

# HELIUM CONTAMINATION FROM THE PROGENITOR STARS OF PLANETARY NEBULAE: THE HE/H RADIAL GRADIENT AND THE $\Delta Y/\Delta Z$ ENRICHMENT RATIO

W.J. MACIEL

*Instituto Astronômico e Geofísico, Universidade de São Paulo, Brazil*  
*E-mail: maciel@iagusp.usp.br*

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**Abstract.** In this work, two aspects of the chemical evolution of  $^4\text{He}$  in the Galaxy are considered on the basis of a sample of disk planetary nebulae (PN). First, an application of corrections owing to the contamination of  $^4\text{He}$  from the evolution of the progenitor stars shows that the He/H abundance by number of atoms is reduced by 0.012 to 0.015 in average, leading to an essentially flat He/H radial distribution. Second, a determination of the helium to heavy element enrichment ratio using the same corrections leads to values in the range  $2.8 < \Delta Y/\Delta Z < 3.6$  for  $Y_p = 0.23$  and  $2.0 < \Delta Y/\Delta Z < 2.8$  for  $Y_p = 0.24$ , in good agreement with recent independent determinations and theoretical models.

## 1. Introduction

The chemical evolution of  $^4\text{He}$  in the Galaxy can be studied on the basis of abundance determinations in photoionized nebulae, namely HII regions and planetary nebulae (Peimbert, 1990, 1995; Pagel, 1989, 1995). Also, recent work on HII regions in blue compact galaxies has given many informations on this problem, especially regarding the pregalactic helium abundance  $Y_p$  (Pagel, 1995; Peimbert, 1995). Recent determinations of this quantity are usually in the range  $Y_p = 0.23$  to 0.24, and in fact most discussions now concentrate on the third decimal place (Olive *et al.*, 2000; Burles *et al.*, 1999; Izotov *et al.*, 1999). On the other hand, some aspects of the chemical evolution of  $^4\text{He}$  have much greater uncertainties, particularly the question of the He/H radial gradient,  $d(\text{He}/\text{H})/dR$ , and the helium to metals enrichment ratio,  $\Delta Y/\Delta Z$ .

Planetary nebulae (PN) are also interesting in the study of these problems, since their He/H abundances are relatively well measured, with estimated uncertainties better than 20%, and large samples are available, spanning a large metallicity range. However, as the offspring of intermediate mass stars, these nebulae can have chemical compositions that are different from the original interstellar abundances. Therefore, in order to study the evolution of elements such as  $^4\text{He}$  on the basis of these objects, it is necessary to take into account the He contamination by the PN progenitor stars. Previous work on these questions has introduced this contamination in an approximate way (Chiappini and Maciel, 1994) or not at all (Maciel,



1988; Maciel and Chiappini, 1994). In the past few years, however, detailed determinations have been published of the He yields and the amount of this element produced during the dredge-up episodes that occur during the late evolution of intermediate mass stars, both as a function of the stellar mass and metallicity.

In the present work, we make use of these calculations in order to estimate the  $^4\text{He}$  contamination for a sample of disk planetary nebulae. Taking into account some relationships involving the nebular abundances, the central star mass and the stellar mass on the main sequence, such contamination can be *individually* determined. As a consequence, the analysis of the He/H radial gradient and of the enrichment ratio can be performed on more solid grounds. In Section 2 the question of the abundance gradients is considered, and in Section 3 the  $\Delta Y/\Delta Z$  ratio is discussed. In Section 4 a simple model to account for the contamination of the progenitor stars is proposed, and the results are presented and discussed in Section 5.

## 2. Radial Abundance Gradients

Radial abundance gradients of element ratios such as O/H and S/H are well known, and amount to  $d \log(\text{O}/\text{H})/dR \simeq -0.07 \text{ dex/kpc}$  (Maciel, 1997, 2000). These gradients can be derived from a variety of objects, comprising HII regions, planetary nebulae, B stars, etc. The study of these gradients includes a determination of their average magnitude, the existence of spatial variations along the disk and the time variation of the gradients, as the objects mentioned have different ages, spanning a few Gyr. Several mechanisms have been proposed to account for the gradients, and the reader is referred to Matteucci and Chiappini (1999) for a recent review on this topic.

The existence of a He/H gradient is much more uncertain. Shaver *et al.* (1983) obtained a zero gradient for the ratio  $\text{He}^+/\text{H}^+$  from radio and optical measurements in galactic HII regions, and suggested a small gradient,  $d \log(\text{He}/\text{H})/dR = -0.001 \text{ dex/kpc}$ . Their derived dispersion was  $\sigma_d \simeq 0.08$ , higher than the estimated observational uncertainty,  $\sigma_{obs} \simeq 0.01$  to  $0.02$ . Earlier work suggested a negative gradient,  $d(\text{He}/\text{H})/dR \simeq -0.005$  to  $-0.008 \text{ kpc}^{-1}$ , corresponding approximately to  $d \log(\text{He}/\text{H})/dR \simeq -0.02$  to  $-0.03 \text{ dex/kpc}$  (D'Odorico *et al.*, 1976; Peimbert and Serrano, 1980).

