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Abundance gradients from disk planetary nebulae: O, Ne, S, and Ar*

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Abstract. A new determination of the radial abundance gradients of O/H, Ne/H, S/H, and Ar/H is made for disk planetary nebulae, that is, those objects of Peimbert types I, II, and III. On the basis of a sample containing 200 nebulae, it can be concluded that these gradients are generally similar, and of the same order of magnitude as the O/H gradient displayed by galactic H II regions. Some distance-independent correlations confirm the accuracy of the abundances and support the interpretation of the gradients in terms of chemical evolution models. The time evolution of the abundance gradients in the Milky Way is investigated, and their variation with the types of PN are compared with predictions of chemical evolution models.

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

1. Introduction

Radial abundance gradients are known in the galactic disk, basically from the study of H II regions and planetary nebulae (Pagel & Edmunds 1981; Shaver et al. 1983; Faúndez-Abans & Maciel 1986, 1987a). Their presence seems now well established both in our Galaxy and in other spirals, although some doubts have remained, especially from the results derived from hot stars in the disk (cf. Pagel 1993).

These gradients were originally derived from oxygen abundances in H II regions, (Pagel & Edmunds 1981; Shaver et al. 1983; Pagel 1987) and are reflected by the electron temperature gradient derived from radio recombination lines in these objects (Churchwell & Walmsley 1975).

In the past few years, other elements produced by massive stars (Ne, S, ...) have also been shown to display radial abundance gradients similar to the oxygen gradient, which amounts to -0.07 dex kpc^{-1}. In addition, planetary nebulae belonging to the intermediate disk population (the so-called "type II", cf. Peimbert 1978) also have gradients of the same order of magnitude as the H II regions (Faúndez-Abans & Maciel 1986, 1987a; Maciel 1992a), and the corresponding electron temperature gradient has been obtained from the analysis of forbidden lines in these objects (Maciel & Faúndez-Abans 1985). More recently, independent studies (Köppen et al. 1991; Acker et al. 1992; Samland et al. 1992) confirm these findings, though some problems remain due to uncertainties in the classification process and inaccurate distances.

The origin of the gradients is not yet clear, although several possibilities have been proposed in the literature, ranging from appropriate gas flows to radial variations of the star formation rate or of the chemical yields (Pagel 1992; Maciel 1992b).

Connected to the origin of the gradients is the question of their time evolution (Köppen 1993; Carigi & Franco 1992; Mollá et al. 1990). Here, planetary nebulae are likely to give an important contribution. Originating from stars with a rather large range of main sequence masses (0.8–8$M_\odot$, cf. Peimbert 1990), PN include objects of different populations, whose properties are reflected by their chemical composition. Therefore, by determining the radial gradients of the main heavy elements in a sample of disk PN, one would be able in principle to study the time evolution of the interstellar medium out of which the PN progenitor stars had been formed.

In this paper, a new determination of the radial gradients of the elements O, Ne, S, and Ar is presented for galactic planetary nebulae. We then compare the gradients and their variations with PN type with predictions from chemical evolution models.

2. The data

In order to make a new determination of the radial abundance gradients and also to study the time evolution of the

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* Tables 1 and 2 are only available in electronic form. See the Editorial in A&A 1992, Vol. 266 No. 2, page E1

gradients in the disk, we have taken into account a sample containing about 200 galactic disk nebulae, for which relatively accurate abundances and distances are available.

The objects are listed in Table 1 (accessible in electronic form), where column 1 gives the common name, column 2 the PK number (Perek & Kohoutek 1967), column 3 the adopted classification type, column 4 the distance in kpc, column 5 the distance source, and column 6 the distance R (in kpc) to the galactic centre projected on the galactic plane, adopting $R_0 = 8.5$ kpc for the distance of the LSR (Local Standard of Rest) to the galactic centre. The distances are generally (about 75% of the sample) from Maciel (1984), apart from statistical or individual data for the remaining nebulae. The classification has been made according to the criteria by Peimbert (1978), supplemented by more recent work by Peimbert & Torres-Peimbert (1983), Faúndez-Abans & Maciel (1987b) and Maciel (1989). The abundances adopted are discussed below, and the kinematical properties implicit in the classification scheme have been studied by Dutra & Maciel (1990) and Maciel & Dutra (1992).

The chemical composition is basically from the IAG/USP group (Freitas Pacheco et al. 1989, 1991, 1992; Maciel et al. 1990), the ESO spectrophotometric survey (Köppen et al. 1991), and Aller and co-workers (Aller & Czyzak 1983; Aller & Keyes 1987), with some data from other groups (e.g. Kingsburgh & Barlow 1992; Pottasch 1984) used to obtain a more complete set of abundances. In a statistical study of this kind it is presently impossible to include completely homogeneous data only. In order to counterbalance this problem, we have considered a large sample of nebulae, keeping only those objects for which different abundance determinations agree within the adopted uncertainties, which we estimate to be in the range 0.1–0.2 dex for most objects. The adopted abundances are given in Table 2 (accessible in electronic form) along with the individual sources. The figure given is $\log(X/H) + 12$, as usual, where X stands for the number abundance of O, Ne, S, and Ar, respectively.

