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# Planetary nebulae and the helium-to-metals enrichment ratio

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**Abstract.** A sample of planetary nebulae (PN), galactic and extragalactic H II regions and blue compact galaxies (BCG) was used in order to obtain the helium-to-metals enrichment ratio, $dY/dZ$. Adopting a simple linear variation for the helium abundance with metals, and taking into account the contamination of the observed helium abundance in PN by the fresh helium produced in their central stars, it is shown that $dY/dZ > 3$, and that the linear model is limited to low metallicities. Finally, we conclude that the simple model of galactic chemical evolution is unable to explain the observed enrichment ratio unless infall of gaseous material on to the galactic disk is considered.

**Key words:** planetary nebulae: general – Galaxy: evolution – Galaxy: abundances

## 1. Introduction

The present helium abundance by mass in the interstellar medium ($Y$) has increased from its pregalactic value ($Y_p$), due to the galactic enrichment by processed material ejected from earlier stellar generations. The pregalactic helium abundance has important cosmological implications (Walker et al. 1991), and is also of crucial interest for galactic chemical evolution models (Chiosi 1986). It can be determined from observed helium abundances provided the helium produced by the galactic evolution is taken into account. In order to minimize this contribution, determinations of $Y_p$ are usually made by taking an average of the helium abundances of extremely metal-poor objects, such as BCG (Kunth & Sargent 1983). Another possibility is to adopt a simple linear variation for the helium abundance with metals, originally proposed by Peimbert & Torres-Peimbert (1974, 1976):

$$Y = Y_p + (dY/dZ)Z \quad (1)$$

where $Z$ is the mass fraction of heavy elements (Lequeux et al. 1979; Peimbert 1986; Pagel et al. 1986, 1992; Pagel 1987; Pagel & Simonson 1989; Torres-Peimbert et al. 1989). In Eq. (1) $dY/dZ$ is the helium-to-metals enrichment ratio, which is also an important parameter in the study of the chemical evolution of the Galaxy. The problems involved in the determination of $Y_p$ and $dY/dZ$ when using H II regions only are discussed by Kunth & Sargent (1983).

Planetary nebulae can also be used in the determination of the pregalactic helium abundance and especially of the enrichment ratio. Maciel (1988) used a sample of type IIb PN (Faúndez-Abans & Maciel 1987; Peimbert 1978) along with BCG and galactic H II regions in order to determine these parameters. According to this approach, the pregalactic helium abundance is essentially defined by the metal poor objects (BCG), while the helium-to-metals enrichment ratio basically depends on the PN (cf. Peimbert 1990). This method has the advantage of extending the metallicity range, consequently reducing the uncertainties in both parameters. A careful analysis of the errors involved in the abundances was given by Maciel & Chiappini (1990).

In this work we present a new determination of these parameters – in particular of the ratio $dY/dZ$ – based on an updated sample of galactic H II regions, H II galaxies (BCG) and planetary nebulae. For the PN with measured abundances of O, N, C, Ne, S, Ar and Cl, a correlation between the total metal abundance $Z$ and the oxygen abundance is investigated, so that the slope $dY/dZ$ can be determined from plots of the helium abundance by mass as a function of both $Z$ and the oxygen abundance by number $O/H$. To correct for the helium produced by the PN progenitor stars, recent theoretical results by Boothroyd & Sackmann (1993) are used. Finally, we compare the prescriptions of some simple models for the chemical evolution of the Galaxy with the derived values of the helium enrichment ratio.

## 2. Chemical abundances and the Z/(O/H) relation

### 2.1. H II regions and blue compact galaxies

We have increased and updated the sample of galactic H II regions and BCG by Maciel (1988), especially by the addition of objects recently analyzed by Pagel et al. (1992). The objects are listed in Table 1, which includes also some BCG from Pagel (1987) and galactic H II regions from Shaver et al. (1983). The table gives the helium abundances by mass, the oxygen and

*Send offprint requests to*: W. J. Maciel nitrogen abundances by number of atoms, and the total metal abundance $Z$ obtained from:

$$Z = 25(O/H). \tag{2}$$

Such relationship has been adopted by a number of people with slight variations (cf. Kunth & Sargent 1983; Peimbert & Torres-Peimbert 1974, 1976; Lequeux et al. 1979; Peimbert 1990), and is confirmed by the results discussed later in this section. Equation (2) implies that oxygen corresponds to 45% of the total metal abundance by mass.

The average uncertainties in the He abundances are 5–7% for BCG and galactic H II regions, respectively (Pagel et al. 1992; Shaver et al. 1983). For oxygen and nitrogen we have $\sigma(O) \simeq$ 0.04 dex (10%) and $\sigma(N) \simeq 0.07$ dex (18%), respectively. The resulting uncertainty in the heavy metal abundance is estimated as about 10%.

It should be noted that our main goal is to determine the *slope* $dY/dZ$, so that the bulk of metal-poor objects given in Table 1 is used as a kind of "zero-point" on the $Y \times Z$ plane.

### 2.2. Planetary nebulae

As has been extensively discussed in the past few years, properties such as the galactic distribution, kinematics, chemical composition, and morphology clearly indicate that planetary nebulae form a rather complex galactic system, comprising objects of different populations (Peimbert 1978; Maciel 1989, 1992; Maciel & Dutra 1992; Maciel & Chiappini 1992; Maciel & Köppen 1993; Schwarz 1993). Maciel (1988) has made use of this fact, and showed that Peimbert type II nebulae are suited to study the pregalactic helium abundance and the helium to metals enrichment ratio. This is especially true for type IIb objects (Faúndez-Abans & Maciel 1987), which presumably include the less massive disk PN. In particular, the metal abundances of type IIb PN and H II regions are similar, and their observed surface enhancements are the smallest of all PN.