Faúndez-Abans and Maciel (1986) obtained an average gradient of  $d(\text{He}/\text{H})/dR \simeq -0.005 \text{ kpc}^{-1}$  or  $d \log(\text{He}/\text{H})/dR \simeq -0.02 \text{ dex/kpc}$  for a sample of galactic PN. Pasquali and Perinotto (1993) obtained negligible gradients,  $d(\text{He}/\text{H})/dR \simeq -0.001 \text{ kpc}^{-1}$  for a sample of disk PN, reaching a maximum value  $d(\text{He}/\text{H})/dR \simeq -0.004 \text{ kpc}^{-1}$  only if objects close to the galactic disk ( $z \simeq 0$ ) were included, but in this case the galactocentric distance variation was small and the result was uncertain. Considering PN of types I and II (Peimbert, 1978) with distances from the galactic plane  $z < 300 \text{ pc}$ , they obtained a gradient  $d(\text{He}/\text{H})/dR \simeq$

$-0.003 \text{ kpc}^{-1}$ , corresponding approximately to  $d(\log \text{He}/\text{H})/dR \simeq -0.009 \text{ dex/kpc}$ . Amnuel (1993) obtained gradients generally in the range  $d \log(\text{He}/\text{H})/dR \simeq -0.002$  to  $-0.026 \text{ dex/kpc}$  for the different classes of his adopted classification system. A discussion of these results has been given by Esteban and Peimbert (1995). Maciel and Chiappini (1994) also obtained very small gradients,  $d(\text{He}/\text{H})/dR \simeq -0.0004 \pm 0.0006 \text{ kpc}^{-1}$  for a sample of type II PN with known distances. Recently, Esteban *et al.* (1999) derived a very small gradient,  $d \log(\text{He}/\text{H})/dR \simeq -0.004 \pm 0.005 \text{ dex/kpc}$ , corresponding to  $d(\text{He}/\text{H})/dR \simeq -0.001 \text{ kpc}^{-1}$  based on He recombination lines of three HII regions (M8, M17 and Orion). This result is apparently independent of temperature fluctuations in the nebulae.

All these determinations involving PN until now have *not* taken into account the He contamination by the progenitor stars during their evolution. It is well known that main sequence stars in the mass interval  $1 \leq M/M_{\odot} \leq 8$  have an important contribution to the He production, especially during the first and second dredge-up episodes (cf. Peimbert, 1990). Therefore, a realistic determination of the He/H gradient from planetary nebulae should take into account the He production of their progenitor stars.

### 3. The Helium to Metals Enrichment Ratio

The helium to metals enrichment ratio is an important parameter in the study of the chemical evolution of the Galaxy, and is usually determined from photoionized nebulae such as HII regions and HII galaxies (Lequeux *et al.*, 1979; Peimbert, 1990, 1995; Pagel *et al.*, 1992; Izotov *et al.*, 1997; Thuan and Izotov, 1998; Esteban *et al.*, 1999). Recent work has also taken into account the fine structure in the main sequence of nearby stars (Pagel and Portinari, 1998; Høgg *et al.*, 1998) and Hipparcos parallaxes for open clusters have been used to stress local variations of this ratio (Efremov *et al.*, 1997). Results obtained from these methods are in the range  $2 \leq \Delta Y/\Delta Z \leq 6$ , and lower values are generally in better agreement with theoretical calculations.

Planetary nebulae can also be used to determine the  $\Delta Y/\Delta Z$  ratio, and earlier determinations of this quantity include D'Odorico *et al.* (1976) and Peimbert and Serrano (1980), with results in the range  $2.2 < \Delta Y/\Delta Z < 3.6$ .

Maciel (1988) determined the pregalactic abundance and the helium to metals enrichment ratio using a sample of type II PN, assuming that the He contamination from the central star was negligible, with the result  $\Delta Y/\Delta Z \simeq 3.5 \pm 0.3$ . Chiappini and Maciel (1994) made a first attempt to take into account the contamination from the PN progenitor stars. For these objects, the observed He abundances by mass  $Y$  can be written as

$$Y = Y_p + \frac{\Delta Y}{\Delta Z} Z + \Delta Y_s \quad (1)$$

(Peimbert and Torres-Peimbert, 1974, 1976), where  $Y_p$  is the pregalactic abundance,  $Z$  is the heavy element abundance by mass and  $\Delta Y_s$  is the contamination from the progenitor star. In the work of Chiappini and Maciel (1994), the contamination  $\Delta Y_s$  was included as a free parameter based on 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. From direct  $Y(Z)$  correlations, the derived ratio was in the range  $3.4 \leq \Delta Y/\Delta Z \leq 5.6$  [see Table 3 of Chiappini and Maciel (1994)]. The results by Chiappini and Maciel (1994) were based on *average* corrections, applied to all nebulae, so that any differences in the individual behaviour of the nebulae were lost. Since there is now some information on the masses of the PN central stars and the corresponding masses on the main sequence, it is interesting to revise these results in order to account for the contamination of the progenitor stars *individually*.

#### 4. He Production in Intermediate Mass Stars

Since the pioneering work of Renzini and Voli (1981), several investigators have presented detailed calculations of yields of the different elements in intermediate mass stars, based on recent evolutionary models (see for example Maeder, 1992; van den Hoek and Groenewegen, 1997; Boothroyd and Sackmann, 1999; Marigo, 2000). Regarding He abundances, these models take into account the dredge-up episodes that occur in intermediate mass stars, particularly the first and second processes. In this work, we have adopted the recent yields by van den Hoek and Groenewegen (1997) for stars with masses in the range  $0.9$  to  $7 M_\odot$  on the main sequence. Their results include all dredge up episodes and are based on evolutionary tracks of the Geneva group up to the AGB branch, coupled with a synthetic AGB model with hot bottom burning. The yields depend on the stellar mass and metallicity, and the standard model takes as parameters the mass loss scaling parameter,  $\eta_{AGB} = 4$ , the minimum core mass for dredge up,  $M_c^{min} = 0.58$  and the third dredge up efficiency,  $\lambda = 0.75$  (see van den Hoek and Groenewegen, 1997 for a detailed discussion).

As a comparison with the van den Hoek and Groenewegen (1997) data, we have used the computations by Boothroyd (private communication, see also Boothroyd and Sackmann, 1999; Sackmann and Boothroyd, 1999) based on earlier theoretical models by Boothroyd and Sackmann (1988). These computations are restricted to the first and second dredge up processes, and show some decrease in the He contamination for masses roughly between one and three solar masses. As a consequence, they produce smaller corrections for stellar masses under  $4 M_\odot$  than the previous set, so that they are used for comparison purposes.

