THE PRIMORDIAL ABUNDANCE OF $^4$He: AN UPDATE

KEITH A. OLIVE
School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455

GARY STEIGMAN
School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455

AND

EVAN D. SKILLMAN
Department of Physics, The Ohio State University, Columbus, OH 43210, and Department of Astronomy, The Ohio State University, Columbus, OH 43210

Received 1996 November 21; accepted 1997 February 12

ABSTRACT

We include new data in an updated analysis of helium in low-metallicity extragalactic H II regions with the goal of deriving the primordial abundance of $^4$He ($Y_p$). We show that the new observations of Izotov et al. are consistent with previous data. However, they should not be taken in isolation to determine $Y_p$, owing to the lack of sufficiently low-metallicity points. We use the extant data in a semi-empirical approach to bounding the size of possible systematic uncertainties in the determination of $Y_p$. Our best estimate for the primordial abundance of $^4$He assuming a linear relation between $^4$He and O/H is $Y_p = 0.230 \pm 0.003$ (stat) based on the subset of H II regions with the lowest metallicity; for our full data set we find $Y_p = 0.234 \pm 0.002$ (stat). Both values are entirely consistent with our previous results. We discuss the implications of these values for standard big bang nucleosynthesis (SBBN), particularly in the context of recent measurements of deuterium in high-redshift, low-metallicity QSO absorption-line systems.

Subject headings: H II regions — ISM: abundances — nuclear reactions, nucleosynthesis, abundances — quasars: general

1. INTRODUCTION

Determining the primordial abundances of the light elements $^2$D, $^3$He, $^4$He, and $^7$Li is crucial for testing the standard model of big bang nucleosynthesis (SBBN) and in using SBBN to set constraints on cosmology (e.g., the baryon density) and on particle properties (e.g., the number of light degrees of freedom contributing to the energy density of the early universe [see Walker et al. 1991]). Each of the light nuclides poses different problems in the quest for its primordial abundance. For example, deuterium is destroyed during the pre-main-sequence evolution of stars. As such, the relation between its observed and primordial abundances depends on the amount of material that has been cycled through stars (i.e., on Galactic chemical evolution). Uncertainties in Galactic evolution currently dominate any attempt to infer the primordial abundance of deuterium from local (“here and now”) observations, although such data do provide a lower bound to its primordial value.

The situation for $^3$He is much worse (i.e., even more subject to uncertainties in stellar and Galactic evolution) since stars of all masses destroy some—but not all—of their prestellar $^3$He, and low-mass stars are expected to be net producers of $^3$He. Thus, to infer the primordial abundance of $^3$He from observations (“here and now”) requires that the balance between destruction, survival and new production be known to an accuracy that eludes us at present. Since $^7$Li is observed in extremely metal-poor stars, Galactic chemical evolution plays virtually no role in using the data to infer its primordial abundance. However, since the very metal-poor stars are also very old, they have had a long time to modify their surface abundance of $^7$Li from its nearly primordial initial value. Uncertain corrections for stellar evolution dominate the uncertainty in the derived primordial abundance of lithium.

Since $^4$He is the most abundant nuclide in the universe (after hydrogen), it may be observed throughout the universe (not only “here and now”) more accurately than any of the other nuclides. For individual, careful observations, the abundance of $^4$He may be determined to 5% or better (0.012 in $Y$, the $^4$He mass fraction). Since its primordial abundance is expected to be quite large (~25% by mass) and $^4$He has been observed in the less processed, metal-poor, extragalactic H II regions, the extrapolation to primordial is minimal (differences in $Y \lesssim 0.002-0.004$). However, in the context of SBBN, the predicted primordial abundance of $^4$He is rather insensitive to (only logarithmically dependent on) the one free SBBN parameter—the nucleon-to-photon ratio $\eta(n = n_n/n_e; \eta_{10} = 10^{10}\eta$). For this reason it is necessary to establish the primordial abundance of $^4$He very accurately. Particular attention must be paid to possible systematic as well as to the usual statistical uncertainties.

Although, compared to the other light isotopes, the primordial $^4$He abundance is rather insensitive to chemical and stellar evolution, corrections for such effects are not entirely absent. In the course of their evolution stars burn hydrogen to helium and when they die they return this processed material (containing new $^4$He along with heavy elements (“metals”) such as C, N, O) to the interstellar medium (ISM) polluting the primordial $^4$He. To minimize the contribution from stellar-produced $^4$He, the best observational targets are those regions whose heavy element abundances are low, suggesting the least contamination from stellar and galactic chemical evolution. This has led virtually all investigators to concentrate on the low-
metallicity, extragalactic \text{H II} regions (Searle \& Sargent 1971; Peimbert \& Torres-Peimbert 1974; Lequeux et al. 1979; Kunth \& Sargent 1983; Torres-Peimbert, Peimbert, \& Fierro 1989; Pagel et al. 1992, hereafter PSTE; Skillman \& Kennicutt 1993; Skillman et al. 1994, 1997, hereafter S; Izotov, Thuan, \& Lipovetsky 1994, 1997 hereafter ITL). However, since in even the lowest metallicity regions observed (with metallicity as low as 1/50 of solar) some \(^4\text{He}\) was produced along with the heavy elements, Peimbert \& Torres-Peimbert (1974) proposed to correlate \(^4\text{He}\) vs nitrogen and to extrapolate to zero metallicity in order to infer \(Y_p\). Since the heavy element mass fraction, \(Z\), is not observed, the abundances of oxygen and/or nitrogen have usually served as surrogates [e.g., \(Z \approx 20(\text{O}/\text{H})\)].

A previous analysis (Olive \& Steigman 1995, hereafter OS), considered the \(^4\text{He}, \text{O}/\text{H}, \text{N}/\text{H}\) data of PSTE and of \(S\) for 49 separate, low-metallicity, extragalactic \text{H II} regions. In that analysis the correlation between \(\text{O}/\text{H}\) and \(\text{N}/\text{H}\) was explored, and it was concluded that the nitrogen observed in these objects is dominated by a primary contribution (i.e., \(\text{N}/\text{H}\) increasing linearly with \(\text{O}/\text{H}\)) with a small but not entirely insignificant secondary component. The fits of \(Y\) versus \(\text{O}/\text{H}\) or \(Y\) versus \(\text{N}/\text{H}\) were not sensitive to the inclusion or exclusion of galaxies that show Wolf-Rayet features or of galaxies that deviated from the mean \(\text{N}/\text{H}\) versus \(\text{O}/\text{H}\) relation. There was, however, a small difference between the values of \(Y_p\) derived from the fits of \(Y\) versus \(\text{O}/\text{H}\) and \(Y\) versus \(\text{N}/\text{H}\). Given that there are both primary and secondary contributions to nitrogen, this is not unexpected (Torres-Peimbert et al. 1989; Fields 1996); we will return to this issue below. Overall, it was found that the data were well described by a linear fit to \(\text{O}/\text{H}\) with an intercept at zero metallicity of \(Y_p = 0.232 \pm 0.003\). In addition to the above statistical uncertainty, various contributions were described that might lead to an overall systematic uncertainty of order \(\pm 0.005\) (see also PSTE).

