

THE ABUNDANCE OF ^3He IN THE SOLAR WIND – A CONSTRAINT FOR MODELS OF SOLAR EVOLUTION

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Abstract. ^3He is an intermediate product in the proton–proton chain, and standard models of the Sun predict a large bulge of enhanced ^3He abundance near $M_r/M_0 = 0.6$ in the contemporary Sun. The relatively low abundance of ^3He at the solar surface, which is derived from solar wind observations, poses severe constraints to non-standard solar models.

Direct measurements of the ^3He abundance in the solar atmosphere are extremely difficult, whereas indirect measurements, e.g., in the solar wind, have been performed with considerable precision. The interpretation of solar wind observations with respect to solar surface abundances has been greatly improved in recent years. Abundance measurements have been performed under a large variety of solar wind conditions and refined models have been developed for the transport processes in the chromosphere and the transition region and for the processes occurring in the solar corona. From these measurements we estimate the present isotopic number ratio $^3\text{He}/^4\text{He}$ to be $(4.1 \pm 1.0) \times 10^{-4}$ at the solar surface, corresponding to the weight abundance $X_3 = (9.0 \pm 2.4) \times 10^{-5}$. The zero-age Main-Sequence abundance of ^3He (after burning of D) might have been slightly lower (by about 10 to 20%) than the present-day value.

Non-standard solar models involving mild turbulent diffusion (Lebreton and Maeder, 1987) could account for a slow secular increase of the $^3\text{He}/^4\text{He}$ ratio in the solar atmosphere. On the other hand it is difficult to reconcile models with severe mass loss as proposed by Guzik, Willson, and Brunish (1987) with this constraint. The slowing down of the solar rotation during the early Main-Sequence evolution was accompanied by stronger differential rotation probably implying a more effective mixing of the inner parts. Again, the surface abundance of ^3He imposes severe limits on the evolution of the distribution of momentum within the early Sun.

1. Introduction

There exist a few light elements and isotopes whose surface abundance can serve as sensitive monitors for processes occurring in stellar interiors. Whereas abundances of some light elements (Li, Be) can be traced in stellar atmospheres by optical means, the detection of isotopes, such as ^3He , is much more difficult. For instance, Ramaty and Murphy (1987) use the 2.223 MeV γ -line to derive the solar photospheric ^3He abundance. From the 1982, June 3 flare they found a $^3\text{He}/\text{H}$ ratio of 2×10^{-5} . This value seems very low and difficult to reconcile with D/H ratios measured in the atmospheres of Jupiter and in the interstellar gas, the putative primordial $^3\text{He}/^4\text{He}$ ratio in meteorites and the presently observed $^3\text{He}^+$ in interstellar matter (Bania, Rood, and Wilson, 1987).

The isotopic composition of helium can, however, be measured in the solar wind. With the information of acceleration and fractionation processes available today, it is

possible to infer the composition of helium in the solar atmosphere and, hence, in the outer convective zone of the Sun.

A second important source of information on solar system helium is provided by meteoritic samples. From the study of meteorites the isotopic composition of helium in solar system material at the time of the formation of the Sun can be inferred. From the record of solar wind helium in lunar samples it is, at least in principle, possible to get insight into the temporal evolution of the isotopic composition of helium in the outer convective zone of the Sun.

${}^3\text{He}$ is an intermediate product of the proton-proton chain. In the central core ($M_r/M_\odot < 0.2$) temperatures are sufficiently high to convert ${}^3\text{He}$ into ${}^4\text{He}$. In the outermost layers ($M_r/M_\odot > 0.9$) the ${}^3\text{He}$ content remains basically unchanged because even the proton-proton reaction does not proceed. Near $M_r/M_\odot \sim 0.6$, where temperatures are sufficiently high to produce ${}^3\text{He}$ but remain too low to further process ${}^3\text{He}$, a ${}^3\text{He}$ -rich region gradually evolves. In the outer convective zone the abundance of ${}^3\text{He}$ reflects the sum of primordial ${}^3\text{He}$ and original ('cosmological') deuterium in the solar nebula, at least for standard models (e.g., Lebreton and Maeder, 1987) as illustrated in Figure 1. D was burned during the pre-Main-Sequence contraction and could not survive conditions at the base of the outer convective zone. Therefore, the simple relation

$$[{}^3\text{He}(\text{today})] = [{}^3\text{He}(t = 0)] + [\text{D}(t = 0)]$$

holds for standard models.