The He excess by mass  $\Delta Y_s$  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  $Z$ . We have considered here  $Z = 0.020$ , which is appropriate for type

II PN in the galactic disk, but different metallicities do not significantly change our results. In this work, we made the simplifying assumption that most of the He excess produced by the progenitor stars and dredged up to the surface is mixed up in the outer layers and ejected into the nebulae. Therefore, the determination of the corrections is straightforward, and our derived contamination  $\Delta Y_s$  corresponds to the largest possible correction for a given mass.

In order to obtain the main sequence mass of the PN progenitor stars, we have adopted a two step procedure. First, we obtained the central star mass  $M_c$  from the observed N/O nebular abundance, and then we have used an initial mass-final mass relation for intermediate mass stars in order to derive  $M_{MS}$ .

The existence of a relationship between the PN core mass and the N/O abundance has been discussed by a number of people, often with conflicting results (see Cazetta and Maciel, 2000 for some references). Until recently, theoretical models were unable to predict some measurable increase in the N/O and He/H ratios for PN with relatively massive progenitors, a situation that has changed with the extension of the models up to 7 solar masses on the main sequence with overshooting (Marigo, 2000) or by the inclusion of hot bottom burning (van den Hoek and Groenewegen, 1997). A calibrated relation has been recently proposed by Cazetta and Maciel (2000) as

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

where  $M_c$  is in solar masses and N/O is the abundance of nitrogen relative to oxygen by number of atoms. We have adopted  $a = 0.689$ ,  $b = 0.056$  and  $c = 0.036$  for  $-1.2 \leq \log(\text{N/O}) \leq -0.26$  and  $a = 0.825$ ,  $b = 0.936$  and  $c = 1.439$  for  $\log(\text{N/O}) > -0.26$ . This relation is valid in the approximate interval  $-1 < \log(\text{N/O}) < 0.2$ , and has been calibrated using synthetic models for AGB stars by Groenewegen and de Jong (1993) and Groenewegen *et al.*, (1995), and NLTE model atmospheres by Méndez *et al.* (1988, 1992). Since the derived core masses are relatively large,  $M_c \geq 0.67 M_\odot$ , leading to relatively large main sequence masses, we will refer to this calibration as *high-mass calibration*.

Alternatively, we have adopted a different calibration which leads to core masses and main sequence masses lower than the values quoted above. In fact, recent work on the mass distribution of PN central stars (Stasińska *et al.*, 1997; Stasińska and Tylenda, 1990) based on self-consistent and distance independent methods, suggest that more than 80% of the PN central stars have masses in the range  $M_c \simeq 0.55$  to  $0.65 M_\odot$ . These results are also in agreement with core masses derived by Zhang (1993) and with the mass-N/O abundance relation by Marigo *et al.* (1996). This calibration can be written as

$$M_c = 0.7242 + 0.1742 \log(\text{N/O}) \quad (3)$$

and replaces Equation 2 for  $\log(\text{N/O}) \leq -0.26$ . Since this calibration produces lower core masses,  $M_c \geq 0.55 M_\odot$  and lower main sequence masses than the first calibration, we will refer to it as *low-mass calibration*.

The average initial mass-final mass relation for the *high-mass calibration* was taken from the gravity distance work of Maciel and Cazetta (1997), and can be written as

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

where  $a_0 = 0.5426$ ,  $a_1 = 0.02093$ ,  $a_2 = -0.01122$ ,  $a_3 = 0.00447$  and  $a_4 = -0.0003119$  (see Figure 1 of Maciel and Cazetta, 1997). This relation was based on models by Schönberner (1983), Blöcker and Schönberner (1990), Groenewegen and de Jong (1993) and Weidemann and Koester (1983), and can be used in the whole range of intermediate star masses, namely  $0.8 < M_{MS}/M_\odot < 7$ . For details the reader is referred to Maciel and Cazetta (1997). Used in conjunction with Equation 2, this equation favours relatively large main sequence masses,  $M_{MS} \geq 3 M_\odot$ , in agreement with the NLTE model atmospheres of Méndez *et al.* (1988, 1992).

For the *low-mass calibration*, we have adopted the following initial mass-final mass relation

$$M_c = 0.4877 + 0.0623 M_{MS} \quad (5)$$

which favours lower masses,  $M_{MS} \geq 1 M_\odot$ . This relation is in better agreement with the corresponding relation of Groenewegen and de Jong (1993) for  $M_{MS} < 3 M_\odot$  and with the relations by Schönberner (1983) and Blöcker and Schönberner (1990) for higher masses. It also produces main sequence masses closer to the values originally proposed for type II PN by Peimbert (1978).

## 5. Results and Discussion

### 5.1. THE HE/H RADIAL GRADIENT

We have applied the procedure outlined in Section 4 to a sample of disk planetary nebulae used by Maciel and Quireza (1999) to study radial abundance gradients of O/H, Ne/H, S/H and Ar/H. This sample includes basically the objects of Maciel and Köppen (1994), Maciel and Chiappini (1994), Costa *et al.* (1996, 1997) and a few objects not included in the previous samples. The set of abundances adopted by Maciel and Quireza (1999) is not a homogeneous one, in the sense that they have been derived by different groups using different computational procedures, such as icf's or a different treatment of the collisional excitation of He lines. However, as previously discussed by Maciel and Quireza (1999) and Maciel and Köppen (1994), the final sample includes only the best determined abundances, for which at least two recent measurements are available, so that the adopted abundances have uncertainties as low as possible. A few objects are low excitation nebulae, which may have some contribution of neutral He, but this paper concerns basically with high excitation objects, which are located at least at 4 kpc from the galactic centre. Furthermore, we have preferentially selected objects studied by our own

group, to keep the inhomogeneity of the sample at a minimum level. For details on the observational and reduction procedures by the IAG/USP group the reader is referred to Costa *et al.* (1996, 1997) and references therein.

