THE PRIMORDIAL HELIUM ABUNDANCE AND THE NUMBER OF NEUTRINO FAMILIES

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RESUMEN

Basados en observaciones de regiones H II y en los nuevos cálculos de los coeficientes de recombinación de las líneas de He I debidos a Porter et al. obtenemos una abundancia primordial de helio por unidad de masa dada por $Y_P = 0.2446 \pm 0.0029$. Consideramos trece fuentes de error en la determinación de Y_P; algunas de ellas se deben principalmente a efectos sistemáticos mientras que el resto se deben principalmente a efectos estadísticos. Comparamos nuestros resultados con otros valores de Y_P determinados por otros grupos. Combinando nuestro valor de Y_P con cálculos de nucleosíntesis primordial encontramos que el número efectivo de familias de neutrinos, N_{eff}, es de 2.90 ± 0.22 y que la vida media del neutrón, τ_ν es de 872 ± 14 s.

ABSTRACT

Based on observations of H II regions and on the new computations of the recombination coefficients of the He I lines by Porter el al. we obtain a primordial helium abundance by mass of $Y_P = 0.2446 \pm 0.0029$. We consider thirteen sources of error for the Y_P determination; some of them are mainly due to systematic effects, while the rest are mainly due to statistical effects. We compare our results with other determinations of Y_P present in the literature. Combining our Y_P value with computations of primordial nucleosynthesis we find a number of neutrino species $N_{eff} = 2.90 \pm 0.22$, and a neutron mean life $\tau_\nu = 872 \pm 14$ s.

1. INTRODUCTION

The determination of Y_P is important for at least the following reasons: (a) it is one of the pillars of Big Bang cosmology and an accurate determination of Y_P permits to test the Standard Big Bang Nucleosynthesis (SBBN); (b) the combination of Y_P and $\Delta Y/\Delta O$ is needed to test models of galactic chemical evolution; (c) the models of stellar evolution require an accurate initial Y value that is given by Y_P plus the additional Y produced by galactic chemical evolution, which can be estimated based on the observationally determined $\Delta Y/\Delta O$ ratio; (d) the determination of the Y value in metal poor H II regions requires a deep knowledge of their physical conditions, in particular the Y determination depends to a significant degree on their density and temperature

distribution. Therefore, accurate Y determinations combined with the assumption of SBBN provide a constraint on the density and structure of H II regions. The first determination of Y_P based on the increase of helium with heavy elements was obtained by Peimbert & Torres-Peimbert (1974). Historical reviews on the determination of the primordial helium abundance have been presented by Peimbert (2008), Pagel (2009), and Skillman (2010); a recent review on big bang nucleosynthesis can be found in Cyburt et al. (2016).

The latest papers on Y_P direct determinations published by each of the three main groups working on this subject are: Aver et al. (2015), Izotov et al. (2014) and Peimbert et al. (2007) (hereinafter Paper 1). In this paper we update the Y_P determination of Paper I taking into account, among other aspects, recent advances in the determination of the He I atomic physical parameters by Porter et al. (2013). We compare our results with those of Aver

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et al. and Izotov et al. and point out possible explanations for the differences among the three determinations.

Paper I may be the most comprehensive attempt to derive the primordial helium abundance to date. It includes: a study of 13 sources of error involved in this determination; a discussion on the importance of some errors that are usually ignored; and a discussion on how to minimize the combined effect of all of them. While the study on the error sources presented in Paper I remains very relevant, the quantitative value needs to be updated, mostly because of the improvements in the theoretical helium recombination coefficients.

2. OUR Y AND Y_P DETERMINATIONS

2.1. Tailor Made Models

Careful studies of Y_P indicate that the uncertainties in most determinations are dominated by systematic errors rather than statistical errors. Increasing the number of objects in the samples used to determine Y_P will, of course, decrease the statistical errors. However, it will not decrease the systematic ones.

Some systematic errors can be diminished by a careful selection of the objects used for the determination as well as by the use of tailor-made models for each object. Normal observational procedures, like reddening correction and underlying absorption correction, include systematic errors; this occurs because both the reddening law and the underlying absorption correction for the different helium lines are not perfectly known, and any error that affects any helium (or hydrogen) line will affect systematically the determinations of each object; such systematic effects can be minimized by selecting objects with small reddening corrections and He I large equivalent widths in emission. Corrections like the ionization correction factor due to the presense of neutral helium, ICF(He), or the collisional contribution to $I(H\beta)$ depend on the particular objects included in the sample. Since each object is unique, there is no such thing as an average ICF(He) or a typical $I(H\beta)$ collisional correction for H II regions; the final error for these effects will be systematic in any sample, hence tailor-made models for each object are required.