In the past year or two the \(^4\text{He}\) abundance, key to the consistency of SBBN, has come under great scrutiny. Most recently, ITL presented new data, which they claimed provides evidence for \(Y_p\) in excess of 0.24. In this paper, we consider the ITL data and ask if they are consistent with those of PSTE and \(S\). We conclude that they are and we propose an explanation for the apparent contradiction. We then use all extant data (PSTE, \(S\), and ITL) to derive the current best estimates for the primordial abundance of \(^4\text{He}\). We also attempt to use the data in a semi-empirical approach to estimating the size of the possible systematic uncertainty in \(Y_p\).

2. THE OLD DATA USED BY OS

OS used the data of PSTE and \(S\) for 49 separate extragalactic \text{H II} regions. In minimizing the extrapolation to zero metallicity, the lowest metallicity \text{H II} regions play a crucial role. As a result a “first cut” was made by OS eliminating those \text{H II} regions (albeit only 8 out of 49) with \(\text{N}/\text{H} \geq 1.0 \times 10^{-4}\) and \(\text{O}/\text{H} \geq 1.5 \times 10^{-4}\). All of the \text{H II} regions retained are metal-poor compared to the Sun where (\(\text{O}/\text{H})_\odot = 8.5 \times 10^{-4}\) and (\(\text{N}/\text{H})_\odot = 1.1 \times 10^{-4}\). Nevertheless, the OS “first cut” data set spans 1 order of magnitude in oxygen abundance (15 \(\leq 10^6(\text{O}/\text{H}) \leq 150\)) and a factor of \(\sim 25\) in nitrogen abundance (4 \(\leq 10^4(\text{N}/\text{H}) \leq 100\)). OS also considered an even more metal-poor subset (“second cut”), retaining the 21 (out of 41) \text{H II} regions with \(\text{O}/\text{H} \leq 8 \times 10^{-5}\) (\(\text{O}/\text{H} \leq 1\)). This more restricted second cut set still has a modest dynamical range in its oxygen and nitrogen abundances: \(15 \leq 10^6(\text{O}/\text{H}) \leq 80\) and \(4 \leq 10^4(\text{N}/\text{H}) \leq 40\).

As mentioned above, OS investigated the correlation between \(\text{N}/\text{H}\) and \(\text{O}/\text{H}\) for these \text{H II} regions. Although the variation of nitrogen with oxygen is of interest for the study of chemical evolution, it must be emphasized that the evolution of the very low-mass host galaxies of these extragalactic \text{H II} regions is likely dominated by local—in space and in time—processes. Different \text{H II} regions may be “caught” at different evolutionary epochs (e.g., just before or just after a starburst, shortly before or immediately after a supernova explosion, etc.). Overall, OS found a strong correlation between \(\text{N}\) and \(\text{O}\), and that at low metallicity nitrogen is predominantly primary (varying linearly with oxygen) with a small, but not insignificant, secondary component (proportional to the square of the oxygen abundance). This can be seen from a power-law fit to the data, \(\text{N}/\text{H} \propto (\text{O}/\text{H})^\alpha\), where OS found \(\alpha = 1.31 \pm 0.07\). This behavior is confirmed with our enlarged data set, now containing 62 distinct extragalactic \text{H II} regions (labeled set \(B\) below), for which we find \(\alpha = 1.21 \pm 0.06\). Alternatively, the predominantly primary nature of nitrogen can be seen by fitting the data with a linear \(\text{N}/\text{O}\) versus \(\text{O}/\text{H}\) relation for which we find:

\[
\frac{\text{N}}{\text{O}} = (0.023 \pm 0.002) + (76 \pm 19)\left(\frac{\text{O}}{\text{H}}\right). \tag{1}
\]

The “primary” component dominates for \(\text{O}/\text{H} \leq 3.1 \times 10^{-4}\), and that for our entire “first cut” range the “secondary” to “primary” ratio varies from 5%–50%. This is in agreement with Pagel \& Kazlauskas (1992), who concluded that “primary” nitrogen dominates at low metallicity.

Pagel, Terlevich, \& Melnick (1986) noted that \text{H II} regions that showed Wolf-Rayet spectral features often had larger abundances of both helium and nitrogen compared to \text{H II} regions with the same oxygen abundance but lacking such features. OS searched for such an effect but found no statistically significant correlation, so OS did not exclude any \text{H II} regions with Wolf-Rayet features and neither will we in our analysis here. This conclusion is supported by ITL and by Kobulnick \& Skillman (1996).

In the previous \(Y\) versus \(\text{O}/\text{H}\) analysis, OS found for the first cut (second cut) set \(Y_p = 0.232 \pm 0.003\) (0.229 \pm 0.005). Since then the data on extragalactic \text{H II} regions have increased significantly. ITL 1994 presented observations of 10 \text{H II} regions, four of which overlap those in the \(S\) set used by OS. These new data were incorporated in the analysis of Olive \& Scully (1996), who found that \(Y_p\) derived from \(Y\) versus \(\text{O}/\text{H}\) for the expanded first cut set (now containing 47 \text{H II} regions) is slightly higher (although within 1 \(\sigma\) of OS): \(Y_p = 0.234 \pm 0.003\).

3. THE NEW DATA OF ITL

In their most recent work, ITL 1997 have data from observations of 28 new \text{H II} regions. Of these one region is included in their 1994 set and four others are contained in the PSTE set, including a reobservation of I Zw 18. Thus, we now have data for 78 distinct extragalactic \text{H II} regions (several of which have been observed by two or more independent groups). In the following analyses we impose the same low-metallicity first cut restriction as in OS, eliminating the same eight regions from the PSTE set. Thus, the largest, low-metallicity set available for analysis consists of
70 regions (set A). However, according to several criteria ITL exclude 10 regions (including I Zw 18) from their analysis; here we accept their judgment and with one notable exception (see below) eliminate the same regions from consideration. Since eight of the ITL-excluded regions are not contained in the PSTE or S sets, our data set is now reduced to 62 distinct H II regions (set B). For our second cut (in this case at O/H < 8.5 × 10^{-3}; [O/H] < −1) we have 32 distinct H II regions (set C). However, before proceeding it is necessary to consider the relation between the ITL data and those of PSTE and S. Are they consistent?

One issue concerns the calculation of the statistical uncertainties reported with the observed line ratios (corrected for reddening). PSTE report uncertainties derived from the total counts in the line and the continuum, and terms accounting for the sky subtraction and the read noise of the detector. Uncertainties were not calculated for the reddening correction, the flat-field correction, or the wavelength-dependence of the sensitivity (the “flux” calibration), but care was taken that such that these uncertainties were of order, or smaller, than the calculated uncertainties (see Simonson 1990). Skillman et al. (1994) include all of these terms in their uncertainties (see e.g., eq. [2] in Skillman et al. 1994).

