On the Abundance of Primordial Helium

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Abstract

We have used recent observations of helium-4, nitrogen and oxygen from some four
dozen, low metallicity, extra-galactic HII regions to define mean $N$ versus $O$, $^{4}He$ versus
$N$ and $^{4}He$ versus $O$ relations which are extrapolated to zero metallicity to determine
the primordial $^{4}He$ mass fraction $Y_{P}$. The data and various subsets of the data, selected
on the basis of nitrogen and oxygen, are all consistent with $Y_{P} = 0.232 \pm 0.003$. For
the $2\sigma$ (statistical) upper bound we find $Y_{P}^{2\sigma} \leq 0.238$. Estimating a 2% systematic
uncertainty ($\sigma_{syst} = \pm 0.005$) leads to a maximum upper bound to the primordial helium
mass fraction: $Y_{P}^{MAX} = Y_{P}^{2\sigma} + \sigma_{syst} \leq 0.243$. We compare these upper bounds to $Y_{P}$ with
recent calculations of the predicted yield from big bang nucleosynthesis to derive upper
bounds to the nucleon-to-photon ratio $\eta (\eta_{10} \equiv 10^{10}\eta)$ and the number of equivalent light
($\lesssim 10$ MeV) neutrino species. For $Y_{P} \leq 0.238$ ($0.243$), we find $\eta_{10} \leq 2.5(3.9)$ and $N_{\nu} \leq
2.7(3.1)$. If indeed $Y_{P} \leq 0.238$, then BBN predicts enhanced production of deuterium
and helium-3 which may be in conflict with the primordial abundances inferred from
model dependent (chemical evolution) extrapolations of solar system and interstellar
observations. Better chemical evolution models and more data - especially $D$-absorption
in the QSO Ly-$\alpha$ clouds - will be crucial to resolve this potential crisis for BBN. The
larger upper bound, $Y_{P} \leq 0.243$ is completely consistent with BBN which, now, bounds
the universal density of nucleons (for Hubble parameter $40 \leq H_{o} \leq 100$ kms$^{-1}$Mpc$^{-1}$
and cosmic background radiation temperature $T = 2.726 \pm 0.010$) to lie in the range
$0.01 \leq \Omega_{BBN} \leq 0.09$ (for $H_{o} = 50h_{50}$kms$^{-1}$Mpc$^{-1}$, $0.04 \leq \Omega_{BBN}h_{50}^{2} \leq 0.06$).
1 Introduction

After hydrogen, helium-4 is the next most abundant nuclide in the Universe. As a result, the primordial abundance of $^4\text{He}$, synthesized in the first $\sim 20$ minutes of the evolution of the Universe, has assumed a crucial role in testing the standard hot big bang model of cosmology and, in placing constraints on particle physics beyond the standard (Glashow-Weinberg-Salam) model. As a consequence of its high abundance, $^4\text{He}$ can be observed throughout the Universe; this is in contrast to the other light elements ($D$, $^3\text{He}$ and $^7\text{Li}$) produced during big bang nucleosynthesis (BBN) which are, to date, only observed in the Galaxy. In addition, the $^4\text{He}$ abundance may be determined to much higher accuracy ($\sim$ few percent) than is the case for the other nuclides synthesized in BBN.

In the context of standard BBN, the predicted primordial abundance of $^4\text{He}$ is large (the mass fraction, denoted by $Y_{BBN}$, is $\sim 0.24$; the ratio by number to hydrogen, $y^4_{BBN} \sim 0.08$) and insensitive (logarithmically dependent) to the one free parameter – the nucleon-to-photon ratio $\eta$ ($\eta \equiv n_N/n_\gamma; \eta_{10} \equiv 10^{10}\eta$). For a review and further references, see Boesgaard & Steigman (1985); for recent status reports see Walker et al. (1991; WSSOK) and Reeves (1993). $Y_{BBN}$ is sensitive to the expansion rate of the early Universe which, at the epoch of BBN, provides a measure of the total energy density (Shvartsman 1969). Therefore, the comparison between the accurately predicted $Y_{BBN}$ with $Y_P$ derived from accurate observational data (hereafter we will distinguish the primordial abundance inferred from observations, $Y_P$, from the primordial abundance predicted by BBN, $Y_{BBN}$), is the keystone of the consistency tests of the standard model of cosmology and, provides constraints on new physics beyond the standard model of particle physics (Steigman, Schramm & Gunn 1977). To take full advantage of this test of cosmology and approach to high energy physics clearly requires accurate values of $Y_P$.

The derivation of $Y_P$ from astronomical observations is complicated by the fact that in the course of their evolution stars burn hydrogen to helium and, when they die, they return this processed material to the interstellar medium (ISM) polluting the primordial $^4\text{He}$. To minimize the contribution from stellar-produced $^4\text{He}$, we concentrate on measurements of the helium abundance in those regions whose low heavy element abundances suggest the least contamination from stellar and galactic chemical evolution. This has led virtually all investigators to the low metallicity, extragalactic HII regions (Searle & Sargent 1971; Kunth & Sargent 1983; Lequeux et al. 1979; Pagel et al. 1992; Skillman & Kennicutt 1993; Skillman et al. 1994a,b). Even for these data, from regions whose metallicities range down to $1/40$ of solar, a correction for newly synthesized $^4\text{He}$ must be made. The standard approach has been that of Peimbert & Torres-Peimbert (1974), to correlate $Y_{OBS}$ with metallicity and, extrapolate to zero metallicity to infer $Y_P$. Since the heavy element mass fraction, $Z$, is not observed, the observed abundances of oxygen and/or nitrogen have usually served as surrogates for $Z$.

Another reason for concentrating on the lowest metallicity extragalactic HII regions
is that the $^4\text{He}$ abundance is derived from the recombination lines of singly and doubly ionized $^4\text{He}$; neutral $^4\text{He}$ is unobserved. If the HII and HeII zones do not coincide, the neglect of HeI will introduce errors into $Y_{\text{OBS}}$. Model HII region calculations show that for the highest excitation regions, ionized by the hottest stars, the HII and HeII zones do coincide (to $\sim 1\%$; Skillman et al. 1994a). The more metal-poor stars are hotter and, therefore, by restricting attention to the most metal-poor HII regions, this systematic correction may be minimized.

Recently, Pagel et al. (1992; PSTE) have assembled a large data set (several dozen) of extragalactic HII regions observed/analyzed in a homogenous fashion. The $Y$ vs. $O/H$ and/or $N/H$ correlations in this data set have been analyzed (Pagel et al. 1992; Olive, Steigman & Walker 1991 (OSW); Fuller, Boyd & Kalen 1991; Pagel & Kazulaskis 1992; Mathews, Boyd & Fuller 1993; Pagel 1993) to derive $Y_P$. Virtually all analyses agree that $0.22 \lesssim Y_P \lesssim 0.24$. The problems – and disagreements – arise in the quest for the 3rd significant figure in $Y_P$. For example, is $Y_P^{MAX} = 0.240$ or $0.243$ or $0.237$ (OSW)? To approach $Y_P$ at the 1–2 % level requires great care with the statistics of the $Y$ vs. $O/H$ or $N/H$ fits, great care in selecting the data sets and, an understanding of possible systematic effects. For example, recently the “standard” He emissivities of Brockelhurst (1972) have been challenged by Smits (1991). Though these latter emissivities were found to be in error (Smits, private communication to Skillman), such a correction could in principle increase $Y_{\text{OBS}}$ systematically by up to 3% ($\Delta Y \approx 0.007$)(Skillman & Kennicutt 1993).