Our sample includes 91 type II planetary nebulae (54 type IIa and 37 type IIb), which are listed in Table 2. Oxygen and nitrogen abundances are given as $\log(X/H) + 12$, as usual. In order to obtain the oxygen, nitrogen, helium and metal abundances, we have used an updated version of the compilation by Faúndez-Abans & Maciel (1986), basically with the inclusion of data from the IAG/USP group (Freitas Pacheco et al. 1989, 1991, 1992; Maciel et al. 1990) and the Strasbourg-ESO group (Köppen et al. 1991). The average uncertainties are slightly larger than for H II regions, namely $\sigma \simeq 0.1$ dex for oxygen and nitrogen, and about 10% for helium (Maciel & Chiappini 1990). As a consequence, the derived $Z$ values have uncertainties up to 30%. For a detailed discussion of the abundances the reader is referred to Maciel & Köppen (1993) and Maciel & Chiappini (1993).

In most applications to date, it is generally assumed that oxygen is representative of the primary heavy elements in the photoionized nebula, so that we may write:

$$\frac{dY}{dZ} = \frac{1}{K}\frac{dY}{d(O/H)} \tag{3}$$

where $K = Z/(O/H)$ is a constant to be determined. Therefore, the helium to metals enrichment ratio is obtained from the observed abundances of He and oxygen. This relation is certainly valid for H II regions and type II PN, whose progenitors are intermediate mass stars, which have not sensibly altered their original oxygen abundance (Peimbert 1990). Alternatively, one can compute $dY/dZ$ directly, provided the total metal abundance $Z$ is known. This can be calculated from the definition, if the main contributors are known:

$$Z = \frac{\sum A_i(n_i/n_H)}{1 + 4(He/H) + \sum A_i(n_i/n_H)} = \frac{Z_a}{1 + 4(He/H) + Z_a} \tag{4}$$

where $A_i$ and $n_i/n_H$ are the mass number and abundance of element $i$ relative to H, respectively, and the sum includes the metals ($A_i > 2$). In order to compute $Z_a$ we have considered the main contributors, namely:

$$Z_a \cong 16\frac{O}{H} + 14\frac{N}{H} + 32\frac{S}{H} + 12\frac{C}{H} + 20\frac{Ne}{H} + 40\frac{Ar}{H} + 35\frac{Cl}{H} \tag{5}$$

Fig. 1 shows a plot of $Z \times O/H$ for all type II planetary nebulae for which at least five of the abundances in Eq. (5) are known. A least squares fit is also shown, and the slope is $Z/(O/H) = 23.9 \pm 0.7$, with a correlation coefficient $r = 0.97$, and a sample containing 63 objects (solid line). For some of the PN in this figure, carbon abundances are not known. From stellar evolution models for AGB stars, it is known that C and N enrichment can be significant for planetary nebulae, especially those with massive progenitors. This is confirmed by the dashed line of Fig. 1, which is a least squares fit to the PN with measured carbon abundances. The slope is now $Z/(O/H) = 27.9 \pm 0.6$, the correlation coefficient $r = 0.98$ and 45 objects have been included (dashed line).

The smallest slope of the solid line in Fig. 1 can be considered as a lower limit to the $Z/(O/H)$ ratio, since the absence of C abundance may imply an underestimate of the total metal abundance. On the other hand, the largest slope is probably an upper limit, since objects with measured carbon abundance are expected to be rich in that element, due to a selection effect. Therefore, we adopted the mean value and (formal) uncertainty is

$$Z = (25.9 \pm 0.9)O/H \tag{6}$$

for type II PN, which is very similar to the adopted ratio for H II regions. The $Z/(O/H)$ ratios for PN of types IIa and IIb are essentially the same within the uncertainties, so that we have adopted Eq. (6) for both subtypes. However, in order to determine $Y_p$ and $dY/dZ$ (Sect. 3), type IIb objects only have been included, owing to their low metallicities. The last column of

