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The primordial abundance of ^{4}He from a large sample of low-metallicity H II regions

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Abstract. We determine the primordial helium mass fraction Y_p using 1700 spectra of low-metallicity extragalactic H II regions. This sample is selected from the Data Release 7 of the Sloan Digital Sky Survey, from European Southern Observatory archival data and from our own observations. We have considered known systematic effects which may affect the ^{4}He abundance determination. They include collisional and fluorescent enhancements of He I recombination lines, underlying He I and hydrogen stellar absorption lines, collisional excitation of hydrogen lines, temperature and ionization structure of the H II region. Monte Carlo methods are used to solve simultaneously the above systematic effects. We find a primordial helium mass fraction Y_p = 0.2512 ± 0.0006(stat.) ± 0.0020 (syst.). This value is higher than the value given by Standard Big Bang Nucleosynthesis (SBBN) theory. If confirmed, it would imply slight deviations from SBBN.

Keywords. galaxies: abundances; galaxies: irregular; galaxies: ISM; ISM: H II regions; ISM: abundances

1. Introduction

The determination of the primordial ^{4}He (hereafter He) abundance and some other light elements (D, ^{3}He, ^{7}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 η.

While a single good baryometer like D is sufficient to derive the baryonic mass density from BBN, accurate measurements of the primordial abundance of He are required to check the consistency of SBBN. The primordial abundance of He, can in principle be derived accurately from observations of the helium and hydrogen 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 H II regions derived Y_p = 0.2472 ± 0.0012 and Y_p = 0.2516 ± 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 ± 0.0029 based on the sample of 5 H II regions, Porter *et al.* (2005) He I emissivities, and adopting non-zero temperature fluctuations. Fukugita & Kawasaki (2006) derived Y_p = 0.250 ± 0.004 for a sample of 31 H II regions by Izotov & Thuan (2004), adopting Benjamin *et al.* (1999,2002) He I emissivities.

Although He is not a sensitive baryometer (Y_p depends only logarithmically on the baryon density), its primordial abundance depends much more sensitively on the expansion rate of the Universe and is very sensitive to any small deviation from 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 one percent. In particular, many known systematic effects need to be taken into account to transform the observed He I line intensities into a 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 excitation of the hydrogen lines (hydrogen enters because the helium abundance is calculated relative to that of hydrogen), (6) possible departures from case B in the emissivities of H and He I 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) that can be much higher, exceeding 10% in the case of the He I λ5876 emission line in hot and dense H II regions. All these effects were analyzed and taken into account by Izotov *et al.* (2007) for a sample of 93 H II regions from Izotov & Thuan (2004) (hereafter HeBCD sample).

In this contribution we are aiming to significantly increase the sample of H II regions for the analysis of the systematic effects and determine the primordial He abundance with more accuracy. For this we select spectra of bright H II regions from the Data Release 7 (DR7) of the Sloan Digital Sky Survey (hereafter SDSS sample) (Abazajian *et al.* 2009). In addition, we use available spectroscopic data from the ESO archive. The use of these additional data greatly increases the sample of objects suitable for the primordial He determination by a factor up to $\sim$ 20 compared to the HeBCD sample of H II regions.

In the present determination of the primordial He abundance, we take into account all eight effects discussed above. The method has been detailed in Izotov *et al.* (2007) and is more concisely discussed in this paper.

2. The sample

We determine Y_p for the sample which includes three different subsamples, HeBCD, VLT, and SDSS. The HeBCD subsample, composed of 93 spectra has been discussed by Izotov *et al.* (2007). The SDSS subsample was selected from the SDSS DR7 and consists of 1534 spectra of H II regions with the Hβ line flux greater than 4×10^{-15} erg s^{-1} cm^{-2}. Finally, we selected 73 spectra of H II regions from the ESO archive which were obtained with the spectrographs UVES, FORS1 and FORS2 mounted on the VLT. The majority of objects in the HeBCD, VLT and SDSS subsamples are low-metallicity H II regions in dwarf emission-line galaxies.