For the previous reasons we consider that a better Y_P determination can be obtained by studying in depth a few H II regions, rather than by using larger sets of objects without a tailor-made model for each of them.

2.2. The New Recombination Coefficients of the He I Lines

To obtain a precise Y_P value it is necesary to have the most accurate atomic physics parameters attainable. Porter et al. (2013) have computed updated effective recombination coefficients for the He I lines that differ from those by Porter et al. (2005). The new values were computed to correct small errors in the implementation of Case B calculations; they also included a finer grid of calculations, useful for high-precision determinations. The differences between both sets of coefficients are small but significant for the determination of Y_P.

From the new atomic data, we present in Table 1 the physical characteristics of our 5 favorite objects derived following the same procedure used in Paper I.

2.3. Updated Y Values

To determine Y_P we have to estimate the amount of helium produced by the stars during the evolution of the galaxies in our sample. To this end we assume that the helium mass increase to oxygen mass increase ratio, $\Delta Y/\Delta Z_O$, is constant. It is possible to determine this ratio self-consistently from the points in our sample, as done by Aver et al. (2015) and Izotov et al. (2014) for their samples. We consider that this procedure for a sample as small as ours increases the error in the $\Delta Y/\Delta Z_O$ value. Instead, we use observations of brighter objects with a metallicity not as low and high quality data, as well as chemical evolution models for galaxies of low mass and metallicity. From Carigi & Peimbert (2008) and Peimbert et al. (2010) we obtain $\Delta Y/\Delta Z = 1.75$, $Z_O/Z = 0.53$ and $\Delta Y/\Delta Z_O = 3.3 \pm 0.7$.

In Table 2 we present the Y and Y_P determinations for each object of our sample as well as the Y values we determined in Paper I. For each determination we have broken down the error into its statistical and systematic components: we first present the statistical and then the systematic ones. By taking a weighted average of these 5 Y_P values we obtain the updated Y_P value of the sample. The final statistical error amounts to 0.0019, the final systematic error amounts to 0.0021; adding quadratically both components the total error adds up to 0.0029.

It can be seen from Table 2 that the extrapolation from Y to Y_P for the objects in our sample is small and amounts to $\Delta Y = 0.0044$.

Once the He I recombination coefficients have been recomputed (Porter et al. 2013), we consider

TABLE 1

PHYSICAL PARAMETERS FOR THE H II REGIONS

	NGC 346	NGC 2363	Haro 29	SBS 0335-052[a]	I Zw 18
$EW_{em}(H\beta)$	250 ± 10	187 ± 10	224 ± 10	169 ± 10	135 ± 10
$EW_{abs}(H\beta)$	2.0 ± 0.5	2.0 ± 0.5	2.0 ± 0.5	2.0 ± 0.5	2.9 ± 0.5
$N(He^{++})/N(H^{+})(t^2 = 0.000)$[b]	22 ± 2	75 ± 12	104 ± 9	275 ± 8	82 ± 23
$ICF(He)$	1.000 ± 0.001	0.993 ± 0.001	0.9955 ± 0.001	0.991 ± 0.001	1.000 ± 0.001
$n_e(t^2 = 0.000)$	44 ± 17	262 ± 77	42 ± 50	282 ± 44	85 ± 84
$\tau_{3889}(t^2 = 0.000)$	0.01 ± 0.02	1.14 ± 0.41	1.44 ± 0.27	2.78 ± 0.32	0.06 ± 0.05
$N(He^{+})/N(H^{+})(t^2 = 0.000)$[b]	8333 ± 44	8460 ± 149	8421 ± 143	8483 ± 115	8259 ± 314
$N(He)/N(H)(t^2 = 0.000)$[b]	8355 ± 47	8476 ± 150	8487 ± 145	8755 ± 117	8341 ± 317
$N(O)/N(H)(t^2 = 0.000)$[b]	12 ± 2	9 ± 1	7 ± 1	2.3 ± 0.3	1.7 ± 0.2
$O(t^2 = 0.000)$[c]	14 ± 2	11 ± 1	9 ± 1	2.7 ± 0.3	2.0 ± 0.2
t^2	0.016 ± 0.008	0.086 ± 0.014	0.029 ± 0.007	0.092 ± 0.019	0.097 ± 0.030
$n_e(t^2 \neq 0.000)$	80 ± 31	468 ± 122	83 ± 65	348 ± 52	143 ± 131
$\tau_{3889}(t^2 \neq 0.000)$	0.03 ± 0.03	0.98 ± 0.39	1.22 ± 0.28	2.75 ± 0.35	0.06 ± 0.05
$N(He^{+})/N(H^{+})(t^2 \neq 0.000)$[b]	8271 ± 60	8223 ± 150	8314 ± 141	8349 ± 153	8088 ± 350
$N(He)/N(H)(t^2 \neq 0.000)$[b]	8293 ± 62	8240 ± 151	8380 ± 143	8622 ± 154	8170 ± 352
$N(O)/N(H)(t^2 \neq 0.000)$[b]	13 ± 2	19 ± 4	9 ± 2	5 ± 1	5 ± 2
$O(t^2 \neq 0.000)$[c]	16 ± 4	23 ± 8	11 ± 2	6 ± 2	6 ± 3

