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On the Destruction of Primordial Deuterium

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Abstract: Agreement between the predictions of standard big bang nucleosynthesis and the observed abundances of the light elements is achieved for a small range in values of the baryon to photon ratio, η near 3×10^{-10} . At that value of η , the primordial deuterium abundance is about 7.5×10^{-5} . ISM measurements of D indicate a present abundance 5 times smaller. Chemical evolution models are explored to achieve this degree of D destruction. Consistency with the ^3He production in low mass stars and with the abundance of cosmo-chronometers is also discussed.

Overall, the standard model of big bang nucleosynthesis is regarded to be a consistent theory on the abundances of the light elements D, ^3He , ^4He , and ^7Li [1]. What's more, consistency is achieved for a narrow range of what is now perhaps the single remaining parameter of the theory, namely the baryon-to-photon ratio $\eta = n_B/n_\gamma \simeq 3 \times 10^{-10}$. At this value of η , the primordial mass fraction of ^4He is $Y_P \simeq 0.24$, and the abundances by number with respect to H, for D, ^3He and ^7Li are: $\text{D}/\text{H} \simeq 7.5 \times 10^{-5}$, $^3\text{He}/\text{H} \simeq 1.5 \times 10^{-5}$ and $^7\text{Li}/\text{H} \simeq 10^{-10}$. This ^4He abundance is consistent (though on the high side) with observations (see eg. [2]) as is the ^7Li abundance [3]. It is difficult to compare the primordial deuterium and ^3He abundances with the observations. Despite the fact that all observed deuterium is primordial, deuterium is destroyed in stars. A comparison between the predictions of the standard model and observed solar and interstellar values of deuterium must be made in conjunction with models of galactic chemical evolution. The problem concerning ^3He is even more difficult. Not only is primordial ^3He destroyed in stars but it is very likely that low mass stars are net producers of ^3He . Thus the comparison between theory and observations is complicated not only by our lack of understanding regarding chemical evolution but also by the uncertainties in production of ^3He in stars.

Given the above primordial D abundance, it appears that D/H has decreased over the age of the galaxy. The (pre)-solar system abundance of deuterium is $\text{D}/\text{H} \approx (2.6 \pm 1.0) \times 10^{-5}$ [4], corresponding to an age $t \sim 9$ Gyr, while the present ($t \sim 14$ Gyr) ISM abundance of D/H is 1.65×10^{-5} [5]. Thus it would appear that significant destruction of deuterium is necessary. Note that there is

a reported detection of D in a high redshift, low metallicity quasar absorption system [6] with an abundance which may be the primordial one. Due to the still somewhat preliminary status of this observation and the fact that it can also be interpreted as a H detection in which the absorber is displaced in velocity by 80 km s^{-1} with respect to the quasar [7], we do not fix the primordial abundance with that value. In any case, such a high value for the D abundance would require an even greater degree of D destruction over the age of the galaxy.

To obtain an overall destruction factor of ~ 5 for deuterium, Vangioni-Flam, Olive and Prantzos [8], considered a number of simple chemical evolution models with various star formation rates (SFRs) and initial mass functions (IMFs).

Table 1. Simple chemical evolution models

	IMF	SFR
I_a	$\propto m^{-2.7}$	$\propto M_{\text{Gas}}$
I_b	Tinsley	$\propto M_{\text{Gas}}$
II_a	Scalo	$\propto e^{-t/\tau}$
II_b	$\propto m^{-2.7}$	$\propto e^{-t/\tau}$

