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Some aspects of the chemical evolution of ^{4}He in the Galaxy: the He/H radial gradient and the $\Delta Y/\Delta Z$ enrichment ratio

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Abstract. Two aspects of the chemical evolution of ^{4}He in the Galaxy are considered on the basis of a sample of disk planetary nebulae by the application of corrections due to the contamination of ^{4}He from the progenitor stars. First, the He/H radial gradient is analyzed, and then, the helium to heavy element enrichment ratio is determined for metallicities up to the solar value.

1. Introduction

The study of radial abundance gradients and of the enrichment ratio between helium and the heavy elements ($\Delta Y/\Delta Z$) can be performed on the basis of photoionized nebulae, comprising HII regions and planetary nebulae (PN, see for example the reviews by Peimbert 1990 and Maciel 1997). The former have the advantage of representing the interstellar composition directly, while for the latter the influence of the contamination from the progenitor stars should be taken into account, particularly for those elements that are dredged up to the outer layers of the progenitor stars, such as helium and nitrogen.

In the case of helium, the contamination from the evolution of the progenitor stars has been recently determined on the basis of different theoretical models (cf. van den Hoek & Groenewegen 1997, Boothroyd & Sackmann 1999), so that it is now possible to apply individual corrections to the observed PN abundances in order to obtain improved values of the He/H radial gradient and of the $\Delta Y/\Delta Z$ ratio. In the present work, these recent calculations are used in order to estimate the He contamination for a sample of disk planetary nebulae recently studied by Maciel & Quireza (1999). The application of corrections to the observed abundances leads to a new determination of the He/H radial gradient $d(\mathrm{He/H})/dR$ and of the slope $\Delta Y/\Delta Z$.

2. The He/H radial gradient and the $\Delta Y/\Delta Z$ ratio

2.1. The He/H radial gradient

The O/H radial gradient is now well known, and can be derived for HII regions, planetary nebulae, hot stars, etc. It amounts roughly to $d\log(\mathrm{O/H})/dR \simeq -0.07$ dex/kpc, and similar values have been obtained for other elements, such as S and Ar (Maciel 1997, Maciel & Quireza 1999). The existence of a He/H

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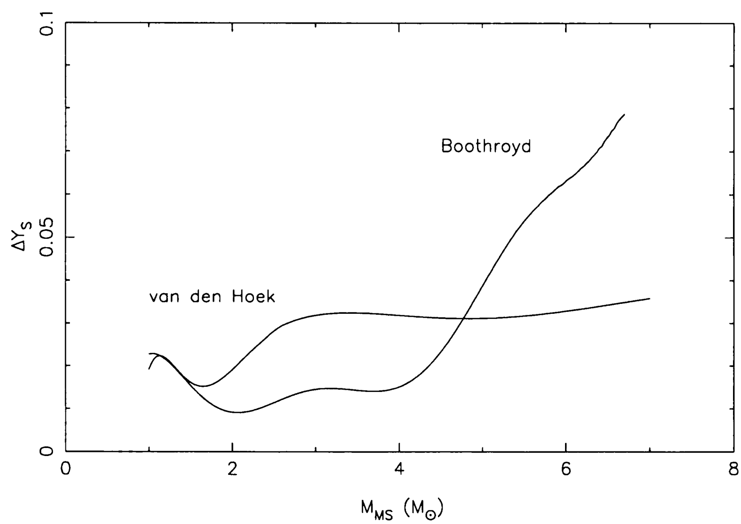

Figure 1. He contamination from PN progenitor stars.

gradient is much more uncertain, and results obtained both from HII regions and planetary nebulae show a very large uncertainty, as seen in Table 1 (see Esteban & Peimbert 1995 for a review).