**Table 1.** Abundances in H II regions and BCG

| Name | Ref. | $Y$ | $10^6 O/H$ | $10^7 N/H$ | $Z$ |
|---|---|---|---|---|---|
| I Zw 18 | 1 | 0.226 | 15 | 4 | 0.0004 |
| TOL 65 | 1 | 0.231 | 39 | 6 | 0.0010 |
| T1214-277 | 1 | 0.233 | 39 | 13 | 0.0010 |
| POX 186 | 1 | 0.242 | 52 | 24 | 0.0013 |
| T1304-353 | 1 | 0.235 | 56 | 20 | 0.0014 |
| UM 461 | 1 | 0.240 | 63 | 17 | 0.0016 |
| C1543+091 | 1 | 0.242 | 63 | 28 | 0.0016 |
| POX 120 | 1 | 0.256 | 77 | 35 | 0.0019 |
| POX 105 | 1 | 0.233 | 78 | 33 | 0.0020 |
| NGC 2363 | 1 | 0.235 | 94 | 29 | 0.0024 |
| C1148-2020 | 1 | 0.245 | 94 | 35 | 0.0024 |
| POX 4 | 1 | 0.237 | 98 | 39 | 0.0025 |
| T1304-38 | 1 | 0.253 | 97 | 65 | 0.0024 |
| Mk 600 | 1 | 0.240 | 102 | 34 | 0.0026 |
| POX 139 | 1 | 0.257 | 102 | 35 | 0.0026 |
| F 30 | 1 | 0.237 | 105 | 46 | 0.0026 |
| NGC 4861 | 1 | 0.242 | 111 | 17 | 0.0028 |
| UM 439 | 1 | 0.233 | 114 | 44 | 0.0029 |
| N 66 SMC | 1 | 0.242 | 110 | 31 | 0.0028 |
| N 81 SMC | 1 | 0.242 | 126 | 43 | 0.0032 |
| POX 108 | 1 | 0.235 | 117 | 61 | 0.0029 |
| NGC 5253[a] | 1 | 0.255 | 115 | 58 | 0.0029 |
| NGC 5253 A | 1 | 0.272 | 120 | 120 | 0.0030 |
| NGC 5253[b] | 1 | 0.255 | 120 | 130 | 0.0030 |
| CS 0341-4045 | 1 | 0.246 | 120 | 32 | 0.0030 |
| NGC 5471 | 1 | 0.242 | 123 | 59 | 0.0031 |
| TOL 35 | 1 | 0.244 | 132 | 38 | 0.0033 |
| T1324-27 | 1 | 0.257 | 145 | 61 | 0.0036 |
| II Zw 40 | 1 | 0.255 | 138 | 98 | 0.0035 |
| II Zw 40 | 1 | 0.253 | 140 | 83 | 0.0035 |
| T 0633-415 | 1 | 0.257 | 145 | 66 | 0.0036 |
| T1004-29 | 1 | 0.246 | 185 | 88 | 0.0046 |
| TOL 3 | 1 | 0.250 | 196 | 89 | 0.0049 |
| NGC 588 | 1 | 0.243 | 200 | 60 | 0.0050 |
| NGC 5455 | 1 | 0.263 | 224 | 138 | 0.0056 |
| NGC 5461 | 1 | 0.261 | 240 | 230 | 0.0060 |
| LMC | 1 | 0.248 | 230 | 140 | 0.0058 |
| II Zw 70 | 2 | 0.246 | 140 | 41 | 0.0035 |
| POX 36 | 2 | 0.239 | 156 | 43 | 0.0039 |
| 6822 | 2 | 0.248 | 169 | 35 | 0.0042 |
| NGC 604 | 2 | 0.258 | 250 | 170 | 0.0063 |
| CG1116+51 | 2 | 0.251 | 48 | 9 | 0.0012 |
| 30 DOR LMC | 3 | 0.248 | 257 | 62 | 0.0064 |
| ORION | 3 | 0.271 | 309 | 324 | 0.0077 |
| S 252-1 | 3 | 0.265 | 219 | 174 | 0.0055 |
| RCW 5-1 | 3 | 0.288 | 214 | 162 | 0.0054 |
| RCW 16-1 | 3 | 0.302 | 490 | 288 | 0.0123 |
| CARINA-2 | 3 | 0.277 | 417 | 437 | 0.0104 |

a: off centre; b: centre; 1: Pagel et al. (1992); 2: Pagel (1987); 3: Shaver et al. (1983)

Table 2 lists the total abundances for PN obtained from Eq. (4). The objects marked with an asterisk have 3 or more missing abundances, so that we have used for them Eq. (6) instead. Also, the objects marked with a cross in Table 2 were not used in the determination of $Y_p$ and $dY/dZ$. Two of them have uncertain helium abundances (NGC 40 and BD+303639). For the remaining PN (IC 4776, He2-158, M1-1, M3-6 and He2-99), classification as type IIb is questionable because of innacurate abundances (Freitas-Pacheco et al. 1992; Köppen et al. 1991; Aller & Czyzak 1983; Kingsburgh & Barlow 1993).

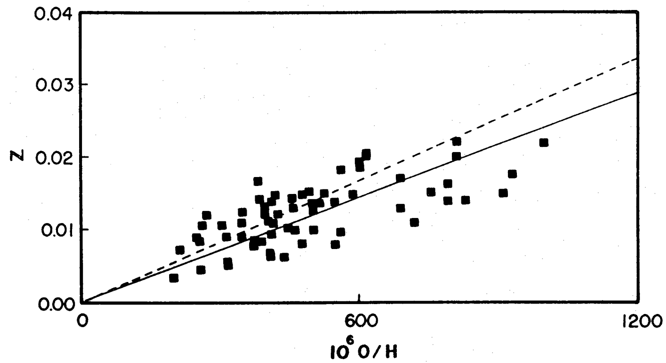


**Fig. 1.** The $Z/(O/H)$ ratio for type II PN. Solid line: all data; dashed line: PN with measured C abundances

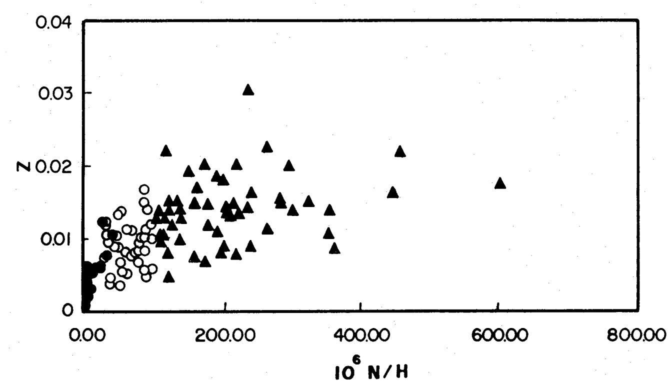


**Fig. 2.** Total abundances ($Z$) as a function of the N abundance for H II regions (dots), type IIb PN (open circles) and type IIa PN (triangles)

The similarity of the $Z/(O/H)$ ratios in H II regions and type II PN can be understood in terms of a moderate importance of the N and C enrichment in the latter (Maciel 1988), and is consistent with the hypothesis that the PN form a sequence with H II regions and BCG in an $Y \times Z$ plane. In fact, applying the same procedure as described above to the other PN types, one concludes that $Z/(O/H) \simeq 28.2$ for type I and $Z/(O/H) \simeq 25.9$ for type III objects, which supports the conclusion that the progenitor masses increase along the sequence of PN types III-II-I (cf. Maciel & Köppen 1993).

