ISOTOPIC COMPOSITION OF H, HE AND NE
IN THE PROTOSOLAR CLOUD

JOHANNES GEISS[1] and GEORGE GLOECKLER[2]

[1] *International Space Science Institute, Hallerstrasse 6, 3012 Bern, Switzerland*
(johannes.geiss@issi.unibe.ch)
[2] *Dept. of Physics and IPST, University of Maryland, College Park, MD 20742, USA*
University of Michigan, Ann Arbor, MI 48109, USA (gg10@umail.umd.edu)

Abstract. Observations and measurements in the solar wind, the Jovian atmosphere and the gases trapped in lunar surface material provide the main evidence from which the isotopic composition of H, He and Ne in the Protosolar Cloud (PSC) is derived. These measurements and observations are reviewed and the corrections are discussed that are needed for obtaining from them the PSC isotopic ratios. The D/H, ^{3}He/^{4}He (D+^{3}He)/H, ^{20}Ne/^{22}Ne and ^{21}Ne/^{22}Ne ratios adopted for the PSC are presented. Protosolar abundances provide the basis for the interpretation of isotopic ratios measured in the various solar system objects. In this article we discuss constraints derived from the PSC abundances on solar mixing, the origin of atmospheric neon, and the nature of the "SEP" component of neon trapped at the lunar surface. We also discuss constraints on the galactic evolution provided by the isotopic abundances of H and He in the PSC.

1. Introduction

Isotopic abundance measurements are invaluable for tracing the origin and evolution of matter in the universe, the galaxy, and the solar system as a whole as well as the sun, planets, asteroids, moons and comets. In this paper we present the best estimates presently available of the isotopic abundances of H, He and Ne in the Protosolar Cloud (PSC) out of which the bodies in the solar system formed. In order to achieve this, the isotopic ratios observed in these bodies of the solar system have to be corrected for chemical or physical isotope fractionation and for possible alterations by nuclear reactions.

Generally, isotope fractionation by physical or chemical processes are most severe in the case of strong element depletion. From this it follows that measurements of the composition in the Outer Convective Zone (OCZ) of the Sun and in the atmosphere of Jupiter gives us the best evidence for deriving elemental and isotopic abundances of H, He and Ne in the PSC.

TABLE I

^{3}He/^{4}He in the "Planetary Component" of Meteorites and in Jupiter.

	^{3}He/^{4}He (10^{-4})
Planetary Component in Meteorites[1,2]	$\approx 1.5 \pm 0.2$
Q-Phase of the Carbonaceous Chondrite Isna[3]	1.23 ± 0.02
Jupiter[4]	1.66 ± 0.06
Protosolar Cloud[5]	**1.66 ± 0.06**

[1] Eberhardt (1974); [2] Frick and Moniot (1977); [3] Busemann et al. (2000, 2001);
[4] Mahaffy et al. (1998); [5] see text.

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

For several decades the ^{3}He/^{4}He ratio measured in the "Planetary Component" of meteorites served as a proxy for the isotopic abundance of helium in the PSC (e.g., Eberhardt, 1974; Frick and Moniot, 1977), see Table I. More recently, it was realized that this Planetary Component is a mixture of components with somewhat different compositions. We have included in Table I the ^{3}He/^{4}He ratio measured in the "Q-phase" of the carbonaceous chondrite Isna (e.g., Busemann et al., 2000). This meteorite has a very short cosmic ray exposure age and, therefore, the data can be relatively well corrected for cosmic ray-produced ^{3}He.

The situation changed when the ^{3}He/^{4}He ratio in the atmosphere of Jupiter 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 I is presently the best approximation to the protosolar value.

In the Jovian atmosphere helium is depleted by $\approx 18\%$ relative to the protosolar cloud (von Zahn et al., 1998). The degree of helium depletion in the OCZ of the Sun is similar, but the processes that led to the helium depletion in the Solar and Jovian atmospheres are quite different, diffusive separation in the case of the Sun, and — probably — descent of helium-rich droplets in the case of Jupiter (Stevenson and Salpeter, 1976; von Zahn et al., 1998). The Jovian process should be less efficient in fractionating isotopes than the solar process, and, therefore, ^{3}He/^{4}He fractionation in the Jovian atmosphere ought to be less than the 2% fractionation that has occurred in the OCZ of the Sun (Gautier and Morel, 1997; Vauclair, 1998). Thus, we adopt the Jovian ^{3}He/^{4}He ratio obtained by Mahaffy et al. (1998) as the protosolar value without correction.