The analysis we present here was stimulated by the desire to determine $Y_P$ (or, at least, $Y_P^{MAX}$) to $\sim 2\%$ accuracy (or better) for comparison to $Y_{\text{BBN}}$ in tests of cosmology and particle physics. It was encouraged by the valuable addition of 11 new, very metal-poor HII regions (Skillman et al. 1994a,b). Skillman et al. (1994b) have graciously provided us with preliminary results of their data analysis.

In the next section we analyze the $N$ vs. $O$ correlations in the PSTE and Skillman et al. (1994a,b) data sets with the goal of resolving the questions of secondary versus primary nitrogen (Fuller et al. 1991; Pagel & Kazulaskis 1992; Mathews et al. 1993), of possible Wolf-Rayet contamination (PSTE) and, of how best to choose a sufficiently homogeneous metal-poor data set to use for exploring $Y_P$. Then, using the subset(s) of the PSTE and (preliminary) Skillman et al. (1994a,b) data we have identified from the nitrogen and oxygen data, we study the $Y$ vs. $O/H$ and $N/H$ correlations to infer $Y_P$. Since, for some tests of particle physics and cosmology we may wish to compare $Y_P^{MAX}$ with $Y_{\text{BBN}}^{MIN}$, we comment on the uncertainty in $Y_P^{MAX}$. Armed with $Y_P$ from our statistical analysis, we next compare to $Y_{\text{BBN}}$ from the latest BBN calculations (Kernan 1993; Kernan, Steigman & Walker 1994) to derive constraints on the consistency of BBN, on the nucleon abundance ($\eta$) and on particle physics beyond the standard model ($N_c$). Finally, we summarize our conclusions and their implications for cosmology, for particle physics, and for further astronomical observations.
2 Classifying Metal-Poor HII Regions

In Figure 1 we show the nitrogen and oxygen abundances observed for all the 49 HII Regions in the PSTE and Skillman et al. (1994b) data sets. Although low metallicity extragalactic HII regions are surely not a homogeneous set, we do want — to the extent possible — to identify a nearly primordial, relatively unpolluted (by the products of stellar evolution) subset. From Figure 1 it is clear that if we focus on those HII regions with $N/H \leq 1.0 \times 10^{-5}$ and $O/H \leq 1.5 \times 10^{-4}$, the 8 HII regions we discard have significantly higher nitrogen and/or oxygen abundances than the 41 HII regions we retain. Our “first cut” metal-poor data set spans one order of magnitude in oxygen abundance ($15 \lesssim 10^6(O/H) \lesssim 150$) and a factor of $\sim 25$ in nitrogen abundance ($4 \lesssim 10^7(N/H) \lesssim 100$). Although the iron abundance in these HII regions is unknown, we may estimate $[Fe/H]$ for our metal-poor data set using oxygen and/or nitrogen as surrogates for iron. The solar oxygen abundance (Grevesse & Anders 1989) is $[O]_{\odot} \equiv 12 + \log(O/H)_{\odot} = 8.93$ so that for $[O/H] \equiv [O] - [O]_{\odot}$ we have, $-1.75 \lesssim [O/H] \leq -0.75$. From studies of metal-poor stars it has been noted that oxygen (and, perhaps, other $\alpha$-nuclei as well) is enhanced with respect to iron: $[O/Fe] \approx 0.5$ (Sneden, Lambert & Whitaker 1979; Barbuy & Erdelyi-Mendes 1988; Wheeler, Sneden & Truran 1989) so that we may infer for our metal-poor HII regions that $-2.25 \lesssim [Fe/H] \lesssim -1.25$. If, instead, we compare to nitrogen: $-2.45 \lesssim [N/H] \lesssim -1.05$ (with a similar estimate for $[Fe/H]$ since $[N/Fe] \approx 0$ for metal-poor stars). Thus, we are dealing with a sample whose contamination (compared, e.g., to the Galaxy) is relatively small.

Later, to probe the robustness of our statistical results, we will also make a “second cut” and consider a very metal-poor subset; here we will choose the 21 HII regions with $O/H \leq 8 \times 10^{-5}$. Again, there is a “gap” in oxygen abundance between the 21 regions we keep and the 20 we discard. This very-metal-poor set has modest dynamical range with $15 \lesssim 10^6(O/H) \lesssim 80$ and $4 \lesssim 10^7(N/H) \lesssim 40$.

Although a study of the nitrogen versus oxygen relation for metal-poor HII regions is of great intrinsic interest for the study of chemical evolution, it must be emphasized that such small regions are likely dominated by local — in space and in time — processes. Different regions may be “caught” at different evolutionary epochs (e.g., just before or just after a starburst). Thus, a study of the $N/H$ versus $O/H$ relation for extragalactic HII regions need not shed much light on the chemical evolution of our — or, any other individual — galaxy. Chemical evolution models (e.g., Mathews, Boyd & Fuller (1993)) may provide a guide which this data set ignores. Here, we are simply hoping to exploit the low oxygen and nitrogen abundances as an aid in extrapolating the helium abundance to its uncontaminated—primordial—value. In so doing, we implicitly presume that for low metallicity regions there exist mean relations among $N$ and $O$, $^4He$ and $O$, $^4He$ and $N$. However, we do have to concern ourselves with those local processes which may have introduced excess dispersion in the $N$ vs. $O$, $He$ vs. $O$ and $He$ vs. $N$ relations we infer.
from the data.

Indeed, Pagel, Terlevich and Melnick (PTM, 1986) noted that some H II regions with observed Wolf-Rayet spectral features often had larger abundances of both helium and nitrogen compared to other regions with the same oxygen abundance. PTM suggested that such regions may have temporary excesses of $He$ and $N$ due to pollution from stellar winds containing the products of hydrogen burning. PSTE identify those HII regions in their set which have detected (D) and/or possible (P) WR features in their spectra and they distinguish them from those “clean” (C) regions lacking such spectral features. PSTE argue that analysis of the data should be restricted to those objects (C or, perhaps, C + P) for which there is no evidence that the pollution effect is present. However A. Maeder, in the discussion of Pagel’s paper (1991) at IAU Symposium No.149, notes that helium will be ejected also before the stars reach the WR phase and, that since the WR phase is very short-lived, the absence of WR spectral features is not evidence of absence of WR pollution. Thus, in a statistical sense, it may not be justified to exclude HII regions from the analysis simply on the basis of the presence (D) or absence (C) of WR features. Therefore, one of our first goals is to explore whether, based on the nitrogen and oxygen data alone, there are statistically significant differences between the C, P and D data sets (note that all the HII regions in the Skillman et al. sample are “C”).

