THE PRIMORDIAL ABUNDANCE OF $^4\text{He}$: EVIDENCE FOR NON-STANDARD BIG BANG NUCLEOSYNTHESIS

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ABSTRACT

We present a new determination of the primordial helium mass fraction $Y_p$, based on 93 spectra of 86 low-metallicity extragalactic H ii regions, and taking into account the latest developments concerning systematic effects. These include collisional and fluorescent enhancements of He i recombination lines, underlying He i stellar absorption lines, collisional and fluorescent excitation of hydrogen lines, and temperature and ionization structure of the H ii region. Using Monte Carlo methods to solve simultaneously for the above systematic effects, we find the best value to be $Y_p = 0.2565 \pm 0.0010$ (stat.) $\pm 0.0050$ (syst.). This value is higher at the 2σ level than the value given by standard big bang nucleosynthesis, implying deviations from it. The effective number of light neutrino species $N_\nu$ is equal to $3.68^{+0.80}_{-0.70}$ (2σ) and $3.80^{+0.80}_{-0.70}$ (2σ) for a neutron lifetime $\tau_n$ equal to 885.4 ± 0.9 s and 878.5 ± 0.8 s, respectively, i.e., it is larger than the experimental value of 2.993 ± 0.011.

Key words: galaxies: abundances – galaxies: irregular – galaxies: ISM – ISM: abundances

1. INTRODUCTION

The determination of the primordial $^4\text{He}$ (hereafter He) abundance and of some other light elements such as D, $^3\text{He}$, and $^7\text{Li}$, plays an important role in testing cosmological models. In the standard theory of big bang nucleosynthesis (SBBN), given the number of light neutrino species, the abundances of these light elements depend only on one cosmological parameter, the baryon-to-photon number ratio $\eta$.

Because of the strong dependence of its abundance on $\eta$, deuterium has become the baryometer of choice. The D/H measurements in damped Lyα systems appear to converge to a mean primordial value, log D/H $=$ $-$4.56 ± 0.04, corresponding to a baryon mass fraction $\Omega_b h^2 = 0.0213 \pm 0.001$ (Pettini et al. 2008). This estimate of $\Omega_b h^2$ is in excellent agreement with the value of 0.02273 ± 0.00062 obtained by Dunkley et al. (2009) from analysis of five years of observations with the Wilkinson Microwave Anisotropy Probe (WMAP).

Although He is not a sensitive baryometer ($Y_p$ depends only logarithmically on the baryon density), its primordial abundance depends much more sensitively than that of D on the expansion rate of the universe and on a possible lepton asymmetry in the early universe (Steigman 2006, 2007). Thus, accurate measurements of the primordial abundance of He are required to check the consistency of SBBN.

However, to detect small deviations from SBBN and make cosmological inferences, $Y_p$ has to be determined to a level of accuracy of less than a few percent. The primordial abundance of He can, in principle, be derived accurately from observations of the He and H emission lines from low-metallicity H ii regions. Several groups have used this technique to derive the primordial He mass fraction $Y_p$, with somewhat different results. In the most recent study, Izotov et al. (2007), based on a large sample of 93 spectra of 86 low-metallicity extragalactic H ii regions (hereafter the HeBCD sample), derived $Y_p = 0.2472 \pm 0.0012$ and $Y_p = 0.2516 \pm 0.0011$, using Benjamin et al. (1999, 2002) and Porter et al. (2005) He i emissivities, respectively. On the other hand, Peimbert et al. (2007) obtained $Y_p = 0.2477 \pm 0.0029$ based on a sample of five H ii regions, Porter et al. (2005) He i emissivities, and adopting non-zero temperature fluctuations. Fukugita & Kawasaki (2006) derived $Y_p = 0.250 \pm 0.004$ for a sample of 31 H ii regions studied by Izotov & Thuan (2004), adopting Benjamin et al. (1999, 2002) He i emissivities.