The initial sample contained 130 PN. We have removed 11 objects without reliable He/H or N/O abundances and 16 PN with very high N/O values, thus partially avoiding the effects of temperature fluctuations (cf. Peimbert, 1995; Gruenwald and Viegas, 1998) and also the large and uncertain corrections needed for these objects. In fact, Gruenwald and Viegas (1998) have presented some empirical evidence that the higher stellar temperatures characteristic of Type I PN are associated with higher helium and nitrogen abundances, increasing the effects of temperature fluctuations. Distances and abundances with sources are given by Maciel and Quireza (1999). The final sample contains 103 PN and is shown in Tables I to III, which include (i) the common name of the nebula, (ii) the galactocentric distance (kpc) adopting  $R_0 = 7.6$  kpc as in Maciel and Quireza (1999, see also Maciel, 1993), (iii) to (v) the observed abundances of He, N and O, given as He/H,  $\log(N/O)$  and  $\epsilon(O) = \log(O/H)+12$ , and (vi) the references for the abundances, which are listed after the tables.

The uncorrected He/H abundances are shown in Figure 1 (top panel) as a function of the galactocentric distance  $R$ . The straight line shows a least squares linear fit. It can be seen that no gradient is present, and that the average abundance is  $\text{He/H} \simeq 0.106 \pm 0.003$ .

The introduction of the correction procedure described in Section 4 does not affect these results appreciably. As an example, Figure 1 (bottom panel) shows the results for the van den Hoek and Groenewegen (1997) correction using the low mass calibration. Note that Figure 1 gives the He/H abundances by number of atoms, as usual, so that the contamination  $\Delta Y_s$  has to be converted into the equivalent quantity by number  $\Delta(\text{He/H})$ . The different calibrations lead to similarly negligible gradients, which can be written as

$$\frac{d(\text{He/H})}{dR} = 0.0000 \pm 0.0004 . \quad (6)$$

In fact, the main effect of the corrections is to *reduce* the average He/H abundances: the van den Hoek and Gronewegen (1997) corrections lead to  $\text{He/H} \simeq 0.091 \pm 0.003$  (high mass calibration) and  $\text{He/H} \simeq 0.094 \pm 0.003$  (low mass calibration). Use of the Boothroyd and Sackmann (1999) data produces larger average abundances by roughly 0.006, as the corrections are generally smaller. Since the He contamination is a function of the stellar mass, apparently central stars with different masses are scattered homogeneously in the whole range of galactocentric distances, thus destroying any systematic variations. It can be concluded that, *in view of the uncertainties involved both in the abundances and distances, it is unlikely that any He/H radial gradient could be presently detected from planetary nebulae*. The fact that some previous determinations led to a small gradient is probably due to the use of small samples, as in the case of the 39 PN by

TABLE I  
Input data for PN

name	$R$	He/H	$\log(N/O)$	$\epsilon(O)$	Ref.
NGC 1535	8.71	0.096	-1.07	8.61	1
NGC 2022	9.69	0.107	-0.53	8.41	1
NGC 2371	9.00	0.101	-0.52	8.63	1
NGC 2392	9.44	0.092	-0.12	8.50	1
NGC 2438	8.61	0.104	-0.69	8.84	1
NGC 2452	9.14	0.111	-0.15	8.61	6
NGC 2792	7.94	0.115	-0.20	8.75	1
NGC 2867	7.54	0.116	-0.60	8.71	1
NGC 3132	7.64	0.121	-0.46	8.95	1,2
NGC 3195	6.89	0.124	-0.52	8.90	1
NGC 3211	7.30	0.119	-0.77	8.70	1
NGC 3242	7.74	0.105	-0.75	8.66	1
NGC 3587	7.93	0.098	-0.30	8.59	1
NGC 3918	6.98	0.109	-0.50	8.78	1
NGC 5307	6.30	0.095	-0.74	8.64	1
NGC 5882	6.32	0.105	-0.59	8.69	1
NGC 6210	6.88	0.116	-0.97	8.70	1
NGC 6309	5.61	0.118	-0.84	8.91	1
NGC 6439	3.96	0.107	-0.37	8.88	1
NGC 6543	7.69	0.112	-0.78	8.72	1
NGC 6563	5.72	0.120	-0.23	8.57	1
NGC 6565	6.11	0.101	-0.44	8.91	1
NGC 6567	6.14	0.107	-0.72	8.50	1
NGC 6572	6.97	0.119	-0.57	8.77	1
NGC 6578	5.55	0.110	-0.71	8.75	1
NGC 6629	6.03	0.100	-0.88	8.61	1
NGC 6720	7.32	0.114	-0.55	8.79	1
NGC 6790	6.49	0.105	-0.62	8.60	1
NGC 6818	6.35	0.116	-0.64	8.74	1
NGC 6826	7.55	0.103	-0.93	8.43	1
NGC 6879	6.40	0.105	-0.72	8.61	1
NGC 6884	7.56	0.117	-0.70	8.66	1
NGC 6886	6.92	0.120	-0.35	8.68	1
NGC 6891	6.57	0.113	-0.97	8.65	1
NGC 6894	7.21	0.100	-0.40	8.60	1
NGC 6905	6.93	0.104	-0.58	8.66	1
NGC 7009	7.03	0.101	-0.63	8.84	1
NGC 7026	7.64	0.113	-0.45	8.79	1



TABLE I  
(continued)

name	$R$	He/H	$\log(N/O)$	$\epsilon(O)$	Ref.
NGC 7027	7.57	0.111	-0.37	8.62	1
NGC 7354	7.88	0.095	-0.43	8.92	5
NGC 7662	7.85	0.113	-0.66	8.61	1
IC 351	10.36	0.100	-0.95	8.48	1
IC 418	8.83	0.100	-0.72	8.54	1
IC 1297	4.81	0.112	-0.47	8.89	1
IC 1747	9.41	0.112	-0.45	8.75	1

