Seven problems related to the determination of the primordial helium abundance

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Abstract. Recent advances on the quest to determine the primordial or pregalactic helium abundance, $Y_p$, are reviewed. There are seven problems affecting the He/H abundance determinations of H II regions that are briefly discussed: the underlying absorption lines in the observed spectra, the ionization, temperature, and density structures of each object, the collisional contribution to the intensity of the He I and H I lines, the optical thickness of the He I lines, and the extrapolation to derive $Y_p$ based on the Y and O/H values.

1. Overview

The determination of helium abundances in H II regions and their extrapolation to derive $Y_p$ have become an important field of research due to its relation to cosmology, to the chemical evolution of galaxies, and to the study of the physical conditions inside H II regions. Roberto and Elena Terlevich have done significant work in two areas related to this field: the search for metal poor H II regions to derive their helium abundance, and the gathering of high quality spectroscopic data to derive the $Y_p$ value (e.g. Terlevich et al. 1991a,b; Pagel et al. 1992). Two recent review papers on $Y_p$ are those by Steigman (2002) and Luridiana (2002). This review will be mainly devoted to seven problems that affect the $Y_p$ determination.

2. Underlying Absorption Lines

The observed spectra of giant extragalactic H II regions is produced by a combination of nebular emission and stellar emission. The stellar emission includes a continuum with the H and He lines in absorption. If the underlying absorption is
not taken into account the intensity of the H and He emission lines will be underestimated. The correction for underlying absorption is larger, and consequently the associated errors, for objects with lower Hβ equivalent width.

There are two ways to minimize the errors introduced by this problem, a) to have enough angular resolution to be able to avoid the light of the early type stars in the observing slit, this can be done only for H ii regions of the local group (e.g. Peimbert, Peimbert, & Ruiz 2000; Peimbert 2003), or b) to have a good model of the starburst and produce the expected stellar spectrum, like the work carried out by González-Delgado, Leitherer, & Heckman (1999). Further extensions of the work by González-Delgado et al. are needed to cover other metallicities and to include the equivalent widths of other He i lines like λλ 5876 and 6678.

3. Ionization Structure

To determine very accurate He/H values of a given H ii region we need to consider its ionization structure. The total He/H value is given by:

\[
\frac{N(\text{He})}{N(\text{H})} = \frac{\int N_e N(\text{He}^0) dV + \int N_e N(\text{He}^+) dV + \int N_e N(\text{He}^{++}) dV}{\int N_e N(H^0) dV + \int N_e N(H^+) dV + \int N_e N(H^{++}) dV},
\]

\[
= ICF(\text{He}) \frac{\int N_e N(\text{He}^+) dV + \int N_e N(\text{He}^{++}) dV}{\int N_e N(H^+) dV}.
\]

For objects of low degree of ionization it is necessary to consider the presence of He^0 inside the H^+ zone, while for objects of high degree of ionization it is necessary to consider the possible presence of H^0 inside the He^+ zone. For objects of low degree of ionization ICF(He) might be larger than 1.00, while for objects of high degree of ionization ICF(He) might be smaller than 1.00. The ICF(He) problem has been discussed by many authors (e.g. Shields 1974; Stasińska 1983; Peña 1986; Vílchez & Pagel 1988; Pagel et al. 1992; Armour et al. 1999; Peimbert & Peimbert 2000; Viegas, Gruenwald, & Steigman 2000; Viegas & Gruenwald 2000; Ballantyne, Ferland, & Martin 2000; Sauer & Jedamzik 2001; Gruenwald, Steigman, & Viegas 2002).

The deviations from unity in the ICF(He) value occur in and near the ionization boundary of a given H ii region, therefore those H ii regions that are density bounded in all directions have an ICF(He) = 1.00. Relaño, Peimbert, & Beckman (2001) from the spectral types of the ionizing stars of NGC 346 find that about half of the ionizing photons escape the nebula favoring an ICF(He) = 1.00, they support this result by fitting the observed line intensities with a photoionization model. From the work by Zurita, Rozas, & Beckman (2000) on the ionization of the diffuse interstellar medium in external galaxies it is expected that a large fraction of the ionizing photons escapes from the most luminous H ii regions, which favors the assumption that the ICF(He) is very close to 1.00. Luridiana, Peimbert, & Peimbert (2003), from tailor made models of I Zw 18, SBS 0335-052, and Haro 29 also find ICF(He) values very close to 1.00.
4. Temperature Structure

$T(4363/5007)$ has been used often to determine the helium abundance, under the assumption of constant temperature. However, from photoionization models of H II regions, it has been found that the mean temperature variation, $t^2$, is in the 0.002 to 0.03 range, with typical values around 0.005 (e.g. Gruenwald & Viegas 1992; Kingdon & Ferland 1995; Pérez 1997). Moreover from photoionized models it is found that in very metal poor H II regions the zones where the [O III] lines originate are several thousand degrees hotter than the regions where the [O II] lines originate, while the He I lines originate in both regions (e.g. Stasińska 1990; Peimbert, Peimbert & Luridiana 2002; Luridiana et al. 2003).