Although ITL do not provide sufficient details to permit us to determine how the uncertainties in their emission line ratios are calculated, there are reasons to suspect that ITL have underestimated their uncertainties. For example, although they state that their spectra are “in excellent agreement” with those previously published in the literature, their brighter lines are often quoted with uncertainties between 0.1% and 0.2%. This is to be contrasted with the analyses of PSTE and S, where the minimum uncertainties usually lie in the range of 1%-2%. It may be interesting that ITL do comment that the residuals in their flux calibration curve are “≤5%.” In general, it is not possible to know relative line ratios with an accuracy better than the calibration of the telescope/spectrograph/detector combination. In assembling a set of spectrophotometric standard stars for use with the HST, Oke (1990) used CCDs that were measured to be linear to within 0.2% and found that standard star measurements were repeatable to “about 1% over most of the spectral range and a little larger in the ultraviolet and near infrared.” Thus, it would seem prudent to adopt 1% as a reasonable lower limit to the uncertainty on any measured emission line ratio. However, for our analysis here we simply accept the ITL reported uncertainties.

ITL have adopted an approach of using the data for four He I lines (λ4471, λ5876, λ6678, λ7065) in a self-consistent analysis whose goal is to determine simultaneously the recombination and the collisional excitation contributions to the observed emissivities. By insisting that the line ratios have their recombination values after correction for collisions, ITL determine the electron densities self-consistently. The virtue of this approach is that it avoids the use of uncertain electron densities determined indirectly from [S II]. The problem with this approach is its reliance on the λ7065 line, which, although sensitive to collisional excitation (albeit with an uncertain collision strength), is well-known (Robbins 1968; PSTE; G. Ferland 1996, private communication) to be subject to fluorescence. The observed λ7065 line strengths may well be providing a measure of the optical depth through the H II regions rather than of the effect of collisional excitation (although ITL argue to the contrary). Unquantified radiative transfer effects, complicated by unknown H II region geometry, dust/gas, etc., may introduce large uncertainties in the ITL approach that call into question the efficacy of their reliance on this line. Further, their approach requires that ITL have good data for all four lines and this forces them to reject otherwise good observations of H II regions when they have sufficiently accurate data for only two or three of the four lines. In contrast to the ITL approach, neither PSTE nor S use the λ7065 line in their analyses, and Peimbert (1996) notes that for the relatively low electron densities common to H II regions the collisional correction is usually quite small.

ITL use their method to analyze their data in a number of different ways. They have compared the He abundances derived from the observed emission line strengths using the independent sets of recombination line emissivities by Brocklehurst (1972, hereafter B72) and Smits (1996, hereafter S96). For λ5876, 4471, and 6678, the new S96 emissivities are in good agreement with those of B72 (see Table 3 of S96 for a comparison). Over the relevant range of electron temperature and density, the B72 and S96 emissivities for λ5876 and λ6678 agree to within 1% and for λ4471 to within 2%. There is roughly a 40% difference for λ7065 where B72 was in error (see discussion by Smits 1991a, 1991b). Given the error in the B72 λ7065 emissivities, it does not make sense to use the B72 emissivities in concert with their method.

ITL also use two different sets of collisional excitation rates to correct for the contribution of emission from collisional excitation from the metastable 2^3S level of He I. Clegg (1987; hereafter C87) calculated these rates from the 19-state (up to n = 4) R-matrix computation by Berrington & Kingston (1987). Kingdon & Ferland (1995; hereafter KF) have calculated new rates, based on the 29-state (up to n = 5) computation of Sawrey & Berrington (1993). Figure 1 compares the results of the C87 and KF calculations for the relative rates of collisionally excited emission to recombination emission (C/R) for the four He lines used by ITL. Note the excellent agreement for λ5876 and λ6678. The small change in the rate for λ4471 is due to both a change in the rate to the n = 4 level, and to the addition by KF of rates to two n = 5 levels. The large change in the λ7065 C/R value is mainly due to the difference between the recombination rates. C87 used B72 for these rates and KF used S96 for these rates. Since the emissivities are implicit in the C/R calculations, it makes no sense to combine C87 with S96 nor KF with B72 as ITL have done. While the differences for λ5876 and λ6678 will be negligible, the differences for λ4471 will be significant, and for λ7065 very large.

Therefore, when using the ITL analysis, the recombination emissivities must be restricted to those from S96 while any analysis that avoids the λ7065 line may use either B72 or S96. Since previous analyses (PSTE; S) have avoided this line (and have employed B72/C87), it is interesting to compare the Y-values derived from the ITL observations using S96/KF (their “best” combination) to those derived using B72 for the recombination emissivities, C87 for the collision strengths, along with the electron densities determined from [S II]. The ITL data reveal these differences to be quite small, in fact a weighted average of difference of the 4He mass fractions, \( \langle Y(\text{S96/KF}) - Y(\text{B72/C87/S II}) \rangle = -0.003 \), which is much less than the typical uncertainties in the individual Y determinations. Indeed, most of
This difference is traceable to the \( \approx 1\% \) differences between the KF and C87 collision strengths, which, however, lead to no significant difference (i.e., \( \lesssim 0.2\% \)) when ITL evaluate \( Y_p \) using S96/KF or S96/C87 (see Table 7 of ITL). Within the uncertainties, \( Y(S96/KF) = Y(B72/S) \). This agreement suggests that the analyses of PSTE and of S have not been biased by their reliance on B72, and that their results using B72/C87/S should be directly comparable to those of ITL.

In contrast, ITL found from linear regressions of \( Y \) on O/H using their own data \( Y_p(S96/KF) = 0.243 \pm 0.004 \), whereas OS, using PSTE and S data, found \( Y_p(B72/S) = 0.232 \pm 0.003 \). Given the relatively small statistical uncertainties such a large difference suggests an inconsistency between PSTE and S on the one hand and ITL on the other. Some have interpreted this apparent discrepancy as an indicator of the true size of the systematic uncertainties in \( Y_p \) determinations and have embraced the larger ITL values as a better probe of \( Y_p \). ITL apparently believe the inconsistency is real and they claim it is traceable to the use by PSTE and S of the older B72 emissivities. But we have just demonstrated, using the ITL data, that this cannot be the case; within the uncertainties for all ITL H II regions: \( Y(S96/KF) = Y(S96/C87) = Y(B72/S) \). Therefore, we must be able to compare the value of \( Y_p \) derived from the ITL observations using the B72/C87/S II combination with that found by OS using the PSTE and S data. For the data from the ITL preferred set of 27 H II regions, a linear regression of \( Y \) on O/H yields \( Y_p = 0.241 \pm 0.004 \), still quite high compared to the OS result.