The ^{3}He/^{4}He ratios in the Planetary Component of meteorites are typically lower by 10 to 20% than the Jovian ratio (cf. Table I). This is not surprising, because in many trapping and loss processes, the lighter isotope is depleted relative to the heavier one. For instance, the diffusion constants D_1 and D_2 of two

TABLE II

Direct ^{3}He/^{4}He Measurements in the Solar Wind.

Apollo / SWC [1]	5 Foil Collections	1969–1972	High Precision
ISEE-3 / ICI[2]	Magnetic Mass Spec	1978–1985	High Time Resolution
Ulysses / SWICS[3]	ToF Mass Spec	1990–	Data from Slow Wind & Fast Streams, High Time Resolution

Publications on ^{3}He/^{4}He: [1] Geiss *et al.* (1970, 1972); [2] Ogilvie *et al.* (1980), Coplan *et al.* (1984), Bochsler (1984); [3] Bodmer *et al.* (1995), Gloeckler and Geiss (1998, 2000).

isotopes of an element are approximately related to the corresponding masses m_1 and m_2 by $D_1/D_2 = (m_1/m_2)^{-1/2}$, resulting in $D(^3\text{He})/D(^4\text{He}) = 1.15$ for the helium isotopes. Thus, the ratio between ^{3}He/^{4}He in Jupiter and in the Planetary Component is of the order of the ratio of the diffusion constants of the two isotopes. This is a modest reduction, considering that helium is depleted by several orders of magnitude in the host mineral of the Planetary Component.

3. The Protosolar (D + ^{3}He)/H Ratio

In the early Sun, D was converted by the (p,γ)-reaction into ^{3}He, which has not been further processed in the OCZ of the Sun, as can be surmised from the existence there of beryllium (Geiss and Reeves, 1972), cf. Section 6. Thus, ^{3}He/^{4}He in the OCZ basically represents the protosolar (D+^{3}He)/H ratio.

Present-day isotopic abundances of noble gases in the OCZ can best be obtained from solar wind (SW) investigations. ^{3}He/^{4}He in the solar wind has been measured by several space-borne instruments. Comprehensive results have been obtained from three investigations (cf. Table II): the Apollo Solar Wind Composition (SWC) experiments, using solar wind collection in foils with subsequent analysis by laboratory mass spectrometry; 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 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 of the three investigations show significant variations in the ^{3}He/^{4}He ratio. Therefore, some understanding of the causes for the changes in ^{3}He/^{4}He is required and a correction method needs to be developed for obtaining the best estimate of the ^{3}He/^{4}He ratio in the present-day OCZ.

We follow here the method introduced by Gloeckler and Geiss (2000), cf. Figure 1. Prior to the Ulysses mission, all solar wind composition data were taken in the ecliptic plane, where the low speed solar wind dominates. Thanks to the polar orbit of Ulysses and the large energy range of the SWICS instrument, it became
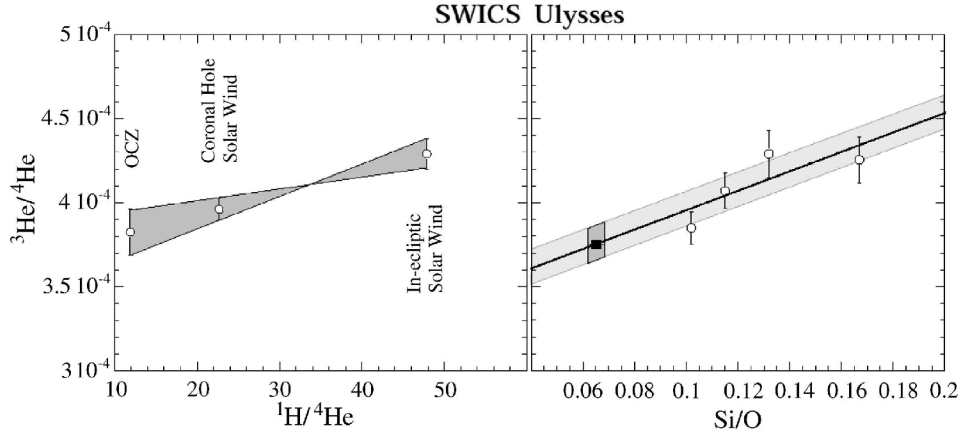
Figure 1. Determination of the ^{3}He/^{4}He ratio in the Protosolar Cloud by extrapolation of solar wind abundance data, updated from Gloeckler and Geiss (2000). *Left:* Correlation of ^{3}He/^{4}He with ^{1}H/^{4}He measured in high-speed streams coming out of the coronal holes and in the slow wind that dominates near the ecliptic. The OCZ value of ^{3}He/^{4}He is obtained by extrapolation to the ^{1}H/^{4}He ratio in the OCZ. *Right:* Correlation of ^{3}He/^{4}He with Si/O measured in two high-speed stream and in two slow solar wind periods. ^{3}He/^{4}He in the OCZ is obtained by extrapolation to the photospheric Si/O ratio of 0.0652, shown as a square symbol. The Si/O ratios are from von Steiger *et al.* (2000), the photospheric abundances of Si and O from Grevesse and Sauval (1998) and Holweger (2001), respectively.