In our first approach to the $N$ vs. $O$ relation, we have fit the data from all 41 regions of our metal-poor data set to a power law of the form $N/H = A(O/H)^\alpha$; we have also fit the C, P and D subsets (with, respectively, 22, 7 and 12 regions). In Table 1 we display the correlation coefficients ($r$) and the reduced chi-squared ($\chi^2/dof$) along with $A$ and $\alpha$ for our fits.

| Set | # Regions | $r$  | $\chi^2/dof$ | $A$         | $\alpha$     |
|-----|-----------|-----|--------------|-------------|--------------|
| All | 41        | 0.91| 2.1          | 0.76        | 1.31 ± 0.07  |
| C   | 22        | 0.94| 1.3          | 0.20        | 1.18 ± 0.08  |
| P   | 7         | 0.91| 3.2          | 828         | 2.06 ± 0.57  |
| D   | 12        | 0.70| 2.1          | 15.5        | 1.65 ± 0.33  |
| P+D | 19        | 0.81| 2.5          | 98.0        | 1.84 ± 0.30  |

Although the P and D sets do seem to differ from the C set, it is noteworthy that the fit for the D set (WR features observed) is as close to that for the C set as it is to the fit for the P set. Indeed, although the numbers are small and the uncertainties large, it is the P set (possible WR features) which seems anomalous. In any case, it
seems difficult to argue that the C and D sets differ statistically. It is clear from the reduced $\chi^2$s that there is more dispersion about the mean fits for the P and D data sets - especially for the P set - than for the C set. Thus, although it is likely that the PTM effect is present in our sample – as well as other effects we discuss below – on the basis of the observed nitrogen and the oxygen abundances alone, it is not possible to identify individual “contaminated” HII regions. Therefore, initially, we will continue to use all 41 HII regions in our subsequent analyses.

The power $\alpha = 1.3 \pm 0.1$ of our fit to the $N$ vs. $O$ data supports neither a “primary” (linear $N$ vs. $O$ relation) nor a “secondary” (quadratic $N$ vs. $O$ relation) origin for nitrogen in the metal-poor HII regions. However, that for the C-set alone, $\alpha_C = 1.2 \pm 0.1$ is marginally consistent with a purely linear relation. Remember, though, that this heterogeneous sample is not likely to track the galactic evolution of the nitrogen and oxygen abundances. Indeed, the poor chi-squareds of our fits are, at least in part, due to the dispersion in the data. However, to further explore the “primary” versus “secondary” nature of the $N$ vs. $O$ relation (for our purposes here, “primary” and “secondary” should be replaced by “linear” and “quadratic” respectively), we have evaluated the $N/O$ ratio for each of the 41 HII regions in our first cut sample and we have fit the data to $N/O = a + b(O/H)$. The data is displayed in Figure 2 along with our best fit

$$10^2(N/O) = 2.5 \pm 0.3 + (1.4 \pm 0.4) \times 10^4(O/H).$$

This data ($N/O$ vs. $O/H$) is not strongly correlated ($r = 0.31$) and the $\chi^2/dof = 2.3$ is not an improvement over our previous power-law fit (also a 2-parameter fit). For our first cut metal-poor sample, the linear term (in $N$ vs. $O$) dominates over the quadratic one; only for $10^4(O/H) \gtrsim 1.8$ does the quadratic term exceed the linear. Here, we are in agreement with Pagel and Kazlauskas (1992) who also conclude that “primary” nitrogen dominates at low metallicity. We both disagree with the claim of Mathews, Boyd and Fuller (1993) that virtually all the nitrogen is secondary. This claim is repeated by Balbes, Boyd and Mathews (1993) who add the caveat that the primary contribution may dominate at times or metallicities for which there is a paucity of data. This latter point is no longer true given the recent, very low metallicity data of Skillman et al. (1994b).

Given the weak $N/O$ vs. $O/H$ correlation, we have also evaluated the (weighted) mean $N/O$ ratio for our data set,

$$10^2\langle N/O \rangle = 3.4 \pm 0.2$$

where the error in (2) is the error in the mean and does not represent the scatter in the data. For this fit the $\chi^2/dof = 3.0$; by the F-test (Bevington 1969) this is not as good a fit, at greater than the 99.9% confidence level, than either of the two-parameter power-law or linear/quadratic fits in (1). Indeed, the poor chi-squareds of our fits suggest that there may indeed be real dispersion about a mean $N$ vs. $O$ relation. If so, this may well bias our $He$ vs. $N$ or $O$ fits. And, so, we examine this issue further in the following.
We have already mentioned the PTM suggestion that HII regions with WR spectral features may be contaminated with excess $N$ and $He$ (relative to their $O$ abundance). There are other sources of dispersion for extragalactic HII regions. For example, in a region where there has been a recent starburst, the HII region may have been contaminated by the products of the evolution of the most massive stars. Such regions would have excess $O$ (relative to their $N$ abundance) and slightly enhanced $^4He$. For the observed $N/H$ ratio, $N/O$ will be low for such regions (for the observed $O/H$ ratio, $N/O$ will also be low). However, at the observed $N/H$, there will be “extra” $^4He$ causing an upward dispersion from a mean $Y$ vs. $N/H$ relation. However, at the observed (“excess”) $O/H$, there isn’t the “normal” contribution to $^4He$ (from the lower mass stars) so that there will be a downward dispersion from a mean $Y$ vs. $O/H$ relation. This is a counter-example to the claim of Campbell (1992) that the dispersion in $Y$ vs. $O/H$ will be, “one-sided, i.e. upward from a minimum value of $He/H$ at each $O/H$” and argues against her proposal that the primordial helium abundance can only be reliably determined by fitting to the lower envelope of the $Y$ vs. $O$ relation.

As another example, suppose that stellar winds and supernovae combine to blow a superbubble (De Young & Gallagher 1990) in the HII region. Such regions may have lost some of their oxygen (and, the accompanying helium) but retained the products of the longer-lived stars (e.g., $N$ and $^4He$). For such regions the observed $N/O$ ratio will be high and there will be an upward dispersion in the $Y$ vs. $O/H$ relation (more $^4He$ from low mass stars relative to the observed oxygen abundance) but, a downward dispersion in the $Y$ vs. $N/H$ relation (some $^4He$ has been lost from the system).

Finally, we return to the PTM effect. If WR activity has contaminated the HII region with “extra” $N$ and $^4He$ (for its observed oxygen abundance) then $N/O$ will be high and there will be an upward fluctuation in the $Y$ vs. $O/H$ relation and a downward fluctuation in the $Y$ vs. $N/H$ relation (since, for the observed $N/H$, the $O/H$ is low, so too will be the $^4He$ contribution corresponding to $O/H$).