Why, then, do ITL find such a large value for \( Y_p \) (0.241) compared to that found by OS from the data of PSTE and of S (0.232)? We believe it is due to the absence of the very lowest metallicity H II regions from the ITL set after they have excluded selected regions from their analysis. Figure 2 shows (with the error bars suppressed) the \( Y \) versus O/H data used by OS (open circles) along with the new ITL data (filled circles). The crossed circles are the 10 H II regions that ITL excluded from their analyses. Where there is overlap in O/H, the ITL \( Y \)-values are intermingled with those from PSTE and S. Indeed, there are six H II regions in common between ITL and OS (not counting those ITL regions, shown in Figure 2, which ITL excluded from their fits) with four having higher and two with lower \( Y \)-values than their PSTE or S counterparts. It is indeed surprising that ITL and OS find such significantly different values for \( Y_p \). However, the ITL data set does not extend to as low an oxygen abundance as the set employed by OS. This more limited range in metallicity for the ITL data set gives them less leverage in determining the slope of the \( Y \) versus O/H relation. Indeed, in the \( Y \) versus O/H fit of the ITL data set, the slope is found to be \( 64 \pm 48 \). This is reminiscent of the earlier work of Kunth & Sargent (1983), whose limited metallicity range also led to a indeterminate slope. Kunth & Sargent (1983) made the appropriate choice based on their data and took a weighted mean of their data to determine \( Y_p \), finding a high value of \( 0.245 \pm 0.003 \), which is very similar to those found by ITL. Indeed, when ITL used S96/KF or S96/C87 they found slopes consistent with zero, which suggests that their \( Y_p \) estimates are effectively weighted means.

To test this hypothesis, we have refitted the \( Y \) versus O/H relation for the OS set excluding the four lowest O/H points. For this modified “first cut” OS set of 37 H II

---

**Fig. 1.**—Comparison of the calculations of the collisionally excited emission recombination emission rates (C/R) for four He I recombination lines using the formulae of Clegg (1987) (based on the recombin- nation emissivities of Brocklehurst 1972 and the collisional rate coefficients of Berrington & Kingston 1987) and Kingston & Ferland (1993) (based on the recombin- nation emissivities of Smits 1996 and the collisional rate coefficients of Sawey & Berrington 1993). The calculations were carried out for an electron density of 100, which is appropriate for most low-metallicity H II regions. The large difference seen for the \( \lambda 7065 \) line arises mostly because Clegg used the recombin- nation coefficients from Brocklehurst (1972), which, for \( \lambda 7065 \), have been shown to be in error by Smits (1991a, 1991b). For comparison, we have recalculated the C/R ratio for \( \lambda 7065 \) using the collisional rate coefficients of Berrington & Kingston (1987) and the recombin- nation coefficients of Smits (1996) (labeled “corrected”). This plot shows that the collisional rates for these He I lines changed very little with the new data of Sawey & Berrington (1993) as emphasized by Kingston & Ferland (1995).

---

**Fig. 2.**—Helium (\( Y \)) and oxygen (O/H) abundances for the extragalactic H II regions of the first cut data sets (OS) from PSTE and S (open circles), and from ITL (filled circles). Regions excluded by ITL are shown as crossed circles. Lines connect the same regions observed by different groups.
regions we find $Y_p = 0.237 \pm 0.004$, significantly higher than the previous result for the full "first cut" set ($0.232 \pm 0.003$). This reflects the high weights in the fits carried by the lowest metallicity H II regions, which tend to have low Y-values with small uncertainties. It is this modified OS value of 0.237, which should be compared to the ITL result of 0.241. Within the statistical uncertainty they are entirely consistent. To explore this further, we have employed the modified "first cut" fit to describe the ITL data. The reduced $\chi^2$ for this fit is 0.50 (to be compared with 0.44 for ITL's own fit). Based on the F-test (Bevington & Robinson 1992) there is a 39% chance that their data is drawn from a distribution described by our fit. In addition, we have used the modified set of 37 H II regions in a "statistical bootstrap" of 40,000 runs (see Olive & Scully 1996), and we found that $Y_p$ exceeded 0.241 13% of the time. This is shown in Figure 3. These tests lead us to conclude that the new ITL data do not differ statistically from the older PSTE and S data used by OS.

With this as justification, we proceed to analyze the combined data of PSTE, S, and ITL. In this analysis we adopt the ITL data derived using the electron densities determined from S II so that we may have an internally consistent data set. Although we avoid using the 10 H II regions discarded by ITL, eight of them are rather insignificant in the sense that since their abundances have large uncertainties (and another is at intermediate metallicity), they would have low weight in our fits and not much influence on our derived value of $Y_p$. The one exception is I Zw 18, which provides the lowest metallicity point and for which ITL have good data. ITL exclude I Zw 18 from their analysis because the $\lambda 5578$ line is subject to absorption by interstellar sodium. Not being able to use all four He I lines in their self-consistent approach, ITL eliminate I Zw 18 from their analysis. Y. I. Izotov (1996, private communication) has kindly provided us with the $^4$He abundance derived from their data using the $\lambda 6678$ line and the $[S II]$ electron density and we use this information to include this data point in our subsequent analysis. When I Zw 18 is included with the other 27 ITL data points, their intercept drops to $0.239 \pm 0.004$ (the effect is minor since the uncertainty is relatively large—in OS the uncertainty in I Zw 18 is diminished due to multiple as well as high-quality observations). If we make our second cut to the ITL data including I Zw 18, the intercept drops to $0.231 \pm 0.006$. This result is now completely consistent with the OS value of $0.229 \pm 0.005$.

4. RESULTS

4.1. $Y_p$ From The Helium-Metallicity Correlation

We adopt several approaches to using the H II region data (set B with 62 separate H II regions and the lower metallicity set C with 32 regions) to infer the primordial abundance of $^4$He, $Y_p$. Since primordial helium has been contaminated with the debris of stellar ejecta, the most common approach has been to use the metallicity information to probe the correlation of $Y$ with $Z$ (either O/H or N/H) and to extrapolate this empirical relation to zero metallicity to find $Y_p$ (Peimbert & Torres-Peimbert 1974). With increasing numbers of very low-metallicity H II regions, this extrapolation is quantitatively quite small ($\Delta Y \approx 0.002–0.004$). In OS we showed that the extant data do, indeed, justify a positive correlation between $Y$ and O/H (N/H). To explore this from a somewhat different perspective, consider the following: For set B we have computed the weighted mean of the helium abundances, $\langle Y \rangle$ and in Figure 4 we plot the residuals, $Y - \langle Y \rangle$ as a function of the oxygen abundance. At low metallicity almost all the residuals are negative, while the positive residuals appear only at higher metallicity. Thus, a one-parameter fit to the

1 We have used the values of $Y$ and $\sigma_Y$ given by ITL. We note that the uncertainty in $Y$ was not statistically propagated from that in the abundance by number, $y$. Thus, the quoted uncertainties are somewhat larger (by $\sim 30\%$) than they should be. We did not correct for this.
$Y$ versus $O/H$ data fails to account for the clear helium—oxygen correlation and is a poor fit to the data. Therefore, we next try to fit the data with linear $Y$ versus $O/H$ ($N/H$) regressions. These two-parameter fits describe the data very well (see Table 1). If instead of our new “first cut” set $B$ we had used the data for all 70 independent $H$ II regions (set $A$), there would be no difference in our derived value of $Y_p$. Similarly, there is no difference exceeding 0.001 in $Y_p$ if we exclude the ITL value (Y. I. Izotov 1996, private communication) for I Zw 18 from our fits.

