Giant Branch Mixing and the Ultimate Fate of Primordial Deuterium in the Galaxy

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ABSTRACT

The observed cosmic abundances of light elements are most consistent with each other, and with the predictions of big bang nucleosynthesis, if, contrary to the usual assumption, galactic chemical evolution reduces \((D + ^3\text{He})/H\) with time. Chemical evolution models which do this require that low mass stars destroy \(^3\text{He}\) in the envelope gas that they return to the interstellar medium. A simple argument based on the rates of limiting nuclear reactions shows that the same giant branch mixing process which appears to be needed to explain the observed \(^{12}\text{C}/^{13}\text{C}\) and \(C/N\) ratios in \(1–2\, M_\odot\) stars would indeed also probably destroy \(^3\text{He}\) by a large factor in the bulk of the envelope material. The conclusion is that Galactic \(^3\text{He}/H\) estimates should not be trusted for setting an upper limit on primordial \((D + ^3\text{He})/H\). This removes the strongest lower bound on the cosmic baryon density from big bang nucleosynthesis and the only argument for abundant baryonic dark matter.

Subject headings: cosmology: theory; Galaxy: abundances
1. Is $D + ^3He$ Destroyed in the Galaxy?

Almost all cosmic deuterium is a relic of primordial nucleosynthesis. But since the big bang, successive generations of stars have destroyed most of it by burning to heavier elements. Constraints on the primordial deuterium abundance $(D/H)_p$ have been deduced from $D$ abundances in the reprocessed material in the Galactic interstellar medium and from the local abundances of the principal immediate product of $D$ burning, $^3He$. I suggest here that these deductions may be wrong, because the $^3He$ abundance in the Galaxy is likely to be strongly affected by the post main sequence mixing that seems to be required by observations of $^{12}C/^{13}C$ and $C/N$ in low mass stars. If this is so, Galactic $^3He/H$ estimates should not be trusted as indicators of the primordial $D/H$ abundance, because they are so sensitive to uncalibrated aspects of stellar evolution models. This argument suggests that primordial $D/H$ should be estimated instead from relatively unprocessed material, such as protogalactic quasar absorbers at high redshift.

It is important to resolve this question. The abundance of $^3He$ currently gives the only upper limit on the primordial $D/H$, and thereby the only strong lower limit on the cosmic baryon-to-photon ratio $\eta$ from standard big bang nucleosynthesis theory (SBBN; see eg Smith, Kawano, and Malaney 1993, Copi, Schramm and Turner 1994)— in particular, the only lower limit appreciably higher than observed density of baryons. It therefore provides the only argument for abundant baryonic dark matter. If this lower limit were relaxed, the range of allowed $\eta$ includes lower values where the predicted $^4He$ abundance lies more comfortably close to observations, where the bound on the number of particle species is relaxed, and where there is almost no baryonic dark matter.

In the standard picture the bulk of primordial $D$ in the Galaxy is burned to $^3He$ in protostellar collapse. Galactic chemical evolution models (Steigman and Tosi 1992, Vangioni-Flam, Olive and Prantzos 1994 [VFOP]) show that $D/H$ can be reduced in this
way to its present interstellar value ($\approx 1.5 \times 10^{-5}$, Linsky et al 1992) from any plausible initial value. However, in the low mass stars which now dominate the chemical recycling of the interstellar medium (ISM), the bulk of the material is assumed to be never heated to the higher temperature required to burn the $^3He$, so the bulk of the primordial $D$ thus reappears in the ISM as $^3He$ when the envelopes are ejected. For the galaxy as a whole, the sum $(D + ^3He)/H$ therefore only increases with time, so that this quantity can be used to set constraints on $(D/H)_p$.

But there are empirical reasons for thinking that stellar populations on average actually get rid of $^3He$.

The most widely used measure of $^3He/H$ comes from measurements of the solar wind, both from direct exposure experiments and from meteorites, of $^3He/^{4}He$ (Geiss 1993). These are used to infer that the abundances of the presolar nebula by number were $D/H = 2.6 \pm 1.0 \times 10^{-5}$, $^3He/H = 1.5 \pm 0.3 \times 10^{-5}$, $(D + ^3He)/H = 4.1 \pm 1.0 \times 10^{-5}$. These are the most common numbers taken as Galactic or solar-circle averages for the purpose of defining constraints on primordial abundances.