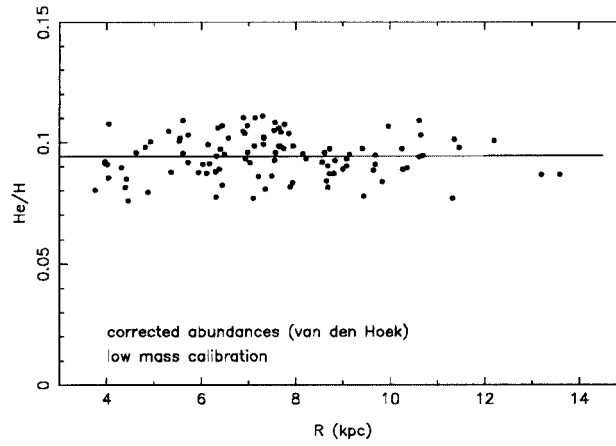
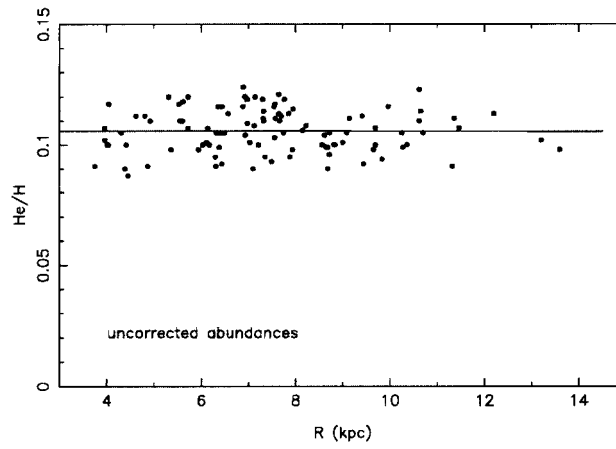


Figure 1. Top panel: uncorrected He/H abundances as a function of the galactocentric distance and least squares linear fit. Bottom panel: The same using corrections for the low mass calibration.

TABLE II  
Input data for PN (continued)

name	$R$	He/H	$\log(N/O)$	$\epsilon(O)$	Ref.
IC 2003	9.83	0.094	-0.58	8.62	1
IC 2149	8.65	0.099	-0.24	8.54	1
IC 2165	9.08	0.105	-0.37	8.42	1
IC 2448	7.35	0.095	-0.31	8.59	1
IC 2501	7.49	0.093	-0.77	8.92	1
IC 2621	7.10	0.090	-0.42	8.90	1
IC 3568	8.68	0.099	-0.87	8.57	1
IC 4406	6.44	0.116	-0.85	8.75	2,4,7
IC 4776	4.39	0.090	-1.08	8.86	1
IC 5117	7.66	0.110	-0.57	8.61	1
IC 5217	8.56	0.100	-0.68	8.70	1
Cn2-1	4.03	0.100	-0.34	9.00	1
Fg 1	7.12	0.108	-0.88	8.45	1
H1-32	4.92	0.110	-1.00	8.58	8
H1-44	4.41	0.100	-0.21	8.67	8
H1-56	4.01	0.100	-1.10	8.72	8
H2-37	5.61	0.110	-0.44	8.62	8
Hb 12	8.72	0.105	-0.74	8.40	1
He2-21	9.96	0.116	-0.86	8.45	2
He2-29	8.22	0.108	-0.40	8.62	6
He2-37	7.76	0.119	-0.59	8.96	1
He2-47	7.32	0.110	-0.74	8.90	7,9
He2-48	8.15	0.106	-0.59	8.53	1
He2-55	7.31	0.111	-0.56	8.54	1
He2-67	7.14	0.120	-0.87	8.91	7
He2-99	5.94	0.098	-0.96	8.79	1
He2-115	6.17	0.100	-0.87	8.62	1
He2-118	4.45	0.087	-0.52	8.98	9
He2-123	5.53	0.117	-0.11	8.67	1
He2-158	5.36	0.098	-0.97	8.90	1
Hu1-1	10.70	0.105	-0.60	8.68	1
J 320	11.46	0.107	-0.87	8.33	1
J 900	9.65	0.098	-0.90	8.60	1
K3-68	13.59	0.098	-0.55	8.11	8
M1-1	10.65	0.114	-0.60	8.30	1
M1-4	9.08	0.105	-0.54	8.50	1
M1-5	9.69	0.100	-1.00	8.54	1
M1-7	13.20	0.102	-0.17	8.71	8
M1-14	10.27	0.099	-0.98	8.40	3

TABLE II  
(continued)

name	$R$	He/H	$\log(N/O)$	$\epsilon(O)$	Ref.
M1-17	12.20	0.113	-0.55	8.80	1,8
M1-25	4.04	0.117	-0.67	8.99	1
M1-50	3.96	0.102	-0.97	8.74	1
M1-54	4.62	0.112	-0.19	8.97	1
M1-57	4.87	0.091	-0.51	8.96	1
M1-60	4.31	0.105	-0.26	8.84	9

TABLE III  
Input data for PN (continued)

name	$R$	He/H	$\log(N/O)$	$\epsilon(O)$	Ref.
M1-74	6.38	0.099	-0.60	8.78	1
M1-80	11.32	0.091	-0.28	8.59	1
M2-2	8.81	0.100	-0.48	8.43	1
M2-10	3.75	0.091	-0.55	9.00	1
M2-27	5.31	0.120	-0.43	8.89	8
M3-1	10.25	0.105	-0.74	8.39	6
M3-4	10.62	0.123	-0.51	8.72	6
M3-5	10.62	0.110	-0.20	8.29	6
M3-6	8.68	0.090	-1.27	8.64	1
M3-15	5.72	0.107	-0.33	8.41	1
MaC 2-1	11.36	0.111	-1.36	8.44	3
Pe1-18	6.31	0.091	-0.37	8.92	1
Th2-A	6.44	0.092	-0.60	8.74	1

## References:

- 1 – Maciel and Köppen (1994)
- 2 – Costa *et al.* (1996)
- 3 – Costa *et al.* (1997)
- 4 – Corradi *et al.* (1997)
- 5 – Hajian *et al.* (1997)
- 6 – Kingsburgh and Barlow (1994)
- 7 – Perinotto *et al.* (1994)
- 8 – Perinotto (1991)
- 9 – Köppen *et al.* (1991).