As an illustration, the effect of the N enrichment can be seen in Fig. 2, which is a plot of $Z \times N/H$ for the H II regions (galactic and extragalactic - dots), type IIb PN (open circles) and type IIa PN (triangles). The progressive flattening shows the increasing importance of the N enrichment as one goes towards metal rich objects.

**Table 2.** Abundances of type II planetary nebulae

| Name | Type | $Y$ | $O/H^a$ | $N/H^a$ | $Z$ |
|---|---|---|---|---|---|
| NGC 40 | IIb | 0.000 | 8.70 | 7.99 | 0.010+ |
| NGC 1535 | IIb | 0.275 | 8.61 | 7.54 | 0.010 |
| NGC 2022 | IIb | 0.297 | 8.41 | 7.88 | 0.008 |
| NGC 2371 | IIa | 0.284 | 8.63 | 8.11 | 0.012 |
| NGC 2392 | IIa | 0.267 | 8.50 | 8.38 | 0.009 |
| NGC 2438 | IIa | 0.290 | 8.84 | 8.15 | 0.013 |
| NGC 2792 | IIa | 0.310 | 8.75 | 8.55 | 0.015* |
| NGC 2867 | IIa | 0.313 | 8.71 | 8.11 | 0.014 |
| NGC 3195 | IIa | 0.326 | 8.90 | 8.38 | 0.016 |
| NGC 3211 | IIb | 0.318 | 8.70 | 7.93 | 0.013* |
| NGC 3242 | IIb | 0.293 | 8.66 | 7.91 | 0.010 |
| NGC 3587 | IIa | 0.279 | 8.59 | 8.29 | 0.008 |
| NGC 3918 | IIa | 0.298 | 8.78 | 8.28 | 0.018 |
| NGC 5307 | IIb | 0.273 | 8.64 | 7.90 | 0.009 |
| NGC 5882 | IIa | 0.291 | 8.69 | 8.10 | 0.015 |
| NGC 6210 | IIb | 0.313 | 8.70 | 7.73 | 0.014 |
| NGC 6309 | IIa | 0.314 | 8.91 | 8.07 | 0.022 |
| NGC 6439 | IIa | 0.295 | 8.88 | 8.51 | 0.015 |
| NGC 6543 | IIb | 0.305 | 8.72 | 7.94 | 0.015 |
| NGC 6563 | IIa | 0.322 | 8.57 | 8.34 | 0.008 |
| NGC 6565 | IIa | 0.282 | 8.91 | 8.47 | 0.020 |
| NGC 6567 | IIb | 0.298 | 8.50 | 7.78 | 0.005 |
| NGC 6572 | IIa | 0.318 | 8.77 | 8.20 | 0.015 |
| NGC 6578 | IIa | 0.303 | 8.75 | 8.04 | 0.010 |
| NGC 6629 | IIb | 0.284 | 8.61 | 7.73 | 0.007 |
| NGC 6720 | IIa | 0.307 | 8.79 | 8.24 | 0.020 |
| NGC 6790 | IIb | 0.292 | 8.60 | 7.98 | 0.012 |
| NGC 6818 | IIa | 0.313 | 8.74 | 8.10 | 0.014 |
| NGC 6826 | IIb | 0.288 | 8.43 | 7.50 | 0.012 |
| NGC 6879 | IIb | 0.294 | 8.61 | 7.89 | 0.007 |
| NGC 6884 | IIb | 0.314 | 8.66 | 7.96 | 0.014 |
| NGC 6886 | IIa | 0.320 | 8.68 | 8.33 | 0.015 |
| NGC 6891 | IIb | 0.308 | 8.65 | 7.68 | 0.010 |
| NGC 6894 | IIa | 0.283 | 8.60 | 8.20 | 0.010* |
| NGC 6905 | IIa | 0.290 | 8.66 | 8.08 | 0.013 |
| NGC 7009 | IIa | 0.283 | 8.84 | 8.21 | 0.017 |
| NGC 7026 | IIa | 0.305 | 8.79 | 8.34 | 0.020 |
| NGC 7027 | IIa | 0.303 | 8.62 | 8.25 | 0.015 |
| NGC 7662 | IIb | 0.308 | 8.61 | 7.95 | 0.011 |
| IC 351 | IIb | 0.283 | 8.48 | 7.53 | 0.011 |
| IC 418 | IIb | 0.283 | 8.54 | 7.82 | 0.011 |
| IC 1297 | IIa | 0.303 | 8.89 | 8.42 | 0.020* |
| IC 1747 | IIa | 0.304 | 8.75 | 8.30 | 0.018 |
| IC 2003 | IIa | 0.270 | 8.62 | 8.04 | 0.011 |
| IC 2149 | IIa | 0.281 | 8.54 | 8.30 | 0.009 |
| IC 2165 | IIa | 0.293 | 8.42 | 8.05 | 0.011 |