possible for the first time to investigate systematically the helium isotopes not only in the slow wind but also in the high-speed streams coming out of the large polar coronal holes. Gloeckler and Geiss (2000) noticed that in the SW ^{3}He/^{4}He and Si/O are correlated, and, using linear regression and the photospheric value of Si/O, they estimated the ^{3}He/^{4}He ratio in the OCZ to be (3.75 ± 0.17[stat. + var.] ± 0.20[sys.]) · 10^{-4} (Figure 1a). The 1-σ errors include statistical and systematic instrumental uncertainties as well as the spread due to solar wind variability.

In a similar way, Gloeckler and Geiss (2000) used the correlated variations of the ^{3}He/^{4}He and ^{4}He/H ratios in the slow solar wind and the high-speed streams. In Figure 1b the average ^{3}He/^{4}He ratios measured in two high-speed stream periods and in two low-speed wind periods are plotted against the ^{1}H/^{4}He ratios for the corresponding periods. Using a linear extrapolation and the value of 11.9 for (H/He)$_{OCZ}$ (from Pérez Hernández and Christensen-Dalsgaard, 1994), the value (^{3}He/^{4}He)$_{OCZ}$ = (3.82 ± 0.14[stat. + var.] ± 0.20[sys.]) · 10^{-4} is obtained (Figure 1b). The two-extrapolation methods lead to essentially the same result, giving the average of the two values (^{3}He/^{4}He)$_{OCZ}$ = (3.78 ± 0.11[stat. + var.] ± 0.20[sys.]) · 10^{-4} — which is in remarkable agreement with earlier values of (^{3}He/^{4}He)$_{OCZ}$ obtained by other methods (cf. Geiss and Gloeckler, 1998).

The (^{3}He/^{4}He) value derived from the extrapolations shown in Figure 1 refers to the present-day OCZ. Two processes, however, could have changed this ratio during the lifetime of the Sun.

TABLE III

Protosolar D/H Ratio.

	$D/H_{Protosolar}$ (10^{-5})
From Solar Wind $^3He/^4He$ and Jupiter $^3He/^4He$	1.97 ± 0.35[1]
From ISO H_2 and CH_4 spectra, corrected for D-Excess in the Ice-Phase	2.1 ± 0.4[2]
Protosolar Cloud	**2.0 ± 0.35**

[1] Updated from Gloeckler and Geiss (2000); [2] Lellouch *et al.* (2001)); cf. Table VI.

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 and 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 present-day $(^3He/^4He)_{OCZ}$ ratio of a few percent (Gautier and Morel, 1997).

The second possible change of $(^3He/^4He)_{OCZ}$ over solar history is due to solar mixing. During the lifetime of the Sun, the pp-reaction produces additional ^3He outside the solar core at intermediate depth in the Sun. A significant increase of ^3He in the OCZ could have been caused by mixing of pp-produced ^3He into the OCZ. This increase is small and depends on solar models and solar rotation (Vauclair, 1998; Turck-Chièze *et al.*, 2001).

Addition of pp-produced ^3He to the OCZ can also be investigated by comparing solar wind helium trapped in very old and more recent lunar surface material. Using this method, Wieler and Heber (2003) concluded, that the increase of $^3He/^4He$ in the OCZ by solar mixing is at most 5%. Combining the two effects, settling of helium out of the OCZ and solar mixing, we thus adopt a correction of $-(4 \pm 2)\%$ for $(^3He/^4He)_{OCZ}$ and obtain $[(D+^3He)/H]_{PSC} = (3.63 \pm 0.35) \cdot 10^{-5}$.