3. Abundance gradients from planetary nebulae

Following the classification scheme originally proposed by Peimbert (1978), disk PN include objects of types I, II, and III. Because of their greater mean height above the galactic plane and their large peculiar velocities (Maciel & Dutra 1992), type III nebulae have presumably been ejected from older, less massive stars than type II objects. Therefore, we may expect that gradients derived from them (i) would be remnants of a longer time in the past, and (ii) could probably be diluted by the motion of the progenitor star away from its birthplace.

On the other hand, type I PN pose a different kind of problem: At the high mass end (masses up to $8M_\odot$), these objects are probably the youngest of all disk PN, so that their chemical abundances should reflect the composition of the present interstellar medium. It is not clear how this would affect objects at different distances from the galactic centre. Furthermore, recent work (see for example Henry 1990; Maciel 1992a) points to some ON cycling in the progenitors of type I PN, which may strongly affect the oxygen abundances of these objects. Again, it is not clear how this would affect objects at different galactocentric radii. Finally, there are some evidences that Ne and O have been more rapidly enriched in the interstellar medium than S and Ar (Maciel 1992a), which would also affect the PN abundances and gradients as well.

Type II PN are free of most of these problems. They are relatively young objects, closely associated with the disk, and participating in the galactic rotation (cf. Maciel & Dutra 1992). Ejected by intermediate mass stars in a limited mass range (Peimbert 1978), they are less affected by differential galactic evolution than their massive type I counterparts. Therefore, the gradients derived from these objects would clearly reflect the interstellar conditions at the time of their formation, and would probably present a smaller scatter compared with type I and type III objects.

The main results concerning radial abundance gradients are given in Table 3. For each ratio O/H, Ne/H, S/H, and Ar/H, we have obtained a least-squares linear fit of the form

$$\log \frac{X}{H} + 12 = aR + b\,, \tag{1}$$

Table 3. Radial abundance gradients from PN

Type	a	$\sigma(a)$	b	$\sigma(b)$	r	n
O/H						
I	−0.030	0.007	8.92	0.06	0.25	67
II	−0.069	0.006	9.25	0.05	0.70	91
III	−0.058	0.008	8.84	0.06	0.47	39
IIa	−0.062	0.007	9.25	0.06	0.66	53
IIb	−0.057	0.010	9.08	0.08	0.73	38
Ne/H						
I	−0.004	0.008	8.07	0.07	0.03	47
II	−0.056	0.007	8.46	0.06	0.50	75
III	−0.041	0.008	8.01	0.06	0.36	29
IIa	−0.059	0.009	8.57	0.07	0.59	41
IIb	−0.030	0.010	8.14	0.10	0.34	34
S/H						
I	−0.075	0.008	7.61	0.06	0.43	52
II	−0.067	0.006	7.46	0.05	0.55	74
III	−0.063	0.010	7.09	0.07	0.40	30
IIa	−0.075	0.008	7.57	0.07	0.61	43
IIb	−0.037	0.010	7.13	0.09	0.36	31
Ar/H						
I	−0.060	0.008	7.07	0.07	0.45	51
II	−0.051	0.006	6.81	0.05	0.47	73
III	−0.034	0.010	6.32	0.07	0.33	24
IIa	−0.054	0.008	6.89	0.06	0.61	45
IIb	−0.016	0.010	6.41	0.09	0.15	28

so that

$$a = \frac{\mathrm{d}\log(X/H)}{\mathrm{d}R} \quad (\mathrm{dex\ kpc^{-1}}), \tag{2}$$

where X = O, Ne, S, and Ar. Table 3 gives the slope a, intercept b, formal uncertainties $\sigma(a)$, $\sigma(b)$, the correlation coefficient r, and number of nebulae n.

