

## PLANETARY NEBULAE: ABUNDANCES AND ABUNDANCE GRADIENTS

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**Abstract.** In this work, a review is given of some recent results and problems involved in the determination of chemical abundances of galactic planetary nebulae, particularly regarding disk and bulge objects.

### 1. Introduction

Chemical evolution models for the Galaxy can be included in one of four main classes: (i) analytical models, (ii) classical models, (iii) multiphase models and (iv) chemodynamical models (see for example Pagel 1997, Matteucci 1996). These models share a common characteristic, that is, they have to satisfy a series of observational constraints, most of which are related to the determination of chemical abundances. Some examples are the average gas metallicity in the disk, the age-metallicity relation and the existence of abundance gradients.

Planetary nebulae (PN) have an important role in the establishment of these constraints. As it is well known, PN are formed from the late evolutionary stages of intermediate mass stars ( $1 \leq M/M_{\odot} \leq 8$ ), and their chemical composition reflects the nucleosynthetic processes that occur in these stars. Elements such as He and N can be significantly enhanced by the stellar chemical evolution, while S and Ar are probably unaltered during the evolution of the progenitor star, so that the nebular abundances of these elements can be taken as the interstellar abundances at the time when the progenitor star was formed.

In the framework of the Peimbert (1978) classification scheme PN can be classified as: Type I (disk objects with massive progenitors), Type II (disk objects with average mass progenitors), Type III (thick disk objects, kinematically detached), Type IV (halo objects), and Type V (bulge objects) (see also Maciel 1989, Torres-Peimbert and Peimbert 1997).

In this work, some recent results concerning the abundance determinations of PN are considered, both regarding the abundances themselves and their spatial and temporal variations. The following sections discuss PN of types I–III (section 2), type IV (section 3) and type V (section 4).

## 2. The galactic disk

### 2.1. ABUNDANCES

Several independent groups have obtained abundances of disk PN, mainly from spectroscopic observations of visible and ultraviolet emission lines coupled with ionization correction factors or photoionization models. Some recent results are given by Kwitter and Henry (1998), Hajian et al. (1997) and Costa et al. (1996a).

Typical errors of the line intensities are of the order of 10–20%, leading to similar uncertainties in the derived electron temperatures. The abundances themselves have generally errors of 0.1–0.2 dex for the best measured elements, such as O/H and S/H, and somewhat higher for Ar/H and Cl/H. Geometrical effects as well as temperature fluctuations may increase these figures, especially for PN with massive central stars (Gruenwald and Viegas 1998). A discussion on the accuracy of the derived chemical abundances based on hydrodynamical models has been recently given by Perinotto et al. (1998).

Table 1 shows average values of the abundances of disk PN (Costa et al. 1996a). Type II has been subdivided into types IIa and IIb, according to Faúndez-Abans and Maciel (1987), and the table also lists types IV and V PN, which will be commented upon later. Only the best observed elements are given, though some recent work includes less abundant elements such as Si, Mg, Na and Fe (Perinotto et al. 1999, Pottasch and Beintema 1999).

The first group of abundances gives  $\epsilon(X/H) = \log(X/H) + 12$ , where X/H is the element abundance relative to hydrogen by number of atoms. For helium, the table gives the He/H ratio directly. The last two rows of the table give the average height  $z$  above the galactic plane (pc) and the peculiar velocity  $\Delta v$  (km/s). It can be seen that the He/H ratio increases in the disk along the sequence III–II–I, similarly to N/H, S/H, Ar/H and Cl/H. For O/H and Ne/H, there is an increase from type III to type II, but the average abundances of type I PN are not clearly higher than for type II, which may be partially due to ON cycling in the progenitor stars.

TABLE 1.

	I	IIa	IIb	III	IV	V
He/H	0.138	0.106	0.104	0.099	0.104	0.104
$\epsilon(\text{O}/\text{H})$	8.68	8.78	8.58	8.42	8.08	8.71
$\epsilon(\text{N}/\text{H})$	8.57	8.29	7.78	7.74	7.41	8.16
$\epsilon(\text{S}/\text{H})$	7.04	7.02	6.83	6.74	5.64	6.87
$\epsilon(\text{C}/\text{H})$	8.67	8.78	8.73	8.48	8.54	
$\epsilon(\text{Ne}/\text{H})$	8.03	8.06	7.87	7.71	7.27	
$\epsilon(\text{Ar}/\text{H})$	6.61	6.47	6.26	6.07	5.22	6.22
$\epsilon(\text{Cl}/\text{H})$	5.43	5.32	5.00	4.99		5.05
$\log(\text{N}/\text{O})$	-0.11	-0.49	-0.80	-0.68	-0.67	-0.55
$\log(\text{Ne}/\text{O})$	-0.65	-0.72	-0.71	-0.71	-0.81	
$\log(\text{S}/\text{O})$	-1.64	-1.76	-1.75	-1.68	-2.44	-1.84
$\log(\text{Ar}/\text{O})$	-2.07	-2.31	-2.32	-2.35	-2.86	-2.49
$\log(\text{Cl}/\text{O})$	-3.25	-3.46	-3.58	-3.43		-3.66
$z$ (pc)	150	280	420	660	7200	
$\Delta v$ (km/s)	20.5	21.3	22.1	64.0	172.8	

The second group of abundances in Table 1 shows abundances relative to oxygen of those elements (Ne, S, Ar, Cl) that are not produced during the evolution of the progenitor stars, so that they can be considered as representative of the interstellar medium at the time of formation of these stars. Except for halo (type IV) PN, all objects have essentially constant ratios, a result that has been confirmed for S, Ne and Ar for HII regions both galactic and extragalactic (Henry and Worthey 1999). The ratio N/O is also included, as it is used to distinguish between type I and non-type I nebulae.