Faúndez-Abans and Maciel (1986). Determinations of the He/H gradient based on HII regions may also be affected by small samples. In this case, the distances are usually better known and no corrections are needed for stellar contamination, but the abundance determinations may depend on somewhat uncertain corrections for the presence of neutral helium in the nebulae (cf. Peimbert, 1979).

The present results can be used to estimate an *upper limit* to the He/H gradient on the basis of the total dispersion  $\sigma_d$  observed. Since  $\sigma_d \simeq 0.04$  in all cases considered, we have

$$\left| \frac{d(\text{He}/\text{H})}{dR} \right| < \frac{\sigma_d}{\Delta R} \simeq 0.004 \text{ kpc}^{-1} \quad (7)$$

corresponding to  $d \log(\text{He}/\text{H})/dR \simeq -0.02 \text{ dex/kpc}$  for  $\Delta R \simeq 10 \text{ kpc}$ . *Therefore, the existence of a He/H radial gradient with magnitude similar to the O/H gradient is extremely unlikely, so that any He/H gradient should be lower than the O/H gradient by at least a factor of 3.* This conclusion is in good agreement with the small gradients recently derived for galactic HII regions by Esteban *et al.* (1999), as discussed in Section 2.

Recent chemical evolution models support the present conclusions. Models by Matteucci and co-workers (Matteucci and François, 1989; Matteucci and Chiappini, 1999) predict very small gradients given by  $d \log(\text{He}/\text{H})/dR \simeq -0.0085 \text{ dex/kpc}$ , approximately  $d(\text{He}/\text{H})/dR \simeq -0.002 \text{ kpc}^{-1}$ . The recent models by Chiappini *et al.* (1997) imply a maximum gradient for the inner Galaxy of  $d \log(\text{He}/\text{H})/dR = -0.006 \text{ dex/kpc}$ , with values smaller by a factor 3 for the outer region, so that these results are consistent with the present investigation.

## 5.2. THE HE TO METALS ENRICHMENT RATIO

We have also applied the procedure of Section 4 to the PN sample of Maciel and Quireza (1999), taking the O/H abundance as representative of the total metallicity. We adopted the relation  $Z \simeq 25 \text{ O/H}$ , where O/H is the oxygen abundance by number relative to hydrogen, so that oxygen comprises 45% of the total abundances by mass. As shown by Chiappini and Maciel (1994), this is essentially the same as their independently derived relation for type II PN. Since it can also be applied to HII regions (see for example Peimbert, 1990), the conversion from O/H to Z for all photoionized nebulae becomes straightforward.

The simple linear relationship 1 is certainly valid for metal-poor objects such as blue compact galaxies and low metallicity HII regions, but it probably breaks up at some maximum metallicity, after which a more sophisticated model would be necessary. As pointed out by Chiappini and Maciel (1994), He abundances of PN show some tendency to flatten out for  $Z \geq 0.010$ , which was taken in their work as an upper limit for the application of Equation 1. Moreover, some large metallicity PN have larger than average N/O ratios, apparently due to ON cycling in the progenitor stars. For these objects the necessary corrections to the He abundance are

also larger, and therefore more uncertain. In this work, we decided to extend a little further the limit set by Chiappini and Maciel (1994) and take into account all PN in our sample having metal abundances up to  $10^6 \text{ O/H} \simeq 700$ , which corresponds approximately to the solar value,  $\epsilon(\text{O}) = \log(\text{O/H}) + 12 = 8.83$  (Grevesse and Sauval, 1998), or  $Z \simeq 0.017$  if we take  $Z = 25 \text{ O/H}$ . This includes 81 objects, or about 80% of the PN in our sample, so that it is still a representative sample of the planetary nebulae in the galactic disk.

Our main goal here is to determine the helium to heavy element enrichment ratio  $\Delta Y/\Delta Z$ . The pregalactic He abundance  $Y_p$  could also be obtained using the PN alone, as in some previous work (see for example Maciel, 1988), but this quantity is clearly better determined on the basis of very low metallicity objects, as mentioned in Section 3. Therefore, we have taken  $Y_p$  as a parameter, with the values  $Y_p = 0.23$  and  $Y_p = 0.24$ . For the purposes of the present investigation, the discussion on the third decimal place is largely irrelevant.

We have then applied Equation 1 to the PN sample and obtained plots of the He abundance by mass  $Y$  both as a function of the O/H abundance by number and the total metal abundance by mass  $Z$ , as shown in Figures 2 and 3 (filled circles). Figure 2 gives the uncorrected abundances and fits, and Figure 3 shows the results using the corrections according to the van den Hoek and Groenewegen data. In both figures, the straight lines are least squares fits using  $Y_p = 0.23$  (dashed lines) and  $Y_p = 0.24$  (solid lines).

In order to have a better idea of the behaviour of the  $Y(Z)$  function at low and high metallicities, Figures 2 and 3 also include the Sun ( $\odot$ ) and a sample of HII regions and metal poor blue compact galaxies (empty circles) from the compilation of Chiappini and Maciel (1994). These objects have *not* been taken into account in the determination of the linear fits, and are included for comparison purposes only. In fact, inclusion of these low metallicity objects would not affect the derived slopes by more than a few percent, since the main constraint at low metallicities is defined by the pregalactic abundance  $Y_p$ .