The effects outlined above show that individual HII regions may experience either upward or downward excursions in $N/O$. Thus, we have searched our data set to identify such “outliers”. To search for discrepant HII regions we have placed two sigma contours around each data point in Figure 2 and asked if any of them do not cross the linear fit in eq. (I). In this manner, we have identified seven regions which we consider to be “outliers”: T 1304-38 (4.9σ, P), N 4861 (2.7σ, D), II ZW 40 (2.7σ, D), TOL 65 (2.7σ, P), TOL 35 (2.4σ, D), CS 0341-40 (2.1σ, P), and SBS0335 (2.0σ, C). They are listed in the order of most to least discrepant (with the discrepancy given in terms of the quoted errors, and the Wolf-Rayet characteristic of the region). Note that six of these seven outliers are P or D. One of the two outliers which have relatively low $O/H$ ($10^6 O/H < 60$) has low $N/O$ while the other has high $N/O$. Of the five regions with higher $O/H$, three have low $N/O$ and two have high $N/O$. Thus, as may be seen in Figure 3, where the outliers are identified, there is no general trend in these discrepant
regions.

With these outliers eliminated, we have refit the $N/O$ vs. $O/H$ relation as well as recalculated $\langle N/O \rangle$ for the remaining 34 HII regions.

\[ 10^2 \langle N/O \rangle_{34} = 3.4 \pm 0.2, \]  
\[ 10^2(N/O)_{34} = 2.5 \pm 0.2 + (1.3 \pm 0.3) \times 10^4(O/H). \]  

For the weighted mean the new $\chi^2/dof$ is 1.6; for the linear fit the correlation coefficient is $r = 0.4$ and $\chi^2/dof = 0.96$. Notice the marked improvement in the $\chi^2$. With respect to the latter fit (4) there are no further outliers in the remaining 34 HII regions. In figure 3, we show the same data (as in figure 2) with the new fit (4) and the outliers identified as filled circles. We note that a power law fit to these 34 HII regions, with $A = 0.44$ and $\alpha = 1.26 \pm 0.05$, also has an excellent reduced $\chi^2$ ($\chi^2/dof = 0.93$).

Statistically, the linear fit is preferred over the simple weighted mean indicating a correlation between $N/O$ and $O/H$ and hence the presence of some secondary nitrogen. This is supported by our power law fit where $\alpha$ differs from unity by some 5 sigma. We note that for this subset of our set of low metallicity HII regions, the “primary” component dominates; a secondary component would dominate only for $10^4(O/H) > 1.9$, beyond the upper bound to the oxygen abundances for our data set. Although there is no justification to extrapolate our fit beyond $10^4O/H = 1.5$, we note that for $[Fe/H] \approx [N/H] \lesssim -1$, $[N/O]_{34}$ ranges from -0.4 to -0.7 which is not an unreasonable fit to the $[Fe/O]$ relation observed in halo stars (Sneden, Lambert & Whitaker 1979; Barbuy & Erdely-Mendes 1988; Wheeler, Sneden, & Truran 1989). Indeed, (4) only slightly overestimates the solar $N/O$ ratio ($10^2(N/O)_{34} \approx 14$ vs. $10^2(N/O)_{\odot} \approx 13$ for $10^4(O/H)_{\odot} \approx 8.5$) and slightly underestimates the Orion $N/O$ ratio ($10^2(N/O)_{34} \approx 7.8$ vs. $10^2(N/O)_{\text{Orion}} \approx 11$ for $10^4(O/H)_{\text{Orion}} \approx 4.1$; Gies & Lambert 1993 and Cunha & Lambert 1993).

As emphasized at the outset, the goal is to identify a sufficiently large, sufficiently metal-poor sample so that the extrapolation to zero metallicity is minimal and statistically meaningful. Our confirmation of the Pagel and Kazlauskas (1992) conclusion that “primary” nitrogen dominates for low $O/H$ ($\lesssim 1.8 \times 10^{-4}$) suggests that we further consider a very low metallicity subset of our metal-poor HII regions. Half – 21 – of our 41 HII regions have $10^6(O/H) \leq 80$; the next highest oxygen abundance is $10^6(O/H) = 94 \pm 6$ (more than $2\sigma$ higher). For this subset we find

\[ 10^2 \langle N/O \rangle_{21} = 3.1 \pm 0.2, \]  
\[ 10^2(N/O)_{21} = 2.1 \pm 0.4 + (2.5 \pm 1.0) \times 10^4(O/H). \]  

For the weighted mean the $\chi^2/dof = 2.0$; for the linear fit the correlation coefficient is $r = 0.37$ and the $\chi^2/dof = 1.5$. For a power law fit we find $A = 0.74$, $\alpha = 1.30 \pm 0.12$, $r = 0.89$ and $\chi^2/dof = 1.4$. 

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In this reduced "second cut" set of 21 points we can repeat our previous procedure to look for outliers with respect to the fit (3). Only the two outliers with $10^6 O/H < 80$ already identified above (see fig.3) are found to be more than $2\sigma$ discrepant with the fit (3). The resulting fit to the remaining 19 HII regions is $10^2(N/O)_{19} = 2.1 \pm 0.4 + (2.6 \pm 0.8) \times 10^4(O/H)$ with a $\chi^2/dof = 0.93$ and $r = 0.49$. The corresponding power law fit has $A = 1.4$, $\alpha = 1.37 \pm 0.11$, $r = 0.94$ and $\chi^2/dof = 0.91$.

3 Towards the Primordial Abundance of $^4He$

The goal of our analysis is to use the $^4He$, $N$ and $O$ data from the metal-poor extra galactic HII regions to define a mean $Y$ vs. $N/H$ or $Y$ vs $O/H$ relation to be used to extrapolate to zero metallicity to infer the primordial abundance of $^4He$, $Y_p$. Since the evolutionary history of higher metallicity HII regions may differ from those more metal-poor, we have culled the 49 PSTE and Skillman, et al. HII regions to a first cut set of 41 regions with $10^6 O/H \leq 150$ and $10^7 N/H \leq 80$. For this first cut set we have explored the PTM and PTSE suggestions that HII regions with observed WR features may have enhanced nitrogen (and, possible $^4He$) relative to its oxygen abundance. Although we find no strong evidence supporting such a view, we did identify enhanced dispersion about a mean (power law) relation for those regions with detected (D) or possible (P) WR features. So, in our $Y$ vs. $O/H$ and $Y$ vs. $N/H$ fits, we will consider the C set (22 regions) as well as the full (41 regions) first cut set; for completeness we will also calculate fits for all 49 PTSE and Skillman, et al. HII regions.

In our power law and linear plus quadratic $N$ vs. $O$ fits for our first cut set we found relatively high reduced chi-squareds. This stimulated us to search for "outliers", regions whose $N/O$ ratio was more than $2\sigma$ discrepant (accounting, simultaneously, for the uncertainties in $N/H$ and $O/H$) from the best fit (Eq. 3) linear/quadratic relation. Here we identified seven such outliers, removed them, and refit the remaining 34 HII regions achieving the fit in (Eq. 3) which has a much lower reduced chi-squared ($\chi^2/dof = 0.96$). In our $Y$ vs. $O$ and $N$ fits we will use this modified, first cut' set (34 regions = first cut set minus the seven outliers) and compare with the first cut (41 regions) set.