From Table 1 we notice that the values of $Y_p$ derived from the $Y$ versus $N/H$ relations are systematically higher (but only by $\leq 1 \sigma$) than those inferred from $Y$ versus $O/H$. This effect is also present in OS and is entirely to be expected on the basis of the primary/secondary origin of nitrogen (Torres-Peimbert et al. 1989; Fields 1996). As Fields (1996) shows, the primary/secondary origin for nitrogen, compared to the primary origin for oxygen implies that when $Y_p$ is derived from a linear correlation with $N/H$ the result will exceed the “true” value derived from the linear $Y$ versus $O/H$ relation. The quantitative difference between the two regressions will depend on the details of chemical evolution models as well as on the observed correlation of $N$ with $O$ and will be explored in future work (Fields, Olive, & Steigman 1997). For this reason we adopt for our estimates of $Y_p$ those values derived from the $Y$ versus $O/H$ regressions for the $B(C)$ sets (Table 1),

$$Y_p = 0.234 \pm 0.002(0.230 \pm 0.003),$$

for which $Y_{pB}^d \leq 0.239(0.237)$. If we assume (PSTE) that the metallicity $Z$ and $O/H$ may be related by $Z \approx 20(O/H)$, the set $B(C)$ $Y$ versus $O/H$ fits imply: $\Delta Y/\Delta Z \approx 6(12)$, consistent with the steep slopes found by PSTE, Olive, Steigman, & Walker (1991), and OS.

4.2. $Y_p$ From A Few Good $H$ II Regions

For the fits described above, the extrapolation from the lowest metallicity $H$ II regions to zero metallicity is minimal ($\Delta Y \approx 0.002$–0.004). Nonetheless, it is true that any extrapolation to zero metallicity could be avoided since the helium abundance inferred from the observations of any one $H$ II region (with nonzero metallicity) should provide an upper limit to $Y_p$. For a very low-metallicity $H$ II region such an upper limit may even provide a reasonable estimate of $Y_p$. In this context, I Zw 18, the most metal-poor $H$ II region, is an ideal candidate (Kunth et al. 1994) since it has been the subject of careful study by several independent groups (PSTE, Skillman & Kennicutt 1993, and ITL). A weighted mean of the five observations of the two separate knots in I Zw 18 yields,

$$Y(I \text{ Zw} 18) = 0.230 \pm 0.004,$$

with a $2 \sigma$ upper bound of 0.237. In terms of statistical accuracy this result is fully competitive with the value of $Y_p$ derived in the previous section from 62 (32) $H$ II regions.

![Graph](image-url)

**Fig. 5.—Running average (weighted means) of the $^4$He abundance, $Y$, for the first $N$ (lowest $Y$) $H$ II regions. Also shown are the $2 \sigma$ bounds to the weighted means.**

Of course, it should be kept in mind that the abundance inferred for any one $H$ II region might be anomalous. Therefore, the value of $Y$ derived from the average of several $H$ II regions is also of interest. In such an analysis, as more regions are included, the mean value (weighted) of $Y$ will increase, but if the uncertainties are statistical, the uncertainty in the mean will decrease. As a result, for $N$ $H$ II regions the 1 (or 2) $\sigma$ upper bound to $Y$ will first decrease with $N$, then level off and, as $N$ is further increased, it will eventually increase monotonically. This behavior is seen in Figure 5, which shows the weighted means, and the $2 \sigma$ bounds to the weighted means of $Y$ derived from the $N$ lowest helium abundance $H$ II regions. For $2 \leq N \leq 13$, the mean varies from 0.229 to 0.231, while for $2 \leq N \leq 14$, $\langle Y \rangle \leq 0.236 (2 \sigma)$. It is not unreasonable to infer from these results that,

$$Y_p \leq 0.230 \pm 0.003,$$

with $Y_{pB}^d \leq 0.236$. If, instead, we take the weighted means of the regions with the lowest values of $O/H$, we obtain a similar result. This illustrates the potentially great value of very careful analyses of a handful of the lowest metallicity (lowest $Y$) $H$ II regions.

4.3. The Systematic Uncertainty In $Y_p$: A Semi-Empirical Approach

Many observers have identified numerous sources of uncertainty affecting $H$ II region helium abundance determinations (see, e.g., Davidson & Kimman 1985; Dinerstein & Shields 1986; PSTE; S; ITL; Peimbert 1996). Peimbert (1996) divides the uncertainties associated with the determination of the primordial helium abundance into three
groups: (I) uncertainties in the determination of the line ratios; (II) uncertainties in the interpretation of the line ratios; and (III) uncertainties in the extrapolation to $Z = 0$. Here we try to infer a reasonable estimate of the systematic uncertainty in $Y$, by inspecting the various possible systematic effects in each group.

In Group I the uncertainties in determining line ratios can be attributed to measurements of the line ratios (including signal-to-noise in the line and sky subtraction), detector calibration, reddening corrections, and lack of corrections for possible underlying stellar absorption. All of the effects in Group I have been discussed in detail by Skillman et al. (1994) and in previous studies. To summarize, if detectors that have been tested for linearity (CCDs) are used, if several standard stars that have been previously observed with linear detectors (preferably the HST standards of Oke) are observed, if the targets are restricted to those objects of high excitation and high Balmer line equivalent width, and if one accumulates in excess of 10,000 photons in each of the He lines used, then it is possible to achieve an accuracy of 2% in the relevant He/H line ratios. Then, of all the effects described above, only unaccounted-for underlying stellar absorption would cause a systematic uncertainty, leading to an underestimate of the He abundance. However, the presence or absence of this effect can be probed by measuring different He lines of different equivalent widths. The general agreement between the different lines, in those cases with careful tests, indicates that the effect of underlying stellar absorption is of order 1% or less.

In Group II the uncertainties in the interpretation of line ratios can be attributed to correcting for the presence of neutral He, variations in temperature structure (“temperature fluctuations”), the accuracy of the atomic data, the correction for the collisional excitation of He I lines (primarily from the metastable triplet 2\,S level), correction for radiative transfer effects, and correction for collisional excitation of the H\,I lines (from the ground state). Taken in order:

1. In principle, the presence of neutral He would systematically lower the observed He abundance. However, none of the tests performed so far have found any evidence of neutral He (see Skillman et al. 1994), and photoionization models indicate that it is not likely to be a problem for the objects included in these studies (see also the discussion by Vilchez & Pagel 1988 and by PSTE).

2. If there are variations in the electron temperature in the gas, the heavy element abundances derived from the collisionally excited lines would be underestimated and the He abundances would be slightly overestimated (owing to the weak dependence of the He lines on the electron temperature, the effect is 1.5% for $\Delta 876$ and $\Delta 678$ for an uncertainty of 1000 K at 15,000 K and about half of that for $\Delta 471$), although at high densities and temperatures the increased collisional contributions can lead to an underestimate of $Y$ (Steigman et al. 1997). Temperature variations appear to be much more likely at higher metallicities, but if supernovae are an important heating source in the H\,II regions, then temperature fluctuations may be important (Skillman 1985; Peimbert, Sarmiento, & Fierro 1991).

3. The comparison of Smits (1996) with Brocklehurst (1972) would indicate that the atomic data and calculations of the recombination emissivities for the He lines of interest are good to better than 1%. However, there are much larger differences in the infrared transitions, and more work (both theoretical and observational) is desirable in this area.

