THE COSMIC HELIUM-3 ABUNDANCE: IMPLICATIONS FOR BIG BANG NUCLEOSYNTHESIS, STELLAR EVOLUTION, AND GALACTIC CHEMICAL EVOLUTION

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The cosmic abundance of the ^{3}He isotope has important implications for many fields of astrophysics. ^{3}He can be used to test the theory of stellar nucleosynthesis; it gives important information needed to evaluate models of Galactic chemical evolution; it can help constrain Big Bang Nucleosynthesis. Any determination of the cosmic ^{3}He abundance is therefore important to make. Here we summarize the ^{3}He abundances derived using various techniques with emphasis placed on observations of $^3He^+$ in Galactic H II regions and planetary nebulae. We discuss the astrophysical implications of these abundances. In particular, the observed lack of substantial ^{3}He enrichment in the Milky Way interstellar medium means that the bulk of solar mass stars do not return significant quantities of ^{3}He to the ISM. We argue that this situation allows us to place an upper limit on the BBNS primordial baryon to photon ratio, η, and, hence, on the baryon fraction of the closure density, Ω_B.

1 Introduction: The 3-Helium Problem

Measurements of ^{3}He in the Galaxy have led to what has been called "The ^{3}He Problem".[1] As with all the light elements, the present interstellar ^{3}He abundance is expected to result from a combination of Big Bang Nucleosynthesis (BBNS)[2] and stellar nucleosynthesis. Standard stellar evolution theory predicts that ^{3}He is produced in significant quantities by stars of 1–$2\,M_\odot$ and that planetary nebulae (PNe) with progenitors in that mass range should have ^{3}He/H abundances $\sim 10^{-4}$ by number.[3,4,5,6] Galactic chemical evolution models which integrate over a range of initial masses predict that ^{3}He is produced in prodigious amounts.[7,8] A survey of 6 PNe produced a detection of ^{3}He in NGC 3242[9,10] and probable detections in two other sources[11] with ^{3}He/H $\sim 10^{-4}$–10^{-3} as predicted by standard stellar evolution models. This PNe sample was highly biased, however, and was selected to maximize the likelihood of a detection.

Observations of ^{3}He in protosolar material,[12] the local interstellar medium,[13,14] Jupiter's atmosphere,[15] and Galactic H II regions,[16,17,18] all indicate a ^{3}He/H abundance ratio of $\sim 2 \times 10^{-5}$. Although H II regions are expected to be zero-age objects there is no evidence for any stellar ^{3}He enrichment during the last 4.5 Gyr.[19] The observed abundances of ^{3}He throughout the Galaxy when combined with the observations that some stars do indeed produce ^{3}He strongly disagree with chemical evolution models.[20,21,22,23,24,25,1]

Standard stellar ^{3}He nucleosynthesis predicts that the ^{3}He/H abundance ratio should grow with time and be higher in those parts of the Galaxy where there has been substantial stellar processing. Specifically: (1) there should be a ^{3}He/H abundance gradient across the Galactic disk with the highest abundances occurring in the highly-processed inner Galaxy; (2) the ^{3}He/H abundance should grow with source metallicity; and (3) the protosolar ^{3}He/H abundance should be less than that found in the present ISM. None of these predictions is confirmed by observations.[19]