The only other useful measure of cosmic $^3He/H$ comes from radio emission maps of highly ionized HII regions in the Galaxy (Balser et al 1994, Wilson and Rood 1994). The column density of $^3He^+$ is estimated from the brightness in the 8.665 GHz hyperfine transition line, and the column (squared) density of $H^+$ or $^{4}He^+$ is estimated from radio recombination lines. Balser et al. use this data and a simple model of the gas distribution to obtain reliable estimates of $^3He/H$ in 7 Galactic HII regions, and “preliminary” abundances and limits in 7 more. Two of the most reliable ones are W43 and W49, with low values $^3He/H = 1.13 \pm 0.1 \times 10^{-5}$ and $^3He/H = 0.68 \pm 0.15 \times 10^{-5}$ respectively. There appears to be a real range of values, with W3 for example measured at $^3He/H = 4.22 \pm 0.08 \times 10^{-5}$, and some are consistent with still higher values. There may be a trend with galactocentric
radius in the sense that lower values tend to lie within the solar orbit and higher values outside it.

Note that these results do not mesh with the standard picture.

1. The Solar System value \((D + ^3He)/H\) is greater than the interstellar one; if \((D + ^3He)/H\) were steadily increasing, it ought to be less, because of the elapsed time since the formation of the solar system.

2. The ISM shows large variations in \(^3He/H\), which argues that one ought not take any one point, such as the solar system, as an average of the Galactic abundance.

3. The gradient with Galactic radius goes the wrong way; if stars are creating \(^3He\) on average, it ought to be highly enriched towards the Galactic center, like other heavier elements are.

4. If we adopt the lowest \(^3He/H\) value in ISM (W49) as the primordial one, assuming that the additional \(^3He\) found at other sites is Galactic in origin as required in the standard picture, the very low value requires a large \(\eta \approx 2 \times 10^{-9}\), in which case SBBN predicts an excessive \(^4He\) abundance \(Y_p \approx 0.26\). The observed value is \(Y_p = 0.228 \pm 0.005\) (Pagel et al 1992, see also Skillman and Kennicutt 1993), which is marginally inconsistent even with the SBBN prediction for solar \(^3He/H\), \(Y_p = 0.242\).

The recent determination of \(D/H \approx 2.5 \times 10^{-4}\) in a high redshift quasar absorber (Songaila et al 1994, Carswell et al 1994) highlights the problems of interpreting the Galactic abundances. This estimate is more than an order of magnitude larger than the interstellar \(D/H\) values and a factor of 5 more than the solar system estimates. If it is a real detection of deuterium it gives a firm upper limit on \(\eta\), since the big bang is the unique source of deuterium. With the small \(\eta \approx 1.5 \times 10^{-10}\) implied by this measurement, SBBN works better, predicting close to the observed \(^4He\) abundance \((Y_p = 0.231)\), and requiring a baryon
density $\Omega h^2 = 0.005$ close to that found today in stars in gas, $\Omega h = 0.003$, so the amount of baryonic dark matter is not large compared to that already seen. Bearing in mind that this is still based on just one object which may be contaminated by a hydrogen interloper masquerading as deuterium, there is also no reason to doubt this number, except for the inconsistency with the standard interpretation of the Galactic $^3He/H$ measurements. In the long run this type of measurement may be much more reliable, since the abundance is measured in pristine material, as demonstrated by its very low observed metal abundances; at the very least, it allows a sampling of a wider variety of environments.

Even without this result, the simplest interpretation of the empirical evidence in the Galaxy is that stellar populations, on average, tend to destroy not only deuterium but also the $^3He$ that comes from it.

This simple picture has been elaborated by quantitative models of Galactic chemical evolution (Vangioni-Flam, Olive and Prantzos 1994). In these models, the fraction of initial $(D + ^3He)/H$ returned is regarded as a free parameter, or as an adjustable function of stellar mass, $g_3$. Motivated by the need to improve SBBN consistency, VFOP showed that $(D + ^3He)/H$ could be reduced in a model of galactic chemical evolution, but only if low-mass stars are net destroyers of $^3He$ (i.e. $g_3 < 1$), in contradiction to the usual assumptions of stellar models. They were unable to identify a mechanism for this, but computed models anyway assuming various modest destruction factors, and found models satisfying a wide range of chemical constraints, including a reduction of $D/H$ by large factors, and matching the presolar $(D + ^3He)/H$. Thus, VFOP showed that a consistent picture is possible if $g_3$ is small for low mass stars, but still lacked an explanation of how this can occur: “we can offer no solution as to why $g_3$ should be lower other than the constraints imposed by the presolar $D + ^3He$ data.”
2. $^3$He Destruction in Low Mass Stars During Giant Branch Mixing

There are two reasons for supposing that Galactic stellar populations are net producers of $^3$He, but neither of them is airtight.