The gradients are better seen in Figs.1–4, where we show the radial variation of the abundances of O/H, Ne/H, S/H, and Ar/H respectively, separating in each case PN of types I, II, and III. Several conclusions can be drawn from the observed gradients:

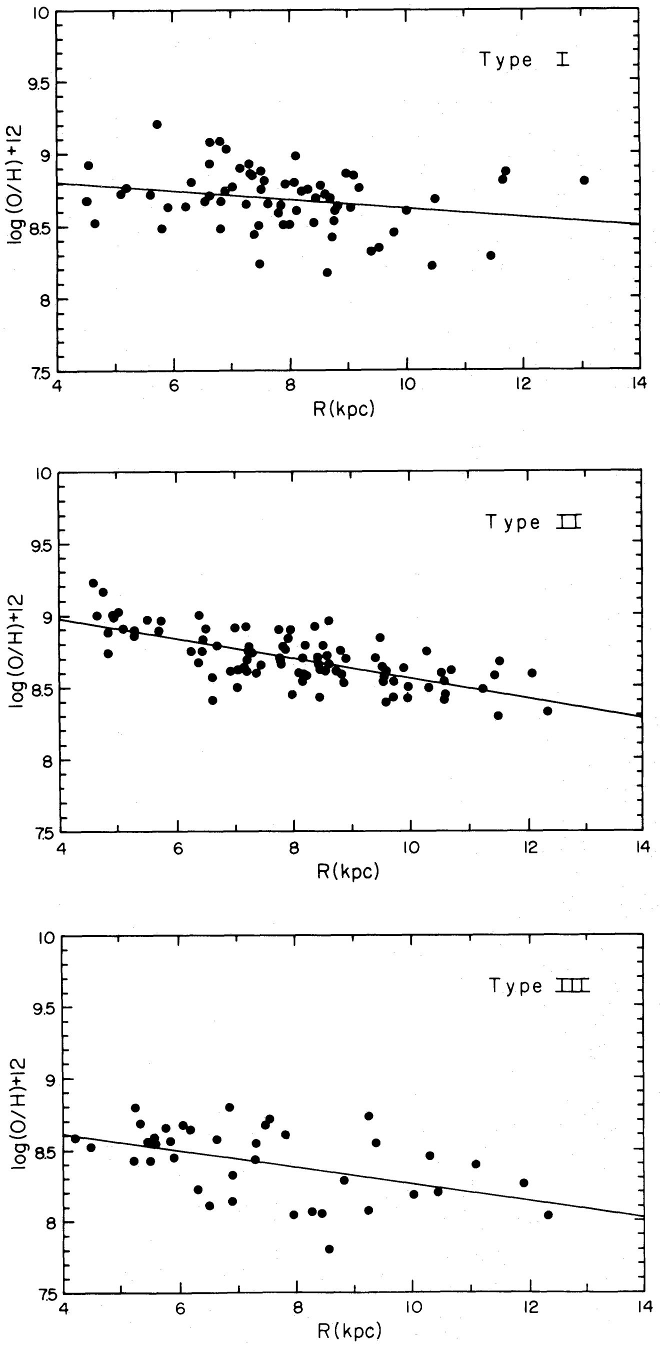

Fig. 1. O/H radial gradients for planetary nebulae: type I (upper panel), type II (middle panel), type III (lower panel)

