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A Reestimate of the Protosolar $(^2\mathrm{H}/^1\mathrm{H})_\mathrm{p}$ ratio from $(^3\mathrm{He}/^4\mathrm{He})_\mathrm{SW}$ solar wind measurements

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Abstract. We reanalyze the inference of the protosolar abundance of deuterium made by Geiss (1993) from measurements of $(^3\mathrm{He}/^4\mathrm{He})_\mathrm{SW}$ in the solar wind. We use an evolutionary solar model with microscopic diffusion, constrained to fit the present age, radius and luminosity, as well as the observed ratio of heavy elements to hydrogen. The protosolar $(^2\mathrm{H}/^1\mathrm{H})_\mathrm{p}$ is obtained from the best fit of $(^3\mathrm{He}/^4\mathrm{He})_\mathrm{SW}$. Taking for the protosolar $(^3\mathrm{He}/^4\mathrm{He})_\mathrm{p}$ the value measured in Jupiter by the Galileo probe (Niemann et al. 1996), we derive $(^2\mathrm{H}/^1\mathrm{H})_\mathrm{p}= (3.01 \pm 0.17) \times 10^{-5}$. Compared to the present interstellar medium value (Linsky et al. 1993), this result is compatible with models of the chemical evolution of the Galaxy in the solar neighborhood; it is also marginally compatible with the Jovian $(^2\mathrm{H}/^1\mathrm{H})_\mathcal{J}= (5 \pm 2) \times 10^{-5}$ ratio measured by Galileo.

Key words: Nuclear reactions, nucleosynthesis, abundances – Sun: abundances – Solar system: formation

1. Introduction

Since the pioneering work of Geiss & Reeves (1972), a number of papers have been devoted to the fundamental question of the estimate of the protosolar abundance of deuterium as reviewed by Geiss (1993), hereafter referred as G93. The current value of $(^2\mathrm{H}/^1\mathrm{H})_\mathrm{p}= (2.6\pm 1.0)\times 10^{-5}$, is that derived by G93 from a reanalysis of the measurements of $(^3\mathrm{He}/^4\mathrm{He})_\mathrm{SW}$ in the Solar Wind (SW).

At the end of the pre-main sequence the young Sun is still fully convective with a temperature, at center, of a few million K; the mixing makes that all the deuterium is converted to $^3\mathrm{He}$ via the reaction $^2\mathrm{H}(p,\gamma)^3\mathrm{He}$. As pointed out by Geiss & Reeves (1972), if $(^4\mathrm{He}/^1\mathrm{H}) \equiv 0.1$ is no longer changed at the surface then, $(^2\mathrm{H}/^1\mathrm{H})_\mathrm{p}$ is equal (G93) to $(^4\mathrm{He}/^1\mathrm{H})_\mathrm{p}$ times the difference between $(^3\mathrm{He}/^4\mathrm{He})_\odot$ presently observed at the surface and the protosolar $(^3\mathrm{He}/^4\mathrm{He})_\mathrm{p}$:

$$\left(\frac{^2\mathrm{H}}{^1\mathrm{H}}\right)_\mathrm{p} = \left(\frac{^4\mathrm{He}}{^1\mathrm{H}}\right)_\mathrm{p} \left[\left(\frac{^3\mathrm{He}}{^4\mathrm{He}}\right)_\odot - \left(\frac{^3\mathrm{He}}{^4\mathrm{He}}\right)_\mathrm{p}\right].$$

$(^3\mathrm{He}/^4\mathrm{He})_\odot$ is measured only in the solar wind, from the data available G93 concluded to $(^3\mathrm{He}/^4\mathrm{He})_\mathrm{SW}= (4.5 \pm 0.4) \times 10^{-4}$. However G93 analyzing the various processes which may fractionate the helium isotopes in the interior and in the atmosphere of the Sun, has estimated that the actual ratio to be considered for inferring $(^2\mathrm{H}/^1\mathrm{H})_\mathrm{p}$ is the solar wind value divided by a factor 1.1 ± 0.2, resulting in $(^3\mathrm{He}/^4\mathrm{He})_\odot= (4.1 \pm 1.0) \times 10^{-4}$. $(^3\mathrm{He}/^4\mathrm{He})_\mathrm{p}$ has been estimated by G93 from meteoritic data to be equal to $(^3\mathrm{He}/^4\mathrm{He})_\mathrm{p}= 1.5 \times 10^{-4}$.