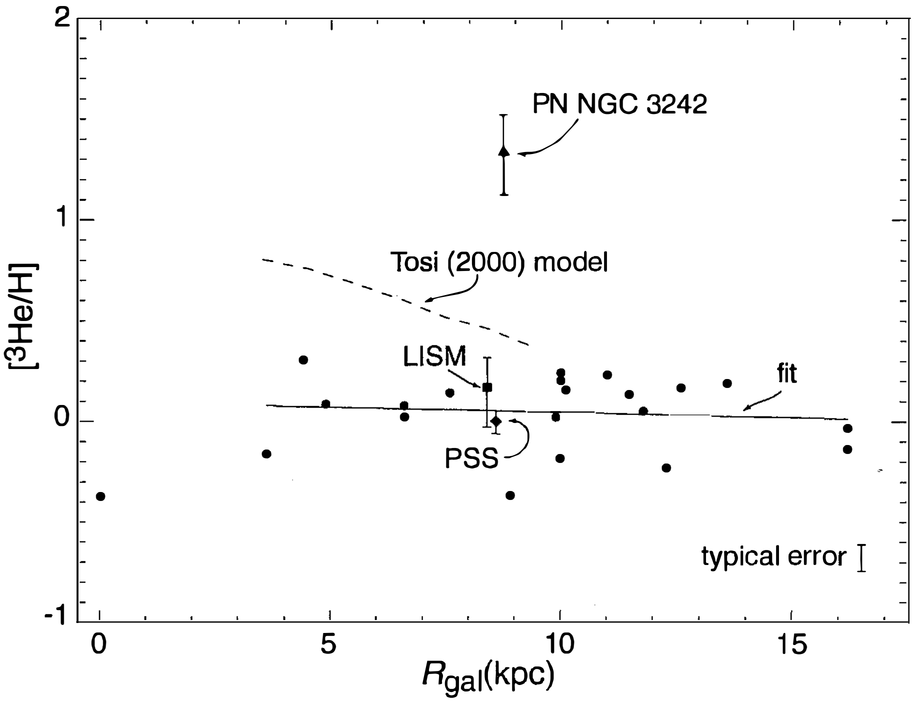

Figure 1: Interstellar ^{3}He/H abundances as a function of Galactic radius. The [^{3}He/H] abundances by number derived for the "simple" H II region sample are given with respect to the solar ratio. The typical error for the H II region abundances (circles) is shown in the right hand corner. Also shown is the abundance derived for the planetary nebula NGC 3242 (triangle), for the local interstellar medium (LISM—square), and the protosolar material (PSM—diamond). Note that there is no gradient in the ^{3}He/H abundance with Galactic position. To be compatible with this result Galactic chemical evolution models[26] require that $\sim$ 90% of solar analog stars are non-producers of ^{3}He.

2 The Cosmic 3-Helium Abundance

We obtain the ^{3}He abundance in Milky Way H II regions and PNe using measurements of the 8.665 GHz (3.46 cm) spin flip transition of $^3He^+$. The source sample is currently comprised of 60 H II regions and 6 PNe. H II regions or molecular clouds are examples of zero-age objects which are young relative to the age of the Galaxy. Therefore these abundance ratios chronicle the results of billions of years of Galactic chemical evolution. PNe probe material which has been ejected from low-mass ($M \leq 2\,M_\odot$) to intermediate-mass ($M \sim 2$–$5\,M_\odot$) stars to be further processed by future generations. Because the Milky Way ISM is optically thin at centimeter wavelengths, our source sample probes a larger volume of the Galactic disk than does any other light element tracer of Galactic chemical evolution.