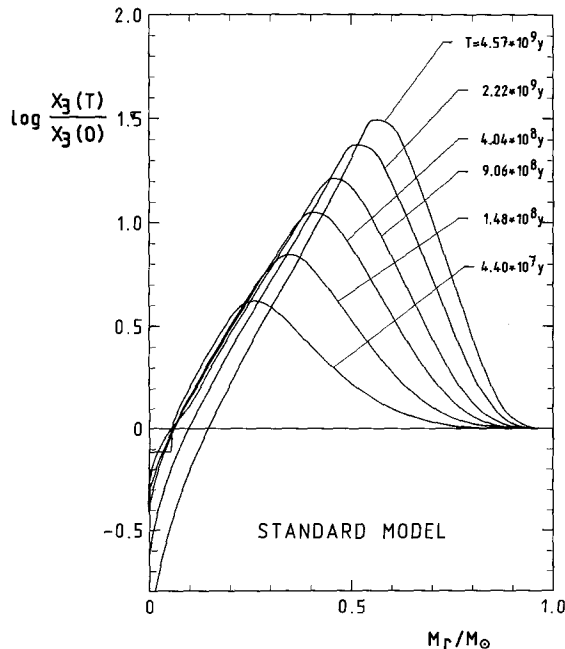


Fig. 1. Evolution of ${}^3\text{He}$ abundance in a standard model. During the lifetime of the Sun the peak of ${}^3\text{He}$ abundance gradually evolves and moves towards $M_r/M_\odot \sim 0.6$.

It was first pointed out by Schatzman (1970) that the strong gradient of the ^3He abundance from $M_r/M_0 \sim 0.6$ to the surface of the Sun makes ^3He to be a sensitive tracer for mixing processes occurring in the solar interior. Bochsler and Geiss (1973) investigated consequences of different mixing scenarios for the surface abundances of light elements.

In this paper we first give a short survey of measurements of ^3He in the solar wind. Then we discuss current, theoretical models about fractionation of solar wind abundances with respect to photospheric abundances. Finally, we briefly summarize the relevance of observational results with respect to non-standard models of solar evolution.

2. Measurement of ^3He in the Solar Wind

2.1. RESULTS FROM THE APOLLO FOIL EXPERIMENT (SWC)

The first precise determinations of the $^3\text{He}/^4\text{He}$ isotopic ratio in the solar wind were performed during the Apollo missions 11, 12, 14, 15, and 16 with the foil-collection technique (Geiss *et al.*, 1970, 1972). During five periods, lasting from one hour to several days, aluminium foils were exposed to the solar wind. The foils were later returned to the Earth and the flux and the isotopic composition of light noble gases trapped in the foil were determined in the laboratory by mass spectrometric analysis.

The results confirmed the large variability of the ^4He flux. The isotopic ratio $^3\text{He}/^4\text{He}$ varied from 4.1 to 5.4×10^{-4} , the average was $(4.2 \pm 0.3) \times 10^{-4}$. Figure 2 shows that there is a clear correlation of $^{20}\text{Ne}/^4\text{He}$ with $^3\text{He}/^4\text{He}$ in the Apollo Foil results. This

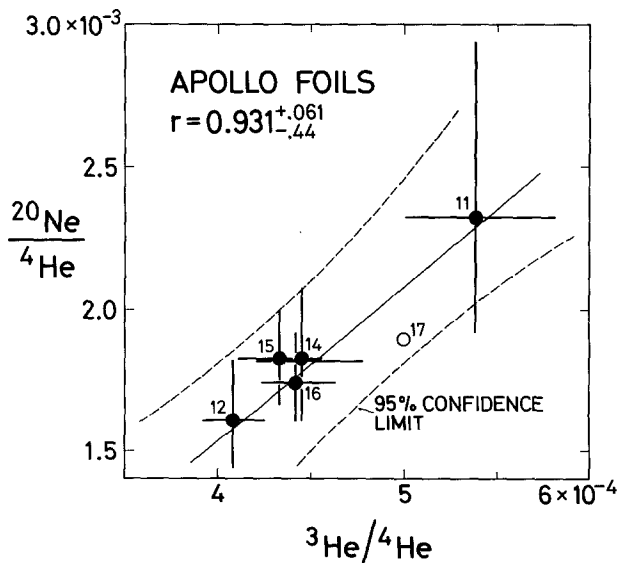


Fig. 2. Correlation of $^{20}\text{Ne}/^4\text{He}$ vs $^3\text{He}/^4\text{He}$ from the Apollo SWC results. The measurements are consistent with a constant $^3\text{He}/^{20}\text{Ne}$ ratio (Geiss *et al.*, 1972).

indicates that ${}^4\text{He}$ has the largest variability among the three species considered. In fact, the ${}^3\text{He}/{}^{20}\text{Ne}$ ratio was the same for the five SWC-experiments within the limits of experimental uncertainties (Geiss *et al.*, 1972).