From observations of galactic and extragalactic H II regions there is growing evidence that temperature variations are higher than those predicted by chemically homogeneous photoionization models, for example: a) the observed $T(4363/5007)$ values are considerably higher than those computed by photoionization models (e.g. Stasińska & Schaefer 1999; Luridiana et al. 2003), b) the Balmer temperatures for Magellanic Cloud H II regions are considerably smaller than the $T(4363/5007)$ values (Peimbert et al. 2000; Peimbert 2003), c) under the assumption of a constant temperature the C and O abundances derived from the recombination lines of C II and O II are considerably higher than those derived from the collisionally excited lines of C III and O III (e.g. Peimbert et al. 1993; Esteban et al. 1998, 2002; Peimbert 2003; Tsamis et al. 2003), d) the self consistent method employed by Peimbert et al. (2000) to derive the He$^+/H^+$ value also indicates that the representative temperature for the He I lines, $T(He\ II)$, is considerably smaller than the representative temperature for the [O III] lines, $T(\ O \ III)$. All these results imply that $T(4363/5007)$ is an overestimate of $T(\ He \ II)$. The self consistent method to derive He$^+/H^+$ requires a higher density for a lower temperature, and the higher the density the higher the collisional contribution to the He I line intensities, which results in a lower He$^+/H^+$ value. This problem has been amply discussed by Peimbert et al. (2002).

5. Density Structure

To produce a good photoionization model and to estimate the collisional excitation of the He I lines a good density structure is needed. H II regions show very large density fluctuations, this is apparent in any high resolution image of those giant extragalactic H II regions that have been used to determine the pregalactic helium abundance. By comparing the root mean square density with those densities derived from forbidden lines it is possible to estimate the filling factor, $\epsilon$, which is given by

$$N_e^2(rms) = \epsilon N_e^2(FL).$$  \hspace{1cm} (2)

Typical values of $\epsilon$ are in the 0.1 to 0.001 range (e.g. Luridiana et al. 1999, 2003). There are five sets of forbidden lines that have been used to estimate the density: [S II], [O II], [Fe III], [Cl III], and [Ar IV]. Each set samples a different part of the H II region, typically the [S II] density samples the outermost 2-4% part, [O II] and [Fe III] sample the 10 to 15% outer parts, [Cl III] samples about
85% of the object, and [Ar IV] samples the innermost 2-4%. Unfortunately for most of the well observed H II regions there are only [S II] densities available.

Often the [S II] density has been used to determine the collisional effect on the He I lines, this has to be considered as a first approximation, but not good enough to derive very accurate Y values. For example for NGC 2363 the [S II] density is smaller than the [Ar IV] density (Peréz, González-Delgado, & Vílchez 2001), for a position in 30 Dor the [O II] and [Fe III] densities are smaller than the [S II] density (Peimbert 2003), and for NGC 346 it has been found that a self consistent method to derive the He abundance, based on 9 He I, lines requires a higher density than that provided by the [S II] lines (Peimbert et al. 2000).

The [S II] lines, in addition to be representative of only a small fraction of the H II region, have the problem that are almost insensitive to values of the density smaller than about 100 cm$^{-3}$. Whenever possible we recommend the use of the [Fe III] lines instead of the [S II] lines on two grounds: they represent a larger fraction of the H II region and they are very sensitive at low densities, specially the 4986/4658 ratio (Keenan et al. 2001).

6. Collisional Excitation of the He I and H I Lines

Recent expressions to correct for the collisional excitation of the He I lines have been presented by Kingdon & Ferland (1995) and by Benjamin, Skillman, & Smits (1999).

Davidson & Kinman (1985) were the first to point out the relevance of collisional excitation of the Balmer lines from the ground level of the H atom. Additional discussion and estimates of the relevance of this process were presented by Skillman & Kennicutt (1993), Stasińska & Izotov (2001), and Peimbert et al. (2002). The importance of this effect is proportional to H$^0$/H$^+$ and to the Boltzmann factor for collisional excitation. In extremely metal poor objects, that have high electron temperatures, the contribution of this effect to the intensity of H$\beta$ can reach values of a few per cent. Since H$^0$/H$^+$ can not be derived directly from observations we need tailor made models for each H II region to properly estimate the importance of this effect. For objects with $T_e > 17000$ K probably the collisional excitation of the Balmer lines introduces the highest source of error in the Y determination (Luridiana et al. 2003).