From Figures 2 and 3 it can be seen that the scatter of the low metallicity objects is lower than for the PN, which is confirmed by considering different samples of metal poor objects in the literature. The higher scatter in the PN data is partially due to the higher uncertainties in the abundances and also to the correction procedure adopted in Section 4, both of which may be improved in the future. In fact, the determination of abundances will benefit from the use of more realistic photoionization models and better empirical formulae including improved icf's. The correction procedure can be also improved as better stellar models are available, which will allow a more accurate determination of the excess helium as a function of the observed abundances and stellar mass. The higher uncertainties in the PN abundances and the fact that the He/H gradient is at most a factor of 3 lower than the O/H gradient are probably responsible for the lack of a  $\text{He/H} \times R$  correlation, while some correlation between  $Y$  and  $Z$  (or O/H) can be observed, particularly from Figure 3. In fact, the application of the correction procedure not only reduces

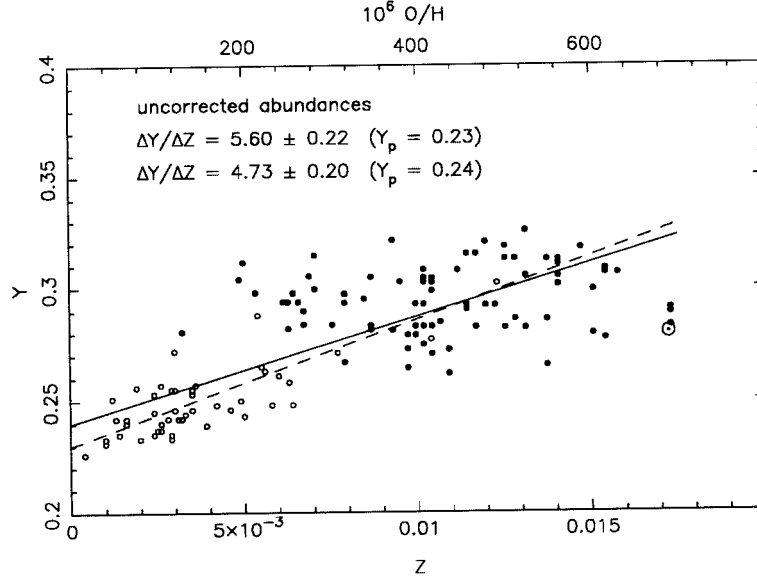


Figure 2. Uncorrected He abundances by mass  $Y$  for PN (solid circles) as a function of the O/H abundances by number (top axis) and total heavy element abundance by mass  $Z$  (bottom axis). Also shown are the Sun ( $\odot$ ) and HII regions (empty circles). The straight lines are least squares fits for  $Y_p = 0.23$  (dashed line) and  $Y_p = 0.24$  (solid line).

the average He abundances and the derived  $\Delta Y/\Delta Z$  ratio, but also decreases the uncertainty of the derived slopes, as can be seen by a comparison of Figures 2 and 3. This effect is similar for both calibrations, being slightly stronger for the high mass calibration, as can be seen in the top panel of Figure 3.

The detailed results of the different calibrations are shown in Table IV. For easier comparison with other investigations, this table also gives the slopes  $\Delta Y/\Delta(\text{O}/\text{H})$  and  $\Delta Y/\Delta Z_{16}$  relative to the oxygen abundance by number and by mass, respectively, which are given by

$$\frac{\Delta Y}{\Delta Z_{16}} = \frac{1}{0.45} \frac{\Delta Y}{\Delta Z} = \frac{1}{25 \times 0.45} \frac{\Delta Y}{\Delta(\text{O}/\text{H})}. \quad (8)$$

Note that our ratio  $\Delta Y/\Delta Z_{16}$  is the same as the ratio  $\Delta Y/\Delta \text{O}$  as defined by Peimbert (1995). As discussed by Esteban *et al.* (1999), the ratio  $\Delta Y/\Delta Z_{16}$  is a better constraint to chemical evolution models, since no corrections for the remaining elements are needed. They derive ratios in the range  $\Delta Y/\Delta Z_{16} = 4.78$  to  $6.55$ , with an average  $\Delta Y/\Delta Z_{16} = 5.87$  for  $Y_p = 0.240 \pm 0.005$ . From Table IV we have  $\Delta Y/\Delta Z_{16} \simeq 5.27$  for  $Y_p = 0.24$ , so that the agreement is very good.

The  $\Delta Y/\Delta Z$  ratio decreases from the range  $4.7 < \Delta Y/\Delta Z < 5.6$ , which is similar to the result of Chiappini and Maciel (1994), to the values