a: The table gives log(X/H)+12

**Table 2.** (continued)

| Name | Type | $Y$ | $O/H$ | $N/H$ | $Z$ |
|---|---|---|---|---|---|
| IC 2448 | IIa | 0.272 | 8.59 | 8.28 | 0.011 |
| IC 2501 | IIa | 0.267 | 8.92 | 8.15 | 0.014 |
| IC 2621 | IIa | 0.261 | 8.90 | 8.48 | 0.014 |
| IC 3568 | IIb | 0.281 | 8.57 | 7.70 | 0.009 |
| IC 4776 | IIb | 0.262 | 8.86 | 7.78 | 0.011+ |
| IC 5117 | IIa | 0.301 | 8.61 | 8.04 | 0.014 |
| IC 5217 | IIa | 0.282 | 8.70 | 8.02 | 0.013 |
| BD+30 3639 | IIb | 0.000 | 8.58 | 7.94 | 0.017+ |
| Cn2-1 | IIa | 0.279 | 9.00 | 8.66 | 0.022 |
| Fg 1 | IIb | 0.299 | 8.45 | 7.57 | 0.007* |
| J 320 | IIb | 0.298 | 8.33 | 7.46 | 0.007 |
| J 900 | IIb | 0.278 | 8.60 | 7.70 | 0.013 |
| Hb 12 | IIb | 0.293 | 8.40 | 7.66 | 0.009 |
| He2-21 | IIb | 0.288 | 8.45 | 7.59 | 0.007* |
| He2-37 | IIa | 0.315 | 8.96 | 8.37 | 0.024* |
| He2-48 | IIb | 0.295 | 8.53 | 7.94 | 0.009* |
| He2-55 | IIb | 0.305 | 8.54 | 7.98 | 0.009* |
| He2-99 | IIb | 0.279 | 8.79 | 7.83 | 0.008+ |
| He2-115 | IIb | 0.283 | 8.62 | 7.75 | 0.011* |
| He2-123 | IIa | 0.315 | 8.67 | 8.56 | 0.012* |
| He2-138 | IIa | 0.000 | 8.83 | 8.31 | 0.018* |
| He2-140 | IIa | 0.000 | 8.75 | 8.25 | 0.015* |
| He2-141 | IIa | 0.314 | 9.00 | 8.34 | 0.026* |
| He2-157 | IIa | 0.000 | 9.22 | 8.37 | 0.043* |
| He2-158 | IIb | 0.279 | 8.90 | 7.93 | 0.010+ |
| Hu1-1 | IIa | 0.293 | 8.68 | 8.08 | 0.008 |
| M1-1 | IIb | 0.312 | 8.30 | 7.70 | 0.003+ |
| M1-4 | IIb | 0.294 | 8.50 | 7.96 | 0.005 |
| M1-5 | IIb | 0.282 | 8.54 | 7.54 | 0.012 |
| M1-25 | IIa | 0.315 | 8.99 | 8.32 | 0.013 |
| M1-34 | IIa | 0.310 | 9.02 | 8.65 | 0.027* |
| M1-38 | IIa | 0.000 | 8.91 | 8.14 | 0.021* |
| M1-50 | IIb | 0.287 | 8.74 | 7.77 | 0.008 |
| M1-54 | IIa | 0.304 | 8.97 | 8.78 | 0.018 |
| M1-57 | IIa | 0.263 | 8.96 | 8.45 | 0.015 |
| M1-74 | IIa | 0.278 | 8.78 | 8.18 | 0.019 |
| M1-80 | IIa | 0.263 | 8.59 | 8.31 | 0.014 |
| M2-2 | IIb | 0.284 | 8.43 | 7.95 | 0.007* |
| M2-10 | IIa | 0.260 | 9.00 | 8.45 | 0.026* |
| M3-4 | IIa | 0.327 | 8.58 | 8.24 | 0.010* |
| M3-6 | IIb | 0.263 | 8.64 | 7.37 | 0.006+ |
| M3-15 | IIa | 0.298 | 8.41 | 8.08 | 0.007* |
| PC 14 | IIa | 0.279 | 9.16 | 8.42 | 0.037* |
| Pe1-18 | IIa | 0.261 | 8.92 | 8.55 | 0.022* |
| Th2-A | IIa | 0.265 | 8.74 | 8.14 | 0.014* |

## 3. Determination of Yp and dY/dZ

### *3.1. Helium contamination by the PN central stars*

Abundances of He, C and N in PN reflect the surface chemical composition of intermediate mass stars at the AGB phase. According to stellar evolution models (cf. Renzini & Voli 1981; Iben & Renzini 1983; Renzini 1984), in this phase processed materials from the stellar interior are mixed to the surface by convective flows. These models include three convective dredge-up episodes, which depend on the stellar mass. For progenitors of type II PN (1.2 - 2.4 M$\odot$), the second dredge-up does not take place, while the importance of the third one is still controversial (Peimbert 1990; Lambert 1992). The dominant process in these objects is certainly the first dredge up, which is essentially responsible for the N and He enhancements. Therefore, the helium abundance in PN can be written as:

$$Y = Yp + (dY/dZ)Z + \Delta Y_s \quad (7)$$

where $\Delta Y_s$ represents the stellar contribution to the He abundance in planetary nebulae, which has to be subtracted from the values given in Table 2. As a first approximation, $\Delta Y_s$ can be considered negligible for type II PN (especially type IIb, cf. Maciel 1988). In this work, however, we are fully including this correction in order to derive more accurate values for the pregalactic abundance and enrichment ratio.