4. Protosolar Deuterium Abundance

Two methods are available for a reliable determination of the deuterium abundance in the PSC. For the first method, the relation

$$(D/H)_{Protosolar} = [(D + ^3He)/H]_{Protosolar} - (^3He/H)_{Protosolar}$$

is used. With protosolar $(D + ^3He)/H = (3.63 \pm 0.35) \times 10^{-5}$ and protosolar $^3He/H = (1.66 \pm 0.06) \times 10^{-5}$ (cf. Table I) we obtain $(D/H)_{Protosolar} = (1.97 \pm 0.36) \times 10^{-5}$ (Table III). The second method is based on a direct deuterium abundance measurement in Jupiter, either by remote spectroscopy (*e.g.* Beer and Taylor, 1973; Drossart *et al.*, 1982; Encrenaz *et al.*, 1996) or by *in-situ* mass spectrometry (Niemann *et al.*, 1996; Mahaffy *et al.*, 1998). The values obtained by infrared spectroscopy are more precise than those obtained by the Galileo Probe Mass Spectrometer

TABLE IV

Deuterium Abundance in Jupiter.

	D/H (10^{-5})
Galileo Probe[1]	2.6 ± 0.7
ISO[2]	
$\quad$ H$_2$	2.4 ± 0.4
$\quad$ CH$_4$	2.2 ± 0.7
$\quad$ H$_2$, CH$_4$ combined	2.25 ± 0.35
$\quad$ Corrected for D-Excess in the Ice-Phase	2.1 ± 0.4

[1] Mahaffy *et al.* (1998); [2] Lellouch *et al.* (2001).

(cf. Table IV). Lellouch *et al.* (2001) measured D/H $=$ $(2.4 \pm 0.4) \times 10^{-5}$ in molecular hydrogen and D/H $= (2.2 \pm 0.7) \times 10^{-5}$ in methane. Recently, Bézard *et al.* (2002) obtained a D/H ratio in the methane even below 2×10^{-5}. We adopt here the results of Lellouch *et al.* (2001) who combined their H$_2$ and CH$_4$ results and obtained D/H $= (2.25 \pm 0.35) \times 10^{-5}$ as representative for Jupiter. Jupiter's 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 (see also Owen and Encrenaz, 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 $(D/H)_{Protosolar} = (2.1 \pm 0.4) \times 10^{-5}$. The agreement between the D/H ratio determined using solar wind data and the ratio based on Jupiter measurements is excellent. We give the solar wind derived value a somewhat higher weight and adopt $(2.0 \pm 0.35) \times 10^{-5}$ as the protosolar D/H ratio.

5. Neon Isotopes in the Protosolar Cloud

The solar wind is by far the best source of information for determining the isotopic composition of neon in the Protosolar Cloud. Very precise results on ^{20}Ne/^{22}Ne in the solar wind were obtained during the 1969–72 period with the Apollo SWC experiments. The solar wind was collected five times during exposure periods lasting from 70 minutes to 40 hours, and afterwards the trapped solar wind particles were analyzed in the laboratory (Table V). The SW was sampled at five different locations on the Moon for differing solar aspect angles. Varying geometrical conditions for the collection periods was considered important, because little was known in the pre-Apollo era about strength and configuration of the lunar magnetic field. The ^{20}Ne/^{22}Ne results of the five SWC experiments were identical within the limits of error (Table V). ^{21}Ne data with reasonably small limits of error were obtained only by the Apollo 15 and Apollo 16 missions.

TABLE V

Apollo SWC Experiments, Neon Isotopes[1].

	$^{20}Ne/^{22}Ne$	$^{22}Ne/^{21}Ne$
Apollo 11	13.5 ± 1.0	—
Apollo 12	13.1 ± 0.6	26 ± 12
Apollo 14	13.65 ± 0.50	—
Apollo 15	13.65 ± 0.30	31 ± 4
Apollo 16	13.80 ± 0.40	31 ± 4

[1] from Geiss et al. (1972)

TABLE VI

Isotopic Abundances in Solar System Material.

	$^{20}Ne/^{22}Ne$	$^{21}Ne/^{22}Ne$
Present-day In-ecliptic Solar Wind		
Apollo SWC[1]	13.7 ± 0.3	0.033 ± 0.003
SOHO/CELIAS[2]	13.8 ± 0.7	0.031 ± 0.008
Protosolar Cloud	**13.7 ± 0.3**	**0.0328 ± 0.0005[3]**
Solar Wind in Lunar Soil[3]	13.8 ± 0.1	0.0328 ± 0.0005
"SEP" in Lunar Soil[3]	11.2 ± 0.2	0.0295 ± 0.0005
Earth Atmosphere[4]	9.77 ± 0.03	0.0292 ± 0.0011

[1] Geiss et al. (1972); [2] Kallenbach et al. (1997); [3] Benkert et al. (1993); [4] Holden (1997).