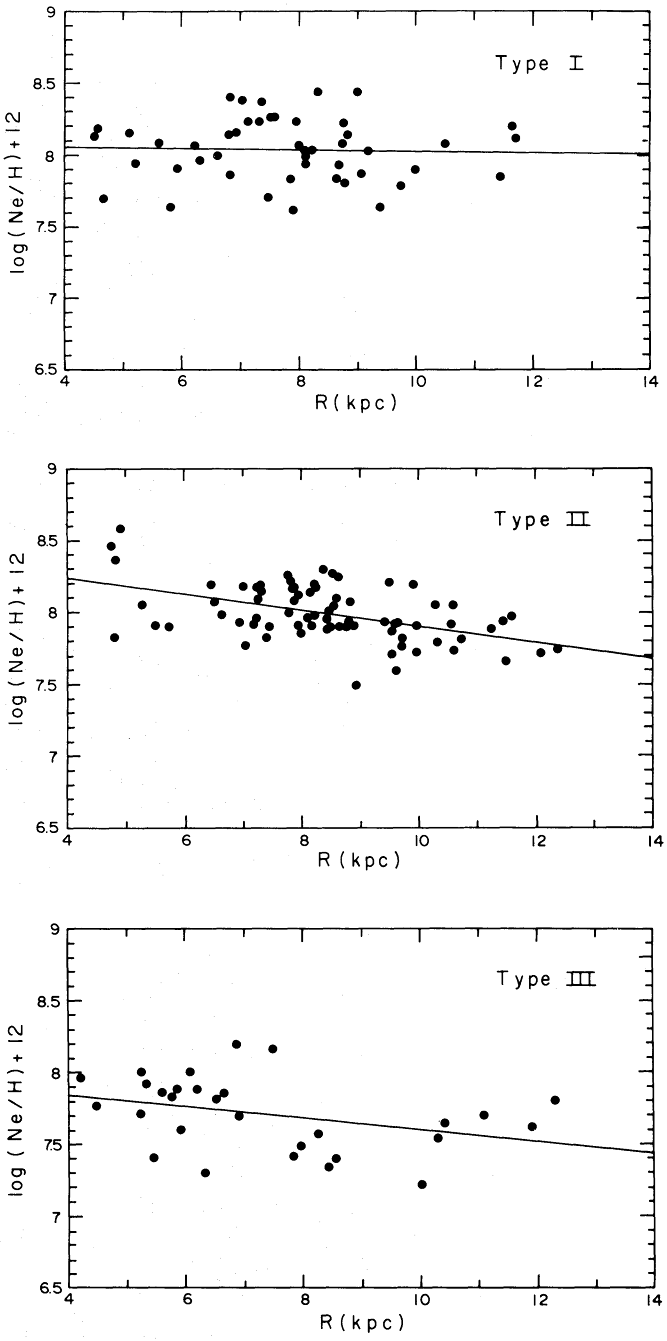

Fig. 2. The same as Fig. 1 for Ne/H

(i) The main conclusions by Faúndez-Abans & Maciel (1986; 1987a) are confirmed, i.e., type II PN display the best determined gradients (with correlation coefficients of about 0.5–0.7). The magnitudes of the gradients are similar for the ratios O/H, Ne/H, S/H, and Ar/H, amounting to $-0.06\,\mathrm{dex\,kpc^{-1}}$, which is somewhat lower than the reported O/H gradient for H II regions ($-0.07\,\mathrm{dex\,kpc^{-1}}$). This conclusion is reinforced by the fact that the electron