It is generally believed that the accuracy of the determination of the primordial He abundance is limited presently, not so much by statistical uncertainties, but by our ability to account for systematic errors and biases. There are many known effects we need to correct for to transform the observed He i line intensities into an He abundance. These effects are: (1) reddening, (2) underlying stellar absorption in the He i lines, (3) collisional excitation of the He i lines which make their intensities deviate from their recombination values, (4) fluorescence of the He i lines which also make their intensities deviate from their recombination values, (5) collisional and (6) fluorescent excitation of the H lines, (7) the temperature structure of the H ii region, and (8) its ionization structure. All these corrections are at a level of a few percent except for effect (3), which can be much higher, exceeding 10% in the case of the He i λ5876 emission line in hot and dense H ii regions. Most of these effects were analyzed and taken into account by Izotov et al. (2007) for their HeBCD sample.

We present here a new determination of the primordial He abundance. A new study is warranted because there are several recent new developments that allow more accurate estimates of some of the systematic effects mentioned above. Thus, González Delgado et al. (2005) have calculated evolutionary stellar population synthesis models with high spectral resolution, so that equivalent widths of H i and He i absorption lines for different ages of single stellar populations and for a wide range of metallicities are now available. Furthermore, Luridiana (2009) has estimated the collisional enhancement of hydrogen Balmer lines, while Luridiana et al. (2009) have considered the fluorescent excitation of Balmer lines in gaseous nebulae (their case D). We incorporate all these new calculations in our new determination of the primordial He abundance.

In Section 2, we briefly discuss the method used to derive He abundances in individual objects and the primordial He abundance from the total sample. In Section 3, we derive the
best value for \( Y_p \) and the linear regression slope \( dY/dZ \). The cosmological implications of our new results are discussed in Section 4. We summarize our conclusions in Section 5.

2. THE METHOD

2.1. Linear Regressions

As in our previous work (see Izotov et al. 2007, and references therein), we determine the primordial He mass fraction \( Y_p \) by fitting the data points in the \( Y-O/H \) plane with a linear regression line of the form (Peimbert & Torres-Peimbert 1974, 1976; Pagel et al. 1992)

\[
Y = Y_p + \frac{dY}{d(O/H)}(O/H),
\]

where

\[
Y = \frac{4y(1-Z)}{1+4y}
\]

is the He mass fraction, \( Z \) is the heavy-element mass fraction, \( y = (y^+ + y^{++}) \times ICF(He^+He^{++}) \) is the He abundance, \( y^+ \equiv He^+/H^+ \) and \( y^{++} \equiv He^{++}/H^+ \) are respectively the abundances of singly and doubly ionized He, and \( ICF(He^+He^{++}) \) is the ionization correction factor for He.

The slope of the \( Y-O/H \) linear regression can be written as

\[
\frac{dY}{d(O/H)} = 12 \frac{dY}{dO} = 18.2 \frac{dY}{dZ},
\]

where \( O \) and \( Z \) are respectively the mass fractions of oxygen and heavy elements.

We also take into account the depletion of oxygen on dust grains. Izotov et al. (2006) demonstrated that the Ne/O abundance ratio for low-metallicity blue compact dwarfs (BCDs) is not constant, but increases with increasing oxygen abundance. This effect is small, with \( \Delta \log \text{Ne/O} = 0.1 \) when the oxygen abundance changes from \( 12 + \log O/H = 7.0 \) to 8.6. We attribute such a change to oxygen depletion, and correct the oxygen abundance for it, using the log Ne/O versus oxygen abundance regression line found by Izotov et al. (2006), and assuming that depletion is absent in galaxies with \( 12 + \log O/H = 7.0 \).

To derive the parameters of the \( Y \) versus \( O/H \) linear regressions, we use the maximum-likelihood method (Press et al. 1992) which takes into account the errors in both \( Y \) and \( O/H \) for each object.

2.2. A Monte Carlo Algorithm for Determining the Best Value of \( y^+ \)

Following Izotov et al. (2007), we use the five strongest \( He\) \( \lambda 3889, \lambda 4471, \lambda 5876, \lambda 6678, \lambda 7065 \) emission lines to derive the electron number density \( N_e(He^+) \) and the optical depth \( \tau(\lambda 3889) \). The \( He\) \( \lambda 3889 \) and \( \lambda 7065 \) lines play an important role because they are particularly sensitive to both quantities. Since the \( He\) \( \lambda 3889 \) line is blended with the \( H\) \( \lambda 3889 \) line, we have subtracted the latter, assuming its intensity to be equal to 0.107 \( I(H\beta) \) (Aller 1984).