$^{20}Ne/^{22}Ne$ data were also obtained by the MTOF detector of the SOHO/CELIAS experiment (Kallenbach et al., 1997). The Apollo SWC and SOHO/CELIAS results are summarized in Table VI. Kallenbach et al. (1998) concluded from Ne, Mg and Si measurements in the solar wind that on average the lighter isotopes of elements in this mass range are enhanced in the slow solar wind by 1 or 2%. For neon this enhancement is well within the limits of error. Therefore, at this time, we do not correct for any mass discrimination of the solar wind $^{20}Ne/^{22}Ne$ ratio, but include the unknown fractionation factor in the limits of error in the adopted $(^{20}Ne/^{22}Ne)_{PSC}$ ratio.

The direct investigations of the present-day solar wind give much larger relative errors for $^{21}Ne/^{22}Ne$ than for $^{20}Ne/^{22}Ne$ (cf. Table V). Therefore, we base the protosolar $^{21}Ne/^{22}Ne$ ratio on investigations of solar wind neon trapped in lunar surface material, and we adopt in Table VI the value given by Benkert et al. (1993).

6. Discussion and Conclusions

In the preceding sections we have summarized the evidence from which the protosolar abundances of the isotopes of H, He and Ne are derived, and we have presented our best estimate for these abundances.

Representative protosolar abundances provide the basis for the interpretation of isotopic ratios measured in various solar system objects and samples, as is demonstrated in several articles of this volume. In this final section of our article, we discuss how the protosolar abundances of the H, He or Ne isotopes are used to constrain solar mixing, to identify excess ^{21}Ne in the Earth atmosphere, to understand the origin of neon trapped in lunar surface material, and to constrain galactic evolution.

6.1. SOLAR MIXING: CONSTRAINTS FROM ISOTOPIC MEASUREMENTS

In the OCZ thermally driven convection evens out and dilutes inhomogeneities that might be produced locally at the solar surface or elsewhere. With ≈2 percent of the solar mass (see Gough and Scherrer, 2001), the OCZ is a huge reservoir. Therefore, neither the loss of matter through the solar wind nor nuclear reactions at the solar surface are likely to have produced significant changes in its composition during the past few Gy.

It was recognized long ago (*e.g.*, Schatzman, 1970; Schatzman *et al.*, 1981) that the abundances of the lightest nuclides at the solar surface can be used to constrain solar history. In the solar core nuclides with $Z \leq 8$ are affected by thermonuclear reactions. With increased distance from the solar center the temperature and the number of species involved in thermonuclear reactions decreases. At the surface we have definite evidence of changes in abundance only for the very lightest species, see Grevesse and Sauval (1998).

The lifetime of a nuclide determines the degree of its depletion. In Figure 2 lifetimes of several light nuclides are plotted as a function of temperature and, for simplicity, normalized to the density and composition at the bottom of the OCZ (reaction rates after Fowler *et al.*, 1975, and other compilations). The observed depletion of nuclides is consistent with the lifetime hierarchy: D and ^{6}Li are absent in the solar OCZ, ^{7}Li is depleted by a factor of ≈160. No depletion is observed for species heavier than ^{7}Li. Recently, Israelian *et al.* (2001) discovered ^{6}Li in the atmosphere of the metal-rich solar-type star H/D 82943, which is orbited by a giant planet. Based on the short lifetime of ^{6}Li (cf. Figure 2) the authors conclude that the observed ^{6}Li would not have survived the early epoch in the life of this star, and they interpret the presence of ^{6}Li as "evidence for a planet (or planets) having been engulfed by the parent star".

