On the Primordial Helium Abundance and the $\Delta Y/\Delta O$ Ratio

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Abstract. We present a review on the determination of the primordial helium abundance, $Y_p$, based on the study of hydrogen and helium recombination lines in extragalactic H II regions. We also discuss the observational determinations of the increase of helium to the increase of oxygen by mass $\Delta Y/\Delta O$, and compare them with predictions based on models of galactic chemical evolution.

1. Why $Y_p$?

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 models of stellar evolution require an accurate initial $Y$ value; this is given by $Y_p$ plus the additional $Y$ produced by galactic chemical evolution, which can be estimated based on the $\Delta Y/\Delta O$ ratio, c) the combination of $Y_p$ and $\Delta Y/\Delta O$ is needed to test models of galactic chemical evolution, d) to test solar models it is necessary to know the initial solar abundances, which are different to the photospheric ones due to diffusive settling, this effect reduces the helium and heavy element abundances in the solar photosphere relative to that of hydrogen, the initial solar abundances can be provided by models of galactic chemical evolution, e) 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 temperature structure of H II regions.

2. Recent Determinations of $Y_p$

Previous reviews on $Y_p$ determinations have been presented by Peimbert et al. (2003) and Luridiana (2003). Recent determinations of $Y_p$ are those by Izotov et al. (1999), Izotov & Thuan (2004), Izotov et al. (2006), Luridiana et al. (2003), Olive & Skillman (2004), Fukugita & Kawasaki (2006), and Peimbert et al. (2007).

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A critical discussion of these determinations has been presented by Peimbert et al. (2007). Most of the differences among these determinations are due to systematic effects.

3. Error Budget

The error budget of the $Y_p$ determination by Peimbert et al. (2007) is presented in Table 1. In this table the sources of error are listed in order of importance. The error budgets of $Y_p$ determinations by other groups are different to that by Peimbert et al. (2007) for many reasons, each error budget depends on the sample of H ii regions used and on the treatment given to the different sources of error.

| Problem                                      | Estimated error |
|----------------------------------------------|-----------------|
| Collisional Excitation of the H I Lines     | ±0.0015         |
| Temperature Structure                        | ±0.0010         |
| $O (\Delta Y/\Delta O)$ Correction          | ±0.0001         |
| Recombination Coefficients of the He I Lines | ±0.0010         |
| Density Structure                            | ±0.0007         |
| Underlying Absorption in the He I Lines      | ±0.0007         |
| Recombination Coefficients of the H I Lines  | ±0.0005         |
| Underlying Absorption in the H I Lines       | ±0.0005         |
| Ionization Structure                         | ±0.0005         |
| Collisional Excitation of the He I Lines     | ±0.0005         |
| Reddening correction                         | ±0.0005         |
| Optical Depth of the He I Triplet Lines      | ±0.0003         |
| He I and H I Line Intensities                | ±0.0003         |

4. The Four Main Sources of Error

The most important source of error is the collisional excitation of Balmer lines. Neutral hydrogen atoms in excited states may form not only by the usual process of H$^+$ recombination, but also through collisions of neutral hydrogen with electrons. The recombination cascade that follows such excitations contributes to the observed intensity of Balmer lines, mimicking a larger relative hydrogen abundance and, hence, a smaller helium abundance. To estimate this contribution it is necessary to have a tailored photoionization model for each object that fits properly the temperature structure. The contribution to the Balmer line intensities depends strongly on the temperature: therefore this effect, and consequently the associated error in its estimate, increases for H ii regions of lower metallicity and consequently higher temperature.