The derived \( y^+ \) abundances depend also on a number of other parameters: the fraction \( \Delta(He\alpha)/I(He\alpha) \) of the \( He\alpha \) emission line flux due to collisional excitation, the electron number density \( N_e(He^+) \), the electron temperature \( T_e(He^+) \), the equivalent widths \( EW_{abs}(\lambda 3889) \), \( EW_{abs}(\lambda 4471) \), \( EW_{abs}(\lambda 5876) \), \( EW_{abs}(\lambda 6678) \), and \( EW_{abs}(\lambda 7065) \) of \( He\)\(1\) stellar absorption lines, and the optical depth \( \tau(\lambda 3889) \) of the \( He\) \( \lambda 3889 \) emission line. To determine the best weighted mean value of \( y^+ \), we use the Monte Carlo procedure described in Izotov et al. (2007), randomly varying each of the above parameters within a specified range.

Additionally, in those cases when the nebular \( He\) \( \lambda 4686 \) emission line was detected, we have added to \( y^+ \) the abundance of doubly ionized helium \( y^{++} \equiv He^{++}/H^+ \) (Izotov et al. 2007).

2.3. Parameter Set for the \( He\) Abundance Determination

For the derivation of \( He\) abundance, we adopt \( He\) emissivities from Porter et al. (2005) and take into account the following systematic effects: (1) reddening; (2) the temperature structure of the \( H\) \( ii \) region, i.e., the temperature difference between \( T_e(He^+) \) and \( T_e(O\iii) \); (3) underlying stellar He absorption; (4) collisional and fluorescent excitation of \( He\) lines; (5) collisional and fluorescent excitation of hydrogen lines; and (6) the ionization structure of the \( H\) \( ii \) region. Most of these effects were analyzed by Izotov et al. (2007) (see also references therein).

We define the following set of parameters:

1. The reddening law of Whitford (1958) is adopted. Izotov et al. (2007) have shown that He abundances are not sensitive to the particular reddening law adopted. For example, use of the Cardelli et al. (1989) reddening curve results in He and other element abundances similar to those obtained with the Whitford (1958) reddening law. The extinction coefficient \( C(H\beta) \) is derived from the observed hydrogen Balmer decrement, after correcting the \( H_e, H\beta, H\gamma, \) and \( H\delta \) line fluxes for the effects of collisional and fluorescent excitation. Finally, all emission lines are corrected for reddening, adopting the derived \( C(H\beta) \).

2. The electron temperature of the \( H^+ \) zone is varied in the range \( T_e(He^+) = (0.95-1.0) \times T_e(O\iii) \). We have chosen this range following the work of Guseva et al. (2006, 2007) who have derived the electron temperature in the \( H^+ \) zone from the Balmer and Paschen discontinuities in the spectra of more than 100 \( H\) \( ii \) regions, and showed that \( T_e(He^+) \) differs from \( T_e(O\iii) \) by not more than 5%. We also assume that \( T_e(He^+) = T_e(H^+) \) because the \( H^+ \) and \( He^+ \) zones in our objects are nearly coincident.

3. Oxygen abundances are calculated by considering two possible values of the electron temperature: (1) \( T_e = T_e(He^+) \) and (2) \( T_e = T_e(O\iii) \).

4. \( N_e(He^+) \) and \( \tau(\lambda 3889) \) are varied respectively in the ranges \( 10-450 \) \( \text{cm}^{-3} \) and \( 0-5 \), typical for extragalactic \( H\) \( ii \) regions.

5. The fraction of \( He\alpha \) emission due to collisional excitation is varied in the range \( 0\% - 5\% \), in accordance with Stasińska & Izotov (2001) and Turidiana (2009). The fraction of \( H\beta, H\gamma, \) and \( H\delta \) emission due to collisional excitation is adopted to be 60% that of the \( He\alpha \) emission, in accordance with Turidiana (2009). We note that Izotov et al. (2007) underestimated that fraction for \( H\gamma \), adopting a value of only 1/3, and neglected altogether to correct the \( H\gamma \) and \( H\delta \) emission lines for collisional excitation.