The evolution of D is a straightforward calculation. It is assumed that D is totally destroyed in stars. The instantaneous recycling approximation can give us a good indication of which models will destroy D efficiently (though this approximation was not used in the calculations). The rate of change for the mass in gas, $\sigma = M_{\text{Gas}}/M_{\text{tot}}$ is given by

$$\frac{d\sigma}{dt} = -(1 - R)\psi(t) \quad (1)$$

where R is the return fraction

$$R = \int (m - m_{\text{rem}})\phi(m)dm \quad (2)$$

for an IMF, ϕ , and a SFR, ψ . m_{rem} is the mass of a remnant. (See [8] for details.) The evolution of the D abundance, X_D , is described by

$$\frac{dX_D\sigma}{dt} = -X_D\psi(t) \quad (3)$$

giving a final D abundance relative to the primordial D, D_p

$$\frac{D}{D_p} = \sigma^{R/(1-R)} \quad (4)$$

With a present-day gas mass fraction $\sigma = 0.1$, one sees that $R \sim 0.2$ gives $D/D_p \sim 1/2$ whereas models with a return fraction $R \sim 0.5$ will give $D/D_p \sim 1/10$. Clearly, the degree to which deuterium is destroyed is very sensitive to the chemical evolution model.

In Figs. 1 and 2, the evolution of D/H is shown for the models considered. As one can see, a total deuterium destruction factor of 5 is certainly achievable in these simple models.

Fig. 1. The evolution of the D/H ratio as a function of time for the different models

Fig. 2. As in Fig. 1 for model IIa with different time constants $\tau = 3$ (a); $\tau = 5$ (b); $\tau = 10$ (c)

The destruction of deuterium, however, is intimately connected to the question of the ^3He abundance. First of all, during the pre-main-sequence, essentially all of the primordial D is converted into ^3He . Some of the pre-main-sequence produced and primordial ^3He will survive in stars and may even be produced [9]. If $g_3 = \frac{(^3\text{He}/\text{H})}{(D + ^3\text{He})/\text{H}}$ is the fraction of ^3He that survives stellar processing, then the ^3He abundance at a time t is at least

$$\left(\frac{^3\text{He}}{\text{H}}\right)_t \geq g_3 \left(\frac{D + ^3\text{He}}{\text{H}}\right)_p - g_3 \left(\frac{D}{\text{H}}\right)_t \quad (5)$$

The inequality comes about by neglecting any net production of ^3He . Of course, this equation can be rewritten as an upper limit on $(D + ^3\text{He})/\text{H}$ in terms of the observed pre-solar abundances ($t = \odot$) and g_3 as was done in [10] and yields a lower bound to η . Neglecting ^3He production, and assuming only that $g_3 > 0.25$ a limit $\eta > 2.8 \times 10^{-10}$ is derived. The evolution of $(D + ^3\text{He})/\text{H}$ for the models shown in Figs. 1 and 2 is shown in Figs 3 and 4.

Finally, I address the question regarding the consistency of deuterium destruction and the nuclear cosmochronometers $^{232}\text{Th}/^{238}\text{U}$ and $^{235}\text{U}/^{238}\text{U}$ [11]. In addition to choosing a SFR and an IMF, to obtain the correct ratio for the chronometers corresponding to a reasonable age to the Galaxy requires some infall of gas onto the Galaxy (assumed primordial) and a burst of star formation providing an initial enrichment [12]. In general the abundance ratio of the chronometers will depend on the lifetime of the radioactive isotopes, their stellar production factors, the infall rate rate, and the degree of initial enrichment. By choosing the latter two, fitting the abundance ratios to their observed values leads to an age for the Galaxy. Indeed, many such models were found [11] which gave consistent ages ranging from 9.8 to 21.6 Gyrs. Best fit solutions however, tended to result in a somewhat low present day gas mass fraction (5%)

Fig. 3. As in Fig. 1, for the evolution of $(D + ^3\text{He})/\text{H}$

Fig. 4. As in Fig. 2, for the evolution of $(D + ^3\text{He})/\text{H}$

Thus, it is clear that models of galactic chemical evolution can be found which destroy D by a significant factor. Cosmochronology imposes restrictions on these models but many solutions can still be found. The main problem will reside with the ^3He abundance when production factors are taken into account [13].

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