[a]Values for the three brightest positions by Izotov et al. (1999).

[b]In units of 10^{-5}.

[c]Oxygen abundance by mass, in units of 10^{-4}.

TABLE 2

Y AND Y_P VALUES($t^2 \neq 0.000$)

	Y Paper I	Y This paper[a]	Y_P This paper[b]
NGC 346	$0.2507 \pm 0.0027 \pm 0.0015$	$0.2485 \pm 0.0027 \pm 0.0015$	$0.2433 \pm 0.0028 \pm 0.0019$
NGC 2363	$0.2518 \pm 0.0047 \pm 0.0020$	$0.2467 \pm 0.0047 \pm 0.0020$	$0.2395 \pm 0.0049 \pm 0.0026$
Haro 29	$0.2535 \pm 0.0045 \pm 0.0017$	$0.2506 \pm 0.0045 \pm 0.0017$	$0.2470 \pm 0.0045 \pm 0.0019$
SBS 0335–052	$0.2533 \pm 0.0042 \pm 0.0042$	$0.2561 \pm 0.0042 \pm 0.0042$	$0.2541 \pm 0.0042 \pm 0.0042$
I Zw 18	$0.2505 \pm 0.0081 \pm 0.0033$	$0.2460 \pm 0.0081 \pm 0.0033$	$0.2442 \pm 0.0081 \pm 0.0033$
Sample	$0.2517 \pm 0.0018 \pm 0.0021$	$0.2490 \pm 0.0018 \pm 0.0019$	$0.2446 \pm 0.0019 \pm 0.0021$

[a]Corrected Y determinations based on the atomic physics values presented by Porter et al.(2013) see text.

[b]Derived from each object under the assumption that $\Delta Y/\Delta O = 3.3 \pm 0.7$ see text.

that the new determinations produce an uncertainty on Y_P of about 0.0010, the value we adopted in Paper I.

A thorough discussion on the systematic and statistical errors adopted in our Y_P determination is presented in Paper I.

2.4. *The Fluorescent Contribution to the H I and He I Lines*

Nonionizing stellar continua are a potential source of photons for continuum pumping of the hydrogen Lyman transitions, the so-called Case D (Luridiana et al. 2009). Since these transitions are

TABLE 3

Y_P VALUES AND PREDICTED EQUIVALENT NUMBER OF NEUTRINO FAMILIES, ΔN_ν,
BEYOND THE SBBN

Y_P(H II)	Y_P(H II+CMB)	ΔN_ν(H II)	ΔN_ν(H II+CMB)	Y_P source
0.2446 ± 0.0029	0.2449 ± 0.0029	-0.16 ± 0.22	-0.14 ± 0.22	This paper
0.2449 ± 0.0040	0.2455 ± 0.0040	-0.14 ± 0.30	-0.09 ± 0.30	Aver et al. (2015)
0.2551 ± 0.0022	0.2550 ± 0.0022	$+0.63 \pm 0.16$	$+0.62 \pm 0.16$	Izotov et al. (2014)

optically thick, de-excitation occurs through higher series lines, in particular excitation to $n_u \geq 3$ produces transitions to $n_l \geq 2$. As a result, the emitted flux in the affected lines has a fluorescent contribution in addition to the usual recombination one; consequently, Balmer emissivities are systematically enhanced above Case B predictions. Moreover, the He I lines are also enhanced by fluorescence. To a first approximation the effect of Case D on the H I lines is compensated by the effect of Case D on the He I lines. We leave for a future paper an estimate of the importance of Case D in the Y_P determination.