In the OCZ ^{3}He could not have been depleted, as is evident from the full preservation of ^{9}Be and the large difference in the lifetimes of ^{3}He and ^{9}Be seen in Figure 2 (Geiss and Reeves, 1972). However, ^{3}He could have been augmented by
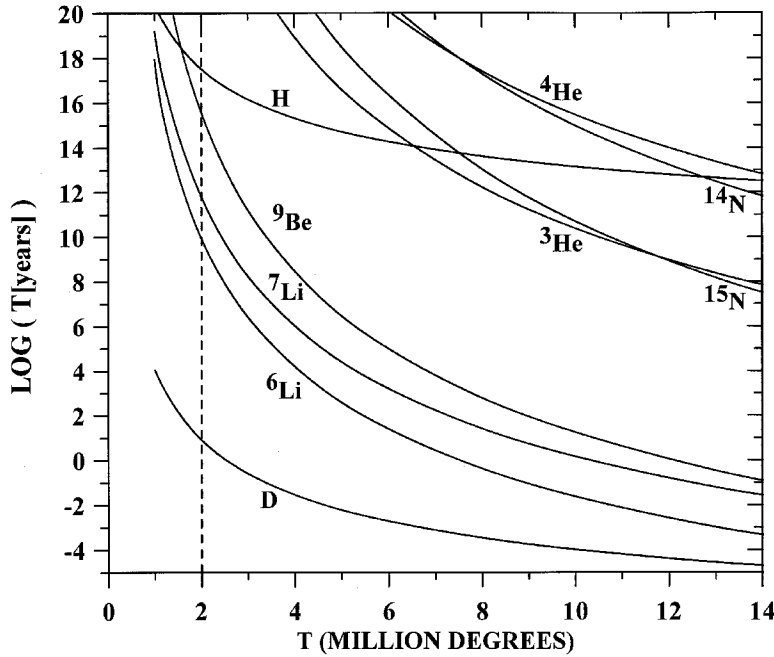
Figure 2. Life-time of light nuclides as a function of temperature. Given are the life-times due to thermonuclear reactions with density and composition normalized to the present conditions at the bottom of the OCZ. The dashed line marks the present temperature at the bottom of the OCZ.

secular mixing (Schatzman, 1970; Bochsler and Geiss, 1973; Schatzman *et al.*, 1981; Bochsler *et al.*, 1990): In the course of solar history a bulge of ^{3}He was built up by incomplete hydrogen burning at intermediate solar depth, and even a modest admixture to the OCZ of material from below could increase ^{3}He/^{4}He at the solar surface. However, the recently established absence of significant differential rotation below $r = 0.7R_\odot$ (Gough and Scherrer, 2001) has made such an increase less likely (Vauclair, 1998). In any case, the addition of surplus ^{3}He would mainly occur late in solar history, *i.e.* during and after the epoch when the older lunar samples received their solar wind irradiation (Geiss, 1973). The most recent data of solar wind helium in lunar surface material indicate that the helium isotopic composition in the solar wind has remained constant within a few percent during the past almost 4 Gy (Wieler and Heber, 2003).

6.2. LUNAR NEON AND ATMOSPHERIC NEON

Figure 3 shows a ^{21}Ne/^{22}Ne vs. ^{20}Ne/^{22}Ne diagram of solar wind and atmospheric neon and of the "SEP" component trapped in lunar surface material. Such three isotope plots are convenient for distinguishing isotopic differences caused by mass fractionation from those caused by mass-independent fractionation or nuclear reactions.
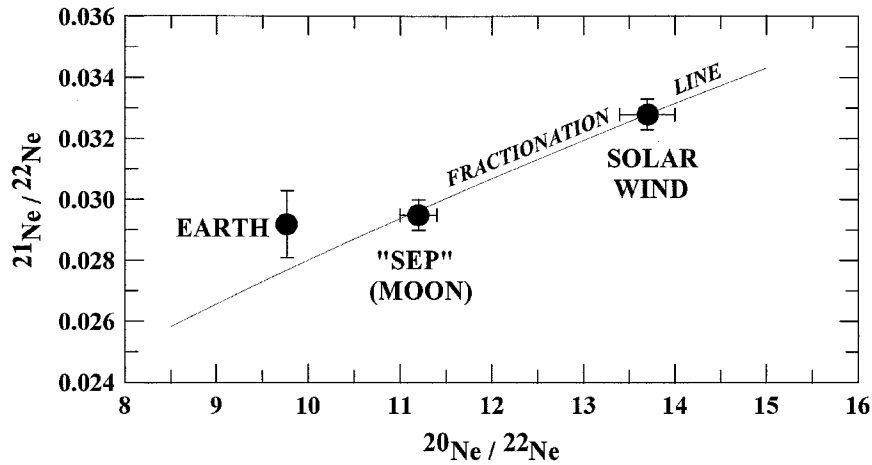
Figure 3. Three isotope plot of neon. The solar wind data and the isotopic composition of the "SEP" component in lunar soil are taken from Table VI. "SEP" neon has a composition that can be produced from solar wind neon by mass dependent isotope fractionation. On the other hand, the neon in the earth atmosphere lies above the "fractionation line". The excess [21]Ne is thought to be produced by nuclear reactions inside the earth (see text).