7. Optical Thickness of the He I Triplet Lines

The He I line intensities of the triplet system are affected by the 2$^3$S level optical depth. Therefore the triplet line intensities have to be corrected for this effect to derive accurate He/H abundance ratios. Benjamin, Skillman, & Smits (2002) have estimated this effect for the case of spherical geometry, they conclude that their computations can be applied to observations for values of $\tau_{3889}$ smaller than 2.

There are H II regions with values of $\tau_{3889}$ larger than 2 and there are H II regions that deviate considerably from spherical symmetry, the triplet lines of these objects need to be corrected for optical depth effects.
What is usually done to correct the line intensities is to determine $\tau_{3889}$ from the ratio of the most affected triplet line to a singlet line (the singlet lines are independent of this effect), and from the derived $\tau_{3889}$, apply the spherically symmetric solution to the $\lambda\lambda\ 5876$ and $4471$ lines to correct their intensities, in general a small correction.

The four more sensitive lines to $\tau_{3889}$ are $\lambda\lambda\ 3188, 3889, 4713,$ and $7065$; two of them, $\lambda\lambda\ 4713$ and $7065$, increase in intensity with increasing $\tau_{3889}$, while two of them, $\lambda\lambda\ 3188$ and $3889$, decrease.

For a region of 30 Doradus Peimbert (2003), based on the computations of Benjamin et al. (2002), found two values of $\tau_{3889}$: a value of 4.4 based on $\lambda\lambda\ 4713$ and 7065 and a value of 10.5 based on $\lambda\lambda\ 3188, 3889$. This result indicates that the computations for spherical geometry by Benjamin et al. (2002) do not apply to the observed region of 30 Dor.

Peimbert (2003) has suggested to use the $\tau_{3889}$ value derived from the $\lambda\lambda\ 4713$ and 7065 line intensities together with the computations by Benjamin et al. (2002) to correct $\lambda\lambda\ 5876$ and 4471 for all objects. His suggestion is based on the following argument: while the $\lambda\lambda\ 3188$ and 3889 line intensities depend on the optical depth along the line of sight, the $\lambda\lambda\ 4713, 7065, 5876,$ and $4471$ lines depend on atoms absorbing the photons from all lines of sight and then re-emitting them towards us, and thus depend on the average optical depth along all angles. Therefore it is expected that the effective $\tau_{3889}$ will be the same for all lines whose flux intensity increases with increasing $\tau_{3889}$; this effective $\tau_{3889}$ might be different to that derived from $\lambda\lambda\ 3188$ and 3889. For 30 Doradus the helium abundances derived from $\lambda\lambda\ 5876$ and 4471 using the $\tau_{3889}$ obtained from $\lambda\lambda\ 4713$ and 7065 are in excellent agreement with the abundances derived from 5 singlet lines which are not affected by this effect, supporting the suggestion by Peimbert.

8. $\Delta Y/\Delta O$

To determine the $Y_p$ value from a given H II region it is necessary to estimate the fraction of helium present in the interstellar medium produced by galactic chemical evolution. Often $Y_p$ has been obtained from

$$Y_p = Y - O \frac{\Delta Y}{\Delta O},$$

(3)

where all quantities are given by mass. Some of the best $\Delta Y/\Delta O$ values in the literature are presented in Table 1. The second column includes irregular, H II, and blue compact galaxies. The observed value in the third column was derived by comparing the abundances of M17 in the Galaxy (Peimbert, Torres-Peimbert, & Ruiz 1992; Esteban et al. 1999) with the primordial helium abundance (Peimbert et al. 2002; Peimbert 2003). The $\Delta Y/\Delta O$ observational values presented in Table 1 were derived under the assumption of temperature variations along the line of sight; by assuming constant temperature the $\Delta Y/\Delta O$ values become twice as large (Peimbert 2003).

The theoretical values for irregular galaxies presented in Table 1 were derived from closed box models and outflow models of well mixed material. For O-rich outflows the models enter in contradiction with the observed C/O values.
Table 1. $\Delta Y/\Delta O$ Values

| Source                           | Irregulars | The Galaxy |
|----------------------------------|------------|------------|
| Carigi et al. (1995), observations | 4.5 ± 1.0  | ...        |
| Izotov and Thuan (1998), observations | 2.7 ± 1.2  | ...        |
| Peimbert (2003), observations    | 2.93 ± 0.85| 3.57 ± 0.67|
| Carigi et al. (1995), theory     | 2.95       | ...        |
| Chiappini et al. (1997), theory  | ...        | 3.15       |
| Carigi et al. (1999), theory     | 4.2        | ...        |
| Carigi (2000), theory            | ...        | 2.9 - 4.6  |

In Table 1 we present also the predictions for the Galaxy based on infall models by Chiappini et al. (1997), and Carigi (2000); the range in the $\Delta Y/\Delta O$ values derived by Carigi comes from the use of seven different sets of stellar yields present in the literature.