2.2. RESULTS FROM THE ION COMPOSITION INSTRUMENT (ICI) ON THE ISEE-3 SPACECRAFT

The Ion Composition Instrument on ISEE-3 has been jointly developed by the NASA Goddard Space Flight Center (K. W. Ogilvie, principal investigator), the University of Maryland (M. A. Coplan), and the University of Bern. The instrument consists of a stigmatic Wien Filter (velocity filter) and a hemispherical energy analyzer. The instrument and its modes of operation are described elsewhere (Coplan *et al.*, 1978; Ogilvie *et al.*, 1980). It is possible to measure energy per charge and velocity of particles simultaneously with the ICI and, therefore, mass per charge can be unambiguously attributed to each measurement. This feature and the resolving power of the instrument allow the identification of ${}^3\text{He}^{++}$ under almost all circumstances in the solar wind. During the years 1978 to 1982, when the spacecraft ISEE-3 was positioned near the Lagrangian point L1, a continuous record of ${}^3\text{He}/{}^4\text{He}$ ratios was obtained. The results were discussed by Coplan *et al.* (1984) and by Bochslér *et al.* (1983). The distributions of the measured ${}^4\text{He}$ fluxes, ${}^3\text{He}$ fluxes, and also ${}^4\text{He}/{}^3\text{He}$ ratios can be described by log-normals (Figure 3). It is difficult to obtain a clear impression from the unweighted

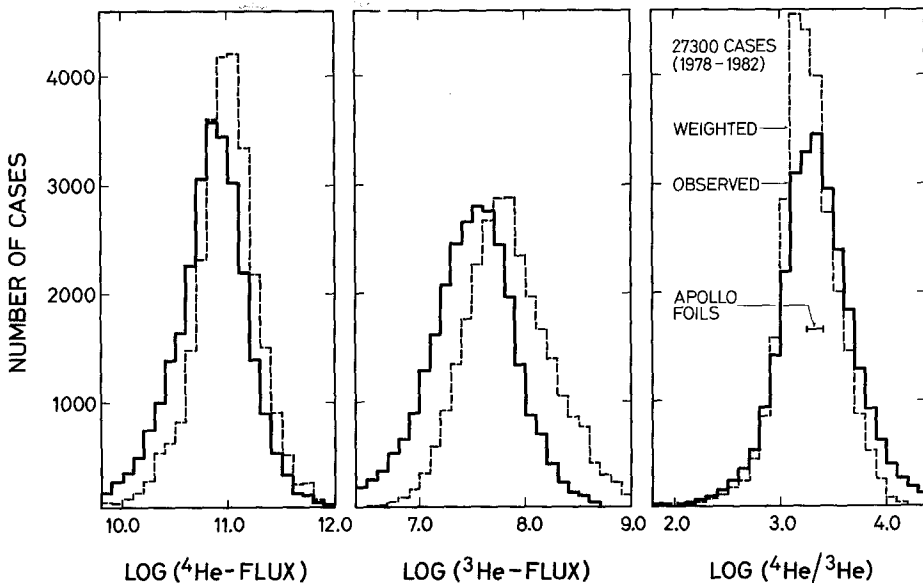


Fig. 3. Histograms of ${}^4\text{He}$ fluxes, ${}^3\text{He}$ fluxes, and ${}^4\text{He}/{}^3\text{He}$ ratios measured with ISEE-3/ICI. The distributions can be described to a good approximation as log-normals. The experimental uncertainties associated with the individual measurements are in some cases rather large. If the measurements are weighted with the inverse squares of the estimated uncertainties, the distribution of ${}^4\text{He}/{}^3\text{He}$ ratios becomes considerably narrower.

distributions (solid lines) because some of the individual measurements are associated with rather large instrumental uncertainties. These are mainly due to low signal to background ratios and poor counting statistics. We have, therefore, attempted to reconstruct the real distributions by giving weights according to the estimated uncertainties of individual measurements. The result of this procedure is shown with dashed lines in Figure 3. For the distribution of fluxes this introduces a bias towards higher values, especially, in the case of ^3He . With this procedure the center of the distribution of ratios remains basically at the same place; the distribution becomes, however, considerably narrower. The typical variation of the $^3\text{He}/^4\text{He}$ ratio is obviously considerably less than one order of magnitude. This conclusion is supported by the autocorrelation analysis of Coplan *et al.* (1984) which yields persistence times of the order of 20 hours for the flux measurements and by the size of the Apollo SWC variations. Figure 4 illustrates the correlation of the ^3He and ^4He fluxes. The correlation is fairly strong ($r = 0.753 \pm 0.002$). We observe a widening of the correlation contours for low ^3He fluxes. An unbiased average flux ratio, which is obtained from the ISEE-3/ICI data by adding individual background-corrected flux measurements of the two ions, thereby allowing negative fluxes in some cases, yields the value $^3\text{He}/^4\text{He} = (4.88 \pm 0.48) \times 10^{-4}$ (Coplan *et al.*, 1984) which is in agreement with the Apollo SWC average of $(4.25 \pm 0.21) \times 10^{-4}$ (Geiss *et al.*, 1972).