A preliminary step has been taken by Maciel & Chiappini (1990), who have taken $\Delta Y_s$ as a free parameter, averaged as $\Delta Y_s \simeq 0.010$ for type II PN, which was confirmed later (cf. Chiappini & Maciel 1993). This would in principle absorb other sources of error, such as the non-linearity of detectors and temperature fluctuations. Recently, however, theoretical calculations for intermediate mass stars have become available (Boothroyd & Sackmann 1993), so that better results can be obtained. According to these models, the helium contribution comes essentially from the first dredge-up for the mass range corresponding to type II PN progenitors. The obtained values are in the range $0.022 > \Delta Y_s > 0.008$, depending on the stellar mass. We note that the mean value is $\Delta Y_p \simeq 0.015$, in agreement with our previous results (Maciel & Chiappini 1990; Chiappini & Maciel 1993). Therefore, we adopted the following values for the helium contamination from the central star: (i) $\Delta Y_s = 0$, that is, no correction, (ii) $\Delta Y_s = 0.022$ (upper limit), (iii) $\Delta Y_s = 0.008$ (lower limit), and (iv) $\Delta Y_s = 0.015$ (average value).

### *3.2. Results and discussion*

The main results from the $Y(O/H)$ and $Y(Z)$ relations are given in Table 3 as a function of the correction $\Delta Y_s$. As an example, Fig. 3a,b shows the data and least squares fits for the average correction, $\Delta Y_s = 0.015$.

It can be immediately seen that the estimates of $Y_p$ and $dY/dZ$ are very similar both for $Y(O/H)$ and $Y(Z)$, which was not the case in the preliminary work by Maciel (1988). In fact, the $Y(O/H)$ and $Y(Z)$ relations will be equivalent only if the $Z/(O/H)$ ratio is similar for PN and H II regions, which is confirmed by Eqs. (2) and (6). In the work by Maciel (1988), the contribution to the total abundance of the heavy elements apart from oxygen was overestimated, so that the pregalactic helium abundance was smaller for the $Y(O/H)$ relation than for the direct $Y(Z)$ relation. As recently discussed (Maciel 1993), the $Z/(O/H)$ ratio for H II regions and *type II* PN are similar, so that the corresponding ratio derived earlier should be more adequate for PN with massive progenitors, near the upper mass limit of type I PN. On the other hand, the $Y(Z)$ relation produces slightly larger values of $Y_p$ and smaller $dY/dZ$ ratios when compared with the $Y(O/H)$ results. This shows the tendency of $Y(Z)$ to flatten out for high $Z$ values, which means that the simple linear model for the chemical evolution of the Galaxy is limited to low metallicities.

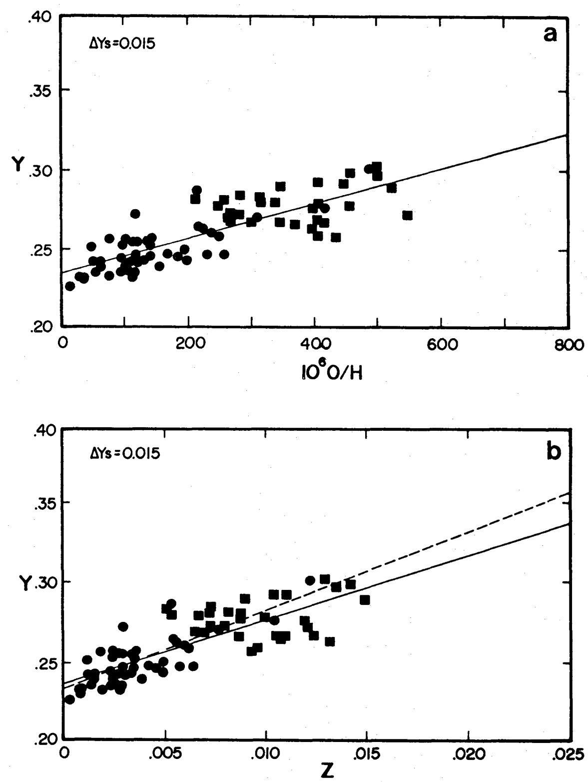


**Fig. 3a and b.** Results for H II regions and BCG (dots) and type IIb PN (squares) with $\Delta Y_s = 0.015$ using the **a** $Y(O/H)$ and **b** $Y(Z)$ relations

From Fig. 3a,b it can be seen that most objects have total abundances $Z < 0.01$, so that a better determination of $Y_p$ and $dY/dZ$ at low metallicities can probably be obtained neglecting the nebulae for which $Z > 0.01$. The results are also shown in Table 3 and in the dashed line of Fig. 3b, and imply a small reduction in the pregalactic helium abundance and a slight increase in the enrichment ratio.

The average formal uncertainties for the results given in Table 3 are $\sigma(Y_p) \simeq 0.002$, $\sigma(dY/dZ) \simeq 0.4$, and $\sigma(dY/d(\mathrm{O/H})$ $\simeq 8.0$. We have considered only the uncertainties in the helium abundance (cf. Maciel 1989; Maciel & Chiappini 1992), for which we adopted $\sigma(Y) \simeq 0.01$, but the results are not particularly sensitive to this hypothesis. These are *formal* $1\sigma$ uncertainties, and a simple statistical analysis suggests that the *real* uncertainty is around $2 - 3\sigma$.

As expected, the pregalactic helium abundance increases with the $\Delta Y_s$ correction, the opposite being true for the enrichment ratio. An important conclusion from Table 3 is that $dY/dZ > 3$, even for large corrections to the helium abundance.