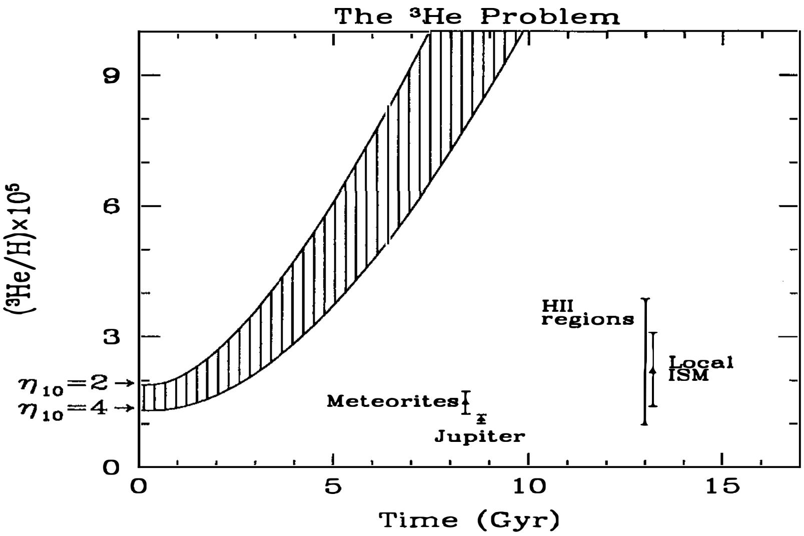

Figure 2: ^{3}He abundances compared with Galactic chemical evolution models. The ^{3}He/H abundances derived for meteorites,[12] Jupiter,[15] the LISM,[14], and H II regions [16,19] are inconsistent with chemical evolution models that use standard stellar yields. Note that this inconsistency is insensitive to the BBNS ^{3}He production. The BBNS models are parameterized by the primordial baryon-to-photon ratio, η, expressed in units of 10^{-10}. This figure adapted from Galli *et al.*[27] and updated.

As is the case for any cosmic abundance determination, converting the measured $^3He^+$ column density into an abundance ratio relative to hydrogen, ^{3}He/H, is nontrivial. For the case of ^{3}He this conversion depends on the density and ionization structure of each nebula. While numerically modeling our $^3He^+$ sources we discovered that a major advantage of large, diffuse H II regions is that they tend to be "simple," i.e., the H II region has a relatively simple density and ionization structure. This allows us to derive abundances from the observed $^3He^+$ emission line parameters without recourse to the rather complex modeling required for most classic H II regions.[16] Because the abundance corrections for simple sources are small, these sources can in principle yield the most accurate ^{3}He/H abundance ratios attainable. Sources that are "simple" in the sense just described were especially well suited for observation with the National Radio Astronomy Observatory (NRAO) 140 Foot telescope, so during the last few years of its operation we worked to increase the size of our simple source sample. Our ^{3}He H II region sample has 21 simple sources for which we can determine abundances. The remaining 39 sources are a mixture of complex sources, $^3He^+$ detections for which we do not yet have adequate continuum data to determine the H column depth, and $^3He^+$ non-detections.

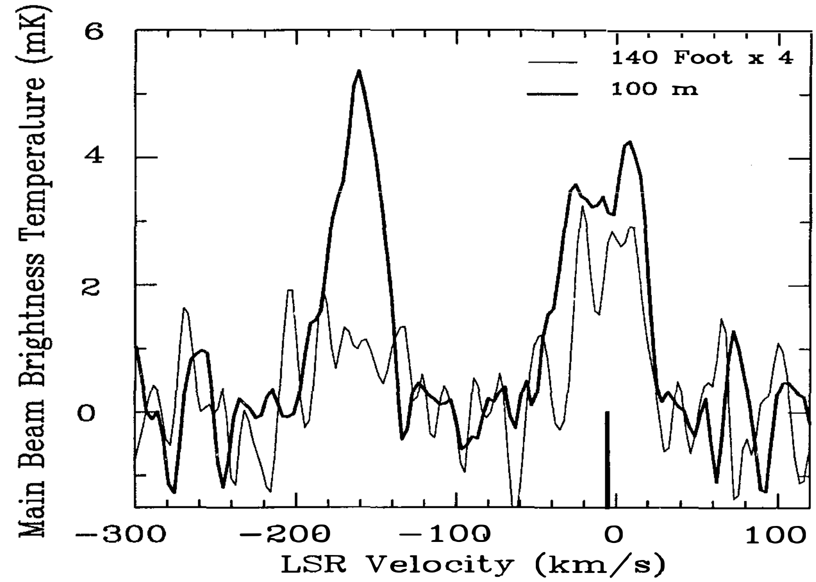

Figure 3: $^3He^+$ emission from the planetary nebula NGC 3242.[9,10] The thick curve is the spectrum taken with the MPIfR 100 meter telescope. The thin curve is the spectrum taken with the NRAO 140 foot telescope with the observed intensity multiplied by a factor of 4. The vertical line at −5.3 kms^{-1} flags the $^3He^+$ emission at the LSR velocity of NGC 3242. The prominent feature in the MPIfR spectrum is the H171η recombination line.