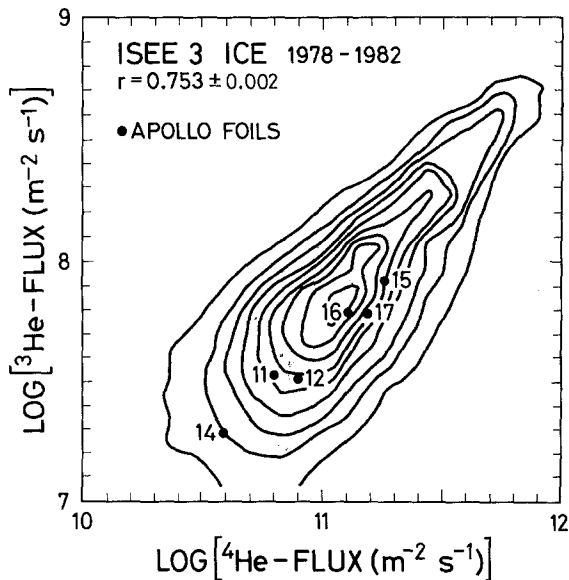


Fig. 4. Correlogram of ^3He and ^4He flux measurements from ISEE-3/ICI. The Apollo SWC measurements are shown with full dots (after Coplan *et al.*, 1984).

2.3. SOLAR WIND HELIUM ISOTOPIC COMPOSITION FROM THE LUNAR RECORD

The surface layer of the Moon consists of an aggregation of a few meters of rocks and grains which have been deposited by the continuous impacts of meteorites and small

planetary bodies since the final solidification of the lunar surface. It is a mixture of primary meteoritic debris and secondary lunar crater ejecta which have episodically been exposed to the solar corpuscular radiations. Although the exposure history of single grains might be rather complicated in general, it is possible – at least in principle – to recover some information about the temporal evolution of the composition of the solar wind. There exist several indicators for the duration and time of exposure and, provided that gas retention properties of mineral grains are understood, the lunar record of solar volatile elements can be deciphered. Benkert *et al.* (1988) have recently performed a detailed investigation on lunar ilmenite grains. They conclude that there are generally two helium components of solar particles. The low-energy component, i.e., typical solar wind, has a ${}^3\text{He}/{}^4\text{He}$ ratio of 4.6×10^{-4} , consistent with the *in situ* measurements by Geiss *et al.* (1972) and Coplan *et al.* (1984). The second component with typical energies $> 1 \text{ keV nucl}^{-1}$ has a significantly lower isotopic ratio, i.e., ${}^3\text{He}/{}^4\text{He} \sim 2.3 \times 10^{-4}$. The mixture of the two components yields a bulk ${}^3\text{He}/{}^4\text{He}$ value of approximately 4×10^{-4} . For a different set of lunar ilmenites, which were irradiated 1 to 3 billion years earlier the same components were found. However, it appears that the relative proportions of the two components are different. The contribution of the energetic component is substantially higher so that the bulk ratio in these samples is 3.6×10^{-4} . It should be noted at this point that Becker and Pepin (1989), who have investigated the same samples with a different analytical method, came to the conclusion that the solar wind helium isotopic ratio had changed by approximately 20%. The final conclusion about secular changes in the lunar record cannot be made at this time, although there exists general agreement on the change being limited to some tens of percents during the last few billion years.

2.4. EVIDENCE FROM METEORITES, INTERSTELLAR MATERIAL, AND PLANETARY ATMOSPHERES

The helium isotopic ratio in the protosun (i.e., the Sun before ignition of nuclear reactions) is best estimated from helium in primitive meteorites. From various stepwise heating experiments on different carbonaceous chondrites a component of relatively strongly bound helium was identified with a ${}^4\text{He}/{}^3\text{He}$ ratio of 7000 (Jeffery and Anders, 1970; Eberhardt, 1974). There is no physical process known to operate in the solar system which produces helium with such an isotopic composition. This allows the conclusion that this meteoritic helium component reflects the original composition of helium as present in the primeval solar nebula from which meteorites and the Sun were formed. A more cautious interpretation would attribute this component to the composition in a *grainy* constituent. Better estimates of the bulk composition of helium in the solar nebula are in principle possible from a measurement of the present-day interstellar gas and/or the composition of the atmospheres of the giant planets.

