gautier, D. & Morel, P. 1997, *A&A*, 323, L9

Geiss, J. 1982, *Space Sci. Rev.*, 33, 201

Geiss, J. & Gloeckler, G. 1998, in *Space Science Series of ISSI*, SSSI-4, and *Space Sci. Rev.*, 84, 239

Geiss, J. & Gloeckler, G. 2003, in *Space Science Series of ISSI*, SSSI-16, and *Space Sci. Rev.*, 106, 3

Geiss, J. & Reeves, H. 1972, *A&A*, 18, 126

Geiss, J., Eberhardt, P., & Signer, P. 1966, *Proposal to NASA for Apollo experiment S-080*, (NASA archive, Record Number 14759)

Geiss, J., Eberhardt, P., Bühler, F., Meister, J., & Signer, P. 1970, *J. Geophys. Res.*, 75, 5972

Geiss, J., Hirt, P., & Leutwyler, H. 1970, *Solar Phys.*, 12, 458

Geiss, J., Bühler, F., Cerutti, H., Eberhardt, P., Filleux, Ch., Meister, J., & Signer, P. 2004, *Space Sci. Rev.*, 110, 307

Gloeckler, G. & Geiss, J. 1996, *Nature*, 381, 210

Gloeckler, G. & Geiss, J. 2000, in *The Light Elements and their Evolution*, Proc. IAU-Symp. Vol. 198, (IAU: Natal, Brazil) pp. 224

Grevesse, N. & Sauval, A. J. 1998, in *Space Science Series of ISSI*, SSSI-5, and *Space Sci. Rev.*, 85, 161

Guillot, T. 1999, *Planet. Space Sci.*, 47, 1183

Heber, V. S. Wieler, R., Baur, H., Olinger, C., Friedmann, T. A., & Burnett, D. S. 2009, *Geochimica et Cosmochimica Acta*, 73, 7414

Isenberg, P. A. & Hollweg, J. V. 1983, *J. Geophys. Res.*, 88, 3923

Lellouch, E., Bézard, B., Fouchet, T., Feuchtgruber, H., Encrenaz, T., & de Graauw, T. 2001, *A&A*, 370, 610

Linsky, J. L. 1998, in *Space Science Series of ISSI*, SSSI-4, and *Space Sci. Rev.*, 84, 285

Mahaffy, P. R., Donahue, T. M., Atreya, S. K., Owen, T. C., & Niemann, H. B. 1998, in *Space Science Series of ISSI*, SSSI-4, and *Space Sci. Rev.*, 84, 251

Mazzitelli, I. & Moretti, M. 1980, *ApJ*, 235, 955

Niemann, H. B., Atreya, S. K., Carignan, G. R., Donahue, T. M., Haberman, J. A., Harpold, D. N., Hartle, R. E., Hunten, D. M., Kasprzak, W. T., Mahaffy, P. R., Owen, T. C., Spencer, N. W., & Way, S. H. 1998, *Science*, 272, 846

Owen, T. 2003, in *Space Science Series of ISSI*, SSSI-28, and *Space Sci. Rev.*, 138, 301

Pérez Hernández, F. & Christensen-Dalsgaard, J. 1994, *MNRAS*, 269, 475

Schatzman, E., Maeder, A., Angrand, F., & Glowinski, R. 1981, *A&A*, 96, 1

von Steiger, R. & Geiss, J. 1989, *A&A*, 225, 222

Stevenson, D. J. & Salpeter, E. E. 1976, in *Jupiter* (University of Arizona Press: Tucson), pp. 85

Tosi, M. 1998, in *Space Science Series of ISSI*, SSSI-4, and *Space Sci. Rev.*, 84, 207

Turck-Chièze, S., Nghiem, P., Couvidat, S., & Turcotte, S. 2001, *Solar Phys.*, 200, 323

Vauclair, S. 1998, in *Space Science Series of ISSI*, SSSI-4, and *Space Sci. Rev.*, 84, 256

Wieler, R. & Heber, V. S. 2003, in *Space Science Series of ISSI*, SSSI-16, and *Space Sci. Rev.*, 106, 197

von Zahn, U., Hunten, D. M., & Lehmacher, G. 1998, *J. Geophys. Res.*, 103, 22815