3. The method

3.1. *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 linear regression line of the form (Peimbert & Torres-Peimbert 1974,1976)

$$Y = Y_p + \frac{\mathrm{d}Y}{\mathrm{d(O/H)}}\mathrm{(O/H)}, \tag{3.1}$$

where

$$Y = \frac{4y(1-Z)}{1+4y} \tag{3.2}$$

is the He mass fraction, Z is the heavy element mass fraction, $y = (y^+ + y^{2+}) \times ICF(\mathrm{He}^+ + \mathrm{He}^{2+})$ is the He abundance, $y^+ \equiv \mathrm{He}^+/\mathrm{H}^+$ and $y^{2+} \equiv \mathrm{He}^{2+}/\mathrm{H}^+$ are

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respectively the abundances of singly and doubly ionized He, and $ICF(\mathrm{He^+ + He^{2+}})$ is the ionization correction factor for He.

We also take into account depletion of oxygen on dust grains. Izotov *et al.* (2006) demonstrated that the Ne/O abundance ratio for low-metallicity BCDs is not constant but is increased with increasing oxygen abundance. This effect is small, with ΔlogNe/O = 0.1 when the oxygen abundance is changed from 12+logO/H = 7.0 to 8.6, and it is attributed to oxygen depletion. We correct oxygen abundance for such depletion, using regression log Ne/O versus oxygen abundance found by Izotov *et al.* (2006) and assuming that depletion is absent in galaxies with 12+logO/H = 7.0.

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

The derived y^+ abundances depend on the He I emissivities, the fraction $\Delta I(\mathrm{H}\alpha)/I(\mathrm{H}\alpha)$ of the Hα emission line flux due to collisional excitation, the electron number density $N_e(\mathrm{He^+})$, the electron temperature $T_e(\mathrm{He^+})$, the equivalent widths $\mathrm{EW}_{abs}(\lambda3889)$, $\mathrm{EW}_{abs}(\lambda4471)$, $\mathrm{EW}_{abs}(\lambda5876)$, EW_{abs} $(\lambda6678)$ and $\mathrm{EW}_{abs}(\lambda7065)$ of He I stellar absorption lines, and the optical depth $\tau(\lambda3889)$ of the He I λ3889 emission line. To determine the best weighted mean value of y^+_{wm} , we use the Monte Carlo procedure described in Izotov & Thuan (2004) and Izotov *et al.* (2007), randomly varying each of the above parameters within a specified range, excluding He I which are not varied.

In those cases when the nebular He II λ4686 emission line was detected, we have added the abundance of doubly ionized helium $y^{2+} \equiv \mathrm{He^{2+}/H^+}$ to y^+.

3.2. *Set of parameters for the He abundance determination*

For the determination of He abundance we adopt Porter *et al.* (2005) He I emissivities 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 $T_e(\mathrm{He^+})$ and T_e(O III); 4) underlying stellar He I absorption; 4) collisional and fluorescent excitation of He I lines; 5) collisional excitation of hydrogen lines; and 6) the ionization structure of the H II region.

The set of parameters, which vary in the range of physically reasonable values and is the same as that considered by Izotov *et al.* (2007), is defined in the following way:

1. We adopted the reddening law by Whitford (1958). Izotov *et al.* (2007) have shown that He abundances are not sensitive to the adopted reddening law. In particular, the use of the Cardelli *et al.* (1989) reddening curve is resulted in He and other element abundances, which are similar to those obtained with the Whitford (1958) reddening law. The extinction coefficient $C(\mathrm{H}\beta)$ is derived from the observed hydrogen Balmer decrement after subtraction of the contribution due to the collisional excitation from the the Hα and Hβ line fluxes. Finally, all emission lines are corrected for reddening adopting the derived $C(\mathrm{H}\beta)$.

2. The electron temperature of the He$^+$ zone is varied in the range $T_e(\mathrm{He^+})$ = (0.95 – 1.0)$\times T_e$(O III). This assumption is adopted following Guseva *et al.* (2006,2007) who derived the electron temperature in the H$^+$ zone from the Balmer and Paschen discontinuities in spectra of more than 100 H II regions and showed that $T_e(\mathrm{H^+})$ differs from T_e(O III) by not more than 5%.