From Table 1 we conclude that, to derive $Y_p$, a $\Delta Y/\Delta O = 3.5 \pm 0.9$ is a good representative value to use in equation (3).

9. Other Problems

The accuracy of the atomic parameters needed to derive the abundances from the He I line intensities seems to be in the 0-3% range. A comparison of the He I recombination coefficients by Benjamin et al. (1999) with those by Bauman, Ferland, & MacAdam (2002) indicate differences up to a few percent for some He I line intensities. Similarly a comparison of the collisional contribution to the helium lines by Benjamin et al. (1999) with those by Porter (2002) indicate differences up to a few percent for some He I line intensities.

The reddening correction can be systematically overestimated if the collisional excitation of the H I lines is not taken into account, introducing an additional correction to the derived He abundances (Luridiana et al. 2003).

Cota & Ferland (1988) have argued that dusty H II regions might show deviations from Case B in the H I lines; this effect, if present, will lower the derived He/H value.

Finally the errors in the derivation of the line intensities have to be considered: calibration of the standard stars, photon statistics, atmospheric extinction, properties of the detector, etc.

10. Discussion and Conclusions

In Table 2 we present our error estimates in the determination of $Y_p$ from a typical set of well observed H II regions. In the second column we present the
Table 2. Error Budget in the $Y_p$ Determination, given in $1/10000$ of the mass fraction.

| Problem                              | Uncorrected | Corrected |
|--------------------------------------|-------------|-----------|
| Underlying Absorption in H\textsc{i} Lines | $-50$       | $\pm 5$   |
| Underlying Absorption in He\textsc{i} Lines | $+70$       | $\pm 7$   |
| He\textsc{i} and H\textsc{i} Line Intensities | ...         | $\pm 2$   |
| Ionization Structure                 | $\pm 12$   | $\pm 5$   |
| Temperature Structure                | $-60$       | $\pm 15$  |
| Density Structure                    | $\pm 45$   | $\pm 10$  |
| Collisional Excitation of the He\textsc{i} Lines | $-90$       | $\pm 7$   |
| Collisional Excitation of the H\textsc{i} Lines | $+50$       | $\pm 20$  |
| Optical Depth of the He\textsc{i} Triplet Lines | $\pm 10$    | $\pm 3$   |
| He\textsc{i} and H\textsc{i} Atomic Parameters | $\pm 30$    | $\pm 15$  |
| $\Delta Y/\Delta O$                  | ...         | $\pm 10$  |

size and sign of the bias on the $Y_p$ determination when the problem is ignored, for some problems we only present the typical size because the sign depends on the specific sample. The third column includes the statistical errors; if the problem is properly taken into account there should be no bias present. It is clear that the errors for a given determination will depend on the included H\textsc{ii} regions. For example if the objects are of relatively low $T_e$ the collisional excitation contribution to the He\textsc{i} and H\textsc{i} lines will be small, and consequently the expected errors due to collisional excitations; on the other hand the error due to the adopted $\Delta Y/\Delta O$ will be relatively large.

Table 3. Primordial Helium Abundance Values

| Source                                | $Y_p$             |
|---------------------------------------|-------------------|
| Izotov et al. (1999), this work       | $0.2452 \pm 0.0015 \pm 0.0070$ |
| Peimbert et al. (2002), this work     | $0.2374 \pm 0.0035 \pm 0.0010$ |
| Prediction (2006), this work          | $0.2??? \pm 0.0020 \pm 0.0005$ |

To derive a very accurate $Y_p$ value it is necessary to minimize the sources of error presented in Table 2. The best objects to determine $Y_p$ should have the following characteristics: a) a high H$\beta$ equivalent width in emission, b) a high degree of ionization, c) a low density to have a low contribution due to collisional
effects, but high enough to be relatively bright, and d) a moderately low O/H value to have a small $\Delta Y$ correction. The metal poorest H II regions might not be the best candidates to derive an accurate $Y_p$ value because due to their high $T_e$ values the corrections due to collisional effects are very large.

In Table 3 we present three values of $Y_p$ together with our estimates of the statistical and systematic errors. The first one is from the work by Izotov et al. (1999), the second one from Peimbert et al. (2002) and Peimbert (2003), and the third one is our prediction for the near future.

Acknowledgments. We are grateful to Evan Skillman and Gary Steigman for several fruitful discussions, and to our colleagues from Granada for such enjoyable meeting.

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Discussion

_Evan Skillman:_

Keith Olive & I have analyses which use the helium line strengths to solve simultaneously for helium abundances, \( \tau_{3889} \), density, underlying absorption, and temperature; we reproduce your result that the appropriate electron temperature is lower than the \([\text{O III}]\) temperature, resulting in lower He abundances.