In the previous section we have also considered an extremely metal-poor subset of the data. This second cut set consists of half of the first cut set; 21 regions with $10^6 O/H \leq 80$. Here, too, the dispersion about the $N$ vs. $O$ fit is large ($\chi^2/dof = 1.5$) and the two outliers from our first cut set with $10^6 O/H \leq 80$ are more than $2\sigma$ discrepant here too. Removing the two outliers results in a modified, second cut' set (19 regions = second cut set minus the two outliers) with a much reduced chi- squared ($\chi^2/dof = 0.93$) around the mean $N$ vs $O$ relation. We have also fit the $Y$ vs. $O$ and $N$ data for these two sets.

In Fig. 4 we display the $Y$ vs. $O/H$ data for all 49 HII regions in the PTSE and
Skillman et al. data sets. The seven regions eliminated by our first cut are shown as filled triangles; note that the three highest $^4\text{He}$ abundances ($Y \geq 0.26$) belong to these regions. Also in Fig. 4 we have distinguished with different symbols the C (open squares), P (open circles) and D (open triangles) regions as well as the seven outliers (filled circles) from the first cut set.

### Table 2: Linear Fits for $Y$ vs. $O/H$

| Set        | # Regions | $r$   | $\chi^2$/dof | $Y_P$   | $10^{-2} \times$ slope | $Y_P^{2\sigma}$ |
|------------|-----------|-------|--------------|---------|------------------------|-----------------|
| All        | 49        | 0.56  | 0.78         | .234 ± .003 | 1.14 ± 0.24             | 0.239           |
| 1st cut    | 41        | 0.51  | 0.61         | .232 ± .003 | 1.38 ± 0.36             | 0.238           |
| -outliers  | 34        | 0.45  | 0.70         | .232 ± .003 | 1.39 ± 0.38             | 0.238           |
| 2nd cut    | 21        | 0.41  | 0.64         | .229 ± .005 | 2.37 ± 1.13             | 0.238           |
| -outliers  | 19        | 0.40  | 0.70         | .229 ± .005 | 2.42 ± 1.15             | 0.238           |
| C          | 22        | 0.35  | 0.71         | .232 ± .003 | 1.58 ± 0.54             | 0.238           |

### Table 3: Linear Fits for $Y$ vs. $N/H$

| Set        | # Regions | $r$   | $\chi^2$/dof | $Y_P$   | $10^{-3} \times$ slope | $Y_P^{2\sigma}$ |
|------------|-----------|-------|--------------|---------|------------------------|-----------------|
| All        | 49        | 0.66  | 0.66         | .236 ± .002 | 1.72 ± 0.33             | 0.240           |
| 1st cut    | 41        | 0.57  | 0.58         | .234 ± .002 | 2.71 ± 0.68             | 0.239           |
| -outliers  | 34        | 0.48  | 0.69         | .234 ± .003 | 2.77 ± 0.76             | 0.239           |
| 2nd cut    | 21        | 0.47  | 0.63         | .231 ± .004 | 4.85 ± 2.27             | 0.239           |
| -outliers  | 19        | 0.44  | 0.70         | .232 ± .004 | 4.79 ± 2.29             | 0.239           |
| C          | 22        | 0.46  | 0.60         | .233 ± .003 | 3.62 ± 1.17             | 0.238           |

In Tables 2 and 3 we show the results of our linear least square fits to $Y$ vs. $O/H$ and $Y$ vs. $N/H$ relations respectively. We list the number of HII regions in each set we fit along with the correlation coefficient ($r$), the reduced chi-squared of the fit ($\chi^2$/dof), the intercept (the inferred, zero-metallicity, primordial $^4\text{He}$ abundance ($Y_P$)) along with its 1σ uncertainty, the slope of the $Y$ vs. $O/H$ and $N/H$ relations respectively and, in the last column, the 2σ (statistical) upper bound to $Y_P$, ($Y_P^{2\sigma}$).
The linear fits in the tables are significantly better, statistically, than is a simple weighted mean of the data. In addition, we have tested three-parameter fits to the data and in these cases we have found that the data is definitely not reliably correlated with respect to these fits. Thus the linear fits, at present, offer the best representation of the data. Notice that all the fits in tables 2 and 3 have very small reduced chi-squareds and, that all the inferred primordial abundances ($Y_P$) in these tables are mutually consistent. From these results we may infer that $Y_P = 0.232 \pm 0.003$ and $Y_P^{2\sigma} \leq 0.238$. Notice, too, the improvement in $\chi^2/dof$ between all (49) HII regions and our first cut. However, unlike the reduced dispersion in the $N$ vs. $O$ relation, eliminating the outliers from the first cut or second cut sets does not result in an improvement in $\chi^2/dof$. And, if we compare the full first cut set with the C set, it is unclear that eliminating regions with possible or detected WR features, results in an improved fit with a reduced dispersion.

The results in Tables 2 and 3 confirm previous analyses (OSW; Pagel et al. 1992) which found steep $Y$ vs. $O/H$ and $Y$ vs. $N/H$ relations. For example, if $Z \approx 20(O/H)$ then the $Y$ vs. $O/H$ slopes in Table 2 correspond to $6 \lesssim \Delta Y/\Delta Z \lesssim 12$. Alternately if, for example, we evaluate the first cut fits at the solar oxygen and nitrogen abundances respectively, we would predict $Y_\odot^{O/H} \approx 0.35, Y_\odot^{N/H} \approx 0.54$, grossly in excess of the solar value $Y_\odot \approx 0.28$. As emphasized at the outset, there need be no connections between the evolution of the extra-galactic HII regions and the solar vicinity of the Galaxy. The role of our $Y$ vs. $O$ and $Y$ vs. $N$ relations inferred from the metal-poor extra galactic HII regions is simply to aid in our extrapolations to the primordial abundance $Y_P$. In Figure 5 we show all the first cut data (outliers in filled symbols) for $Y$ vs. $O/H$ along with the first cut fit from Table 2. In Fig. 6 we show the corresponding data set for $Y$ vs. $N/H$ along with the first cut fit from Table 3.

In OSW we explored an alternate approach to a $2\sigma$ upper bound to $Y_P$. Consider the HII region with the lowest value of $Y + 2\sigma$ (0.238 for I Zw18). Since this - or any other of our set - region may have been contaminated by stellar produced $^4He$, $Y_P^{2\sigma} \leq (Y + 2\sigma)_{min} = 0.238$, consistent with our $2\sigma$ bound from Tables 2 and 3. However, as we average in the next lowest helium abundance regions, although $\langle Y \rangle$ will increase, $\langle \sigma \rangle$ will decrease ($\langle \sigma \rangle^{-2} = \sigma_1^{-2} + \sigma_2^{-2} + \ldots$) and, for some number of the HII regions, $\langle Y \rangle + 2\langle \sigma \rangle$ will achieve a minimum (eventually, the increase in $\langle Y \rangle$ overpowers the decrease in $\langle \sigma \rangle$) so that $Y_P^{2\sigma} \leq (\langle Y \rangle + 2\langle \sigma \rangle)_{min}$. For the PTSE and Skillman et al. data sets we find that $(\langle Y \rangle + 2\langle \sigma \rangle)_{min} = 0.236$ so that $Y_P^{2\sigma} \leq 0.236$. Very recently, Skillman and Kennicutt (1993) and Skillman et al.(1994a) have performed especially detailed and careful analyses of three of the most metal-poor HII regions. In order to assess the quality of their derived statistical uncertainties and, to estimate some of the possible systematic uncertainties, they have acquired data with several different telescope/instrument combinations and they have taken great care in reducing their data. For each of these three HII regions (two in IZw18 and one in UGC4483) they derive helium abundances to better than 3% accuracy. A weighted
mean of their results provides an upper bound to the primordial helium abundance: \( Y_P \leq 0.234 \pm 0.004 \) which is competitive with those we have derived from some 3-4 dozen HII regions. This illustrates the potentially great value of very detailed and careful analyses of a handful of the lowest metallicity HII regions and we would urge observers to focus their efforts in this direction.