From the set of values presented in Table 3, we have $0.236 \geq Y_p \geq 0.229$ and $6.3 \geq dY/dZ \geq 4.0$, or equivalently:

$$Y_p = 0.233 \pm 0.003 \quad (8)$$

$$dY/dZ = 5.2 \pm 1.1 \quad (9)$$

**Table 3.** Results from the $Y(O/H)$ and $Y(Z)$ relations

| $\Delta Y_s$ | $Y_p$ | $dY/d(O/H)$ | $dY/dZ$ | $r$ |
|---|---|---|---|---|
| $Y(O/H)$ | | | | |
| 0.000 | 0.231 | 151. | 5.9 | 0.86 |
| 0.008 | 0.233 | 130. | 5.0 | 0.84 |
| 0.015 | 0.234 | 111. | 4.3 | 0.82 |
| 0.022 | 0.236 | 93. | 3.6 | 0.77 |
| $Y(Z)$ | | | | |
| 0.000 | 0.233 | | 5.6 | 0.85 |
| 0.008 | 0.234 | | 4.8 | 0.83 |
| 0.015 | 0.236 | | 4.1 | 0.81 |
| 0.022 | 0.237 | | 3.4 | 0.76 |
| $Y(Z)(Z < 0.01)$ | | | | |
| 0.000 | 0.229 | | 6.7 | 0.83 |
| 0.008 | 0.230 | | 5.9 | 0.83 |
| 0.015 | 0.232 | | 5.1 | 0.81 |
| 0.022 | 0.234 | | 4.4 | 0.77 |

Therefore, the helium contribution for type II PN progenitors are in the range $0.008 < \Delta Y_s < 0.015$, which is consistent with our previous results (Maciel & Chiappini 1990).

The results given in Eqs. (8) and (9) are in agreement with some recent work based on H II regions only. Pagel et al. (1992) find from an $Y(O/H)$ correlation $dY/dZ = 5.0$ and $Y_p = 0.228 \pm 0.005$ for $Z = 25(O/H)$. The pregalactic value obtained by Pagel et al. could be underestimated owing to the reduced number of objects. Skillman et al. (1993), including new metal-poor objects to Pagel's sample, obtain $Y_p = 0.238 \pm 0.003$.

The derivation of the helium to metals enrichment ratio $dY/dZ$ or its integral over the history of the Galaxy, $DY/DZ$, is also affected by temperature fluctuations, as measured by the $t^2$ parameter (cf. Peimbert 1990). Peimbert et al. (1992), adopting $Y_p = 0.230$, obtained $DY/DZ = 4.47$ for $t^2 = 0.00$ and $DY/DZ = 2.50 \pm 0.5$ for $t^2 = 0.04$ for the galactic HII region M17. In the case of Orion, they found $DY/DZ > 3$ for $t^2 \leq 0.035$. Our abundances implicitly assume $t^2 = 0.00$ and that no oxygen is trapped in dust grains, so that our values for the enrichment ratio should be somewhat decreased. However, the agreement of our results with those quoted above shows that the present analysis produces results consistent with the helium enrichment ratio derived from younger objects, even though our sample includes objects in later evolutionary phases.

Our pregalactic value is also consistent with the theoretically predicted value by the standard Big Bang nucleosynthesis theory, $0.236 \leq Y_p \leq 0.243$ (cf. Walker et al. 1991). Finally, it can be concluded that the inclusion of PN in the $dY/dZ$ determination not only decreases the uncertainties in this parameter but also gives us a good idea of its behaviour in the high metallicity limit.

**Table 4.** Results from the simple model without infall

| case | $dY/dZ$ | case | $dY/dZ$ |
|---|---|---|---|
| 1 | 1.38 | 6 | 0.64 |
| 2 | 3.14 | 7 | 0.71 |
| 3 | 1.13 | 8 | 1.49 |
| 4 | 0.72 | 9 | 0.62 |
| 5 | 1.48 | 10 | 1.13 |

## 4. Comparison with theoretical models

The derived enrichment ratio can be used to constrain galactic chemical evolution models. Since this ratio is essentially defined by disk planetary nebulae, the $dY/dZ$ values can be compared with prescriptions of some simplified models for the galactic disk. With this aim, we have used two sets of models: (i) simple models (cf. Tinsley 1980), and (ii) infall models (cf. Tosi 1988).

We assumed that the system has a total mass $M$ that may increase as a result of an infall rate $f(t)$. The total gas mass $M_g$ is consumed to form stars at a rate $\Psi(t)$, and increases at a rate $E(t)$ owing to the gas returned by the stellar deaths. In the framework of the simple model with the instantaneous recycling approximation (IRA, cf. Tinsley 1980; Maeder 1992), the conservation equation for any elemental species $i$ can be written as:

$$M_g \frac{dX_i}{dt} = y_i(1 - R)\Psi(t) + (X_{if} - X_i)f(t) \qquad (10)$$

where $X_i$ is the mass fraction of element $i$, $y_i$ is the yield, $R$ is the returned mass fraction to the interstellar gas, and $X_{if}$ is the mass fraction of $i$ that was already present in the infalling material (cf. Chiosi & Mateucci 1984). Equation (10) gives the evolution of an elemental species $i$ and can be used to derive the enrichment ratio $dY/dZ$.