Table 1. Determinations of the He/H radial gradient

Reference	PN/HII	d(He/H)/dR (kpc^{-1})	$d\log$(He/H)/dR (dex/kpc)
D'Odorico et al. (1976)	PN	−0.007	−0.03
Peimbert & Serrano (1980)	PN	−0.005	−0.02
Shaver et al. (1983)	HII	−0.0003	−0.001
Faúndez-Abans & Maciel (1986)	PN	−0.005	−0.02
Pasquali & Perinotto (1993)	PN	−0.003	−0.009
Amnuel (1993) [min]	PN	−0.0005	−0.002
Amnuel (1993) [max]	PN	−0.006	−0.026
Maciel & Chiappini (1994)	PN	−0.0004	−0.002
Esteban et al. (1999)	HII	−0.001	−0.004

All determinations involving PN until now have *not* taken into account the He contamination by the progenitor stars, so that it is interesting to revise the values of the He/H gradient by considering the amount of He produced and dredged up to the outer layers of the stars and eventually shed into the nebulae.

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2.2. The $\Delta Y/\Delta Z$ enrichment ratio

The helium to metals enrichment ratio $\Delta Y/\Delta Z$ is generally determined adopting a linear variation for the helium abundance by mass with the metallicity Z of the form $Y(Z) = Y_p + (\Delta Y/\Delta Z)\, Z$, where Y_p is the pregalactic helium abundance, as proposed by Peimbert and Torres-Peimbert (1974, 1976). Photoionized nebulae such as HII regions and blue compact galaxies are generally used (cf. Izotov et al. 1997, Thuan & Izotov 1998, Esteban et al. 1999), and recent work has also taken into account the fine structure in the main sequence of nearby stars (Pagel & Portinari 1998). Results are generally in the range $2 \leq \Delta Y/\Delta Z \leq 6$, as shown in Table 2.

Table 2. Determinations of the $\Delta Y/\Delta Z$ ratio

Reference	object	$\Delta Y/\Delta Z$
D'Odorico et al. (1976)	PN	2.95
Peimbert & Serrano (1980)	PN	$2.2 - 3.6$
Maciel (1988)	PN	3.5 ± 0.3
Pagel et al. (1992)	HII	6.1 ± 2.1
Chiappini & Maciel (1994)	PN/HII	$3.4 - 5.6$
Pagel & Portinari (1998)	MS stars	3 ± 2
Thuan & Izotov (1998)	HII	2.3 ± 1.0
Esteban et al. (1999)	HII	$1.9 - 3.9$

Maciel (1988) determined Y_p and $\Delta Y/\Delta Z$ using a sample of type II PN (Peimbert 1978), and assuming that the He contamination from the central star was negligible. Chiappini & Maciel (1994) made a first attempt at including this contamination in a systematic way, and added a term ΔY_s to the $Y(Z)$ relation, which can be written as

$$Y = Y_p + \frac{\Delta Y}{\Delta Z}\, Z + \Delta Y_s\ . \tag{1}$$

The stellar contribution ΔY_s was obtained on the basis of some calculations by Boothroyd (private communication). The adopted values were $\Delta Y_s = 0.0$, 0.008, 0.015 and 0.022, which were applied to all nebulae in the sample, so that any differences in their *individual* behaviour were lost.

3. He contamination from the PN progenitor stars

The He excess by mass ΔY_s can be estimated from the yields of the intermediate mass stars as a function of the stellar mass on the main sequence M_{MS} and total metallicity Z, adopting $Z = 0.020$, which is appropriate for type II PN. The stellar mass on the main sequence can be obtained by an initial mass-final mass relation as a function of the PN core mass M_c, which can in principle be determined from the observed nebular abundances, particularly the N/O ratio.

In this work, we have adopted the recent yields by van den Hoek & Groenewegen (1997), using as comparison the calculations by Boothroyd & Sackmann