3. Oxygen abundances are calculated adopting an electron temperature equal to T_e(O III) and $T_e(\mathrm{He^+})$.

4. $N_e(\mathrm{He^+})$ and $\tau(\lambda3889)$ vary respectively in the ranges 10 – 450 cm^{-3} and 0 – 5, typical for extragalactic H II regions.

5. The fraction of Hα emission due to collisional excitation is varied in the range 0% – 5%, in accordance with Stasińska & Izotov (2001). The fraction of Hβ emission due to the collisional excitation is assumed to be 1/3 that of Hα emission.

6. The equivalent width of the He I λ4471 absorption line is fixed to $\mathrm{EW}_{abs}(\lambda4471) = 0.4$Å. The equivalent widths of the other absorption lines are fixed according to the ratios $\mathrm{EW}_{abs}(\lambda3889)$ / $\mathrm{EW}_{abs}(\lambda4471) = 1.0$, $\mathrm{EW}_{abs}(\lambda5876)$ / $\mathrm{EW}_{abs}(\lambda4471) = 0.3$, $\mathrm{EW}_{abs}(\lambda6678)$ / $\mathrm{EW}_{abs}(\lambda4471) = 0.1$ and $\mathrm{EW}_{abs}(\lambda7065)$ / $\mathrm{EW}_{abs}(\lambda4471) = 0.1$. This set of the EWs is justified by Izotov *et al.* (2007) as the most likely one.

7. He I emissivities from Porter *et al.* (2005) are adopted.

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

4. The primordial He mass fraction Y_p

Our sample constitues the largest sample for the primordial He determination and thus greatly reduces the uncertainties caused by the statistical errors in He abundances. This allows us to study systematic effects on firm statistical grounds.

Linear regressions Y – O/H for the total sample of 1700 spectra with the basic set of parameters are shown in Figs. 1a and 1b. The difference between these two regressions is that the oxygen abundance in Fig. 1a is derived adopting the temperature of the O^{++} zone equal to $T_e(\mathrm{He}^{+})$, while the temperature T_e(O III) derived from the [O III] $\lambda4363/(\lambda4959+\lambda5007)$ line flux ratio is used in Fig. 1b to obtain the oxygen abundance. The primordial value obtained from the regression in Fig. 1a of $Y_p = 0.2512 \pm 0.0006$ is very close to the value of $Y_p = 0.2516 \pm 0.0011$ obtained for HeBCD sample by Izotov *et al.* (2007) for the same set of parameters. It is seen from this comparison that the use of the large sample reduces statistical errors in Y_p by a factor of two. The value of Y_p derived here is by 1.3% greater than the SBBN value obtained from the WMAP data.

The variation of the parameter ranges, similar to that done by Izotov *et al.* (2007), shows that the primordial He abundance is always larger than the standard one and varies in the range $\sim 0.249 - 0.252$. Finally, we adopt as the best the regression in Fig. 1a with Y_p= 0.2512 $\pm$ 0.0006. This regression is obtained with the basic set of parameters and the temperature $T_e(\mathrm{He}^{+})$ for the oxygen abundance determination. Adding a systematic error caused by the uncertainties in He I emissivities (Porter *et al.* 2009) we obtain Y_p= 0.2512 $\pm$ 0.0006(stat.) $\pm$ 0.0020(syst.).