### 4.1. The simple model

One of the hypotheses of the simple model is that the system is isolated, or equivalently, $f(t) = 0$. From Eq.(10) we have:

$$\frac{dY}{dZ} = \frac{y_{He}}{y_Z}. \qquad (11)$$

In this model, $dY/dZ$ does not depend on $Y$ and $Z$. We have evaluated this ratio adopting the yields given by Chiosi & Mateucci (1984, Table 2; Chiosi 1986). These authors consider 10 different cases that take into account different stellar evolution models, initial mass functions and nucleosynthesis inputs. The main parameters include the slope of the IMF, $0.6 < x < 2.0$, the fraction of stars in the IMF more massive than 1 $M_\odot$, $0.25 < \zeta < 0.50$, the mass limits $0.007 < m_l(M_\odot) < 0.16$ and $m_u \simeq 100 M_\odot$, the mass loss rate, and the existence of convective overshooting. The main results are given in Table 4, which shows that $dY/dZ \leq 3$ for all cases, so that the simple model is unable to reproduce our derived values.

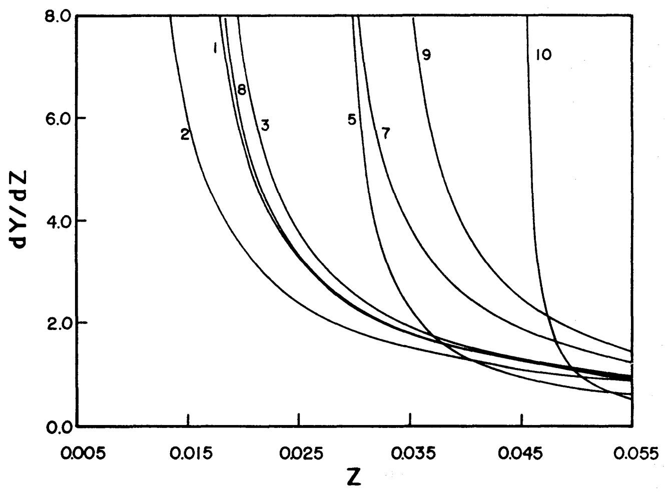


**Fig. 4.** Prescriptions of the simple model with infall, according to cases 1-10 from Chiosi & Mateucci (1984)

### 4.2. Infall model

In this case we adopt the simplifying hypothesis that the infall rate $f(t)$ is balanced by the star formation rate $\Psi(t)$ (Chiosi 1986), so that

$$f(t) = (1 - R)\Psi(t) \tag{12}$$

With Eqs.(10) and (12), the helium enrichment ratio can be written as:

$$\frac{dY}{dZ} = \frac{y_{He} + (Y_f - Y)}{y_Z + (Z_f - Z)} \tag{13}$$

where $Y_f$ and $Z_f$ are the helium and metal abundances of the infalling gas, respectively.

According to Tosi (1988, 1991), models with $Z_f \leq 0.3Z\odot$ (with $Z\odot \simeq 0.020$, Anders & Grevesse 1989) are compatible with several galactic properties such as the radial abundance gradients. Adopting $Z_f \simeq 0.005$ and $Y_f \simeq 0.23$, which characterizes an unprocessed material, and $Y \simeq 0.28$ for the mean helium abundance, we have evaluated the $dY/dZ$ ratio for the metallicity range $0.050 > Z > 0.008$. Adopting the yield values from Chiosi & Mateucci (1984), we obtain the results shown in Fig. 4.

The first thing to note is the strong dependence of $dY/dZ$ with the metallicity. Except for cases 4 and 6 (Chiosi & Mateucci 1984, Table 2), which give $dY/dZ < 0$, all the other models give $dY/dZ$ values that are compatible with our derived values [$4 < dY/dZ < 6$, Eq. (9)] for a given metallicity range. The metallicity interval is $0.015 < Z < 0.025$ (cases 1, 2, 3, and 8); $0.031 < Z < 0.040$ (cases 5, 7, and 9); and $0.046 < Z < 0.048$ (case 10). A realistic estimate of the metal abundance range in the galactic disk is similar to the first one (cf. Trimble 1991), which corresponds to cases 1, 2, 3 and 8. Models 1, 2 and 3 have bimodal initial mass functions, differing only by the mass loss rate and the existence of core overshooting, while case 8 assume a Salpeter (1955) IMF.

Values of $dY/dZ$ depend on the infall chemical composition. For $Y$ and $Z$ fixed, the $dY/dZ$ ratio increases as $Z_f$ increases, and as $Y_f$ decreases. Also in this case, for a combined set of these parameters, infall models are able to predict values of $dY/dZ$ that are compatible with our determinations. The $dY/dZ$ dependence on the $f(t)/\Psi(t)$ ratio was discussed by Chiosi & Mateucci (1984) and is also important.

From this section, we can conclude that even with a simplified model is it possible to obtain $4 < dY/dZ < 6$, provided the hypothesis of closed model is discarded. Also, it can be seen that the simple model of galactic chemical evolution seems to be unable to explain the observed $^4$He enrichment ratio unless infall of material to the galactic disk is taken into account. However, this is not the only possibility, and such conclusions must be viewed with care, as the prescriptions of infall models are extremely model dependent, and consequently are not unique (cf. Tosi 1988). Also, the adoption of a primordial infalling gas, which seems to be favoured by the observational constraints in the solar vicinity (cf. Matteucci & François 1989), would affect the derivation of the enrichment ratio. On the other hand, it should be stressed that Eq. (13) gives the *differential* ratio $dY/dZ$, while the values derived from the observations correspond to the *integrated* $DY/DZ$. Therefore, a complete analysis of the enrichment ratio with non primordial infalling gas would require a detailed knowledge of the time variations of all involved parameters, which is beyond the scope of the present paper.

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