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The influence of systematic effects on the determination of the primordial helium abundance

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Various tests of the Primordial Nucleosynthesis (PN) theory and Early Universe cosmology require an accurate determination of the primordial helium abundance (Y_p). Metal deficient HII regions located in blue compact dwarf (BCD) galaxies are commonly used to determine Y_p. Since the measured fluxes of He and H lines emitted from such objects often deviate from their pure recombination values due to the influence of several systematic effects, one has to correctly account for these effects to determine Y_p with high accuracy. In this paper, we present an updated estimate of Y_p based on analyses of a large sample of SDSS objects and objects from HeBCD+NIR database. Using improved treatment of the HII region systematics we obtain $Y_p = 0.2466 \pm 0.0019$, which is the most accurate estimate up to date, and is in good consistency with other independent estimates as well as the PN+Planck prediction of $Y_p = 0.2470 \pm 0.0002$.

Keywords: Primordial Nucleosynthesis, Primordial Helium, HII regions

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1. Introduction

Precise observational estimate of the primordial helium abundance (Y_p) is a strong probe of self-consistency of the ΛCDM cosmological model as well as it can be used to tight constraints on any non-standard Physics during PN era. The most used method to estimate Y_p is the spectroscopic study of metal deficient HII regions located in blue compact dwarf galaxies (BCD), which interstellar medium has its elemental composition close to the primordial one. We can expect a correlation between the observed ^{4}He abundance Y and metallicity Z, since both of this quantities are produced over time due to stellar nucleosynthesis. Thus the primordial ^{4}He abundance Y_p can be estimated by extrapolating of the $Y - Z$ dependence to zero metallicity. This technique was firstly proposed in [1] and is still in use (e.g., see [2] and refs. therein).

The abundances in HII regions can be estimated using the ratio of intensities of recombination lines. However, there are numerous systematic effects which shift measured intensities of the lines from their pure recombination values. They include interstellar reddening, underlying stellar absorption, collisional excitation, self-absorption etc. In order to account for the systematics the photoionization models of HII regions are used. In our previous paper [2]) we used the photoionization model described in [3] to estimate current helium abundances Y. Recently, [4] proposed an update to their model, which revisits how the underlying absorption, collision excitation of HI and self-absorption in He lines are treated. In addition, we propose a modified method for the estimation of Z of an object, as well as a new selection criterion associated with it.

In this paper we update our photoionization model according to the proposed changes and apply it to our spectroscopic database, described in [2], and discuss how the changes affect the estimate of Y_p.

2. Photoionization model improvements

2.1. Model improvements

In recent paper [4] presented updated scaling coefficients for underlying absorption in H and He lines, recalculated contribution of collisionally excited transitions in HI to Balmer series intensities, and proposed a new method of treating of the blended H8+Heλ3889 line. Besides, authors proposed to include additional weak H and He lines to the analyses. In this paper we focus on first three suggested changes due to the following reason. Our spectroscopic database (while being larger compared to other ones from the literature) mostly consists of SDSS objects with medium to low quality of spectra, where such weak lines are almost never confidently detected.

2.2. New OH estimation

The oxygen abundance O/H, which is commonly used as the metallicity tracer of an HII region, is defined as sum of abundances of the two most relevant ionization states: O/H = OII/H + OIII/H. These abundances can be estimated using the observed fluxes of forbidden lines of OII and OIII and the temperatures of the corresponding ionization zones. According to the two-zone temperature model of an HII region, OIII is distributed in the high-ionization zone characterized by temperature T_e(OIII). OII is distributed in the low-ionization zone characterized by temperature T_e(OII). In other surveys, authors often estimate T_e(OII) using model relations $T_e(\mathrm{OII}) = f(T_e(\mathrm{OIII}))$, and T_e(OIII) is estimated directly from [OIII] lines ration $(\lambda4959+\lambda5007)/\lambda4363$. We propose to estimate both of these temperatures directly using [OII] lines ratio $(\lambda3727)/(\lambda7320 + \lambda7330)$ and [OIII] lines ration mentioned above. We find out that usage of the relations $T_e(\mathrm{OII}) = f(T_e(\mathrm{OIII}))$ can significantly shift the estimated OII/H as well as lead to underestimation of O/H uncertainty.