In the above discussions we have, in preparation for our comparison with the predicted BBN abundance \( Y_{BBN} \), determined a 95\% CL upper bound to \( Y_P \) based on the statistical uncertainties above: \( Y_P^{2\sigma} \lesssim 0.236 - 0.238 \). To have the most generous comparison, we will adopt \( Y_P^{2\sigma} \leq 0.238 \). However, it must not be forgotten that there are possible systematic uncertainties as well. For example, although for the high excitation metal-poor HII regions in our sample it is expected that the HII and HeII zones coincide (Skillman et al. 1994a), nonetheless there could be differences at the 1-2\% level. Similarly, although corrections for collisional excitation (Ferland 1986; Clegg 1987) are estimated to be negligible in most cases, 1-2\% corrections may not be excluded. If there is significant dust, not expected for our metal-poor HII regions, then trapping of H-recombination photons followed by dust absorption should be, but is generally not, accounted for (Baldwin et al. 1991; Skillman & Kennicutt 1993). These, and possibly other systematic effects, suggest that a one sigma estimate of the systematic uncertainty is \( \sigma_{syst} \approx 0.005 \). Thus, in our comparisons discussed next, we will use \( Y_P^{2\sigma} \leq 0.238 \) and \( Y_P^{2\sigma} + \sigma_{syst} \leq 0.243 \) as our estimates for \( Y_P^{MAX} \).

4 Discussion

The fits to all the data sets in Tables 2 and 3 are mutually consistent with a zero-metallicity, primordial \(^4\)He mass fraction

\[
Y_P = 0.232 \pm 0.003 \pm 0.005
\]  

(7)

Notice that for the full (49 regions) data set, which extends to higher metallicity, the slopes in the \( Y \) vs. \( O/H \) and \( Y \) vs. \( N/H \) relations are shallower and, the intercepts, \( Y_P \) correspondingly higher \( Y_P^{all} \approx 0.235 \pm 0.003 \). Nonetheless, all the fits are consistent with a two-sigma (statistical) upper bound of

\[
Y_P^{2\sigma} \leq 0.238
\]  

(8)

To account for possible systematic uncertainties we have adopted a \( \sim 2\% \) estimate, \( \sigma_{syst} \approx 0.005 \). Thus, in our comparisons with the predictions of BBN, we shall use the statistical upper bound in (8) as well as a maximum primordial abundance of

\[
Y_P^{MAX} = Y_P^{2\sigma} + \sigma_{syst} \leq 0.243
\]  

(9)

We will also consider the uncertainties in our results from uncertainties in our adopted values of \( Y_P^{2\sigma} \) and \( Y_P^{MAX} \).
In his recent thesis, Kernan (1993) has considered in great detail the ingredients necessary for an accurate calculation of $Y_{BBN}$. The work of Kernan (1993), Seckel (1994) and Gyuk and Turner (1994) has led to small but significant corrections to the calculation of $Y_{BBN}$ in WSSOK. These differences have been summarized by Kernan, Steigman and Walker (1994) who find for the standard case of $N_\nu = 3$ and for the same adopted neutron lifetimes ($\tau_n$)

$$Y_{BBN}(K) - Y_{BBN}(WSSOK) = 0.0021 + 0.0004 \ln \eta_{10}$$  \hspace{1cm} (10)

Thus, in the “interesting” range of nucleon to photon ratio $2 \lesssim \eta_{10} \lesssim 4$, $Y_{BBN}(K) - Y_{BBN}(WSSOK) = 0.0024 - 0.0027$. Furthermore, since WSSOK, the $2\sigma$ lower bound to the neutron lifetime has increased (Review of Particle Properties 1992) from $\tau_n \geq 882\text{s}$ to $\tau_n \geq 885\text{s}$ and this adds 0.0006 to the WSSOK results. Thus, overall, the predicted $Y_{BBN}$ has increased by $\approx 0.003$ at fixed $\eta_{10}$; with the same observational upper bounds to $Y_P$ (OSW), this would result in reduced upper bounds to $\eta_{10}$ and $N_\nu$. The constraints we present here are based on the BBN calculations of Kernan (1993) and Kernan, Steigman and Walker (1994) and the upper bounds to $Y_P$ in equations (8) and (9).

First let us consider the upper bound to the nucleon abundance, $\eta_{10}$ which follows from the upper bound to $Y_P$ and from $Y_{BBN}$ with $N_\nu = 3$ and $\tau_n \geq 885\text{s}$. For $Y_P \leq 0.238(0.243)$,

$$\eta_{10} \leq 2.5(3.9)$$  \hspace{1cm} (11)

In the past, (e.g. in WSSOK) the logarithmic dependence of $Y_{BBN}$ on $\eta$ has prevented us from using $Y_P$ to provide a significant bound to $\eta$. This effect is still noticeable in (11). Nonetheless, even our conservative bound $Y_P^{MAX} \leq 0.243$, combined with the newer calculations of $Y_{BBN}$, does lead to a restrictive upper bound (e.g. in WSSOK it was the primordial abundance of $^7\text{Li}$ which was used to provide the bound $\eta_{10} \leq 4.0$). And, the more restrictive statistical bound, $Y_P^{2\sigma} \leq 0.238$, leads to an upper bound to $\eta$ in apparent conflict with the lower bound of $\eta_{10} > 2.8$ from WSSOK. Before exploring the predicted lower bounds to the primordial abundances of $D$ and $^3\text{He}$ from the upper bounds to $\eta$ in (11), we note that the uncertainty in $\eta$ is related to the uncertainty in $Y_P$ by

$$\frac{\Delta \eta}{\eta} \approx \frac{\Delta Y}{0.012}$$  \hspace{1cm} (12)

which for $\Delta Y = 0.001$ and $\eta_{10} = 2.5(3.9)$, corresponds to $\Delta \eta \approx 0.21(0.33)$.