The second most important source of error is the temperature structure. Most determinations neglect the possible presence of temperature variations across the H ii region structure and assume that $T(\text{O III})$ is representative of the zone where the He i recombination lines form. However, other temperature
determinations based on different diagnostics yield lower values; furthermore, photoionization models do not predict the high \( T(\text{O} \text{ iii}) \) values observed. These results indicate that temperature variations are indeed present in \( \text{H} \text{ ii} \) regions, and this result should be included in the \( Y \) determination (Peimbert et al. 2002). The best procedure to take into account the temperature structure is to self-consistently determine \( T(\text{He} \text{ ii}) \) from a set of \( \text{He} \text{ i} \) lines by means of the maximum likelihood method. The \( Y \) abundances derived from \( T(\text{He} \text{ ii}) \) are typically lower by about \( 0.0030 - 0.0050 \) than those derived from \( T(\text{O} \text{ iii}) \). The difference between both temperatures does not have a significant trend with the metallicity of the \( \text{H} \text{ ii} \) region, hence the systematic error introduced by the use of \( T(\text{O} \text{ iii}) \) in the \( Y \) determination is similar for objects with different metallicities. The error quoted under “Temperature Structure” in Table 1 is the residual error due to the uncertainty in the \( T(\text{He} \text{ ii}) \) determinations of the dataset by Peimbert et al. (2007).

The third most important source of error is the extrapolation of the derived \( Y \) values to zero metallicity through the \( \Delta Y/\Delta O \) ratio. This problem will be discussed in the next section. The fourth most important source of error is the uncertainty on the recombination coefficients of the \( \text{He} \text{ i} \) lines.

5. \( \Delta Y/\Delta O \) from Models and Observations

To determine the \( Y_p \) value it is customary to use the \( Y \) values of a set of \( O \)-poor galaxies and to extrapolate the \( Y \) values to the case of \( O = 0 \) using the following equation:

\[
Y_p = Y - O \frac{\Delta Y}{\Delta O},
\]

where \( O \) is the oxygen abundance per unit mass. To obtain an accurate \( Y_p \) value, a reliable determination of \( \Delta Y/\Delta O \) for \( O \)-poor objects is needed.

The \( \Delta Y/\Delta O \) value derived by Peimbert et al. (2000) from observational results and models of chemical evolution of galaxies amounts to \( 3.5 \pm 0.9 \). More recent results are those by Peimbert (2003) who finds \( 2.93 \pm 0.85 \) from observations of 30 Dor and NGC 346, and by Izotov et al. (2006) who, from the observations of 82 \( \text{H} \text{ ii} \) regions, find \( \Delta Y/\Delta O = 4.3 \pm 0.7 \). We have recomputed the value by Izotov et al. considering two systematic effects not considered by them: the fraction of oxygen trapped in dust grains, which we estimate to be 10% for objects of low metallicity, and the increase in the \( O \) abundances due to explicit taking into account the presence of temperature fluctuations, which for this type of \( \text{H} \text{ ii} \) regions we estimate to be about 0.08 dex (Relaño et al. 2002). From these considerations we obtain for the Izotov et al. sample a \( \Delta Y/\Delta O = 3.2 \pm 0.6 \).

From chemical evolution models of galaxies it is found that \( \Delta Y/\Delta O \) depends on: the stellar yields, the initial mass function, the star formation rate, the age, and the \( O \) value of the galaxy in question. Models with substantial outflows of \( O \)-rich material can produce large \( \Delta Y/\Delta O \) ratios but they are ruled out by the low C/O values observed in irregular galaxies (Carigi et al. 1995, 1999, 2006). Carigi & Peimbert (2007) have produced chemical evolution models of the following types: closed box, inflow of gas, and outflow of gas of well-mixed
Two chemical evolution models for NGC 6822 with different gas infall and outflow histories, and the same star formation rate derived from observations. The models are the 7L and 8S (continuous and dashed lines, respectively) studied by Carigi et al. (2006). The first panel shows the increase of the helium and oxygen abundances relative to the primordial values, the second panel shows the gaseous content as a function of time, which is widely different for the two models, and the third panel shows the star formation history, which is the same one in both models.

They find that $\Delta Y/\Delta O$ is practically constant for models with the same IMF, the same age, the same star formation history, and an $O$ abundance smaller than $\sim 4\times 10^{-3}$. They find also that $2.4 < \Delta Y/\Delta O < 4.1$ for models with different star formation histories and different values of the upper mass limit of the IMF. The results derived from the chemical evolution models are in very good agreement with the observations mentioned above.