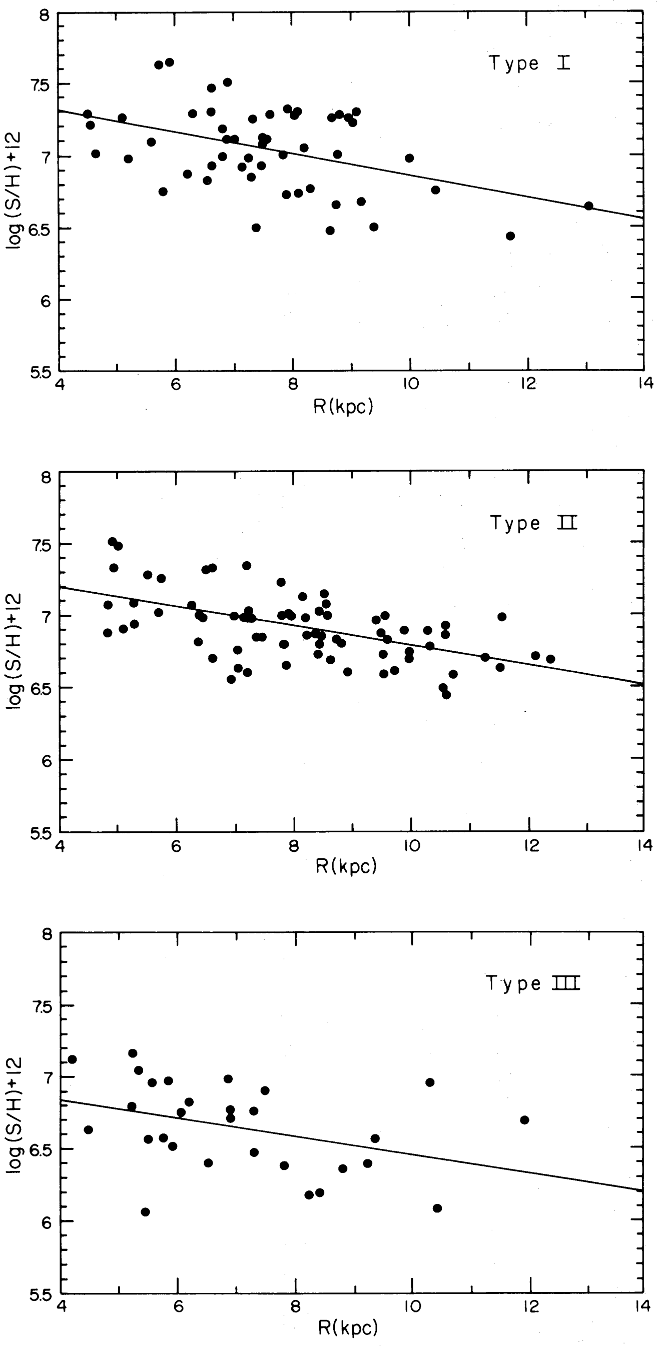

Fig. 3. The same as Fig. 1 for S/H

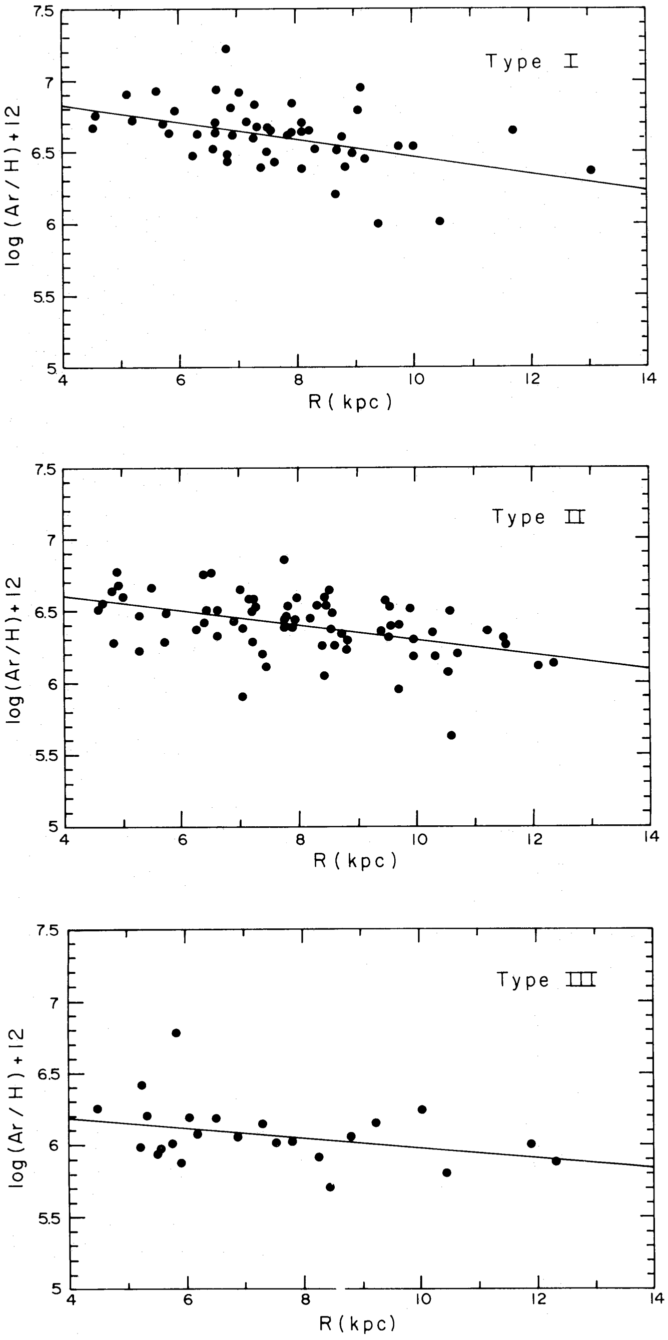

Fig. 4. The same as Fig. 1 for Ar/H

temperature of type II nebulae present a well defined gradient, $dT_e/dR \simeq 700$ K kpc^{-1} with a correlation coefficient $r = 0.75$, in agreement with previous results based on a smaller sample (Maciel & Faúndez-Abans 1985). Although the temperature gradients may be affected by other processes (central star temperature, dust, etc.), it is expected that they reflect the gradients in the abundance of the coolants (O, S, ...) in the nebulae.

(ii) The gradients from PN of types II and III are generally similar, within the estimated average (formal) uncertainty $\sigma \simeq 0.01$ dex kpc^{-1}. Type I PN have similar gradients for S/H and Ar/H, but not for O/H and Ne/H, as discussed below. Therefore, apart from the data of type I PN, in a first approximation all other gradients could be taken as roughly constant, although the scatter of the data is higher of non-type II nebulae, in agreement with our previous discussion.

(iii) There is some indication that *the gradients become steeper along the sequence of types III–II–I*, which can be considered as a progression in time. The differences are quite small (often at the third decimal place in Table 3), and are best seen in sulphur and argon. For oxygen and neon, the behaviour of type I PN shows some discrepancies, as discussed below.

(iv) The analysis of the gradients for the sub-types of PN IIa and IIb (Faúndez-Abans & Maciel 1987b) confirms the above findings: the gradients for type IIa are steeper than for IIb, although the small number of the latter and their confinement to a small range of galactocentric distances increase the uncertainty of the derived gradients.

The behaviour of type I PN is not yet clear, in the sense that O/H and Ne/H seem to display lower gradients than the other elements (cf. Table 3). Several explanations are possible:

1. Uncertainties in the determination of the abundances may particularly affect the classification of this group of objects. This is especially true for the He abundances, for which recent work indicates several discrepancies (Freitas Pacheco et al. 1992).

2. Uncertainties in the nebular distances, in particular those at larger galactocentric distances, may alter the derived gradients. For example, the exclusion of the 3 outermost nebulae in Fig. 1 suffices to bring the gradient from -0.030 to -0.057 dex kpc^{-1}, closer to the remaining gradients. For Ne/H, this is not enough to produce steeper gradients, and the lack of nebulae with large abundances closer to the inner limit of 4.0 kpc is more likely to be responsible for the low gradient observed.