In a major effort Bania, Rood, and Wilson (1987) derived the ${}^3\text{He}$ abundance in the galactic interstellar medium from the 8.7 GHz hyperfine line of ${}^3\text{He}^+$ observed in various H II regions. Their ${}^3\text{He}/\text{H}$ number ratios range from 1.4 to 14.7×10^{-5} . The large variations of this ratio without clear trend with increasing galactocentric distance makes

it difficult to interpret their data. Their lower values, which have the smallest experimental uncertainties, are consistent with the protosolar $^3\text{He}/^4\text{He}$ ratios derived from meteorites. A simple minded interpretation of the results of Bania, Rood, and Wilson (1987) would then ascribe the local enhancements of $^3\text{He}^+$ in some H II regions to local sources. It should be noted, however, that, as Bania, Rood, and Wilson (1987) state, there is no excess of ^{13}C associated with these locations, contrary to what is expected from models of the chemical evolution of interstellar matter.

D/H was measured in the interstellar gas in the vicinity of the Sun by observations of line widths of Lyman lines of D I and H I along the line of sight to various nearby stars (e.g., Rogerson and York, 1973; York and Rogerson, 1976; Murthy *et al.*, 1987). To some extent the determinations are model dependent. Murthy *et al.* (1987), who did a careful analysis of the model dependence of their results derived from IUE observations, conclude that a value of $\text{D}/\text{H} = 2 \times 10^{-5}$ is consistent with all observations in the directions to late-type stars. They also indicate that lower values of D/H towards several hot stars might be evidence for real variability of the deuterium abundance in the local interstellar medium.

Blitz and Heiles (1987) have recently searched for the 92 cm line of D I in the galactic anticenter direction and state that their results support a D/H value of $2-3 \times 10^{-5}$ in the solar neighbourhood. From this it is possible to derive a D/H ratio in the protosun by applying a correction for astration of the interstellar medium during the lifetime of the Sun. It should be noted at this point that in the interstellar medium deuterium might be strongly enriched in the dust component. This might not be relevant for the bulk D/H ratio of the interstellar medium, since the grain fraction is rather small. On the other hand, it cannot *a priori* be excluded that the dust component and, hence, D, was either depleted or enriched in the protosolar material during the formation of the Sun. This should be taken into account for the assessment of the protosolar D/H ratio from interstellar D/H values. Calculations by Morfill and Völk (1984) indicate that grain-gas separation could have depleted the grain component in the Sun by a factor of two. If hydrogen in the grainy fraction has a typical D/H ratio of 10^{-4} , the relative change of D/H in the protosun would only be 0.1 per mill, indistinguishable from the bulk interstellar material with $\text{D}/\text{H} = 2 \times 10^{-5}$.

A simple way of estimating possible contributions from grain-gas fractionation in the early solar nebula is obtained from the following considerations. Assume that both, the D/H and the C/H ratios in the interstellar gas, differ significantly from the grainy component according to the following list:

$$\left. \begin{aligned} (\text{H}/\text{C})_{\text{gas}} &= 2760 \\ (\text{D}/\text{C})_{\text{gas}} &= 0.094 \end{aligned} \right\} \text{ solar surface and solar nebula at } t = 0, \text{ respectively,} \\ \left. \begin{aligned} (\text{H}/\text{C})_{\text{grains}} &= 7.0 \\ (\text{D}/\text{C})_{\text{grains}} &= 0.0007 \end{aligned} \right\} \text{ Orgueil, carbonaceous chondrite.} \\ \text{(Anders and Grevesse, 1989)}$$

Then it is possible to compute the D/H ratio in any grain–gas mixture from these data:

$$D/H = \frac{x(D/C)_{\text{grains}} + (D/C)_{\text{gas}}}{x(H/C)_{\text{grains}} + (H/C)_{\text{gas}}};$$

x is the contribution ratio of carbon in the grainy and the gaseous form in the final mixture:

$$x = \frac{C_{\text{grains}}}{C_{\text{gas}}}.$$

Similarly, one can predict D/H ratios in various objects of the solar system. Using the H/C value of 1000 estimated by Gautier and Owen (1983) for the Jovian atmosphere, we obtain a value of $x = 1.8$ for Jupiter and practically no deviation of the Jovian D/H ratio from the primordial solar value. Uranus with a significantly lower estimated H/C ratio of 100 would give a D/H ratio of 4×10^{-5} , etc. For comet Halley, which exhibits a typical H/C ratio of 8 in the gas phase, very close to the Orgueil value, we would expect a D/H ratio of 10^{-4} , which is consistent with the estimate from the Giotto Neutral Mass Spectrometer data reported by Eberhardt *et al.* (1987).