Based on the observations and models discussed, Peimbert et al. (2007) adopted a value of $\Delta Y/\Delta O = 3.3 \pm 0.7$ in the computation of the error budget presented in Table 1 and the $Y_p$ value presented in Table 2.
For models of galactic chemical evolution that reach values of $O > 4 \times 10^{-3}$ at present time, the $\Delta Y/\Delta O$ ratio of the interstellar medium increases with the $O$ abundance due to two effects: the helium production by low and intermediate mass stars and the increase of the helium yield of massive stars due to stellar winds.

As an example of the minor role that well mixed outflows play in the chemical evolution of galaxies in Figure 1 we present the $\Delta Y$ versus $\Delta O$ behavior for two chemical evolution models of NGC 6822 (Carigi et al. 2006; Carigi & Peimbert 2007). These models have the same SFH, which was derived from observations, but are drastically different in their gas flow histories and show practically the same $\Delta Y/\Delta O$ behavior.

To compute stellar evolution models with $O < 4 \times 10^{-3}$ we propose to use the following relation for the initial $Y$ and $O$ abundances

$$Y = 0.2474 \pm 0.0028 + (3.3 \pm 0.7)O.$$  

For $O > 4 \times 10^{-3}$ (Carigi & Peimbert 2007), $Y$ increases faster with the increase of $O$ than in the previous equation.

The ratio $\Delta Y/\Delta O$ can also be expressed in terms of $\Delta Y/\Delta Z$ if the fraction of $O/Z$ is known. Based on observations of galactic and extragalactic H II regions, we propose to assume that, for models with $O < 4 \times 10^{-3}$, $O$ constitutes $55\% \pm 5\%$ of the total $Z$ value, implying $\Delta Y/\Delta Z = 2.0 \pm 0.6$. For $O > 4 \times 10^{-3}$ the fraction of $Z$ due to $O$ decreases due to the increase of the C/O, N/O and Fe/O ratios with the increase of $O$. From the chemical composition of the Orion nebula and M17 it is found that the fraction of $Z$ due to $O$ drops to about 42% for $0.0057 < O < 0.0082$ (e.g. Peimbert 2003; Esteban et al. 2004; García-Rojas et al. 2007, and references therein).

Previous determinations of the $\Delta Y/\Delta Z$ ratio based on models or observations have been in the 1.0 to 6.0 range (e.g. Peimbert 1995; Fukugita & Kawasaki 2006, and references therein). It is interesting to note that 25 years ago Chiosi & Matteucci (1982) determined a value of $\Delta Y/\Delta Z \sim 2.0$, in excellent agreement with the recent results by Carigi & Peimbert (2007).

6. Discussion

In Table 2 we present some of the best $Y_p$ determinations of the last few years. The $Y_p$ values and their statistical errors are the ones presented in the original papers. After the statistical error we list the systematic error estimated by us, which depends on one or more of the following sources: a) the change in the published emissivities of the He I lines (Porter et al. 2003); b) the change in the published collisional excitation coefficients of the H I lines (Anderson et al. 2000, 2002); and c) the temperature structure of the H II region. Adopting the new He I emissivities, the $Y$ determination of individual H II regions is increased by about 0.004. The change in the H I collisional excitation coefficients goes in the same direction (Peimbert et al. 2007), although in this case the size of this effect varies from object to object and a tailored photoionization model for each object is needed to obtain a good estimate of it. Both effects produce an increase in the $Y_p$ determination: for the sample of H II regions used by Peimbert et al. (2007), the increase in $Y_p$ due to the adoption of the new He I emissivities amounts to
about 0.0040, while the increase due to the adoption of the new H II collisional excitation coefficients amounts to 0.0025. Finally, the Y value of individual H II regions decreases when the temperature structure of the H II region is taken into account, since in the self-consistent solutions for all the observed He II line intensities, the lower T(He II) values imply higher densities, the higher densities produce a higher collisional contribution to the He II intensities, and consequently lower helium abundances. For the objects in the sample used by Peimbert et al. (2002) and Peimbert et al. (2007), this effect decreases the Y determinations by amounts ranging from 0.003 to 0.009.