6. Turidiana et al. (2009) have shown that the fraction of \( H\beta \) emission due to fluorescent excitation by the far-UV non-ionizing stellar continuum could be as high as 2%, and somewhat lower for the \( He\alpha \) emission (their case D). We have adopted the conservative value of 1% for the fraction of \( He\alpha, H\beta, H\gamma, \) and \( H\delta \) emission due to fluorescent excitation, since a similar effect could affect the \( He\) \( i \) emission lines and partly compensate the effect for the Balmer H lines (the \( He \) abundance is calculated relative to that of H).
7. The equivalent width of the He I λ4471 absorption line is chosen to be EW_{abs}(λ4471) = 0.4 Å, following Izotov et al. (2007) and González Delgado et al. (2005). The equivalent widths of the other absorption lines are fixed according to the ratios EW_{abs}(λ3889)/EW_{abs}(λ4471) = 1.0, EW_{abs}(λ5876)/EW_{abs}(λ4471) = 0.8, EW_{abs}(λ6678)/EW_{abs}(λ4471) = 0.4 and EW_{abs}(λ7065)/EW_{abs}(λ4471) = 0.4. The EW_{abs}(λ5876)/EW_{abs}(λ4471) and EW_{abs}(λ6678)/EW_{abs}(λ4471) ratios were set equal to the values predicted for these ratios by a Starburst99 (Leitherer et al. 1999) instantaneous burst model with an age of 3–4 Myr and a heavy element mass fraction Z = 0.001–0.004, 0.8 and 0.4, respectively. These values are significantly higher than the corresponding ratios of 0.3 and 0.1 adopted by Izotov et al. (2007). We note that the value chosen for the EW_{abs}(λ5876)/EW_{abs}(λ4471) ratio is also consistent with the one given by González Delgado et al. (2005). Since the output high-resolution spectra in Starburst99 are calculated only for wavelengths ≤ 7000 Å, we do not have a prediction for the EW_{abs}(λ7065)/EW_{abs}(λ4471) ratio. We set it to be equal to 0.4, the value of the EW_{abs}(λ6678)/EW_{abs}(λ4471) ratio.

8. The He ionization correction factor ICF(He\textsuperscript{+}+He\textsuperscript{++}) is adopted from Izotov et al. (2007).

3. THE PRIMORDIAL HE MASS FRACTION Y\textsubscript{p} AND THE SLOPE dY/dZ

Two Y–O/H linear regressions for the HeBCD galaxy sample of Izotov et al. (2007), with the above set of parameters, are shown in Figure 1. The two regression lines differ in the way oxygen abundances have been calculated. For the first regression line (Figure 1(a)), oxygen abundances have been derived by setting the temperature of the O\textsuperscript{++} zone equal to T_e(He\textsuperscript{+}), while for the second (Figure 1(b)), they have been derived by adopting the temperature T_e(O iii) derived from the [O iii] λ4363/(λ4959+λ5007) line flux ratio.

The primordial values obtained from the two regressions in Figure 1, Y_p = 0.2565 ± 0.0010 and Y_p = 0.2560 ± 0.0011, are very similar but are significantly higher than the value Y_p = 0.2516 ± 0.0011 obtained by Izotov et al. (2007) for the same galaxy sample. The 2% difference is due to the inclusion of the correction for fluorescent excitation of H lines, the correction for a larger correction for collisional excitation to the H\textbeta\ flux, and larger adopted equivalent widths of the stellar He II 5876, 6678, and 7065 absorption lines. We adopt the value of Y_p from Figure 1(a), where both O/H and Y are calculated with the same temperature T_e = T_e(He\textsuperscript{+}).