In concluding this section we state that grain–gas separation probably played an important role in establishing the D/H ratio in the planetary bodies of the solar system, but not for the Sun itself. In other words, the solar D/H value can be considered as representative of the solar nebula. Caution has to be applied when inferring D/H ratios of the primitive solar nebula from the atmospheres of the outer planets and, of course, from comets (Geiss and Reeves, 1981).

3. Fractionation of Solar Wind Abundances with Respect to Solar Photosphere

It is well known that coronal abundances as derived from Solar Energetic Particles (SEP) show a clear ordering with respect to the first ionization potential of the elements involved. The same is true for solar wind abundances (see Gloeckler and Geiss, 1989, for a recent reference). Several mechanisms were proposed to explain the observed features (Geiss, 1982; Vauclair and Meyer, 1985; Geiss and Bochsler, 1985; Axford, 1986; von Steiger and Geiss, 1989a). In these models atom-ion separation is achieved by diffusion or transport out of magnetic structures in the chromosphere and the transition zone. The model of von Steiger and Geiss (1989a) succeeds in reproducing qualitatively and quantitatively the observed trends. For the subject of interest it is important to note that according to von Steiger and Geiss (1989a) the helium abundance in the corona is strongly influenced by the effective residence time of the gas within the magnetic structures. Fractionation by loss of neutral helium from such a structure might account for the apparent step between the relative abundances of neon and helium.

Since the fractionation effect involves mainly ionization properties of elements, and since M/Q ratios are involved only marginally, not much fractionation among the helium isotopes can be expected from this mechanism. From Figure 5 (von Steiger and Geiss,

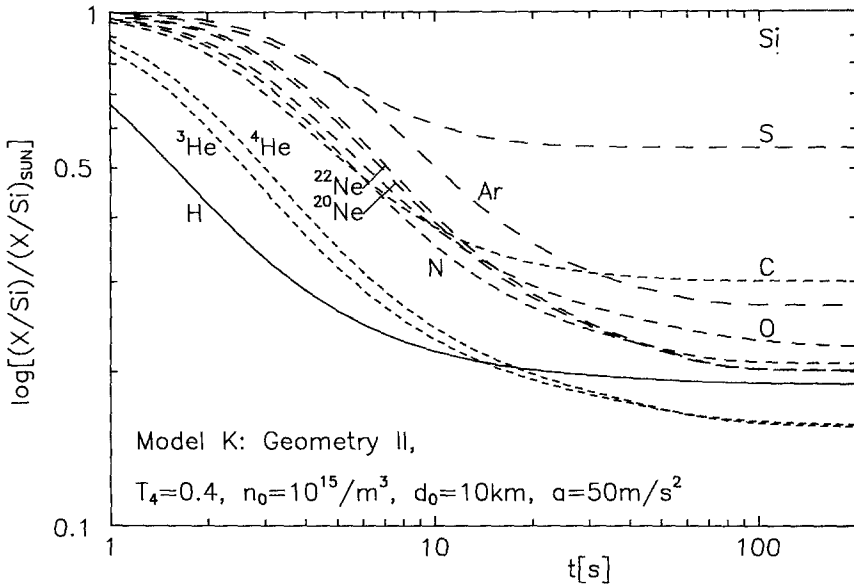


Fig. 5. Temporal evolution of isotopic abundances in the fractionation model of von Steiger and Geiss (1989a, b). Abundances in the solar wind are normalized with respect to oxygen and solar surface abundances. Results are given for model K which gives a particularly good match with observed elemental abundances. In this model material in a slab of 10 km diameter is experiencing an effective gravity of 50 m s^{-2} beginning from time $t = 0$. The fractionation effect for the helium isotopes is (typical for all models investigated so far) limited to 10 or 20%.