4. The recent work by Kingdon & Ferland (1995) gives us confidence that we are able to correct accurately for collisional excitation of He I. These corrections are usually of order 1%–3%. Not correcting would systematically overestimate the He abundance. The main problem here is to determine the density sufficiently accurately. ITL have argued that densities derived from [S II] emission lines are not appropriate. Since the different He I emission lines have different density dependences, by using several lines it is possible to solve for the density, and thus the correction (this is essentially how ITL propose to solve for the electron density). In general, the densities derived in this manner by ITL agree well with those derived using the [S II] lines.

5. Since the work of Robbins (1968), it has been generally agreed that radiative transfer effects are unimportantly small for the bright lines that are used to derive the He abundances, particularly the singlet lines. Based on the results of photoionization modeling, in which the effects of collisional coupling of the singlets and triplets, radiative transfer effects, and collisional excitation were all treated simultaneously, Sassev & Goldwirth (1995) claimed that the He/H line ratios lead to systematic underestimates. However, no He/H line ratios were presented in their paper. Until such effects on the He/H line ratios are identified and quantified, it seems reasonable to ignore this claim.

6. Davidson & Kinman (1985) showed that at the high temperatures found in the lowest metallicity H II regions, collisional excitation of the H I lines may be important. Skillman & Kennicutt (1993) showed that this effect, which is dependent on the neutral hydrogen fraction, is not significant for neutral H fractions less than 0.0001. Straightforward calculation of the photoionization balance in an H II region usually results in neutral H fractions less than this. Photoionization codes often produce higher neutral H fractions, but this may be due to the approximations made in the treatment of the ionizing radiation field. This could be a very difficult uncertainty to pin down, since the geometry of the gas distribution relative to the ionizing source has a strong influence on the neutral H fraction. If this effect were important, it would result in an underestimate of the He abundance. Perhaps 2% represents a reasonable upper limit on the uncertainty of this effect.

Group III uncertainties are concerned with the extrapolation of the observed helium abundances to zero metallicity. The “classical” approach (Peimbert & Torres-Peimbert 1974) has been to fit the observations with a linear $Y$ versus $Z$ relation (where the oxygen abundance usually serves as a surrogate for $Z$) and to extrapolate to $Z = 0$. For observations of low-metallicity H II regions this linear fit may be thought of as the lowest order contribution to a more general $Y(Z)$ relation. For the set B(C), this extrapolation from the lowest metallicity data is quite small: $\Delta Y = 0.002 \pm 0.001$ (0.003 ± 0.001). Since He/H is only expected to increase with $Z$, it is unlikely that this approach can systematically underestimate $Y_p$. While this linear fit may yield an upper bound on $Y_p$, it does not necessarily provide a lower bound. Indeed, as our second cut set (set C) shows, the $Y$ versus $Z$ slope appears to steepen at the very lowest metallicities. If the assumption of linearity is relaxed, then, in principle, $Y_p$ can be significantly lower.
Given the different production sites of He and O, He/H may not be expected to track O/H well. Indeed, Steigman, Gallagher, & Schramm (1989) suggested that helium may correlate better with nitrogen and/or carbon than with oxygen. The observation by Pagel et al. (1992) that the dispersion in the He vs. N regression is less than that of the He vs. O regression lends some support to this expectation. However, the observed linearity of Y with Z [where \( Z \approx 20(O/H) \)] over more than a decade in Z (e.g., OS) may reflect a balance between losses due to galactic winds (most important for low-mass, low-metallicity systems) and the metallicity dependence of the yields (O yield decreasing with increasing metallicity due to the increasing importance of stellar winds in the massive stars). Future work on accurate increasing metallicity due to the increasing importance of metallicity dependence of the yields (O yield decreasing with increasing metallicity) would be of great value.

Since the data are entirely consistent with a linear Y vs. Z relation, the uncertainty in the intercept should be of order the uncertainties in the best measured points at low metallicities (i.e., 2%–3%). Calculating the uncertainty in the intercept depends on knowledge of the source of the scatter in Y at a given Z, which presently is dominated by measurement uncertainties.

In the analysis presented here we have, to some extent, avoided the issue of the extrapolation to zero metallicity by considering the helium abundance determined from the best observed H II regions \( (Y_p \leq Y_{\text{obs}}) \). From five independent observations of I Zw 18 we found, \( Y_p \leq 0.230 \pm 0.004 \); from the 13–14 H II regions with the lowest helium abundances we derived, \( Y_p \leq 0.230 \pm 0.003 \).

Finally, there remains the important question of how to combine different sources of systematic uncertainties. Since the possible uncertainties are not correlated, it makes no sense to add (linearly) all imaginable systematic uncertainties to obtain an estimate of the total systematic uncertainty. Many potential sources of uncertainty can be classified as unlikely, with bounds constrained observationally. Therefore, it is even more unlikely that a single data point (let alone all of them) would suffer from more than one of the potential systematic uncertainties at the amplitude of the observationally constrained limits. The salient point is that all imaginable systematic uncertainties appear to be limited to about 2% or less. Thus, it seems reasonable to adopt as an estimate for the overall systematic uncertainty, 0.005, as proposed by PSTE.

We can also attempt to exploit the data itself to provide a bound on the size of possible systematic sources of uncertainty. Although many of the sources of potential uncertainties listed above might shift \( Y \) and/or O/H in a systematic fashion, modifying the intercept and/or slope inferred from the \( Y \) versus O/H relation, their variation from source to source and observer to observer (telescope/detector to telescope/detector) would also contribute to the overall dispersion of the data around the “true” \( Y \) versus O/H relation. We have therefore taken our best fit for set B (see Table 1) and examined the residuals, \( Y - Y(B) \), as a function of O/H. For the variance of the residuals we find 0.007; this should be compared to the uncertainty estimates for individual H II region Y determinations that are, on average, 0.010. It appears that the observers have been generous, perhaps overly generous, in their uncertainty estimates as first pointed out by PSTE. Indeed, this was already suggested by the small values of the reduced \( \chi^2 \) seen in Table 1. We stress that since the variance of the residuals is small, there is no real statistical significance to the ITL claims that S96/KF improves the scatter.

As a further check on the stability of our \( Y_p \) estimates and to constrain many of the sources of possible systematic uncertainty, we have performed 40,000 runs of a statistical bootstrap (Olive & Scully 1995) using all the data (set A) with, and without the uncertainty estimates (we thank Tim Beers for suggesting this test to us and Sean Scully for doing the runs). Figure 6 shows the resulting distributions for \( Y_p \) (when uncertainties are included). In both cases the distributions are closely Gaussian with \( Y_p = 0.234 \pm 0.002 \) and 95% CL upper bounds \( \lesssim 0.238 \). This test suggests that unless all values of \( Y \) should be systematically shifted (e.g., due to inaccurate atomic data), 0.238 might provide a good upper bound to \( Y_p \), including systematic uncertainties. However, to err on the side of conservatism, instead of an upper bound of 0.238 (including systematic uncertainties), we will adopt the set C (B) results in the subsequent discussion,

\[
Y_p = 0.230 \pm 0.003 \pm 0.005(0.234 \pm 0.002 \pm 0.005),
\]

where 0.003 (0.002) represents the (Gaussian) statistical uncertainty \( [Y_p^{\text{stat}} \leq 0.237 (0.239)] \) and 0.005 is a possible systematic offset in \( Y_p \) (leading to “firm” 2 \( \sigma \) upper bounds to \( Y_p \) of 0.242 or 0.244). We will also explore the consequences of a larger value for \( \Delta Y_{\text{sys}} \).