3. COMPARISON WITH OTHER Y_P DETERMINATIONS

The three best Y_P determinations in the literature are presented in Table 3; we will call these determinations Y_P(H II). The three groups use different approaches. Izotov et al. (2014) use 28 objects, Aver et al. (2015) use 15 objects and we use 5. We put the main emphasis in the study of the systematic effects and try to reduce them by means of tailor-made models for each object, while Izotov et al. (ibid.) put the main emphasis on the statistical effects, and Aver et al. (ibid.) use a subset of the best objects studied by Izotov et al. (ibid.). Case D produces a systematic effect that has not been considered by any of the three groups.

While these three determinations should give the same result, there are substantial differences in Y_P between that by Izotov et al. (2014) and those by Aver et al. (2015) and us, the differences amount to about 3σ.

One of the main reasons for the difference between our Y_P determination and that by Izotov et al. (2014) is due to our use of considerably larger temperature variations than those used by them. They use the direct method to derive the temperature given by the 4363/5007 [O III] intensity ratio, and assume that there are very small temperature variations within each object, and that T(He I) varies statistically around T(O III). Alternatively, we consider temperature variations to derive Y_P defined by

the t^2 parameter (Peimbert 1967) . For our sample we obtain $\langle t^2 \rangle = 0.064$. The average t^2 for 27 well observed galactic and extragalactic H II regions is 0.044 and the t^2 range goes from 0.019 to 0.120 (Peimbert et al. 2012); this in turn makes T_e(He I) systematically smaller than T_e(O III).

Our Y_P result is in very good agreement with that of Aver et al. (2015); while they do not include temperature inhomogeneities in their calculations, they use a temperaure derived from He I lines, which, in the prescence of temperature inhomogeneities, remains similar to the mean temperature. The main differences between our determination and that of Aver et al. are that we make a deeper study of each object (having a tailor-made model for each object), and we include information from chemical evolution models regarding the determination of $\Delta Y/\Delta O$ (Carigi & Peimbert 2008; Peimbert et al. 2010). On the other hand, Aver et al. (2015) and Izotov et al. (2014) make use of λ 10830 of He I that permits them to have a good handle on the electron density.

Observations of the CMB anisotropy with the Planck satelite can estimate Y_P in two different ways: (1) by determining the number of free electrons in the very early universe from the high order multipole moments; we will call this determination Y_P(CMB); or (2), by measuring the barionic mass with the low order multipole moments and using the SBBN to determine the resulting Y_P (Planck Collaboration 2015). The first method is rather direct and self consistent producing Y_P(CMB) $= 0.252 \pm 0.014$, with unfortunate large error bars; the second method is much more precise and yields $Y_P = 0.2467 \pm 0.0001$, but is sensitive to the inputs of the SBBN models. It is particularly sensitive to the N_ν and τ_n adopted values. The first method is a robust independent determination of Y_P, that is in agreement with all three H II region determinations, and which we have used as an additional constraint to our determinations. The second method has internal errors of the order of 0.0001, but external errors at least 100 times larger; instead of using this determination to improve

TABLE 4

Y_P VALUES AND THE NEUTRON MEAN LIFE, τ_n

$Y_P(\text{H\,II})$	$\tau_n(\text{H\,II})(\text{s})$	$\tau_n(\text{H\,II+CMB})(\text{s})$	Y_P source
0.2446 ± 0.0029	870 ± 14	872 ± 14	This paper
0.2449 ± 0.0040	872 ± 19	875 ± 18	Aver et al. (2015)
0.2551 ± 0.0022	921 ± 11	921 ± 11	Izotov et al. (2014)

the determination of Y_P, it can be used to try to constrain the external factors to which it is sensitive; Specifically we can use the second method to constrain the determinations of N_ν and τ_n.

4. DETERMINATION OF N_ν AND τ_n

The determination of Y_P based on BBN depends on several input values, like the number of neutrino families N_ν and the neutron life time τ_n. In this section we will take advantage of our determination of Y_P to check the validity of these BBN adopted values. With only one additional restriction (Y_P), we have to fix one of these two physical quantities to estimate the value of the other.

4.1. Determination of N_ν from Y_P and BBN

There is still no good agreement on the value of τ_n, see for example the discussion in Salvati et al. (2016). There are three values of τ_n that are relevant: (a) five determinations based on the bottle method that yield $\tau_n = 879.6 \pm 0.8$ s (Pignol 2015); (b) two determinations based on the beam method that yield $\tau_n = 888.0 \pm 2.1$ s (Pignol ibid.), and (c) the average over the best seven measurements presented by the Particle Data Group (Olive et al. 2014) that yield $\tau_n = 880.3 \pm 1.1$ s.