3. Some type I PN have He/H and N/O both enhanced, while others present enhancements in only one of these ratios. The inclusion of both types on the same plot would probably contribute to mask any gradients.

4. ON cycling: as discussed in the beginning of this section, there are evidences for ON cycling in some of the type I nebulae. For these objects, there seems to be an anticorrelation between N/O and O/H (cf. Maciel 1992a; Peimbert 1984; Henry 1990, and the next section), that is, PN with low O/H (8.0–8.5) tend to have high N/O (0.0–0.5 dex). This means that some oxygen has been turned into nitrogen, decreasing O/H and further increasing N/O, thus reducing the gradients. Since neon follows oxygen closely, this could qualitatively explain the low O/H and Ne/H gradients for type I PN in Table 3.

5. As younger objects, type I central stars were formed out of an interstellar medium richer in heavy elements, compared with the remaining types. This will move the abundances upwards, and would also contribute to increase the dispersion, since in our sample there may be some confusion with objects with different ages.

Abundance gradients from galactic planetary nebulae have been recently investigated by Amnuel (1993), using a classification scheme which includes some additional criteria relative to the Peimbert system. Broadly speaking, Amnuel's "L" nebulae include out type III and probably type IIb objects, the "In" nebulae include low mass type I and probably type IIa PN, and "M" nebulae are all type I. A comparison with the gradients given here shows that a reasonable agreement exists for the nebulae ejected by the more massive stars (type I or "M"). For the remaining nebulae, our average gradients are generally steeper than those derived by Amnuel (1993), except for the subgroup of "L" nebulae with larger (> 300 pc) distances to the galactic plane. However, a direct comparison of the two classification systems is rather uncertain, especially in view of the fact that the central star mass – a basic parameter in the scheme by Amnuel (1993) – is not known for individual nebulae, and correlations of this parameter with the chemical abundances are controversial (cf. Pottasch 1993a). This is strengthened by the lack of Ar/H and S/H gradients from stars in the low mass range in the work of Amnuel (1993), in contrast with the results shown in Table 3. In fact, from stellar evolution models for these stars, these elements are expected to follow oxygen and neon, so that their gradients should be similar.

4. Distance effects

It is well known that distance determinations for planetary nebulae remain an extremely difficult issue, despite the large effort put in the last decade (cf. Terzian 1993; Pottasch 1993b). Therefore, it is interesting to investigate the possibility that the adopted distances might be introducing some systematical effect on the derived gradients. This can be performed (i) by adopting a different set of distances and abundances, as done by Köppen et al. (1991), whose results are not very different from those given here, provided the adopted classification is made in similar terms.

As another test, (ii) Fig. 5 shows the O/H abundances for type II nebulae from Table 2 plotted against position adopting recently published distances from Cahn et al. (1992). As shown by comparing this figure with the middle panel of Fig. 1, the correlation is similar, and the obtained slope is only slightly smaller, due to the fact that the distances by Cahn et al. (1992) are up to 40% larger than given in Table 1, especially for the distant nebulae.

Finally, (iii) the relative chemical abundances of the galactic planetary nebulae can also be investigated on the basis of distance-independent correlations, as discussed for example by Henry (1990) and Maciel (1992a). This is

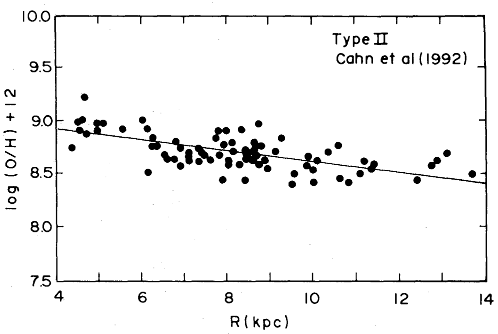

Fig. 5. O/H radial gradient for type II PN with distances from Cahn et al. (1992)

shown in Figs. 6–8, where we have plotted Ne/H, S/H and Ar/H, respectively, against O/H for all nebulae of Table 2. The slopes are close to unity, and it can be concluded that the presently enlarged sample provides good correlations in all cases, so that Ne, S and Ar are confirmed as tracers of interstellar abundances in the same way as O, which is consistent with the previous conclusions by Henry (1990) and Maciel (1992a). In fact, it can be shown that, from the data of Table 2, consistent conclusions can be obtained regarding not only the elements synthesized by large mass stars (O, Ne, S, Ar), but also those elements synthesized by intermediate mass stars (He, N, and C), which are not discussed here.