5. DISCUSSION

First let us ignore any possible systematic uncertainty in our adopted value of \( Y_p \) (eq. [5]) to identify the range in the 

![Fig. 6.—Distribution of the error weighted determinations of \( Y_p \) (open circles) from a 40,000 run statistical bootstrap using the full data set (A). The solid curve is the best-fit Gaussian.](image-url)
nucleon abundance ($\eta_{10}$), which follows from SBBN (including uncertainties in the neutron lifetime and any relevant nuclear reaction rates; Hata et al. 1995). For $Y_p = 0.234 \pm 0.002$,

$$\eta_{10} = 1.8 \pm 0.3 \ .$$

For an upper bound of $Y_p \leq 0.239 (0.244)$, the corresponding 95% CL upper bound on $\eta_{10}$ is 2.4 (3.8). Furthermore, the very low value of $\eta$ in equation (6), which is derived directly from $^4$He, corresponds to a very low universal density of baryons:

$$\Omega_b h^2 = 0.007 \pm 0.001 \ .$$

Even for $Y_p \leq 0.239(0.244)$, $\Omega_b h^2 \leq 0.009 (0.014)$. For the lower value of $Y_p = 0.230 \pm 0.003$,

$$\eta_{10} = 1.4 \pm 0.3 \ .$$

In this case for $Y_p \leq 0.237(0.242)$, the upper bound on $\eta_{10}$ is 2.1 (3.2). Consequently, the density of baryons is even lower:

$$\Omega_b h^2 = 0.005 \pm 0.001 \ .$$

and for $Y_p \leq 0.237(0.242)$, $\Omega_b h^2 \leq 0.008 (0.012)$.

Although these estimates for $\eta$ are based solely on $^4$He, concordance of SBBN with the observational data requires that the same value of $\eta$ yield acceptable abundances for the other light elements. For example, in a likelihood analysis based on $^4$He and $^7$Li (the latter inferred from the metal-poor halo stars), Fields & Olive (1996) and Fields et al. (1996) found consistency for a similarly low value of $\eta$. Using $Y_p = 0.234 \pm 0.003$, they found $\eta_{10} = 1.8$ as the most likely value and a 95% CL range from 1.4 to 4.3. Repeating this $^4$He/$^7$Li analysis for the lower value of $Y_p = 0.230 \pm 0.003$ we find for the best-fit value $\eta_{10} = 1.7$ and a 95% CL range from 1.3 to 4.0.

For such low nucleon abundances there is consistency (Dar 1995) between the SBBN predictions and the primordial abundances not only of $^4$He and $^7$Li, but also with the deuterium abundance as determined from observations of some QSO absorption line systems (Songaila et al. 1994; Carswell et al. 1994; Rugers & Hogan 1996; but, see Tytler, Burles, & Kirkman 1996). The very high D abundance does pose a challenge to Galactic evolution models since it requires that the Galaxy has destroyed more than 90% of its initial deuterium. To do so while avoiding the over-production of heavy elements may require the presence of supernovae driven Galactic winds (Scullly et al. 1996). When the likelihood analysis is extended to include the high primordial D/H, Fields et al. (1996) find that the peak value of $\eta_{10}$ is 1.7 with a 95% CL range between 1.5 and 2.4; we find that this range remains essentially the same for either $Y_p = 0.234$ or 0.230. The corresponding value for the combination $\Omega_b h^2$ is now 0.006 with a 95% CL range between 0.005 and 0.009.

Alternatively, we may use either of the two recent determinations of primordial deuterium in high-redshift, low-metallicity QSO absorption systems to pin down $\eta$ and the corresponding range for $Y_p$ predicted by SBBN, which we may then compare to our adopted value (range) for $Y_p$.

5.1. High-D

If the high abundance of deuterium derived from the observations of Songaila et al. (1994), Carswell et al. (1994), and Rugers & Hogan (1996) is representative of the primordial D abundance, then $1.3 \leq \eta_{10} \leq 2.7$ and $0.231 \leq Y_{SBBN} \leq 0.239$ (95% CL) (Hata et al. 1996). Recently, however, new spectra have challenged these high D/H ratios and questioned whether any deuterium (rather than a hydrogen interloper) at all has been detected (Tytler, Burles, & Kirkman 1996; C. Hogan 1996, private communication). Nonetheless, for “high-D,” this range in $\eta_{10}$ and $Y_{SBBN}$, as already seen above, is in excellent agreement with our adopted range for $Y_p$ (eq. [5]) and may be used to infer a restrictive upper bound to the effective number of equivalent light neutrinos ($\Delta N_e \equiv N_e - 3$). For a systematic offset to $Y_p$ of $\Delta N_{sys}$ = 0 (0.005),

$$\Delta N_e \leq 0.5(0.8) \ .$$

Notice that if $Y_p > 0.239$, $N_e > 3.0$ would be required. The 95% CL upper limit on the number of light degrees of freedom from the likelihood analysis of Fields et al. (1996) based on $^4$He and $^7$Li is (Olive & Thomas 1997) $\Delta N_e < 1.0$ for $Y_p = 0.234 \pm 0.002$ and $\Delta N_e < 0.7$ for $Y_p = 0.230 \pm 0.003$ (in both cases $\sigma_{sys} = 0.005$ was assumed).

5.2. Low-D

In contrast, if the deuterium abundances derived for two different lines of sight from the data of Tytler, Fan, & Burles (1996) and of Burles & Tytler (1996) provide good estimates of the true primordial value, then $5.1 \leq \eta_{10} \leq 4.2$ and $0.246 \leq Y_{SBBN} \leq 0.252$ (95% CL) (Hata et al. 1996). Recently, these low deuterium values have been challenged by Songaila, Wampler, & Cowie (1997). For “low-D,” consistency with SBBN ($N_e \geq 3.0$) can only be recovered if systematic effects in deriving $Y_p$ from the data have led to an underestimate by an amount $\Delta N_{sys} \geq 0.009$ (i.e., consistency would require that $Y_p \geq 0.246$ compared to our upper bound of 0.237). Alternatively, if $\Delta N_{sys} < 0.005$, $N_e > 2.7$.