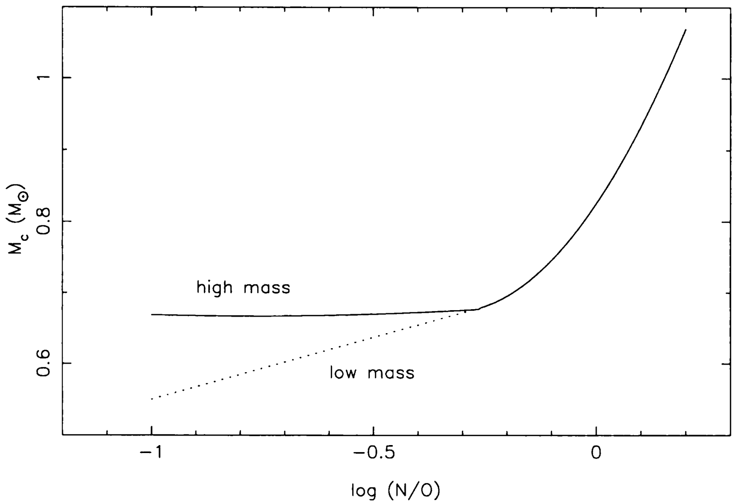

Figure 2. The adopted $M_c\times$ N/O calibrations.

(1999). The former includes all three dredge up processes that occur in the late stages of the intermediate mass stars, and generally produce larger yields than the latter, as can be seen in Figure 1. We have assumed that most of the He excess that are dredged up to the surface is mixed up in the outer layers and ejected into the nebulae, so that our derived ΔY_s is the largest possible correction for a given mass.

In view of the uncertainties on the PN central star masses, we have adopted two different calibrations, referred to as *high mass* and *low mass* calibrations, respectively. For the *high mass calibration*, we adopted the $M_c \times$ N/O relation recently proposed by Cazetta & Maciel (2000),

$$M_c = a + b\ \log(\mathrm{N/O}) + c\ [\log(\mathrm{N/O})]^2 \tag{2}$$

where $a = 0.689$, $b = 0.056$ and $c = 0.036$ for $-1.2 \leq \log(\mathrm{N/O}) \leq -0.26$ and $a = 0.825$, $b = 0.936$ and $c = 1.439$ for $\log(\mathrm{N/O}) > -0.26$. The average initial mass-final mass relation was taken from the gravity distance work of Maciel & Cazetta (1997), and can be written as

$$M_c = a_0 + a_1\ M_{MS} + a_2\ M_{MS}^2 + a_3\ M_{MS}^3 + a_4\ M_{MS}^4 \tag{3}$$

where $a_0 = 0.5426$, $a_1 = 0.02093$, $a_2 = -0.01122$, $a_3 = 0.00447$ and $a_4 = -0.0003119$. This calibration leads to core masses $M_c \geq 0.67 M_\odot$ and main sequence masses $M_{MS} \geq 3\, M_\odot$, showing a good agreement with the results from NLTE model atmospheres of Méndez et al. (1988, 1992).

For the *low-mass calibration* we can still use equation 2, replacing the coefficients by $a = 0.7242$, $b = 0.1742$ and $c = 0$ for $\log(\mathrm{N/O}) \leq -0.26$. For the initial mass–final mass relation we have the coefficients $a_0 = 0.4877$, $a_1 = 0.0623$, $a_2 = a_3 = a_4 = 0$. This calibration produces masses in the ranges $M_c \geq 0.55\, M_\odot$ and $M_{MS} \geq 1 M_\odot$, which agree with the recent determinations of PN central

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star masses of Stasińska et al. (1997) and with the masses of type II PN originally proposed by Peimbert (1978). Both $M_c\times$ N/O calibrations are shown in figure 2, and the initial mass-final mass relation for the high-mass calibration can be seen in the figure 1 of Maciel & Cazetta (1997).

4. Results and discussion

We have applied the corrections outlined in the previous section to a sample of disk planetary nebulae in order to derive the He/H radial gradient and the $\Delta Y/\Delta Z$ enrichment ratio. For details on the objects and abundances, the reader is referred to Maciel & Quireza (1999) and Maciel (2000).

4.1. The He/H radial gradient

The average He/H abundances by number of atoms are shown in Table 3, using the van den Hoek & Groenewegen (1997) and Boothroyd & Sackmann (1999) data, both for the high- and low-mass calibrations.