$$2.8 < \frac{\Delta Y}{\Delta Z} < 3.6 \quad (Y_p = 0.23) \quad (9)$$

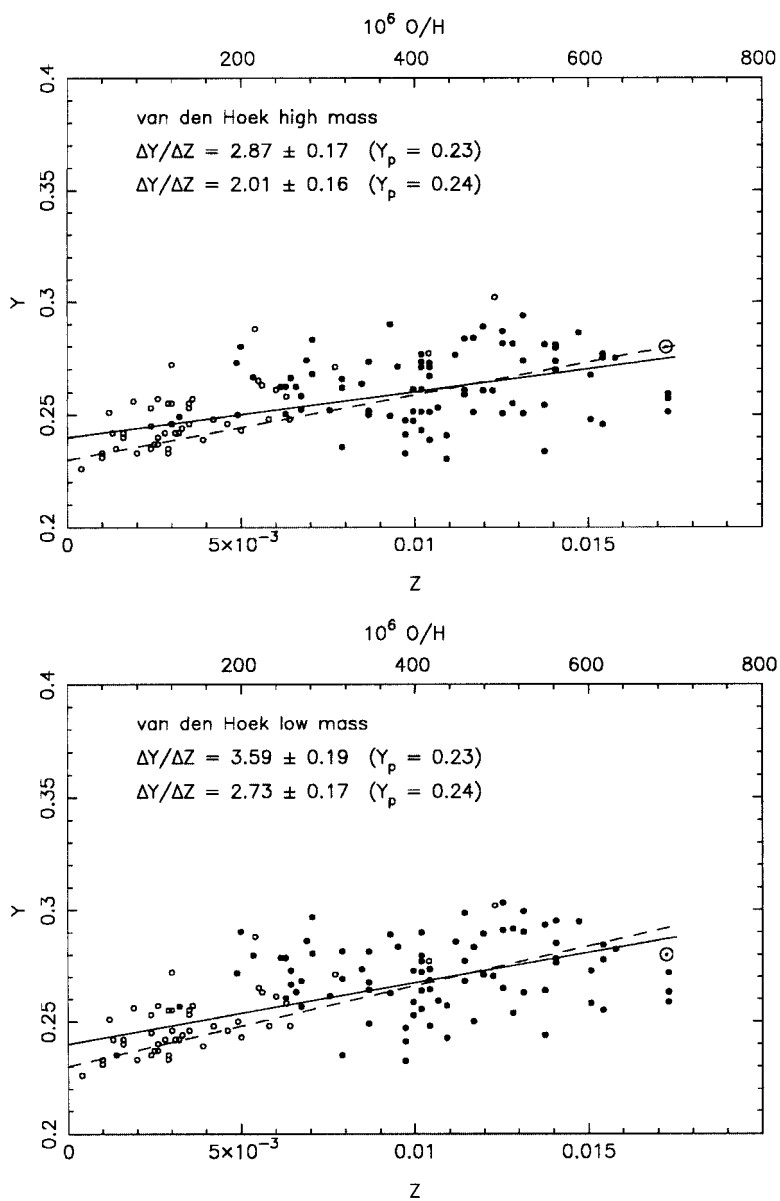


Figure 3. The same as Figure 2 using corrected abundances according to the van den Hoek and Groenewegen (1997) data for the high mass calibration (top panel) and low mass calibration (bottom panel).

TABLE IV  
Results for the  $\Delta Y/\Delta Z$  ratio

	uncorrected	high $M$	low $M$
$Y_p = 0.23$			
$\Delta Y/\Delta(\text{O/H})$	$139.9 \pm 5.6$	$71.9 \pm 4.2$	$89.7 \pm 4.7$
$\Delta Y/\Delta Z_{16}$	$12.44 \pm 0.50$	$6.39 \pm 0.37$	$7.98 \pm 0.41$
$\Delta Y/\Delta Z$	$5.60 \pm 0.22$	$2.87 \pm 0.17$	$3.59 \pm 0.19$
corr. coeff.	0.94	0.89	0.91
$Y_p = 0.24$			
$\Delta Y/\Delta(\text{O/H})$	$118.3 \pm 5.1$	$50.2 \pm 3.9$	$68.1 \pm 4.3$
$\Delta Y/\Delta Z_{16}$	$10.52 \pm 0.45$	$4.47 \pm 0.35$	$6.06 \pm 0.38$
$\Delta Y/\Delta Z$	$4.73 \pm 0.20$	$2.01 \pm 0.16$	$2.73 \pm 0.17$
corr. coeff.	0.93	0.82	0.87

$$2.0 < \frac{\Delta Y}{\Delta Z} < 2.8 \quad (Y_p = 0.24). \quad (10)$$

These results are closer to independently derived ratios, as we have seen in Section 3. If we consider the Boothroyd and Sackmann data, these values are increased by 35% approximately.

Predicted values for the enrichment ratio are usually lower than  $\Delta Y/\Delta Z \simeq 3$ , a condition that can be fulfilled by the present results both for  $Y_p = 0.23$  and  $Y_p = 0.24$ . Recent models by Allen *et al.* (1998) and also models based on two main infall episodes for the formation of the thin disk and halo/thick disk (Chiappini *et al.*, 1997) predict ratios as low as  $\Delta Y/\Delta Z = 1.6$ , which is closer to our lower limit for  $Y_p = 0.24$ .

It should also be noted that, while the derived  $\Delta Y/\Delta Z$  ratios are similar to recent determinations in the literature, the average *uncertainties* are smaller, which is a consequence of the fact that a large number of objects has been included, with a larger metallicity spread, leading to a more reliable determination. As an example, the recent value by Pagel and Portinari (1998) is  $\Delta Y/\Delta Z = 3 \pm 2$ , and results from blue compact dwarf galaxies by Thuan and Izotov (1998) are  $\Delta Y/\Delta Z = 2.3 \pm 1.0$ . An average including both calibrations of Table IV 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  $Y_p = 0.24$ . These results are similar to the recent determinations of Esteban *et al.* (1999) for the HII regions M8, M17 and Orion assuming temperature fluctuations characterized by a  $t^2$  parameter greater than zero. It may be remarked that both the uncorrected results of Table IV and the ratios derived by Esteban *et al.* (1999) for  $t^2 = 0.0$  are larger by roughly 50%. According to Peimbert (1995), temperature fluctuations and the possibility of grain condensation imply some increase in the oxygen abundance for a given value of



the He abundance, decreasing the slope  $\Delta Y/\Delta Z$ . The same effect is attained here by correcting the He abundance by a certain amount  $\Delta Y_s$ . Tables I to III include several objects for which relatively large temperature fluctuation parameters  $t^2$  are estimated, such as NGC 2392, NGC 3211 and NGC 3242 (Liu and Danziger, 1993). These objects are a small fraction of the sample, and display the same dispersion in Figures 1 to 3 as the remaining objects, confirming that the adopted correction procedure is also adequate for these nebulae.

It is interesting to note from Figure 3 that there seems to be some continuity from the very low metallicity blue compact galaxies ( $10^6 O/H < 120$ ) to the HII regions ( $10^6 O/H < 300$ ) and disk PN ( $10^6 O/H > 120$ ). This might seem surprising, as these objects have apparently had different chemical evolution histories. However, it could be argued that 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, or at least to have only small local variations (see for example Padoan *et al.*, 1997; Maciel and Rocha-Pinto, 1998). The SFH is clearly 'bursty' in blue compact galaxies, but it is generally assumed as constant in the Galaxy. However, recent work by Rocha-Pinto *et al.* (2000) has shown that our Galaxy presents clear evidences of past enhanced star formation periods, or bursts, followed by periods of depressed star formation, or lulls. As a consequence, only the *average* star formation rate can be considered as constant, so that the similarity in the chemical evolution of the different systems shown in Figure 3 is probably not surprising at all.

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*Address for Offprints:* Instituto Astronômico e Geofísico, Universidade de São Paulo, Av. Miguel Stefano 4200, 04301-904 São Paulo SP, Brazil