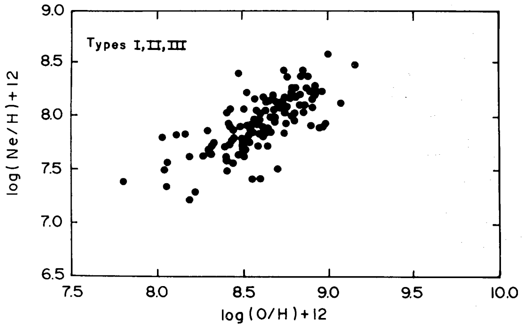

Fig. 6. Ne/H as a function of O/H for planetary nebulae of types I, II, and III

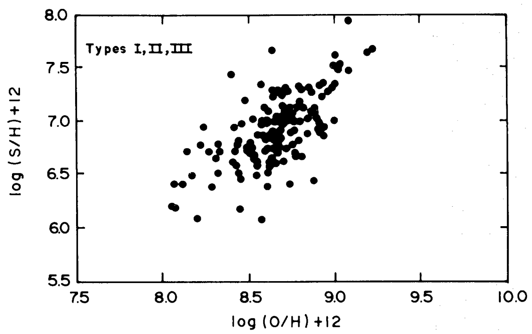

Fig. 7. The same as Fig. 6 for S/H

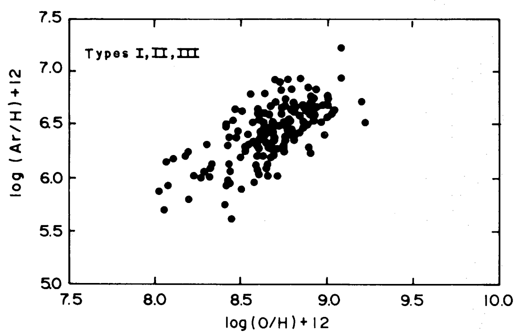

Fig. 8. The same as Fig. 6 for Ar/H

As a general conclusion of items (i)–(iii), the adopted abundances form a consistent set of data, and the gradients derived in the previous section can be considered as independent of the particular distance scale adopted, within the estimated uncertainties. On the other hand, it must be kept in mind that any uncertainties in the distances would probably contribute in the sense as to mask existing gradients, rather than creating them.

5. Time evolution of abundance gradients

From the previous discussion, two different approaches could be taken when interpreting the abundance gradients from planetary nebulae: Firstly, one might take a *conservative* view, i.e. that all PN types give the same gradient, within the error bars. On the other hand, one may adopt an *evolutionary* approach, accepting that the small steepening observed in the sequence of III, II, and I PN types is real. Then, type III PN, the oldest objects, show a *flatter* gradient than types II, I (within the limitations discussed in Sect. 3), and H II regions. This could be explained by assuming that either (i) the interstellar gradient did not change very much, but the PN central stars moved away from their birthplaces, thus washing out the existing abundance differences, or (ii) the interstellar conditions evolved with time so as to enhance the metallicity gradients. At present, it is difficult to distinguish between these possibilities, although some order-of-magnitude calculations may help us to understand this situation. Let us check hypothesis (i): Assuming that the interstellar abundance gradient was like that of the present H II regions, $d\log(X/H)/dR \simeq -0.07\,\mathrm{dex\,kpc^{-1}}$, which makes an abundance difference over the observed range of $R = 6$ kpc to $R = 12$ kpc of about -0.42 dex. During their lifetime, the stars can move easily in the azimuthal direction, but their radial motion is restricted to about 1 kpc (R. Wielen, private communication). Therefore, the maximum decrease in the gradient will occur if the stars born at $R = 6$ kpc move to $R = 5$ kpc, and those from $R = 12$ kpc go to $R = 13$ kpc. Since the abundances are essentially the same, the new gradient is $d\log(X/H)/dR \simeq -0.42/8 \simeq -0.05\,\mathrm{dex\,kpc^{-1}}$, that is, we get a *maximum decrease* of about $0.02\,\mathrm{dex\,kpc^{-1}}$, twice the average difference between type III and type II PN. Thus, within the uncertainties involved, this process could well explain the observed behaviour of the PN abundance gradients.

In order to investigate hypothesis (ii), we must take into account predictions from theoretical models for the determination of the gradients and their time evolution. Calculations based on the simple model may predict the right order of magnitude of the gradient, but are probably unable to distinguish among the different PN types. As an example, Maciel (1992b, 1993) used the simple model to explain the O/H gradient from type II planetary nebulae. In this model, a larger fraction of the gas has turned into stars in the inner regions of the Galaxy as compared to the outer regions (cf. Pagel 1979), which explains the amount of the gradient detected. However, in order to obtain different gradients for the PN types, one has to assume further some dependence of the yield with the galactocentric radius for a given stellar mass. Since the observed differences in the gradients are very small, it can be concluded that more sophisticated models are necessary.