3 Stellar and Galactic Evolution

The standard view of ^{3}He chemical evolution is relatively simple. It is indeed dominated by the net production of this element by low-mass stars thanks both to the destruction of D on the pre-main sequence and to the pp-chains which build up a ^{3}He peak inside the main sequence star. This fresh ^{3}He is then engulfed by the deepening convective envelope of the star during the first dredge-up on the lower red giant branch (RGB). Once in the convective layers of the red giant, ^{3}He is preserved against nuclear destruction, and it is ejected into the ISM in the late stages of stellar evolution both through the stellar winds and also the planerary nebula ejection. A substantial increase of the ^{3}He abundance in the Galaxy is thus expected as soon as low-mass stars start to die and to pollute the ISM. As we previously mentioned, these standard predictions are in conflict with the observational data (see Figs. 1 and 2).

A very elegant solution to the ^{3}He problem based on nuclear physics was proposed,[28] which required an hypothetical low-energy resonance in the cross-section of the ^{3}He + ^{3}He reaction. However this resonance has not been confirmed by experiments.[29] In addition, this solution is in conflict with the measurement of ^{3}He in NGC 3242. For this PN the ^{3}He/H abundance ratio is more than one order of magnitude larger than that found in any H II region, the LISM or the protosolar system. This ^{3}He abundance, which is in fact in agreement with the standard stellar predictions, rules out the nuclear physics solution. Thus a process has to be found that destroys ^{3}He in some stars and preserves it in others.

Rood *et al.*[30] suggested that the problem could be related to striking chemical anomalies in red giant stars. Over the years much observational evidence has accumulated which shows that low-mass RGB stars undergo an extra-mixing event. This extra-mixing adds to the standard first dredge-up to modify the surface abundances. In particular, observations of the ^{12}C/^{13}C ratios allowed us[31,32] to determine that this process occurs just after the so-called "bump" on the RGB. At this evolutionary point, the hydrogen burning shell crosses the discontinuity in molecular weight built by the convective envelope during the first dredge-up. Before the discontinuity, the molecular weight gradient probably acts as a barrier to mixing in the radiative zone. Beyond this point, however, no gradient of molecular weight exists above the hydrogen burning shell so the extra-mixing, whatever its nature, is free to act.

Several attempts have been made to simulate the extra-mixing in RGB stars. We investigated the influence of rotation by taking into account recent analyses of the transport of chemicals and angular momentum in stellar interiors.[33] We showed that rotation-induced mixing can not only account for the observed behavior of the carbon isotopic ratio but also explain other abundance anomalies in low mass giants. Simultaneously, when this extra-mixing begins to act, ^{3}He is rapidly transported down to the regions where it burns by the ^{3}He$(\alpha,\gamma)^7$Be reaction. This leads to a decrease of the surface value of ^{3}He/H compared to the standard case. Under peculiar mixing conditions, a thermal instability can occur, which transports the resulting ^{7}Be outwards and leads to an increase of the surface ^{7}Li abundance during a very short period. A few giant stars with very high ^{7}Li abundance have been discovered at the RGB bump. These so-called Li-rich stars are actually caught in the act of burning their ^{3}He.[34,35]

Stars with different rotation and mass loss histories are expected to suffer different mixing efficiency and to display different chemical anomalies. Significantly, all the relevant data indicate that the extra-mixing occurs in $\sim$ 90 to 95% of the low-mass stars.[36,37] This brings a solution to the apparent inconsistency between the galactic constraints and the high ^{3}He abundance in PNe. NGC 3242 should then belong to the $\sim$ 5 to 10% of stars which do not suffer from extra-mixing on the red giant branch. Such "standard" PNe should also show "normal" carbon isotopic ratios. This crucial test has already been verified for two PNe of the Balser *et al.*[10] sample. NGC 6720 has a ^{12}C/^{13}C ratio of 23 which is in perfect agreement with the "standard" predictions.[38] Furthermore, NGC 3242 itself has an HST-based limit on its ^{12}C/^{13}C ratio which suggests that it is the outcome of the evolution of a standard, ^{3}He-producing, low-mass star.[39]