An other way to determine the protosolar deuterium abundance is to evaluate $(^2\mathrm{H}/^1\mathrm{H})_\mathcal{J}$ in Jupiter. This approach is based on the fact that Jupiter is mainly made of hydrogen which originates from the primordial solar nebula. According to current models of formation of Jupiter, some amount of ices, presumably enriched in deuterium with respect to the protosolar value, may have been mixed to hydrogen during the planetary formation, but their mass is currently considered as too small to have significantly increased $(^2\mathrm{H}/^1\mathrm{H})_\mathcal{J}$ (Hubbard & MacFarlane 1980). Although the various estimates of $(^2\mathrm{H}/^1\mathrm{H})_\mathcal{J}$ from remote sensing observations of HD and of CH_3H are uncertain, it was generally considered, prior to the arrival of the Galileo mission to Jupiter, that the Jovian deuterium abundance is consistent with the G93 value (Lecluse et al. 1996). The preliminary result of the mass spectrometer aboard the Galileo atmospheric probe – $(^2\mathrm{H}/^1\mathrm{H})_\mathcal{J}= (5 \pm 2) \times 10^{-5}$ (Niemann et al. 1996) – is however substantially higher than the G93 value. This result, if confirmed, would have profound cosmological implications.

Compared to the present day InterStellar Medium (ISM) value of $(^2\mathrm{H}/^1\mathrm{H})_\mathrm{IMS}= (1.47 - 1.72) \times 10^{-5}$ (Linsky et al. 1993), it suggests a deuterium destruction in

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4.55 Gyr, the solar age, inconsistent with current models of chemical evolution of galaxies. Alternatively, it might be that $(^2H/^1H)_{IMS}$ varies upon the line of sight so that, the concept of a well defined ISM deuterium abundance is not reliable, as advocated by some authors e.g., Ferley et al. (1995). A third possibility is that the current protosolar value $(^2H/^1H)_p$, is underestimated.

Two circumstances prompted us to reanalyze the determination of G93: – *First*, Niemann et al. (1996) have measured in Jupiter $(^3He/^4He)_{\mathcal{J}} = 1.1 \times 10^{-4}$ which must be the exact ratio in the primitive solar nebula. As pointed out by these authors, this results in an increase of the estimation of $(^2H/^1H)_p$. – *Second,* since 1993 the introduction of microscopic diffusion in solar modeling have significantly increased the accuracy of models (e.g., Basu et al. 1996). A consequence of the microscopic diffusion is the change, with respect to time, of surface values of $(^4He/^1H)$ and $(^3He/^4He)$. A result directly relevant to this Letter is the inferred helium mass fraction at the surface namely $Y_\odot = 0.242 \pm 0.003$ (Pérez Hernández & Christensen-Dalsgaard 1994) substantially less than the protosolar value $Y_p = 0.275$ (Bahcall & Pinsonneault 1995). Therefore, we propose here to complete the approach of G93 by using a solar evolutionary model with microscopic diffusion. The modeling of the solar evolution and the data employed are described in Section 2; Section 3 is devoted to results and discussions. We conclude in Section 4.

2. Solar modeling and data

The calibrated solar models discussed in this paper include the pre-main sequence evolution. The calibration consists in the adjustment of, i) the ratio of the mixing-length to the pressure scale height, ii) the initial mass fraction X_p of hydrogen and, iii) the initial protosolar mass fraction of heavy elements to hydrogen, in order that the models have at present solar age, the observed luminosity, radius (Guenter et al. 1992) and mass fraction of heavy elements to hydrogen (Grevesse & Noels 1993). The models have been computed using the code CESAM (Morel 1997). The relevant features are: the changes due to nuclear reactions, microscopic diffusion and convective mixing are explicitly computed for ^{1}H, ^{2}H, ^{3}He, ^{4}He, ^{7}Li, ^{7}Be, ^{12}C, ^{13}C, ^{14}N, ^{15}N, ^{16}O and ^{17}O which enter into the most important nuclear reactions of the PP+CNO cycles; the protosolar abundance of each heavy element is derived from X_p according to the nuclide abundances of Anders & Grevesse (1989); $(^3He/^4He)_p$ is taken equal to $(^3He/^4He)_{\mathcal{J}} = 1.1 \times 10^{-4}$ as measured by the Galileo probe into Jupiter; the microscopic diffusion coefficients of Michaud & Proffitt (1993) are used, all species, but ^{1}H and ^{4}He, are trace elements. $(^2H/^1H)_p$ is taken as a parameter and constrained to fit $(^3He/^4He)_\odot$.