The time evolution of the O/H gradient has been studied for three galaxies by Mollá et al. (1990), on the basis of chemical evolution models with star formation rates decreasing exponentially with time and infall of unenriched gas (Díaz & Tosi 1984, 1986; Tosi & Díaz 1985). As a result of the "Standard Model", in the Galaxy the oxygen gradient shows a definite increase in the last few Gyr, as measured in three galactic rings at 3.5, 7.5 and 9.5 kpc from the centre. Similar results are also obtained for the galaxy M 101. Although the absolute value of the derived gradients may be affected by some adopted stellar evolution parameters, it seems clear that the steepening of the oxygen gradient with time is real.

In order to present numerical results, let us consider the chemical evolution models developed by köppen (1993). In these models, the time evolution of the abundance gradients is computed taking into account infall and radial gas flows. An analytical approximation can be written as (for details see Köppen 1993)

$$\frac{\mathrm{d}\log Z}{\mathrm{d}R} = A + Bt\,, \tag{3}$$

where the initial gradient A is determined by the *radial gradient* of chemical yield y and/or the *radial gradient* of the star formation timescale, while this value can be changed by a combination of radial inflows and slow gas infall into the disk, the parameters of which determine B. A linear dependence of the star formation rate (SFR) on the gas density (g) gives a constant star formation timescale (SFR/g), resulting in a zero initial metallicity gradient. A non-linear dependence gives a negative initial gradient, the value of which depends on the exponent. Equation (3) is a linear approximation to the real evolution, which can be computed numerically.

In order to compare these models with the PN data, we must assign mean ages to the different types of PN. As a first approximation, we adopted

0–2 Gyr for type I,
4–6 Gyr for type II,
8–10 Gyr for type III.

This has been "calibrated" by the younger type I nebulae, and by the fact that type II objects in the solar vicinity have approximately solar abundances, so that their age is roughly 5 Gyr.

The association of age groups with the different PN types is consistent with the recent analysis of galactic planetary nebulae by Freitas Pacheco (1993). The sample considered by him is smaller (122 nebulae), but has a higher degree of homogeneity, as it is based on observations by two groups only. A different age-metallicity relation was used, so that the absolute ages are different, especially in the older groups. However, from his results, the general conclusions derived in this section remain the same.

In Fig. 9 we show the PN abundance gradients along with results from numerical models from Köppen (1993). The behaviour of the PN gradients can be explained by several models. A nonlinear SFR (power 1.5) without any appreciable radial flows gives a fairly constant metallicity gradient, in agreement with the PN gradients (in the *conservative* view). However, this model gives a present gradient somewhat flatter than observed with the H II regions. A more serious disagreement would be the absence of abundance gradients in old disk stars (Köppen 1993), since this model would have a steep initial metallicity gradient (-0.05 dex kpc^{-1}). A quadratic SFR with some mild radial flows could also explain the PN data, but would need an even steeper initial gradient. Nonlinear star formation rates with power less than 2.5 have been recently derived by Carigi & Franco (1992) from analytical models based on the instantaneous recycling approximation with radial flows.

Models where the gradient steepens in time (the *evolutionary approach*) would be an attractive possibility: a slightly non-linear SFR (power 1.2) and radial gas flows with a flow velocity in the solar neighbourhood of 1 km s^{-1} would be in very good agreement not only with the PN

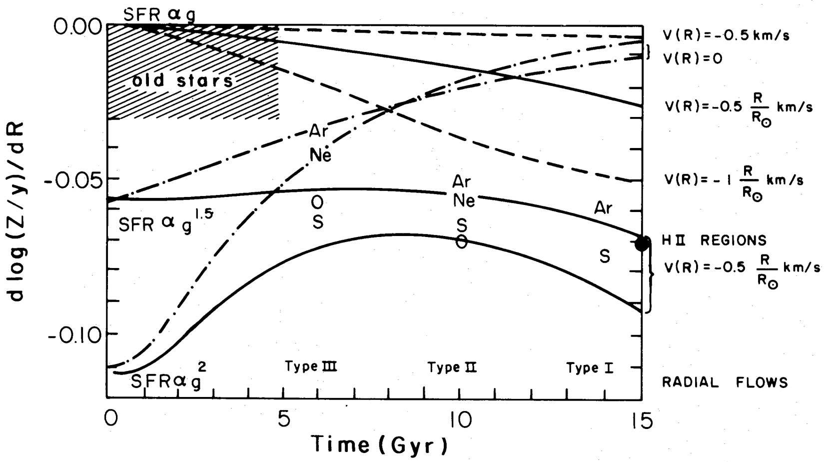

Fig. 9. Time evolution of the abundance gradients: models from Köppen (1993) and PN data from Table 3

and H II region data, but also with the evidence from old disk stars and disk globular clusters. Therefore, it can be concluded that the results presented in Sect. 3 are consistent with a slight increase of the gradients since the formation of the first PN still observed in the galactic disk.

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