Table 3. The He/H average abundances

	He/H
Uncorrected abundances	0.106 ± 0.003
Boothroyd, low mass calibration	0.100 ± 0.003
Boothroyd, high mass calibration	0.100 ± 0.003
van den Hoek, low mass calibration	0.094 ± 0.003
van den Hoek, high mass calibration	0.091 ± 0.003

The derived gradients are negligible, and can be written as $d(\mathrm{He/H})/dR = 0.0000 \pm 0.0004$, irrespective of the calibration used, as shown for example in Figure 3 for the van den Hoek & Groenewegen (1997) data with the low mass calibration. We have adopted $R_0 = 7.6$ kpc as in Maciel & Quireza (1999).

It can be seen that the correction procedure simply reduces the average He/H abundances, so that stars with different masses are probably scattered homogeneously in the whole range of galactocentric distances, thus destroying any systematic variations. In view of the uncertainties involved in the abundances (and distances), it is unlikely that any He/H radial gradient could be presently detected from planetary nebulae, and previous determinations were probably affected by the use of small samples.

On the other hand, an upper limit to the He/H gradient can be derived on the basis of the total dispersion σ_d observed. Taking $\sigma_d \simeq 0.04$, we have $|d(\mathrm{He/H})/dR| < \sigma_d/\Delta R \simeq 0.004$ kpc^{-1}, or $d\log(\mathrm{He/H})/dR \simeq -0.02$ dex/kpc. Therefore, any existing He/H radial gradient should be lower than the O/H gradient by at least a factor of 3. This conclusion is in agreement with the small gradients derived for galactic HII regions by Esteban et al. (1999) and with some recent chemical evolution models for the Galaxy (Chiappini et al. 1997, Chiappini, this conference).

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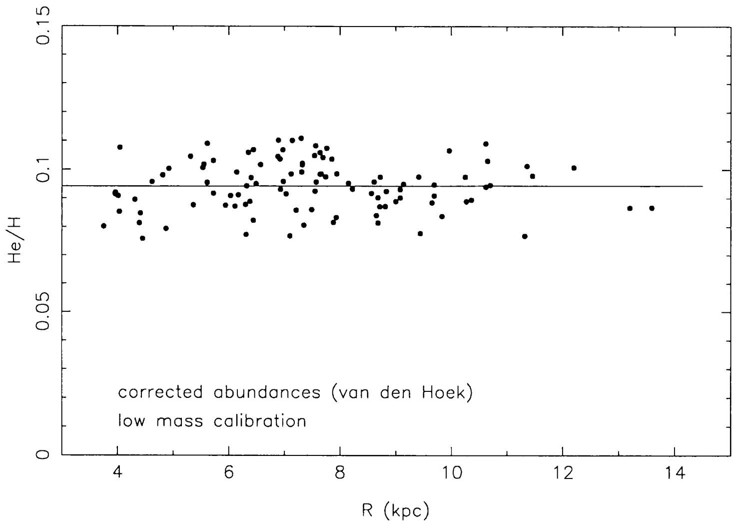

Figure 3. He/H abundances as a function of the galactocentric distance for the van den Hoek and Groenewegen (1997) data with the low mass calibration.

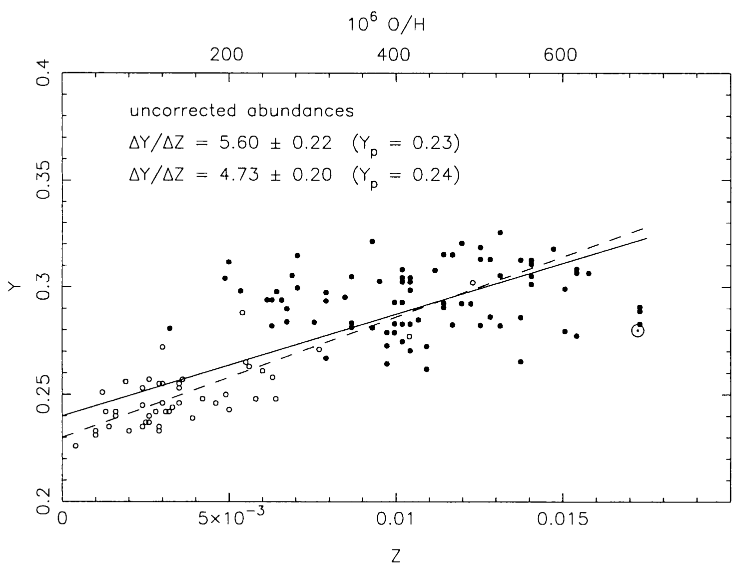

Figure 4. Uncorrected He abundances by mass Y for PN (solid circles) as a function of O/H (top axis) and Z (bottom axis). Also shown are the Sun ($\odot$) and HII regions (empty circles). The straight lines are least squares fits for $Y_p = 0.23$ (dashed line) and $Y_p = 0.24$ (solid line).