The change in the relative abundances of three isotopes A, B and C of an element is approximately given by (see Clayton, 2003)

$$d(n_A/n_C)/(n_A/n_C) = k \; d(n_B/n_C)/(n_B/n_C), \tag{1}$$

with

$$k = [(m_A - m_C)/(m_A + m_C)]/[(m_B - m_C)/(m_B + m_C)], \tag{2}$$

where n_i is the number of atoms of isotope i and m_i is its mass. For the case of neon $k = 0.49$, and integrating Equation (1) gives the "fractionation line".

$$(^{21}Ne/^{22}Ne)/(^{21}Ne/^{22}Ne)_0 = [(^{20}Ne/^{22}Ne)/(^{20}Ne/^{22}Ne)_0]^{0.49} \tag{3}$$

The fractionation line for protosolar neon is shown in Figure 3. Atmospheric neon lies slightly above the fractionation line. This is — at least in part — due to a small excess of [21]Ne produced by nuclear reactions inside the Earth (Wetherill, 1954; Eikenberg *et al.*, 1993).

The neon contained in lunar surface material consists of three major components: (1) Trapped solar wind neon, (2) neon produced by spallation, and (3) "SEP" neon. The acronym "SEP" was originally chosen because it was thought that this component consisted of solar energetic particles. An alternative explanation is that the "SEP" component consists of solar wind particles that are isotopically mass fractionated by diffusion or other processes.

Recently, Wimmer-Schweingruber and Bochsler (2001) proposed an interstellar origin for the "SEP" particles. Since, however, the "SEP" data point lies virtually
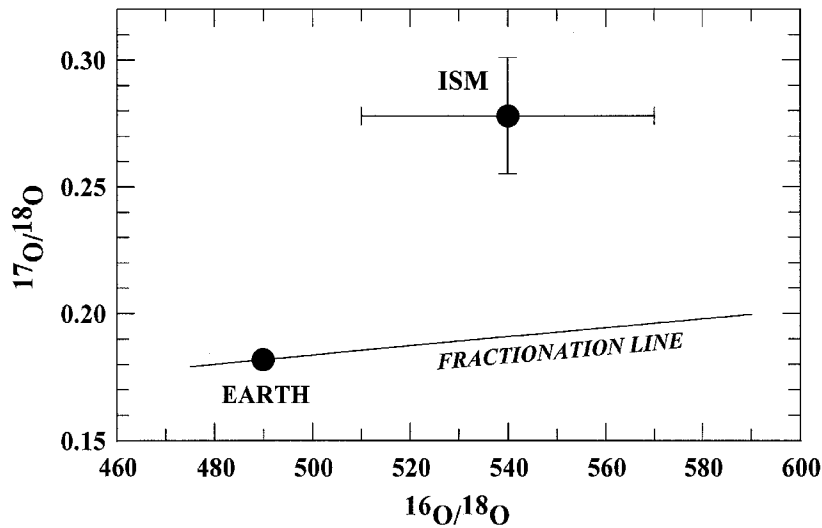
Figure 4. Three isotope plot of oxygen. The "fractionation line" defines isotopic ratios that could be obtained from terrestrial oxygen by mass dependent isotope fractionation. The ISM data point is an average of oxygen isotope measurements in the interstellar medium (after Prantzos *et al.*, 1996). Terrestrial oxygen could not be derived from ISM oxygen by mass dependent isotope fractionation, demonstrating that the nucleosynthetic origin of the two types of oxygen is significantly different.

on the fractionation line, it is much more likely that its origin is the protosolar cloud (see also Wieler and Heber, 2003).

Figure 4 shows a 3-isotope plot for oxygen. It is seen that the average isotopic composition of oxygen in the present-day interstellar medium (ISM) given by Prantzos *et al.* (1996) lies ≈40 percent above the fractionation line for terrestrial oxygen. Terrestrial oxygen could isotopically differ from PSC oxygen (see Clayton, 2003), but only by a few percent. Thus, in any case, ISM oxygen will lie far away from the fractionation line through PSC oxygen, proof for a significantly different nucleosynthetic origin of the oxygen in the PSC and in the ISM. Recently, Geiss *et al.* (2002) have presented evidence that the infall of matter into the galactic disc carries the compositional signature of dwarf galaxies, which is characterized by a high ratio of primary to secondary nuclides, thus explaining the low abundance of N in the LIC and of ^{18}O in the ISM.