The predicted primordial abundances of $D$ and of $^3\text{He}$ decrease with increasing $\eta_{10}$. For the upper bounds to $\eta_{10}$ in (11), standard BBN calculations yield (WSSOK; Kernan (1993)),

$$10^5(D/H)_P \geq 10.1(4.9)$$  \hspace{1cm} (13)

$$10^5(^3\text{He}/H)_P \geq 1.7(1.4)$$  \hspace{1cm} (14)
The abundances of $D$ and $^{3}He$ for $\eta_{10} \leq 2.5$ ($Y_{P} \leq 0.238$) are large and possibly in conflict with the solar system and interstellar data (WSSOK; Steigman and Tosi 1992); however, see Vangioni-Flam, Olive, and Prantzos (1994). The problem here, is that today the ISM deuterium abundance is observed to be $10^{5}(D/H) = 1.5$ (Linsky et al. 1992) with very small errors. This would require a destruction factor of nearly 7. While models were found (Vangioni-Flam et al. 1994) which could destroy deuterium by a factor of 5 (the value needed when $\eta_{10} = 3$) and could probably be pushed to get the additional deuterium destruction, the real problem lies with $^{3}He$. Models which destroy deuterium tend to produce $^{3}He$ and yield too large a value for the sum $(D + ^{3}He)/H$ when evaluated at the age corresponding to the formation of the solar system. Unless stellar models for the survival of $^{3}He$ in low mass stars have been overestimated, this constraint will be difficult to overcome.

For $\eta_{10} \leq 3.9$ ($Y_{P} \leq 0.243$) there is consistency with earlier analyses (e.g., WSSOK) which now require $2.18 \leq \eta_{10} \leq 3.9$. Corresponding to any uncertainties in our adopted upper bounds to $Y_{P}$, there are uncertainties in the predicted lower bounds to primordial $D$ and $^{3}He$,

\[
\frac{\Delta y_{2P}}{y_{2P}} \approx -\frac{\Delta Y_{P}}{0.007}
\]

\[
\frac{\Delta y_{3P}}{y_{3P}} \approx -\frac{\Delta Y_{P}}{0.024}
\]

So, for $\Delta Y_{P} \approx \pm 0.001$ and $10^{5}y_{2P} = 10.1(4.9), 10^{5}\Delta y_{2P} \approx \pm 1.4(0.7); \text{ for } \Delta Y_{P} \approx \pm 0.001$ and $10^{5}y_{3P} = 1.7(1.4), 10^{5}\Delta y_{3P} \approx \pm 0.1$. The bottom line is that, if $Y_{P} \leq 0.238$, the predicted primordial abundance of D is large and potentially detectable (Webb et al. 1991; Carswell et al. 1994; Songaila et al. 1994) in the QSO Lyman- $\alpha$ absorption systems. This will provide a crucial test of the consistency of BBN and the standard hot big bang cosmology.

Upper bounds to $\eta_{10}$ imply upper bounds to the cosmological density of baryons (nucleons), with implications for the question of the nature of the cosmologically dominant dark matter. Using $\Omega_{BBN}$ for the baryon density parameter from BBN, a CBR temperature of $2.726 \pm 0.010K$ and, a Hubble parameter of $H_{o} = 50h_{50}kms^{-1}Mpc^{-1}$, for $\eta_{10} \leq 2.5(3.9)$, we predict

\[
\Omega_{BBN}h_{50}^{2} \leq 0.037(0.058)
\]

For a lower bound to the Hubble parameter of $H_{0} \geq 40(h_{50} \geq 0.8)$ we find an upper bound to $\Omega_{BBN} \leq 0.058(0.090)$ which makes the case for non-baryonic dark matter even stronger.

Finally we turn to the implications for particle physics, specifically physics beyond the standard model, of our upper bounds to primordial helium. The above comparisons have been for the standard case of three massless (or, very light: $\lesssim 0.1$ MeV) neutrino flavors, $N_{\nu} = 3$. The effect of the presence of “new” particles (beyond the standard model) which enhance the total energy density at BBN is to speed-up the universal expansion rate (Schwartzman 1969) and leave available more neutrons to form more $^{4}He$. Thus, the
predicted helium mass fraction increases with $N_{\nu} \geq 3$ (Steigman, Schramm and Gunn 1977): $\Delta Y_{BBN} \approx 0.012\Delta N_{\nu}$. Now, recall that compared to WSSOK the predicted $Y_{BBN}$ - for the same $N_{\nu}$ - has increased by $\sim 0.003$. Thus, our current comparison, even if we used the WSSOK value of $Y_{P} \leq 0.240$, will yield a much more restricted upper bound to $N_{\nu}$. In the past, to find the new upper bound to $N_{\nu}$, we compared the upper bound to $Y_{P}$ with the lower bound to $Y_{BBN}$ evaluated for $\tau_{n} \geq 885$ s and $\eta \geq \eta_{min}$, the most favorable limits -in the sense that they maximize $N_{\nu}$- for these quantities. In WSSOK the bound to the primordial abundance of $D + ^{3}He$, inferred from solar system and interstellar observations, was used to bound $\eta_{10} \geq 2.8$. We have already noted above that the $2\sigma$ statistical upper bound, $Y_{P}^{2\sigma} \leq 0.238$, corresponds to $\eta_{10} \leq 2.5$ so that, for this bound to $Y_{P}$, we will find $N_{\nu} < 3$. On the other hand, including an estimate of the possible systematic uncertainty to bound $Y_{P}^{MAX} \leq 0.243$, permits $N_{\nu} > 3$ but leads to a slightly more restrictive bound than that in WSSOK. Thus for $Y_{P} \leq 0.238(0.243)$ we now find

$$N_{\nu} \leq 2.9(3.3)$$

This bound, however, is not really a $2\sigma$ upper bound to $N_{\nu}$ as each of $Y_{P}$, $\eta_{10}$, and $\tau_{n}$ have been allowed to take their extreme values. If we take for the observed value, $Y_{P} = 0.232 \pm 0.003 \pm 0.005$, and we use the BBN prediction of $^{4}He$ evaluated for $\tau_{n} = 889.1 \pm 2.1$ s and $\eta_{10} = 3.0 \pm 0.3$, we can derive the best fit value of $N_{\nu}$. Note that the latter value for $\eta$ is chosen for consistency with the other light elements $D$, $^{3}He$, and $^{7}Li$. The best fit value of $N_{\nu}$ now becomes

$$N_{\nu} = 2.17 \pm 0.27 \pm 0.42$$

Thus a $2\sigma$ upper limit (statistical) would be $N_{\nu} < 2.71$ and $N_{\nu} = 3$ is consistent at the $3.1\sigma$ level. When “systematics” are included, however, we see that the $2\sigma + \sigma_{syst}$ upper bound to $N_{\nu}$ is 3.13 which is consistent with standard model physics. Note that the bounds in (18) correspond to the upper bound on $D + ^{3}He$, $10^{5}y_{23P} \leq 10.0$. Corresponding to any uncertainty in this bound, there will be uncertainty in $N_{\nu}^{MAX}$. For example, if the $D + ^{3}He$ bound is only relaxed from $10^{5}y_{23P} \leq 10.0$ to $\leq 11.7$, $Y_{P} \lesssim 0.238$ is then consistent with $N_{\nu} \lesssim 3.0$. Alternatively, the possible inconsistency in (18), $N_{\nu}^{BBN} < 3$, could be evidence for a massive ($\gtrsim 5$-10 MeV), unstable ($\lesssim 40$ sec.) tau-neutrino (Kawasaki et al. 1994).