We will adopt $\tau_n = 880.3 \pm 1.1$ s, the recommended value by the Particle Data Group (Olive et al. 2014), and the Y_P values derived from H II regions to determine the number of neutrino families and we will compare these numbers with that adopted by SBBN to check the validity of the adopted number of neutrino families.

Based on the production of the Z particle by electron-positron collisions in the laboratory and taking into account the partial heating of neutrinos produced by electron-positron annihilations during BBN, Mangano et al. (2005) find that $N_{eff} = 3.046$. Therefore the difference between the number of neutrino families and the SBBN number of neutrino families is given by $\Delta N_\nu = N_{eff} - 3.046$.

Discussions on the implications for N_{eff} values different from 3.046 have been presented by Steigman (2013) and Nollett & Steigman (2014, 2015).

From the SBBN $N_{eff} = 3.046$ value and the relation $\Delta N_\nu = 75\Delta Y$ (Mangano & Serpico 2011), it follows that our Y_P determination implies that $N_{eff} = 2.90 \pm 0.22$ and consequently that ΔN_ν amounts to -0.16 ± 0.22 (68% confidence level, CL), a result in good agreement with SBBN.

In Table 3 we present the ΔN_ν values derived from the three Y_P determinations; we also present the $Y_P(\text{H\,II+CMB})$ values that combine the $Y_P(\text{H\,II})$ and the $Y_P(\text{CMB})$ values as well as the ΔN_ν derived from such Y_P determinations.

Izotov et al. (2014) find $Y_P = 0.2551 \pm 0.0022$, which implies an effective number of neutrino families, $N_{eff} = 3.58 \pm 0.25$ (68% CL), ± 0.40 (95.4% CL), and ± 0.50 (99% CL) values. This result implies that a non-standard value of N_{eff} is preferred at the 99% CL, suggesting the prescence of a fourth neutrino family with a fractional contribution to N_{eff} at the time of decoupling.

4.2. Determination of τ_n from Y_P and BBN

It is possible from the Y_P values and the SBBN to determine τ_n. Following Salvati et al. (2016), we present in Table 4 the τ_n values obtained from the Y_P values derived by Izotov et al. (2014), Aver et al. (2015) and ourselves. Also in Table 4 we present the $\tau_n(\text{H\,II+CMB})$ values that combine the $\tau_n(\text{H\,II})$ and the $\tau_n(\text{CMB})$ values.

The τ_n results by Aver et al. (2015) and ourselves are within 1σ from the average presented by the Particle Data Group (Olive et al. 2014), and while consistent with both the bottle and the beam τ_n determinations, they slightly favor the determination based on the bottle method. On the other hand, the determination of Izotov et al. (2014) is more than 3σ away from both laboratory determinations.

The τ_n values from the three groups derived from Y_P are within 1σ from the result of the SBBN obtained by Planck based on the TT, TE, and EE spec-

tra that amounts to $\tau_n(\mathrm{CMB}) = 907 \pm 69\,\mathrm{s}$ (Planck Collaboration 2015). The τ_n Planck result is independent of the Y_P values derived from H II regions.

5. CONCLUSIONS

We present new Y values for our five favorite H II regions, see Paper I. From these values we obtain that $Y_P = 0.2446 \pm 0.0029$. The main difference with our Paper I result is due to the use of updated atomic physics parameters. The new estimated error is similar to that of Paper I because the quality of the data is the same and we are not modifying our estimates of the uncertainty in the systematic errors.

Our Y_P value is consistent with that of Aver et al. (2015), but in disagreement with that of Izotov et al. (2014) by more than 3σ.

Y_P together with BBN can be used to constrain N_ν and τ_n.

The adoption of $\tau_n = 880.3 \pm 1.1\,\mathrm{s}$ and our Y_P value imply that $N_{eff} = 2.90 \pm 0.22$, consistent with three neutrino families but not with four neutrino families.

The adoption of $N_{eff} = 3.046$ and our Y_P value imply that $\tau_n = 872 \pm 14\,\mathrm{s}$, consistent with both high and low values of τ_n in the literature.

An increase in the quality of the Y_P determination from H II regions will provide stronger constraints on the N_ν and τ_n values.

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