Because models with rotation-induced mixing are not yet available for stars with various initial masses and metallicities, large uncertainties still remain on the actual ^{3}He yields. In our preliminary Pop II models with rotation ^{3}He decreases by a large factor in the ejected envelope material, but low mass stars remain net producers of ^{3}He (although they are far less efficient than in the case of models without RGB extra-mixing).

4 Big Bang Nucleosynthesis

In sum, observations of ^{3}He (ours, PSM, & LISM), observations of the ^{12}C/^{13}C abundance ratio in red giant stars, and rotating stellar models all indicate that: (1) the stellar contribution to the ^{3}He abundance evolution is positive (i.e., ^{3}He increases), and (2) ^{3}He ISM enrichment is small compared to the size of the present observational errors. We now believe that we can estimate the primordial ^{3}He abundance because the existence of "The ^{3}He Plateau" for our sample of large, diffuse Galactic H II regions suggests that there is a floor value to the ^{3}He/H abundance. If, as seems plausible, stellar processing enriches the ISM ^{3}He abundance by a positive-definite (but perhaps nearly zero) amount, this floor value provides an upper limit to the primordial ^{3}He abundance produced by BBNS. A very conservative estimate for the floor abundance can be made by adopting the plateau value itself, ^{3}He/H $= (1.9 \pm 0.6) \times 10^{-5}$ (s.e.) by number, which can serve as a strong upper limit to the BBNS production. In principle, one could set an upper limit to the primordial ^{3}He abundance from one well observed simple source at large $R_{\rm gal}$ and with high helium ionization. The H II region S209 is such a source. We observed S209 during many epochs spread over 15 years; our total integration time is 133 hours. These data allowed us to construct a detailed, high quality model[10] showing that S209 is simple. The degree of He ionization is high and our ^{4}He$^+$ data are good enough to allow us to make an ionization correction. The nearby very low density H II region, S209S, has an abundance that is the same as S209, within the errors. At this point after almost 20 years of work our best *upper limit* on the primordial ^{3}He abundance is $(1.1 \pm 0.2) \times 10^{-5}$ by number.

Primordial abundances can be directly related to the baryon-to-photon ratio of the Universe, η.[40] The amount of ordinary baryonic matter in the Universe, Ω_B, can be derived from η and the current rate of expansion as measured by the Hubble constant, h, expressed in units of 100 km sec^{-1} Mpc^{-1}. Our values for η and $\Omega_B h^2$ are given in Table 1 together with some other recent determinations. Because of its simple post-Big Bang evolution measurements of deuterium (D) in high redshift quasars[40] have the potential of giving the "cleanest" primordial abundance. However, because the largest errors are systematic and hence poorly known, a truly robust cosmological conclusion can be drawn only when concordance between different determinations is achieved. The problem with systematic errors is illustrated by the debate over estimates of the cosmological ^{4}He abundance in the last few years. To get η from ^{4}He requires very high precision. Results split into two camps, one with low[41] ^{4}He and another with high[42] ^{4}He. Such a dichotomy clearly indicates a systematic error much larger than the internal error.

A consistent picture is now emerging from experiments attempting to constrain the parameters of Big Bang cosmology. Table 1 shows that the values of η derived from our S209 result and that from quasar D are in excellent agreement and clearly fall on the side of the higher ^{4}He abundance. Measurements of fluctuations in the cosmic microwave background radiation can also give estimates for $\Omega_B h^2$. Recent results from the DASI experiment[43] are also listed in Table 2. These different estimates for the primordial baryon density expressed as a fraction of the closure density are in excellent agreement and give for $h = 0.72 \pm 0.08$[44] a value $\Omega_{\rm B} = 0.04$.