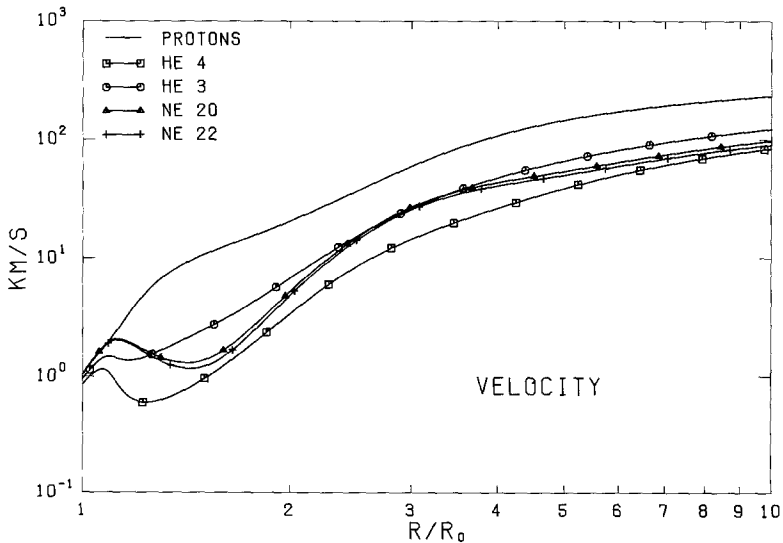


Fig. 6. Evolution of velocities of protons, ^4He , ^3He , ^{20}Ne , and ^{22}Ne in a coronal model of Bürgi and Geiss (1986). Due to the low Coulomb drag factor of $^4\text{He}^{++}$ this ion exhibits a dynamical behaviour significantly different from $^3\text{He}^{++}$ and the other ions. This might temporarily lead to a significant fractionation of helium isotopes in the corona (from Bürgi and Geiss, 1986).

1989b) it is evident that ^3He could be depleted relative to ^4He at most by 10–20% below the corona.

On the other hand, it was emphasized already twenty years ago (Geiss, Hirt, and Leutwyler, 1970) that the Coulomb drag factors of $^3\text{He}^{++}$ and $^4\text{He}^{++}$ differ substantially. Bürgi and Geiss (1986) have investigated models in which acceleration of ions by thermal pressure, waves, electric fields, and drag were taken in detailed account.

Their results show (Figure 6) that indeed substantial fractionation within the inner corona might occur. $^4\text{He}^{++}$ could be depressed relative to the minor ions including $^3\text{He}^{++}$ by several tens of percents under certain circumstances. Such a variation of ^4He relative to ^3He is supported by observations, e.g., from the SWC-experiment (Figure 2) and the ISEE-3/ICI-experiment (Figures 3 and 4).

4. Conclusions

We are now in a position to assess possible changes in the ^3He content of the outer convective zone during the Main-Sequence life of the Sun.

From the initial D/H ratio in the solar nebula (e.g., Murthy *et al.*, 1987; Anders and Grevesse, 1989),

$$\text{D/H}(0) = (3 \pm 1) \times 10^{-5},$$

and the initial $^3\text{He}/^4\text{He}$ ratio (Jeffery and Anders, 1970; Eberhardt, 1974),

$$^3\text{He}/^4\text{He}(0) \cong 1.4 \times 10^{-4},$$

we derive an overall pre-Main-Sequence $^3\text{He}/\text{H}$ ratio (after deuterium burning)

$$^3\text{He}/\text{H}(\text{PMS}) = (4.4 \pm 1.5) \times 10^{-5}.$$

Our best estimate for this ratio at the surface today is

$$^3\text{He}/\text{H} = (4.1 \pm 1.0) \times 10^{-5},$$

the corresponding relative mass number ratio is

$$X_3 = (9.0 \pm 2.4) \times 10^{-5}.$$

We have discussed the lack of evidence for a secular increase of the solar wind $^3\text{He}/^4\text{He}$ ratio in the lunar record in a previous section. The conclusions above show independently that there is not much room for such an increase.

The surface abundance of ^3He constitutes a most valuable test of the internal solar evolution, since it is very sensitive to transport processes occurring between the solar surface and deep interior regions. In standard models of the Sun at 4.6 Gy a peak of ^3He concentration is found near $r/R_0 = 0.28$ ($M_r/M_0 = 0.57$), the ^3He abundance is enhanced by a factor 30 over the initial value. At $r/R_0 = 0.505$ or $M_r/M_0 = 0.905$, the ^3He abundance is calculated to be 10% higher with respect to the initial value and there should be no increase at the surface according to these models (Figure 1). The other tracers Li and Be have a sensitivity limited to mixing processes in the outer layers,

while the $^{13}\text{C}/^{12}\text{C}$ ratio could potentially test deeper zones (peak at $r/R_0 = 0.179$ or $M_r/M_0 = 0.282$). Among recently proposed solar models, there are three sets on which ^3He may put constraints.