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4.2. The $\Delta Y/\Delta Z$ enrichment ratio

In order to apply the correction procedure to the PN sample, we have considered the O/H abundances as representative of the total metallicity, adopting $Z \simeq 25$ O/H (Peimbert 1990, Chiappini & Maciel 1994). Since the pregalactic abundance can be better determined on the basis of very low metallicity objects, we have taken Y_p as a parameter, with the values $Y_p = 0.23$ and $Y_p = 0.24$ (see for example Olive et al. 1999, Izotov et al. 1999, Steigman, this conference).

We have taken into account all PN in our sample having metal abundances up to 10^6 O/H $\simeq 700$, which corresponds approximately to the solar value, $\epsilon(\mathrm{O}) = \log(\mathrm{O/H}) + 12 = 8.83$ (Grevesse & Sauval 1998), or $Z \simeq 0.017$. As pointed out by Chiappini & Maciel (1994), He abundances of PN show some tendency to flatten out for very large Z, where a more sophisticated relation than eq. (1) would be needed. Moreover, some large metallicity PN have larger than average N/O ratios, so that the corrections to the He abundance are also larger and more uncertain.

The main results are shown in Table 4 and in figures 4 and 5, where the PN are shown as filled circles. Figure 4 shows the uncorrected abundances and fits, and figure 5 shows the results using the corrections according to the van den Hoek and Groenewegen data both for the high- and low-mass calibrations. In both figures, the straight lines are least squares fits using $Y_p = 0.23$ (dashed lines) and $Y_p = 0.24$ (solid lines).

Table 4. The $\Delta Y/\Delta Z$ ratio

	$\Delta Y/\Delta Z$
$Y_p = 0.23$	
uncorrected	5.60 ± 0.22
Boothroyd low mass	4.42 ± 0.20
Boothroyd high mass	3.95 ± 0.19
van den Hoek low mass	3.59 ± 0.19
van den Hoek high mass	2.87 ± 0.17
$Y_p = 0.24$	
uncorrected	4.73 ± 0.20
Boothroyd low mass	3.55 ± 0.19
Boothroyd high mass	3.08 ± 0.17
van den Hoek low mass	2.73 ± 0.17
van den Hoek high mass	2.01 ± 0.16

For comparison purposes, figures 4 and 5 also include the Sun ($\odot$) and the HII regions and metal poor blue compact galaxies (empty circles) from the compilation of Chiappini & Maciel (1994). These objects have *not* been taken into account in the determination of the linear fits, and are included for comparison only.

It can be seen that the scatter in the PN data is somewhat higher, which is partially due to the higher uncertainties in the abundances and also to the

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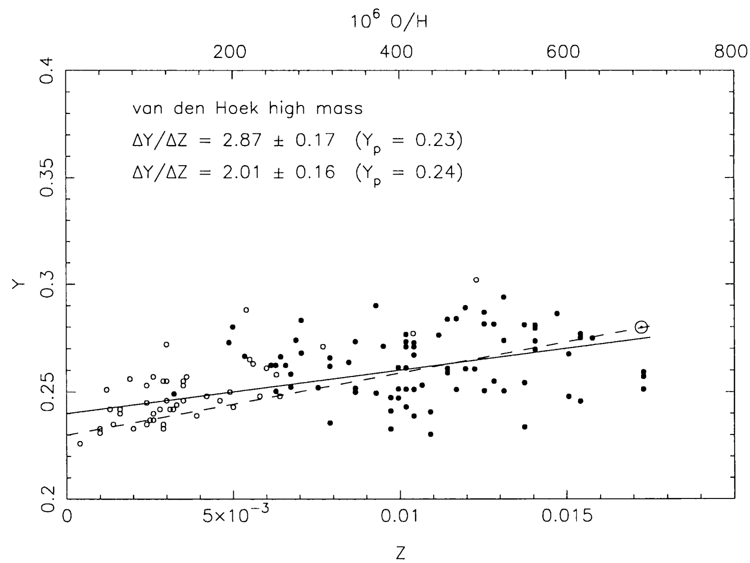