5 Summary

The availability of a large data set (PTSE) of homogeneously analyzed observations of metal-poor extra-galactic HII regions, recently supplemented by a sample of very metal-poor regions (Skillman et al. 1994b) encouraged us to employ this data to derive the primordial abundance of $^{4}He$ which is key to testing the consistency of Big Bang
Nucleosynthesis. Our goal has been to define a mean relation between the observed abundances of oxygen and/or nitrogen and helium and, to use this relation as an aid in extrapolating to the zero-metallicity, primordial helium abundance. As an aid in establishing this relation, we first analyzed the nitrogen and oxygen data to see if we could identify regions with excess or depleted nitrogen or oxygen which might contribute to dispersion around a mean helium vs. nitrogen or helium vs. oxygen relation. For our “first cut” data set, with $10^6(O/H) \leq 150$ and $10^7(N/H) \leq 100$, we found that the data is reasonably well fit by either a power law ($N/H \sim (O/H)\alpha$, with $1 < \alpha < 2$) or a linear/quadratic relation ($N/H \sim a(O/H) + b(O/H)^2$). In the latter case, the linear (“primary”) term dominates over the quadratic (“secondary”) term at low metallicity (typically, for $O/H \lesssim 10^{-4}$). We used the latter fit to identify “outliers”, HII regions which differ by more than 2σ from the mean $N$ vs. $O$ relation. With such discrepant regions removed the reduced chi-squareds about the mean relations are quite small.

We have emphasized that the metal- poor extra-galactic HII regions are likely a very heterogeneous set which need not give us a glimpse of the early evolution of nitrogen and oxygen in the Galaxy. Nonetheless, our simple power-law and linear/quadratic relations may be extrapolated to provide not bad fits to the observed nitrogen and oxygen abundances in halo stars, Galactic HII regions and, even the sun.

Next, we fit the observed helium mass fractions to linear relations with $O/H$ and $N/H$. For all of our subsets of the data (based on $N$ vs. $O$) we find mutually consistent fits with small dispersion around the mean relations and we infer: $Y_P = 0.232 \pm 0.003$, with a two σ (statistical) upper bound $Y_P^{2\sigma} \leq 0.238$. We confirm previous analyses which found steep slopes in the $Y$ vs. $O$ and $Y$ vs. $N$ relations ($\Delta Y/\Delta Z \approx 6 - 12$). Thus, it is clear that these relations cannot be extrapolated to interstellar or solar metallicities.

It is much more difficult to estimate the magnitude of possible systematic uncertainties. Here, we have agreed with previous analyses and adopted a 2% uncertainty which corresponds to $\sigma_{syst} \approx 0.005$. This then led us to a “maximum” value for primordial helium: $Y_P^{MAX} = Y_P^{2\sigma} + \sigma_{syst} \leq 0.243$. We have used both bounds $Y_P^{2\sigma}$ and $Y_P^{MAX}$, in our comparisons with the predictions of BBN.

Recent attempts (Kernan 1993; Seckel 1993; Gyuk and Turner 1993) to calculate to high accuracy the BBN yield of $^4He$ have led to an overall increase in $Y_{BBN}$ ($\sim 0.003$ compared to WSSOK; residual uncertainty, including the uncertainty in the neutron lifetime, $\lesssim 0.002$). Thus, the comparison between $Y_P$ and $Y_{BBN}$ leads to tighter constraints on the nucleon-to-photon ratio ($\eta_{10}$) and on the number of equivalent light neutrino flavors ($N_\nu$). For $Y_P \leq Y_P^{2\sigma} \leq 0.238$, we found $\eta_{10} \leq 2.5$ and $N_\nu \leq 2.7$. This suggestion of a crisis in BBN does, however, depend crucially on the precise value of the primordial abundance of $D + ^3He$. There is apparent inconsistency (over-production of $D$ and $^3He$) if $10^6y_{23P} \leq 10.0$ (WSSOK), but, there would be consistency for the weaker bound of $10^6y_{23P} \leq 11.7$. If, indeed, the primordial abundance of $D$ were as large as $10^6y_{2P} \approx 10$, deuterium may well be observable in the QSO Lyman - $\alpha$ absorption systems.
Our bounds to the nucleon abundance ($\eta_{10} \leq 2.5(3.9)$) imply reduced upper bounds to the nucleon density in the Universe: $\Omega_{BBN} h^2_{50} \lesssim 0.04(0.06)$; for $h_{50} \geq 0.8$, $\Omega_{BBN} \lesssim 0.06 (0.09)$. These lower upper bounds (compared, e.g., to WSSOK) strengthen the case for non-baryonic dark matter.

The $2\sigma$ statistical upper bound to $Y_P$ is sufficiently small that, if the primordial abundance of $D + ^3He$ is no larger than $10^5 y_{23P} = 10$, then the bound on the number of equivalent, light ($\leq 10 MeV$) neutrinos is $N_\nu \leq 2.7$, in apparent conflict with the LEP result, ($N_{\nu}^{LEP} = 3$). However, recall that LEP will probe neutrinos as massive as $M_Z/2$ while BBN is sensitive to light neutrinos. Indeed, Kawasaki et al. (1994) have noted that a massive ($5 - 10 \lesssim m_\nu \lesssim 31 MeV$), unstable ($\tau_\nu \lesssim 40$ sec) tau-neutrino would lead to lower $^4He$ production than in the case of three massless neutrinos.

On the other hand, with allowance for possible systematic uncertainties, $N_\nu \leq 3.1$ is allowed for $10^5 y_{23P} \leq 10$. Thus, there may be no conflict with the standard model and, very little room for new light particles beyond the standard model.

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Figure Captions

Figure 1: The nitrogen and oxygen abundances observed for all 48 HII regions in the PSTE and Skillman et al. (1994b) data sets. Our “first cut” data set is indicated by the dashed lines and our “second cut” data set is further restricted by the dotted line.

Figure 2: $N/O$ plotted vs. $O/H$ for the first cut sample of 40 HII regions. Also shown is the linear fit (Eq. [1]) derived for this data.

Figure 3: The same data as in Figure 2 is shown and the $2\sigma$ outliers are identified by filled circles. Also shown is the new linear fit with the outliers removed from the data set.

Figure 4: The helium and oxygen abundances for all 48 HII regions. The eight regions eliminated by our first cut are shown as filled triangles. Also shown are the eight outliers (filled circles) from the first cut set. The remaining points are distinguished by their observed WR features: C (open squares), P (open circles) and D (open triangles).

Figure 5: $Y$ vs. $O/H$ for the first cut data set of 40 HII regions. Outliers in $N/O$ vs. $O/H$ are shown as filled circles.

Figure 6: $Y$ vs. $N/H$ for the first cut data set of 40 HII regions. Outliers in $N/O$ vs. $O/H$ are shown as filled circles.
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