As pointed out by G93, ^{3}He could be somewhat favored over ^{4}He in the solar wind acceleration process (Burgi & Geiss 1986). However, the first results of the SWICS instrument aboard the Ulysses spacecraft (Bodmer et al. 1995) do not provide evidence that such a fractionation could exceed the uncertainties on the measurements of the helium isotopic ratio. Moreover, the chromospheric process is not expected to result in a significant mass fractionation (G93). Therefore we assume that $(^3He/^4He)_\odot$ is equal, within uncertainties, to $(^3He/^4He)_{SW}$. The values

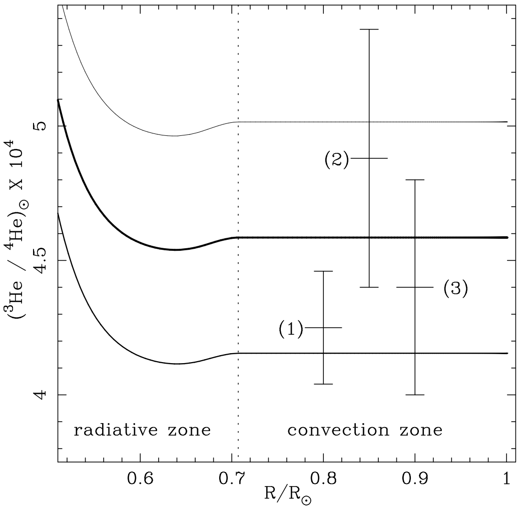

Fig. 1. Profiles of $(^3He/^4He)$ in envelopes of solar models computed with $(^2H/^1H)_p$: $3.2\,10^{-5}$ (thick), $3.6\,10^{-5}$ (medium) and $2.8\,10^{-5}$ (thin). The observed $(^3He/^4He)_{SW}$ from APOLLO (1), ISEEE-3 (2) and Ulysses (3) are plotted with their error bars.

of $(^3He/^4He)_{SW}$ obtained by three experiments on three different space missions are:

(1) Apollo $(^3He/^4He)_{SW} = (4.25 \pm 0.21) \times 10^{-4}$ (Geiss et al. 1972),
(2) ISSEE-3 $(^3He/^4He)_{SW} = (4.88 \pm 0.48) \times 10^{-4}$ (Coplan et al. 1984, Bochsler 1984),
(3) Ulysses $(^3He/^4He)_{SW} = (4.4 \pm 0.4) \times 10^{-4}$ (Bodmer et al. 1995).

3. Results and Discussion

For models initialized for various values of $(^2H/^1H)_p$, the $(^3He/^4He)$ profiles are plotted Fig. 1 for $R \gtrsim 0.55 R_\odot$ and compared to the three observed $(^3He/^4He)_{SW}$ values. According to these models, $(^2H/^1H)_p$ can be fitted by the quadratic polynomial:

$$(^2H/^1H)_p = 2.675 \times 10^{-5} + (9.364 \times 10^{-2} - 2.452x)x. \quad (1)$$

here $x \equiv (^3He/^4He)_\odot - 4.0 \times 10^{-4}$, $(^3He/^4He)$ profiles within $0 \leq R \leq 1.2 R_\odot$ are plotted Fig. 2 at various ages of a solar model computed with $(^2H/^1H)_p = 3.01 \times 10^{-5}$. During the pre-main sequence ^{2}H is converted to ^{3}He and,

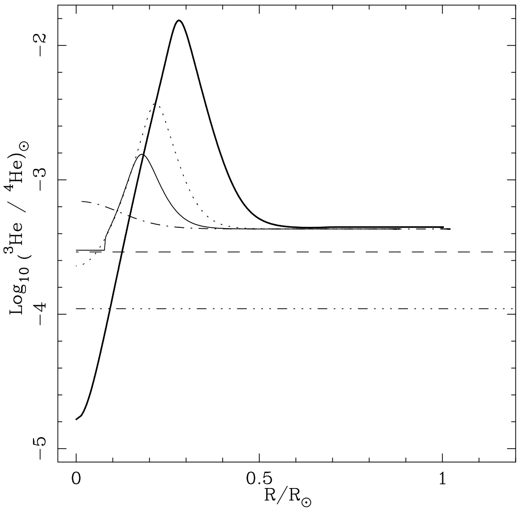

Fig. 2. (^{3}He/^{4}He) profiles for $R \leq 1.2R_\odot$, in a solar model initialized with (^{2}H/^{1}H)$_\mathrm{p}$= 3.01×10^{-5} for various ages: 0 Myr (dash-dot-dot-dot), 0.138 Myr (dashed), 20 Myr (dash-dot-dash), 49.1 Myr (thin full), 200 Myr (dotted) and 4550 Myr (thick full).