The Yp determination by Izotov et al. (1999) is affected by all three of the above sources of systematic error; those by Luridiana et al. (2003) and Izotov & Thuan (2004) are affected by sources a) and b), while the one by Izotov et al. (2006) is affected by source b). The disagreement between the Yp derived by Luridiana et al. (2003) with the Yp derived from WMAP under the assumption of SBBN implies the need for “new physics”. The new physics needed to reconcile the two Yp values turned out to be the “new atomic physics” by Anderson et al. (2000, 2002) and Porter et al. (2005). With the new physics Peimbert et al. (2007) found agreement, within the observational errors, between the observed Yp value and that derived from the WMAP results under the assumption of SBBN.

The Yp derived by Peimbert et al. (2007) together with SBBN implies that \( \Omega_b h^2 = 0.02054 \pm 0.00639 \) (Steigman 2006a,b), where \( \Omega_b \) is the baryon closure parameter, and \( h \) is the Hubble parameter. This value is in excellent agreement with the value derived by Spergel et al. (2006) from the WMAP results under the assumption of SBBN, which amounts to \( \Omega_b h^2 = 0.02233 \pm 0.00082 \).

The comparison of the Yp derived by Peimbert et al. (2007) with the Yp derived by Spergel et al. (2004) from the WMAP data together with the assumption of SBBN provides strong constraints for the study of non SBBN (e.g. Cyburt et al. 2005; Coc et al. 2006, and references therein).

In Table 2 we also present our Yp prediction for 2010. We consider that in the next few years it will be possible to reduce the statistical errors in the Yp determination to about 0.0020 by obtaining a new set of observations of brighter and slightly O-richer H II regions than the ones that have been used so far. A more extensive discussion of the relative advantages of these H II regions with respect to more metal-poor ones can be found in Peimbert et al. (2007).

7. Summary and conclusions

In this contribution we have presented some recent determinations of Yp and discussed the reasons underlying the differences between them. For the most recent determination, the one by Peimbert et al. (2007), we have presented the error budget in terms of thirteen different sources of error. The \( \Delta Y/\Delta O \) ratio, which enters as a crucial factor in one of the three main sources of error, has been discussed in the light of recent observations and models of galactic chemical evolution.

The Yp determinations by different groups are slowly converging among them as systematic errors are progressively identified and corrected for. The need for “new physics” that had been suggested by recent results (e.g. Luridiana et al.
Table 2. Primordial helium abundance values $^a$

| Source | $Y_p$ |
|--------|-------|
| Izotov et al. (1999), this work | 0.2452 ± 0.0015 ± 0.0100 |
| Luridiana et al. (2003), this work | 0.2391 ± 0.0020 ± 0.0070 |
| Izotov & Thuan (2004), this work | 0.2421 ± 0.0021 ± 0.0075 |
| Izotov & et al. (2006), this work | 0.2462 ± 0.0025 ± 0.0040 |
| Peimbert et al. (2007) | 0.2474 ± 0.0028 |
| Prediction (2010), this work | 0.2???? ± 0.0020 |
| Spergel et al. (2006) | 0.2482 ± 0.0004 |

$^a$ Direct $Y_p$ determinations based on observations of H II regions, with the exception of that by Spergel et al. (2006), which is based on the baryon to photon ratio derived from WMAP and the assumption of SBBN.

2003) seems now to be fulfilled by new atomic physics, i.e. the atomic data by Anderson et al. (2000, 2002) and Porter et al. (2003). On the other hand, the temperature structure of H II regions is still a source of systematic error if an appropriate scheme for temperature is not adopted. The proper temperature to determine the helium abundance is $T(\text{He} \ II)$, derived self-consistently from the intensities of the helium lines. Adopting this temperature, the $Y_p$ value derived from H II regions agrees with the $Y_p$ derived from the WMAP data under the assumption of SBBN. On the other hand, the use of $T(\text{O} \ III)$ to determine the $Y$ values from H II regions produces $Y_p$ values from 0.003 to 0.006 higher than those found adopting $T(\text{He} \ II)$, that is $Y_p$ values more than 1σ higher than the one predicted by the WMAP observations combined with the assumption of SBBN.

It is important to continue the effort on the study of the physical conditions in H II regions, this effort will permit us to lower the error on the $Y_p$ determination, which in turn will permit us to improve our knowledge on the possible importance of non SBBN.

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