We have varied the ranges of some parameters to study how the value of Y_p is affected by these variations. We have found that varying the fraction of fluorescent excitation of the hydrogen lines between 0% and 2%, and/or setting T_e(He\textsuperscript{+}) = T_e(O iii) or changing T_e(He\textsuperscript{+}) in the range (0.9–1.0) × T_e(O iii) (instead of making it change between 0.95 and 1.0 × T_e(O iii)), result in a change of Y_p between 0.254 and 0.258. Additionally, adding a systematic error of 1% caused by uncertainties in the He emissivities (Porter et al. 2009) gives Y_p = 0.2565 ± 0.0010 (stat.) ± 0.0050 (syst.), where “stat” and “syst” refer to statistical and systematic errors, respectively. Thus, the value of Y_p derived in this Letter is 3.3% greater than the value of 0.2482 obtained from the three-year WMAP data, assuming SBBN (Spergel et al. 2007). However, it is consistent with the Y_p = 0.25\textsuperscript{+0.10}_{−0.07} obtained by Ichikawa et al. (2008) from the available WMAP, ACBAR, CBI, and BOOMERANG data (actually, the peak value in their one-dimensional marginalized distribution of Y_p (their Figure 3) is equal to 0.254).

Using Equation (3), we derive from the Y–O/H linear regression (Figure 1(a)) the slopes dY/dO = 2.46 ± 0.45(stat.) and dY/dZ = 1.62 ± 0.29(stat.). These slopes are shallower than the ones of 4.33 ± 0.75 and 2.85 ± 0.49 derived by Izotov et al. (2007).

4. DEVIATIONS FROM SBBN

We now use our derived value of the primordial He abundance along with the observed primordial abundances of other light elements to check the consistency of SBBN. Deviations from the standard rate of Hubble expansion in the early universe can be caused by an extra contribution to the total energy density, for example, by additional flavors of neutrinos. The total number of different species of weakly interacting light relativistic particles can be conveniently be parameterized by N_e, the “effective number of light neutrino species.”
To perform the study, we use the statistical \( \chi^2 \) technique, with the code described by Fiorentini et al. (1998) and Lisi et al. (1999). This code allows us to analyze the constraints that the measured He, D, and \( ^7\text{Li} \) abundances put on \( \eta \) and \( N_\nu \). For the primordial D abundance, we use the value obtained by Pettini et al. (2008). As for \( ^7\text{Li} \), its value derived from observations of low-metallicity halo stars (Asplund et al. 2006) is \( \sim 5 \) times lower than the one obtained from the WMAP analysis (Dunkley et al. 2009). Because mechanisms that may lead to a reduction of the \( ^7\text{Li} \) primordial abundance, such as diffusion or rotationally induced mixing, are not well understood and we do not know how to correct for them, we have adopted the value of the primordial abundance of \( ^7\text{Li} \) as derived from the five-year WMAP data of Dunkley et al. (2009). The predicted primordial abundances of light elements depend on the adopted neutron lifetime \( \tau_n \). We have considered two values, the old one, \( \tau_n = 885.4 \pm 0.9 \) s (Arzumanov et al. 2000), and the new one, \( \tau_n = 878.5 \pm 0.8 \) s (Serebrov et al. 2005, 2008).

We present here a new determination of the primordial helium mass fraction \( Y_p \) by linear regressions of a sample of 93 spectra of 86 low-metallicity extragalactic H II regions.

In this new determination of \( Y_p \), we have taken into account the latest developments concerning several known systematic effects. We have used Monte Carlo methods to solve simultaneously for the effects of collisional and fluorescent enhancements of He I recombination lines, of collisional and fluorescent excitation of hydrogen emission lines, of underlying stellar He absorption, of possible temperature differences between the He\( ^+ \) and [O\( \text{iii} \)] zones, and of the ionization correction factor ICF (He\( ^+ \) + He\( ^{2+} \)). We have obtained the following results:

1. Our best value is \( Y_p = 0.2565 \pm 0.0010 \) (stat.) \( \pm 0.0050 \) (syst.), or 3.3\% larger than the value derived from the microwave background radiation fluctuation measurements assuming SBBN. In order to bring this high value of \( Y_p \) into agreement with the deuterium and five-year WMAP measurements, an equivalent number of neutrino flavors in the range \( 3.68-3.80 \), depending on the lifetime of the neutron, is required. This is higher than the canonical value of 3 and implies the existence of deviations from SBBN.

2. The \( dY/dZ \) slope derived from the \( Y - \text{O/H} \) linear regression is equal to 1.62 \( \pm 0.29 \) (stat.), shallower than the previous determination by Izotov et al. (2007).

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