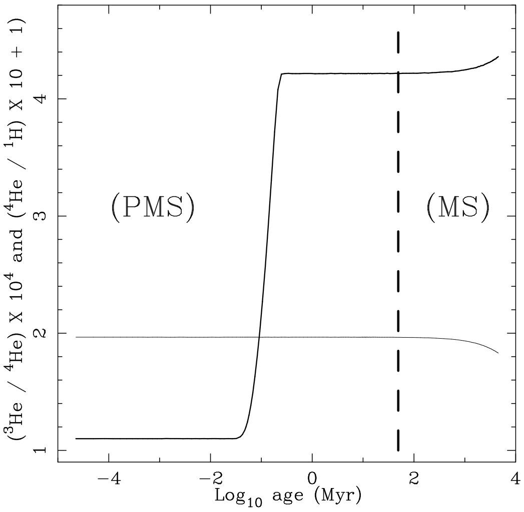

Fig. 3. Changes of (^{3}He/^{4}He) (thick) and ^{4}He/^{1}H (thin) ratios (*with different scaling*) at surface with respect to time for the solar model of Fig. 2. The dashed heavy line (49 Myr) separates the pre-main sequence (PMS) from the main sequence (MS).

due to mixing, (^{3}He/^{4}He) increases through the model. At time t =∼ 20 Myr the convection zone has receded almost to its present days location, at center, the temperature is not high enough to convert ^{3}He into ^{4}He via He^3(He^3,2p)^{4}He, then (^{3}He/^{4}He) is maximum there. At t =∼ 49 Myr i.e., zero age main sequence, the flat profile of (^{3}He/^{4}He) for radius $R \lessapprox 0.1R_\odot$, is due to the mixing in the convective core resulting form the conversion of ^{12}C into ^{14}N; then the nuclear reactions reach their equilibrium. Around the center the increase of ^{4}He depresses (^{3}He/^{4}He) and its maximum progressively reaches its present days location around $0.3R_\odot$; the gravitational settling being more efficient for ^{4}He than for ^{3}He, at surface (^{3}He/^{4}He) *slowly increases* until present days. As seen in Fig. 3, along the evolution, (^{3}He/^{4}He) varies from 1.10×10^{-4} to 4.361×10^{-4} and (^{4}He/^{1}H) from 0.0966 to 0.0830.

Using Eq. 1 the three observed (^{3}He/^{4}He)$_\mathrm{SW}$ values allow to infer:

(1) (^{2}H/^{1}H)$_\mathrm{p}$= $(2.91 \pm 0.19) \times 10^{-5}$,
(2) (^{2}H/^{1}H)$_\mathrm{p}$= $(3.50 \pm 0.43) \times 10^{-5}$,
(3) (^{2}H/^{1}H)$_\mathrm{p}$= $(3.05 \pm 0.36) \times 10^{-5}$.

Assuming no systematic errors, the weighted mean of these determinations results in:

$$(^2\mathrm{H}/^1\mathrm{H})_\mathrm{p} = (3.01 \pm 0.17) \times 10^{-5}.$$

Niemann et al. (1996) have derived a similar value but using our (^{3}He/^{4}He)$_\mathrm{p}$= 0.0966 value, they would have found (^{2}H/^{1}H)$_\mathrm{p}$= $(2.9 \pm 1) \times 10^{-5}$.

Our new estimate of (^{2}H/^{1}H)$_\mathrm{p}$ overlaps within the domain of uncertainty the Galileo result. At this point, we can thus consider that it is consistent with Galileo. However, it rules out Jovian values higher than (^{2}H/^{1}H)$_\mathcal{J} \gtrsim$ $3.18\,10^{-5}$ if we assume that Jupiter is representative of the isotopic composition of the nebula. As mentioned in Sect. 1, (^{2}H/^{1}H)$_\mathcal{J}$ results from a mixing of hydrogen originating from the nebula – and thus in protosolar abundance – with ices more or less enriched in deuterium. Assuming that the two reservoirs equilibrated at high temperature at the time of the formation of the planet, the present hydrogen in Jupiter may have been somewhat enhanced in deuterium if the amount of ices was large enough. This question deserves to be reexamined in the light of the most recent models of interiors of Jupiter. Following Hubbard & MacFarlane (1980), the deuterium enhancement is a function of the mass M_i of the ices embedded in Jupiter and of their deuterium enrichment f with respect to the protosolar value. According to Guillot et al. (1997), the amount of ices should not exceed 32 Earth masses in the extreme case. The value of the enrichment f depends on the origin of Jovian protoices. They may have been formed in the solar nebula, which implies that f not to exceed 2.5. In such a case, the deuterium enhancement in Jupiter is negligible. Alternatively, ices may have originated directly from the protosolar cloud following the scenario discussed by Lunine et al. (1991) and would have then kept their interstellar isotopic signature. The recent determinations of (^{2}H/^{1}H) in water in P/Halley (Eberhardt et al. 1995) and in Hyakutake comet (Gautier et al. 1996) suggest f of the order of 10. This *maximum* scenario then results in a deuterium enhancement of 20%. Accordingly, (^{2}H/^{1}H)$_\mathcal{J}$