The first is that some sites have been found with really substantial overabundances of $^3$He. For example, a huge enhancement $^3$He/$^4$He $\approx 0.7$ is found (Hartoog 1979) in Feige 86; 3 Cen A is another example (Sargent and Jugaku 1961). This may however be purely an atmospheric effect in rare stars where isotopic settling in thin photospheric layers leads to an incorrect estimate of the true stellar composition (Vauclair and Vauclair 1982). In another situation, hyperfine emission in the planetary nebula N3242 reveals (Rood, Bania and Wilson 1992) a large enrichment $^3$He/H $\approx 10^{-3}$, which seems to demonstrate at least one local source. However, it still could be that such enhancements are rather rare, and that the generic behavior averaged over the stars that dominate the recycling of the interstellar gas is destruction.

The second reason comes from stellar evolution models, which predict that low mass stars produce $^3$He and eject it into the ISM when they throw off their envelopes. Although these models are successful at predicting the shapes of HR diagrams, temperatures, luminosities, lifetimes, and principal nuclear burning products, they cannot however be trusted when it comes to predicting the envelope abundances of trace elements. These elements can be changed significantly by effects not in the models, which have little effect on the other properties of the stars.

There is indeed evidence that stars below about 2 $M_\odot$ mix a substantial fraction of their envelope material to a nuclear burning zone at high temperature after they leave the main sequence for a long enough time to affect composition. The best evidence comes from high resolution spectroscopy of a variety of main sequence and giant branch stars in Galactic
open and globular clusters (Gilroy 1989; Gilroy and Brown 1991; Brown, Wallerstein, and Oke 1990; Sneden, Pilachowski and VandenBerg 1986). The abundances of the carbon isotopes and of nitrogen are observed to follow a consistent pattern. The models correctly predict the $^{12}C/^{13}C$ and $C/N$ ratios on the main sequence and part way up the first giant branch, including “first dredge up” of processed material as the convection zone penetrates downwards to the core—providing reassuring confirmation of the model predictions for the element profiles right down to the core. But near the top of the giant branch the ratios are observed to fall well below the model predictions. There appears to be a concrete confirmation of significant alterations in the nuclear abundances of trace elements in the envelopes of typical low mass stars, which is what we are seeking.

The observed ratios indicate that the material of the stars may have been processed to high enough temperatures, for a long enough time, for the elements to approach $CN$ equilibrium. Note that the amount of burning time needed to change these ratios appreciably is only one $CN$ cycle time, which corresponds roughly to a fraction $C/H$ of the star’s giant branch lifetime. The data make sense if all the material in the envelope of the stars has been mixed down to a hot burning zone, and each fluid element spends a total of at least one $CN$ cycle time there after a star leaves the main sequence.

Charbonnel (1994) offers an explanation of why this should happen in low mass stars particularly. At low masses, the chemical composition discontinuity left behind at the lowest point of contact reached by the convective envelope after dredge up, which inhibits mixing below this level by the steep gradient in molecular weight, occurs inside the maximum radius achieved by the hydrogen-burning shell after the core becomes degenerate. Thus for a time on the giant branch the envelope can mix down to the hydrogen burning zone. The actual mechanism of the mixing is not known. Although candidate mechanisms have been suggested (Zahn 1992), they are not yet included in current stellar models (eg, Schaller et
If this explanation of the observed $^{12}C/^{13}C$ and $C/N$ ratios is correct, the same process would likely have a strong influence on $^{3}He$. The observed reduction of $^{12}C/^{13}C$ to nearly equilibrium values implies that the bulk of the material in the envelope reaches a high enough temperature long enough for thorough conversion; as we see below, the high temperatures are more than adequate to also burn the $^{3}He$ in the time available. A similar argument applies for the $C/N$ ratios.