4.1. MODELS WITH TURBULENT DIFFUSION (cf. Schatzman and Maeder, 1981; Schatzman, 1983; Lebreton and Maeder, 1987)

In such models, the cascade of turbulence from horizontal meteorology-like motions due to rotation produces a 3-dimensional turbulence leading to a mild mixing of chemical species. Schatzman and Maeder (1981) and Lebreton and Maeder (1987) use an effective turbulence diffusivity D which is enhanced by a factor Re^* over the microscopic viscosity ν . An increase of ^3He by, say, 15% during the solar life corresponds in the framework of Lebreton and Maeder (Equations (3), (4), (5a)) to a value of $\alpha = 1.3$ or $\text{Re}^* = 25$ to 40 in regions where diffusion is not inhibited by the μ -gradient ($r/R_0 > 0.37$). Figure 7 is an illustration for the evolution of the ^3He abundance within a model calculated with the assumption $\alpha = 1.2$.

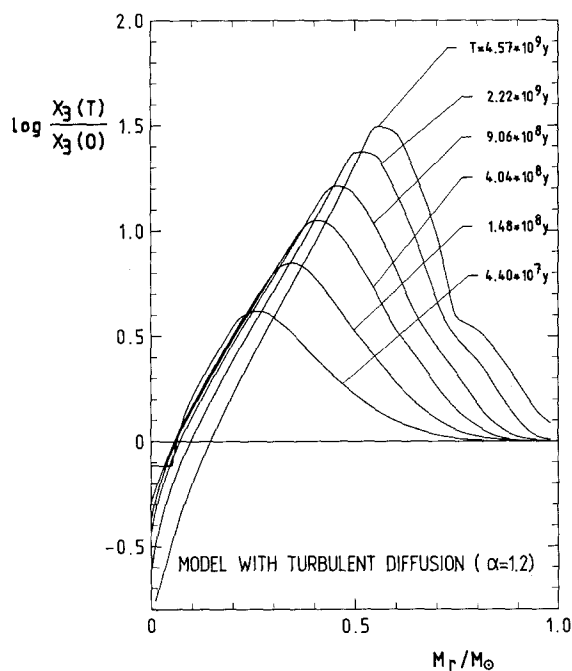


Fig. 7. Evolution of ^3He abundance in a model with turbulent diffusion (Lebreton and Maeder, 1987) with $\alpha = 1.2$. An enhancement of 22% occurs at the surface after 4.57×10^9 years.

However, these conclusions can be made less model dependent. Let us consider a diffusion of the form $D = \text{Re}^* \nu$ where Re^* is taken constant. Then, a maximum increase of ^3He at the solar surface of 10 to 20% imposes a maximum value for Re^* of 25 to 35. If we want to express this more generally in terms of the diffusion coefficients we

find $D = 78, 90, 105, 130, 205, 480, 610 \text{ cm}^2 \text{ s}^{-1}$ at $M_r/M_0 = 0.01, 0.2, 0.4, 0.6, 0.8, 0.95, 0.98$, respectively (for $\text{Re}^* = 30$). We notice that this mixing regime permitted by the ^3He data is of the same magnitude as the one permitted to account for solar oscillations in low-order g -modes (cf. also Cox *et al.*, 1985; Christensen-Dalsgaard, 1986; Lebreton and Maeder, 1987).

4.2. MODELS WITH TRANSPORT OF ANGULAR MOMENTUM (cf. Pinsonneault *et al.*, 1989)

These models involve the loss of angular momentum by magnetic winds and the redistribution of angular momentum by some rotational instabilities. Thus, the evolution of the internal angular velocity can be followed during the evolution. The various models made for different choices of the input parameters predict only small (i.e., 3%) enrichments in ^3He , which is well within the present observational requirements. On the other hand, if an enrichment of 10–20% were confirmed, these models could have some difficulty to account for it.

4.3. MODELS WITH A HIGH MASS LOSS (cf. Guzik *et al.*, 1987)

In these models the Sun is assumed to have started from an initial mass of about $2 M_\odot$ and to have reached its final mass in a few 10^8 years after losses by a very massive solar wind. These models predict an increase of the ^3He at the solar surface by an order of magnitude within the Sun's lifetime. Thus, such models are completely ruled out by the present data on ^3He . Moreover, the observations of Li in young clusters like the Pleiades (cf. Pilachowski, Booth, and Hobbs, 1987) show little depletion with respect to the interstellar matter. This constitutes a very severe constraint and shows that the total mass loss in the first 10^8 years is certainly smaller than about 3% of the stellar mass in solar-like stars.

As an overall conclusion, we emphasize again that the ^3He abundance places the most stringent constraint on the deep internal mixing in the Sun to a similar degree as the solar oscillations presently do.

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