Table 1: Determinations of the Cosmological Baryon to Photon Ratio, η.

Method	Abundance	η	$\Omega_B h^2$
Primordial ^{3}He/H (based on S209)	$1.1 \pm 0.2 \times 10^{-5}$	$5.4^{+2.2}_{-1.2} \times 10^{-10}$	$0.020^{+0.007}_{-0.003}$
^{3}He/H Plateau	$1.9 \pm 0.6 \times 10^{-5}$	$> 2.4^{+1.8}_{-0.7} \times 10^{-10}$	$> 0.009^{+0.014}_{-0.008}$
Quasar D	$3.0 \pm 0.2 \times 10^{-5}$	$5.6 \pm 0.5 \times 10^{-10}$	0.020 ± 0.002
High ^{4}He (Y_p mass fraction)	0.244 ± 0.02	$4.0^{+0.9}_{-0.4} \times 10^{-10}$	$0.015^{+0.003}_{-0.002}$
Low ^{4}He	0.234 ± 0.02	$1.8^{+0.3}_{-0.2} \times 10^{-10}$	0.007 ± 0.001
DASI CMB Experiment	...	...	$0.022^{+0.004}_{-0.003}$

5 Summary

• – The ^{3}He isotope is expected to be produced both during the era of primordial nucleosynthesis and also in the course of the normal evolution of stars of roughly solar mass. Because these stars return mass to the ISM during their planetary nebula phase, the primordial abundance of ^{3}He is thus expected to grow with time and be higher in those parts of the Milky Way where there has been substantial stellar processing.
• – The cosmic ^{3}He abundance in the Milky Way has been derived from experiments which count atoms directly in the Local ISM, in lunar material, and in the Jovian atmosphere. It has also been determined using spectroscopic measurements of the 3.5 cm spin-flip transition of $^3He^+$ in Galactic H II regions and planetary nebulae. Contrary to the predictions of standard ^{3}He evolution, there is no evidence for significant enhancement of the ^{3}He abundance since the formation of the solar system and there is no evidence for significant ^{3}He enrichment in Galactic regions that have undergone substantial stellar processing.
• – Nonetheless *some* Galactic planetary nebulae have ^{3}He abundances that are compatible with standard models of stellar evolution. This confusing situation—stars are observed to produce ^{3}He but then this ^{3}He does not show up elsewhere—is called "The ^{3}He Problem".
• – These results strongly constrain Galactic chemical evolution models. All realistic Galactic evolution models which match both the ^{3}He abundance and also all the other observational constraints must adopt alternative nucleosynthesis with a strongly reduced ^{3}He contribution from low- and intermediate-mass stars.
• – The ^{3}He produced during the main sequence can be depleted during the red giant phase by extra internal mixing driven by stellar rotation above some critical value. Observed $^{12}C/^{13}C$ ratios suggest that $\sim 90\%$ of evolved low-mass stars go through this stage and deplete at least some of their ^{3}He.
• – Even those stars with a low $^{12}C/^{13}C$ abundance ratio and depleted ^{3}He still have a ^{3}He abundance which is comparable to or slightly larger than the initial value at stellar birth. Regarding chemical evolution such stars are *non-producers* rather than *destroyers* of ^{3}He.
• – Since stellar processing enriches the ISM ^{3}He abundance by a positive-definite (but perhaps nearly zero) amount, then the Galactic H II regions with the smallest ^{3}He abundances provide an upper limit to the primordial ^{3}He abundance produced by Big Bang Nucleosynthesis.
• – The best *upper limit* on the primordial ^{3}He abundance comes from the H II region S209: $^3He/H = (1.1 \pm 0.2) \times 10^{-5}$ by number. This gives an estimate for the primordial baryon density expressed as a fraction of the closure density: $\Omega_B = 0.04$ for a Hubble Constant of $h = 0.72 \pm 0.08$.

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