We can use the data from one of Charbonnel’s models (a 1.25 $M_{\odot}$, $Z = 0.02$ star) to estimate the timescales and temperatures involved. The data imply that conversion begins after the onset of mixing; for this model, the shell reaches the chemical discontinuity, and mixing can start, at step 33 of Schaller et al’s table 19, at $5.43 \times 10^9$y. The conversion must be complete well before the star leaves the giant branch at the helium flash (step 51, $5.55 \times 10^9$y); thus the conversion of envelope material must take place in substantially less than $12 \times 10^7$y. From Charbonnel’s figure 9, the mass of the shell where the $^{12}C \rightarrow ^{13}C$ process occurs is only about 0.001 of the total mass of the star. By continuity, since the entire envelope is processed in the conversion zone then the cumulative time spent by any mass element in the zone is less than 0.001 of the total available time, or about $10^5$y. But for any reasonable density, for the $^{12}C \rightarrow ^{13}C$ reaction to occur in $10^6$y or $10^5$y the temperature reached must be at least $T_6 > 15$ or $T_6 > 17$ respectively, where $T_6 = T/10^6K$ (see e.g. Clayton 1968). (Note that the central temperature at the onset of mixing is $T_6 = 34$.)

Although we cannot observe the $^{3}He$ in these giants directly, we can make a quantitative estimate of the effect on $^{3}He$ by comparing its destruction rate with that of $^{12}C$. The dominant destructive interaction will be $^{3}He(\alpha, \gamma)^7Be$ (rather than $^{3}He(^3He, 2p)^4He$ which dominates for abundances $\geq 10^{-4}$). The rate-limiting reaction of the $CN$ processing is $^{12}C(p, \gamma)^{13}N$, which we already know must be important— that is, a typical $C$ nucleus
must undergo at least of the order of one reaction. Assuming a ratio of $\alpha$ to $p$ of 0.1 by number, and using reaction rates from Fillipone (1986) and Caughlan and Fowler (1988), we estimate the ratio of the $^{12}C$-destruction time to the $^3He$-destruction time, independent of other abundances or density (e.g. Clayton 1968):

$$R \equiv \frac{\tau_{12}}{\tau_3} = \exp[14.3T_6^{-1/3} - 2.5].$$

At the required $T_6 = 15$, $R = 27$; for $T_6 = 17$, $R = 21$. Thus over the likely range of maximum temperatures reached by the envelope material, the near equilibration of the $^{12}C \rightarrow ^{13}C$ implies equilibration of $^3He \rightarrow ^4He$; in fact the $^3He$ will be destroyed more quickly, and could occur even in stars which do not show the $^{12}C/^{13}C$ anomaly.

Since the $^3He \rightarrow ^4He$ rates are faster than the $CN$ rates, which has apparently approached equilibrium at high temperature, the local abundance $^3He/^4He$ in the high temperature region must also have reached the equilibrium value. For $T_6 > 15$, the equilibrium abundance is $^3He/H < 10^{-5}$. Thus the $CN$ data imply that the bulk of the envelope material must have been processed through conditions where $^3He/H < 10^{-5}$.

It is not clear from these simple arguments that this is the abundance of the material when it returns to the upper envelope, for it must pass through lower-temperature regions to get there, where its abundance might increase again. The actual returned abundance depends on the detailed temperature history of a fluid element. But quantitatively, to maintain net destruction requires only that the upward flow pass through the region where $T_6 \approx 10$ in less than about $10^6$y, the time for regenerating the $^3He$, which is certainly plausible. Recall that each fluid element spends an integrated total of less than $10^5$y lingering in the hotter $T_6 \approx 15$ zone, which would be an upper limit for the flow timescale in a “typical” process where the material turns over more than once. (Note that if the upward flows are concentrated in narrow plumes or updrafts, the fluid velocity is higher going up and the time spent traversing the region where $^3He/H$ increases is even shorter.)
Whether or not the material reaches the upper envelope without also having $^{3}\text{He}/H$ increase significantly can only be determined in the context of a detailed stellar model including both the mixing flow and the nuclear reactions, but it would not be surprising if red giant branch mixing reduces the initial $(D + ^{3}\text{He})/H$ in the ejected envelope by a large enough factor ($g_3 < 0.1$) to solve the empirical difficulties discussed above.

The conclusion is not that $^{3}\text{He}$ must be destroyed, but that there are good reasons to suspect that it might be, and that therefore Galactic $(D + ^{3}\text{He})/H$ should not be used as an indicator of or constraint on primordial $D/H$.

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