Could ISM neon accidentally lie as close to the PSC fractionation line as lunar "SEP" neon does (see Figure 3)? The best isotopic result on interstellar neon is the $^{22}Ne/^{20}Ne = (13.0 + 5.5 - 6.8)$ ratio obtained by Leske *et al.* (1996) in the Anomalous Cosmic Rays (ACR). For distinguishing between different hypotheses concerning the nature of the "SEP" data, however, the error limit of this result is too large. Also, galactic evolution modeling of neon comparable to the oxygen modeling by Prantzos *et al.* (1996) has not yet been done. We note however, that ^{16}O and ^{20}Ne are both primary nuclides released by supernovae, ^{18}O and ^{22}Ne are typical secondary nuclides produced from ^{14}N during He-burning. ^{17}O and ^{21}Ne
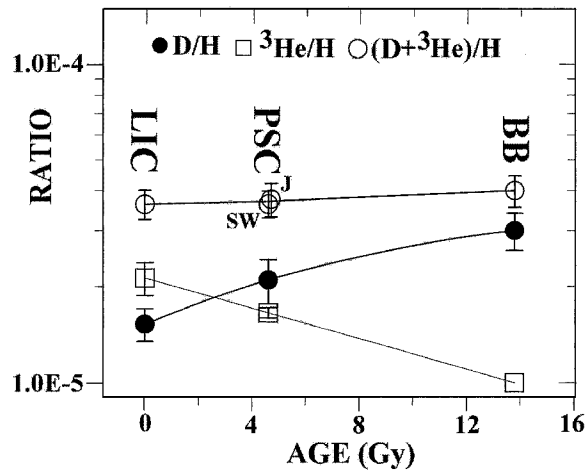
Figure 5. D/H, ^{3}He/H, and (D+^{3}He)/H in the Local Interstellar Cloud (LIC), the Protosolar Cloud (PSC) and in the baryonic matter produced in the Big Bang (BB) are plotted as a function of age. As expected from the theory of nucleosynthesis and galactic evolution, D/H decreases with time and ^{3}He/H increases. This leads to a relatively constant (D+^{3}He)/H ratio over time (see text). The PSC data points are from this paper, for (D+^{3}He)/H in the PSC there are two independent values, from solar wind (SW) data and from Jupiter (J) data. D/H in the LIC is from Linsky and Wood (2000) and ^{3}He/H in the LIC is the average of the results of Gloeckler and Geiss (1996, 1998) and Salerno *et al.* (2001). The primordial D/H ratio is from O'Meara *et al.* (2001). The ^{3}He/H ratio is a theoretical value (cf. Geiss *et al.*, 2002).

are produced from ^{16}O and ^{20}Ne, respectively, ^{17}O by core H burning, and ^{21}Ne by neutron capture mostly during He- and C-burning (Prantzos *et al.*, 1996; Prantzos, 2002). Thus, the three neon isotopes are as different in nucleosynthetic origin as the oxygen isotopes. We consider it to be unlikely therefore, that neon in the present-day ISM could lie as close to the fractionation line as does the SEP neon. In order to resolve this question definitely, it would be important to have improved neon isotope data in the interstellar gas entering the heliosphere and also to develop models for the nucleosynthesis and galactic evolution of the neon isotopes. Data on neon isotope abundances in the LIC and a better understanding of the nucleosynthesis of these isotopes would also provide a further test for the "Mixing Model" of late galactic evolution introduced by Geiss *et al.* (2002).

6.3. GALACTIC EVOLUTION OF DEUTERIUM AND ^{3}HE

D is the only nucleus that is produced exclusively in the Big Bang. Also ^{3}He is in a category of its own. It is produced by three processes: (1) Big Bang nucleosynthesis; (2) D-burning in the early life of stars of all sizes; and (3) incomplete H-burning. The third process operates at intermediate depth in small stars (see Charbonnel and do Nascimento, 1998), and the gas relatively rich in ^{3}He is released into interstellar space when the star had left the main sequence, *i.e.* $\approx 10^{10}$ years

after its birth. Therefore, this mode of ^{3}He production came into effect only in the later stages of the life of the galaxy. However, rotating stellar models predict that the net effect of this process is small (Charbonnel and do Nascimento, 1998; Tosi, 1998). From the limited importance of process (3) it follows that (D+^{3}He)/H is relatively constant. This is shown in Figure 5. The PSC and the LIC are the only representative galactic samples for which we have both D and ^{3}He determinations. It is seen that (D+^{3}He)/H has decreased by only $\approx$10 percent from the BB to the PSC and the LIC. We propose that (D+^{3}He) could become useful as an approximate invariant for modeling the chemical evolution in galaxies. Since the chemical evolution in dwarf galaxies proceeds under conditions different from those in our own galaxy, it would be important if a representative abundance of both D and ^{3}He could be measured in one of the Magellan clouds or another dwarf galaxy.

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