2.3. Final database

The final regression database is formed as follows. Firstly, from 588 objects, which were manually picked up from the SDSS catalog [2], and 83 high-quality spectra from HeBCD+NIR database [5, 6], we select objects whose spectrum allows a direct estimation of T_e(OII) and T_e(OIII). Secondly, from these objects we select ones where all lines required for the analyses with photoionization model are detectable on a CL of $\geq 3\sigma$. This cuts leave 133 objects to analyse.

In order to check how each individual change affects the final Y_p estimation we separately insert each one into the "original" photoionization model and get a separate sample for each change. We determine physical properties, current oxygen abundance O/H and current helium to hydrogen density ratio y using photoionization model described above. For the regression analyses we select objects using "goodness of fit" statistical χ^2 criteria (95% CL for a model with one degree of freedom corresponds to $\chi 2 \leq 4$). Thus we get four independent samples to analyse: sample $\mathrm{S_{UA}}$ (obtained with new UA scaling), sample $\mathrm{S_{CR}}$ (obtained with new CR coefficients), sample $\mathrm{S_{3889}}$ (obtained with new deblending method), and sample $\mathrm{S_{tot}}$ (obtained with all changes incorporated). They consist of 68 objects for the sample $\mathrm{S_{UA}}$, 67 objects for the sample $\mathrm{S_{CR}}$, 52 objects for the sample $\mathrm{S_{3889}}$, and 65 for the sample $\mathrm{S_{tot}}$.

3. Results and conclusion

We perform a regression analyses of y versus O/H using the following expression:

$$y = y_\mathrm{p} + \frac{dy}{d(\mathrm{O/H})} \times \mathrm{O/H} \tag{1}$$

Here y_p denotes the primordial helium to hydrogen density ratio and is connected to the primordial helium abundance Y_p via the relation:

$$Y_\mathrm{p} = \frac{4y_\mathrm{p}}{1 + 4y_\mathrm{p}} \tag{2}$$

We estimate y_p and slope $dy/d(\mathrm{O/H})$ using MCMC routine for all samples $\mathrm{S_{UA}}$, $\mathrm{S_{CR}}$, $\mathrm{S_{3889}}$ and $\mathrm{S_{tot}}$. The results are summarized in Table 1. As can be seen the results for all studied samples are consistent with each other within margin of errors, while there is a noticeable scatter between their nominal values (with the largest shift corresponding to the new H8+Heλ3889 deblending method). This shift may be due to the fact that the method does not work quite correctly on the SDSS spectra of medium and low quality, since, as shown in [4], for spectra of high quality the method work correctly. Thus the deblending method should be refined to be used for processing of the SDSS spectra.

Table 1: Estimates of Y_p and $dy/d(\mathrm{O/H})$ for the samples described in Sec. 2.3.

Sample	Y_p	$dy/d(\mathrm{O/H})$
$\mathrm{S_{UA}}$	0.2464 ± 0.0020	27 ± 7
$\mathrm{S_{CR}}$	0.2457 ± 0.0020	29 ± 7
$\mathrm{S_{3889}}$	0.2506 ± 0.0023	18 ± 7
$\mathrm{S_{tot}}$	0.2504 ± 0.0021	18 ± 7

According to this, we insert only the updates in UA scaling and updated HI collisional excitation rates into the photoionization model, and, after preforming the regression analyses as described above, we get the following estimate of Y_p:

$$Y_p = 0.2466 \pm 0.0019 \tag{3}$$

It is the most precise Y_p estimation up to date, and is in a good consistency with Planck's results $Y_p = 0.2470 \pm 0.0002$ [7] and other independent estimation (see [2] and refs. therein).

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