should then be equal to $(^2\mathrm{H}/^1\mathrm{H})_{\mathcal{J}} = (3.65 \pm 0.2) \times 10^{-5}$, entirely within the error bars of the Galileo value.

Ground based remote sensing determinations of $(^2\mathrm{H}/^1\mathrm{H})_{\mathcal{J}}$ conclude to values less than 3.0×10^{-5} (Lecluse et al. 1996), in conflict with the *maximum* enrichment scenario. The preliminary analysis of observations from ISO suggest similar results (Encrenaz et al. 1996). In contrast, the reanalysis of the Voyager infrared observations by Carlson et al. (1993) results in $(^2\mathrm{H}/^1\mathrm{H})_{\mathcal{J}}$ between 3.7×10^{-5} and 6.0×10^{-5} (Lecluse et al. 1996), a value compatible with the *maximum* enrichment scenario. Preliminary results of HST observations of the Lyman α emission of Jupiter (Ben Jaffel et al. 1996) give $(^2\mathrm{H}/^1\mathrm{H})_{\mathcal{J}} = (5.9 \pm 1.4) \times 10^{-5}$, a value much higher than the upper limit of the *maximum* enrichment case.

In summary, we cannot yet decide whether the abundance of deuterium in Jupiter is representative of the protosolar value or if it has been somewhat enhanced during the planetary formation.

The lower limit of our revised protosolar $(^2\mathrm{H}/^1\mathrm{H})_{\mathrm{p}}$ value, namely $(^2\mathrm{H}/^1\mathrm{H})_{\mathrm{p}} = 2.83 \times 10^{-5}$, is higher than the upper limit of the ISM determination of Linsky et al. (1993), by a factor 1.6. This is consistent with the evolution in 4.55 Gyr of the deuterium abundance in the solar neighborhood, estimated from models of chemical evolution of the Galaxy with infall of primordial composition (Prantzos 1996). Obtaining higher depletion factors requires different models which invoke galactic winds in the Galaxy (Vangioni-Flam & Casse 1995).

4. Conclusion

We propose for the protosolar deuterium abundance: $(^2\mathrm{H}/^1\mathrm{H})_{\mathrm{p}} = (3.01 \pm 0.17) \times 10^{-5}$. This result is based on observed values of $(^3\mathrm{He}/^4\mathrm{He})_{\mathrm{SW}}$ in the solar wind and of $(^2\mathrm{H}/^1\mathrm{H})_{\mathcal{J}}$ on Jupiter; it takes into account the microscopic diffusion of elements in solar modeling. Systematic errors could occurs: i) although not yet detected, a fractionation between ^{3}He and ^{4}He could occur between the surface and the solar wind, resulting in a small decrease of the inferred $(^2\mathrm{H}/^1\mathrm{H})_{\mathrm{p}}$, ii) microscopic diffusion coefficients could be revised, affecting the calculation of $(^3\mathrm{He}/^4\mathrm{He})_{\odot}$. The new protosolar value is consistent with the lower range of the preliminary determination of $(^2\mathrm{H}/^1\mathrm{H})_{\mathcal{J}}$ in Jupiter obtained by the Galileo mass spectrometer. The difference between our value and the present ISM value of Linsky et al. (1993) is compatible with some models of the chemical evolution of the Galaxy. Our result does not significantly changes the sum $(^2\mathrm{H}/^1\mathrm{H})_{\mathrm{p}} + (^3\mathrm{He}/^1\mathrm{H})_{\mathrm{p}} = 4.07 \times 10^{-5}$, from its previous estimate of 4.1×10^{-5} by G93. In fact, using our value $(^4\mathrm{He}/^1\mathrm{H})_{\mathrm{p}} = 0.0966$, this author would have found 4.05×10^{-5}.

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