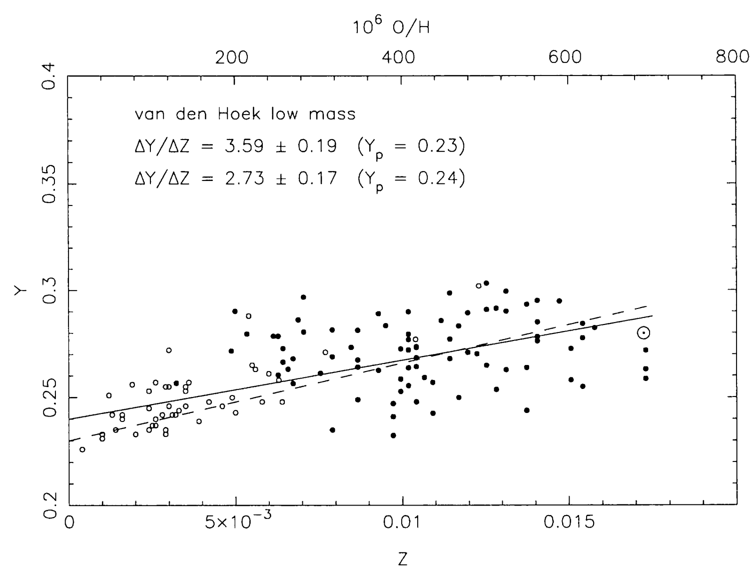

Figure 5. The same as figure 4 using corrected abundances according to the van den Hoek & Groenewegen (1997) data for the high mass calibration (top panel) and low mass calibration (bottom panel).

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adopted correction procedure, so that future improvements along these lines would be desirable. The higher uncertainties in the PN abundances and the lower He/H gradient are probably responsible for the lack of a He/H $\times$ R correlation, while some correlation between Y and Z (or O/H) can be observed.

The application of the correction procedure reduces the average He abundances and the $\Delta Y/\Delta Z$ ratio, and also decreases the uncertainty of the derived slopes. The $\Delta Y/\Delta Z$ ratio decreases from the range 4.7 – 5.6 to values in the range 2.8 – 3.6 for $Y_p = 0.23$ and 2.0 – 2.8 for $Y_p = 0.24$. These results are closer to recent independently derived ratios, as seen in Table 2 (see also Thuan, this conference), and to the predictions of theoretical models (Allen et al. 1998, Chiappini et al. 1997), particularly for the high mass calibration using the van den Hoek & Groenewegen (1997) data.

The average uncertainties in the derived slopes are smaller as a consequence of the fact that a large number of objects has been included, with a larger metallicity spread. An average including both calibrations would give $\Delta Y/\Delta Z = 3.2 \pm 0.5$ for $Y_p = 0.23$ and $\Delta Y/\Delta Z = 2.4 \pm 0.5$ for $Y_p = 0.24$, which can be compared with the uncertainties shown in Table 2.

Finally, the apparent continuity between the low metallicity and high metallicity objects of figure 5 suggests that their chemical evolution may not have been very different. In fact, the chemical evolution of a system is basically defined by its initial mass function (IMF) and star formation history (SFH). The IMF is now believed to be universal (Maciel & Rocha-Pinto 1998, Padoan et al. 1997). Blue compact galaxies have bursts of star formation, a feature that has been recently reinforced in our own Galaxy, as shown by Rocha-Pinto et al. (2000) on the basis of chromospheric ages. Therefore, the similarity in the chemical evolution of the different systems shown in figure 5 is probably not surprising.

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