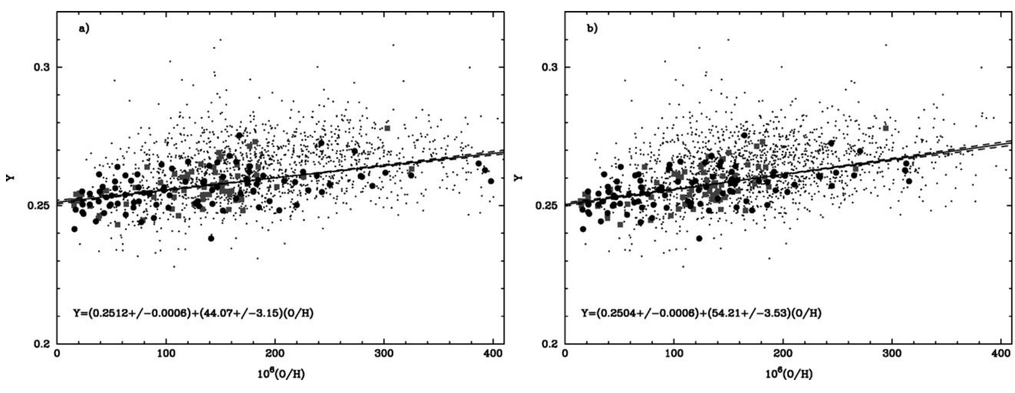

Figure 1. Linear regressions helium mass fraction Y vs. oxygen abundance O/H. The HeBCD H II regions are shown by filled circles, the archival VLT data by grey squares and the SDSS objects by dots. The oxygen abundance O/H is derived adopting (a) $T_e(\mathrm{He}^{+})$ and (b) T_e(O III).

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5. Cosmological implications

We now investigate whether our derived values of Y_p are consistent with the predictions of SBBN and whether the baryonic mass density corresponding to Y_p agrees with the one derived from measurements of the CMB. We follow here the analysis by Izotov *et al.* (2007) with our new value $Y_p = 0.2512 \pm 0.0006$. With this value, and with an equivalent number of light neutrino species equal to 3, the SBBN model gives $\eta_{10} = 10^{10}\eta = 8.7 \pm 0.5$, where the error bars denote 1σ errors. This value corresponds to a baryonic mass fraction $\Omega_b h^2 = 0.032\pm$ 0.002 and is significantly higher than $\Omega_b h^2 = 0.02273\pm0.00062$ derived from measurements of the fluctuations of the microwave background radiation by WMAP (Dunkley *et al.* 2009). Thus, the deviations from the SBBN are likely present. However, if the systematic error of 0.0020 in Y_p is taken into account because of uncertainties in the He I emissivities, then our value within 2σ is consistent with the SBBN value $Y_p = 0.2482^{+0.0003}_{-0.0004} \pm 0.0006$ (syst.) inferred by Spergel *et al.* (2007).

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 active or sterile neutrinos) which can conveniently be parameterized by an equivalent number of neutrino flavors N_ν. Combining $\Omega_b h^2 = 0.002273 \pm 0.00062$ obtained by WMAP (Dunkley *et al.* 2009) with $Y_p = 0.2512 \pm 0.0006$, we obtain $N_\nu \sim 3.25$ (Steigman 2005,2007).

6. Summary

We present the determination of the primordial helium mass fraction Y_p by linear regressions of a large sample of low-metallicity extragalactic H II regions.

In the determination of Y_p, we have considered several known systematic effects. We have used Monte Carlo methods to take into account the effects of collisional and fluorescent enhancements of He I recombination lines, of collisional excitation of hydrogen emission lines, of underlying stellar He I absorption, of the difference between the temperature T_e(He$^+$) in the He$^+$ zone and the temperature T_e(O III) derived from the [O III]λ4363/(λ4959+λ5007) flux ratio, and of the ionization correction factor ICF(He$^+$ + He^{2+}).

We have obtained the following results:

1. For the determination of the primordial He abundance we construct a sample of 1700 spectra of low-metallicity extragalactic H II regions which includes the HeBCD sample Izotov *et al.* (2007), archival VLT spectra and spectra from the Data Release 7 (DR7) of the Sloan Digital Sky Survey (SDSS). This sample is the largest data sets in existence for the determination of Y_p.

2. We obtain $Y_p = 0.2512 \pm 0.0006$(stat.) $\pm$ 0.0020(syst.), corresponding to $\Omega_b h^2 = 0.032 \pm 0.002$(stat.), significanly larger than the $\Omega_b h^2$ values derived from the deuterium abundance and microwave background radiation fluctuation measurements. If we take the higher value of Y_p at its face value, then this would imply the existence of small deviations from SBBN. In order to bring the high value of Y_p into agreement with the deuterium and WMAP measurements, we would need an equivalent number of neutrino flavors equal to 3.25 instead of the canonical 3.

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