6. SUMMARY

For nearly two decades low-metallicity, extragalactic H II regions have been studied as a probe of the primordial abundance of helium. From observations of 10 such regions Lequeux et al. (1979) derived $Y_p = 0.233 \pm 0.005$. Using four carefully studied H II regions, Torres-Peimbert et al. (1989) found $Y_p = 0.230 \pm 0.006$, establishing the competitiveness of quality with quantity. On the basis of 19 extragalactic H II regions PSTE inferred $Y_p = 0.228 \pm 0.005$, and building on this data set OS added the data of S to find for 41 (21) low-metallicity H II regions $Y_p = 0.232 \pm 0.003$ (0.229 \pm 0.005). In this paper we have considered the new data from ITL that, at first glance, seems to yield a much larger value for $Y_p$. In contrast, we have found that the ITL data are fully consistent with those of PSTE and S and therefore we have combined these sets in an analysis of 62 (32) H II regions. From the Y versus O/H correlation we derive (see Table 1) $Y_p = 0.234 \pm 0.002$ (0.230 \pm 0.003). We have also considered the five independent observations (PST; Skillman & Kennicutt 1993; ITL) of the two knots in I Zw 18 to derive an upper bound to $Y_p$ of 0.230 \pm 0.004, and in an extension of this approach to $Y_p$ we have considered the weighted mean (and the weighted mean plus 2 $\sigma$) for the H II regions with the lowest values of Y to derive $Y_p \leq 0.230 \pm 0.003$. These results have led us to adopt a “95% CL” upper bound to $Y_p$ of 0.237 (for set B with 62 H II regions, this upper bound is 0.239).

The availability of large numbers of carefully observed, low-metallicity H II regions has permitted estimates of $Y_p$.
whose statistical uncertainties are very small ($\approx 1\%$). However, there remains the possibility that in the process of using the observational data to derive the abundances, contamination by unacknowledged systematic uncertainties has biased the inferred value of $Y_p$. The observers have identified many potential sources of such systematic uncertainties (Davidson & Kinman 1985; PSTE; S; TLT; Peimbert 1996) and, where possible, have designed their observing programs to minimize such uncertainties and/or to account for them. Here we have noted that many of the identified sources of potential systematic uncertainties would vary from H II region to H II region and from observer (telescope/detector) to observer, introducing not only a systematic offset in the derived value of $Y_p$, but also an accompanying dispersion in the $Y$ versus O/H relation. The very small values of the reduced $\chi^2$ for our fits suggest that the observers' uncertainty estimates may already account for some sources of systematic uncertainty. We have performed several tests confirming this and conclude that our determinations of $Y_p$ are robust in the absence of some yet to be identified systematic offset that shifts all the data uniformly. Nonetheless, in discussing the consequences of our derived value of $Y_p$ for cosmology and for particle physics we have allowed for a possible systematic offset $\Delta Y_{sys} = 0.005$.

For SBBN the low value we derive for $Y_p$, consistent with previous results (Lequeux et al. 1979; Torres-Peimbert et al. 1989; PSTE; OS), implies a low nucleon abundance but is entirely consistent with the inferred primordial abundances of $^7$Li and D (from the QSO absorbers studied by Rugers & Hogan 1996). Provided that the systematic uncertainty in $Y_p$ is not large, there is a meaningful constraint on the effective number of equivalent light neutrinos (Steigman, Schramm, & Gunn 1977). If, instead, the low deuterium abundance inferred from the data of Tytler, Fan, & Burles (1996) and of Burles & Tytler (1996) is the "true" primordial value, there is a challenge to SBBN unless $\Delta Y_{sys}$ is large (so that $Y_p \geq 0.246$).

We owe a debt of gratitude to R. C. Kennicutt, E. Terlevich, and R. J. Terlevich for sharing their unpublished data with us. We thank S. Scully for running the statistical bootstrap and for preparing Figures 3 and 6. We also are pleased to thank T. Beers, D. Garnett, N. Hata, Y. Izotov, D. Kunth, B. Pagel, D. Schaerer, S. Viegas, and T. Walker for very informative and valuable discussions. The work of K. A. O. is supported in part by DOE grant DE-FG02-94ER-40823 and that of G. S. by DOE grant DE-FG02-91ER-40690. E. D. S. is grateful for partial support from a NASA LTSARP grant no. NAGW-3189 and a Bush Sabbatical Fellowship from the Graduate School of the University of Minnesota and would especially like to thank the Max-Planck-Institute for Astrophysics for their hospitality during his sabbatical year. Parts of this work were carried out while K. A. O. and G. S. were participants in the INT Workshop on Nucleosynthesis in Stars, Supernovae, and the Universe and also while G. S. was a visitor at the Instituto Astronomico e Geofisico of the University of Sao Paulo (Brazil), and they are grateful for the hospitality provided.

REFERENCES

Berrington, J. A., & Kingston, A. E. 1987, J. Phys. B, 20, 6631
Bevington, P. R., & Robinson, D. K. 1992, Data Reduction and Error Analysis for the Physical Sciences (New York: McGraw-Hill)
Brocklehurst, M. 1972, MNRAS, 157, 211 (B72)
Burles, S., & Tytler, D. 1996, ApJ, 460, 584
Carswell, R. F., Rauch, M., Weymann, R. J., Cooke, A. J., & Webb, J. K. 1994, MNRAS, 268, L1
Clegg, R. E. S. 1987, MNRAS, 229, 31P (C87)
Danz, A. 1995, ApJ, 449, 550
Davidson, K., & Kinman, T. D. 1985, ApJS, 58, 321
Dinerstein, H. L., & Shields, G. A. 1986, ApJ, 311, 45
Fields, B. D. 1996, ApJ, 456, 478
Fields, B. D., Kauniainen, K., Olive, K. A., & Thomas, D. 1996, New Astron., 1, 77
Fields, B. D., & Olive, K. A. 1996, Phys. Lett. B, 368, 103
Fields, B. D., Olive, K. A., & Steigman G. 1997, in preparation
Hata, N., Scherrer, R. J., Steigman, G., Thomas, D., Walker, T. P., Bludman, G., & Langacker, P. 1995, Phys. Rev. Lett., 75, 3977
Hata, N., Steigman, G., Bludman, S., & Langacker, P. 1996, Phys. Rev. D, 55, 540
Izotov, Y. I., Thuan, T. X., & Lipovetsky, V. A. 1994, ApJ, 435, 647 (ITL)
--- 1997, ApJ, 108, 1
Kingdon, J., & Fetland, G. J. 1995, ApJ, 442, 714 (KF)
Kobulnicky, H. A., & Skillman, E. D. 1996, ApJ, 471, 211
Kunth, D., Lequeux, J., Sargent, W. L. W., & Viallefond, F. 1994, A&A, 282, 709
Kunth, D., & Sargent, W. 1983, ApJ, 273, 81
Lequeux, J., et al. 1979, A&A, 80, 155
Oke, J. B. 1990, AJ, 99, 1621
Olive, K. A., & Scully, S. T. 1995, IJMPA, 11, 409
Olive, K. A., & Steigman, G. 1995, ApJS, 97, 49 (OS)
Olive, K. A., Steigman, G., & Walker, T. P. 1991, ApJ, 380, L1
Olive, K. A., & Thomas, D. 1997, Astropart. Phys. in press
Pagel, B. E. J., & Kazlauskis, A. 1992, MNRAS, 256, 49P
Pagel, B. E. J., Simonson, E. A., Terlevich, R. J., & Edmunds, M. 1992, MNRAS, 255, 152 (PSTE)