Abundance correlations are particularly important in order to understand the nucleosynthetic processes occurring in the progenitor stars, since they do not depend on the often uncertain distances. Examples are the S/H  $\times$  O/H and Ne/H  $\times$  O/H as well as N/O  $\times$  He/H correlations, which can in principle be used to separate the different PN types according to the mass of the progenitor star (Costa et al. 1996a, Henry 1998).

A potentially interesting source of information on PN abundances is their morphology, particularly since the publication of detailed high resolution images by Schwarz et al. (1992), Manchado et al. (1996) and Górný et al. (1999). Recent results based on HST observations show a clear evidence of N/O enhancements in bipolar nebulae (class B), and a corresponding un-

derabundance for round PN (class R) (Stanghellini et al. 1999, Stanghellini 1999). On the other hand, elliptical PN (class E), which form the majority of galactic PN, show a wider range of N/O abundances. The immediate conclusion is that B nebulae have relatively massive progenitors, in agreement with their being generally closer to the galactic plane, while R nebulae are ejected from stars near the lower bracket of the intermediate mass stars. E nebulae are probably formed by stars in the whole mass interval. As an example, the abundances of 13 bipolar nebulae studied by Perinotto and Corradi (1998) agree very well with those of type I objects given in Table 1. Previous evolutionary models for AGB stars did not predict the He and N enhancements observed in these objects, a situation that has recently changed with the extension of the theoretical calculations to stars with  $M \simeq 6M_{\odot}$  with overshooting (Marigo, this conference).

Abundance variations inside the nebula may be important, and are presently poorly known (Pottasch 1997). A recent study of bipolar nebulae (Perinotto and Corradi 1998) suggests that their observed sample is chemically homogeneous.

## 2.2. ABUNDANCE GRADIENTS

The study of radial abundance gradients includes basically (i) the average magnitudes of the gradients, (ii) the possible change of slope along the galactic disk, and (iii) the time variation of the gradients. The first item is relatively well established (cf. Maciel 1996, 1997, Henry and Worthey 1999), and it seems clear that an average gradient of  $-0.05$  to  $-0.07$  dex/kpc can be observed in the Galaxy for O/H, S/H, Ne/H and Ar/H. The PN derived gradient (Maciel and Quireza 1999, Maciel and Köppen 1994, Amnuel 1993, Pasquali and Perinotto 1993, Köppen et al. 1991) is close to – and slightly lower than – the well known gradient observed from HII regions in the Galaxy (Shaver et al. 1983, Afflerbach et al. 1997) and in other spiral galaxies (Kennicutt and Garnett 1996, Ferguson et al. 1998). Recent work on open cluster stars confirms these results (Friel 1999, Phelps, this conference), and also data on B stars, as recently discussed by Smartt and Rolleston (1997), Gummersbach et al. (1998), and Smartt (this conference), in contradiction with earlier work on these objects, which reported essentially flat gradients. The radial variations of O/H, S/H, Ne/H and Ar/H are consistent with essentially constant ratios of S/O, Ne/O and Ar/O from PN and HII regions, as can be seen from Table 1 and from a recent discussion on the gradients in the Galaxy and in other galaxies (Henry and Worthey 1999).

As an illustration, figure 1 shows the O/H gradient derived from HII regions in several spiral galaxies (Henry et al. 1994), along with the average

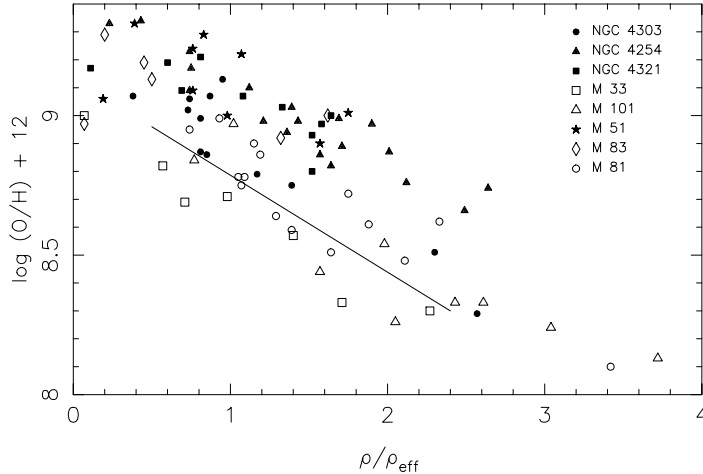


Figure 1. O/H radial gradient in spiral galaxies and PN (straight line).

gradient for disk PN in the Galaxy (straight line) from Maciel and Quireza (1999). In this figure, the abscissa gives the distance to the centre of the galaxy in terms of the effective radius, defined as the radius where half of the optical emission is contained (cf. Maciel 1997). The similarity of the PN and HII region gradients suggests that orbital diffusion is probably mild in the radial direction, since the PN population is at least a few Gyr older than the HII regions. Azimuthal diffusion could be much higher, however, as the PN are sampled all over the galactic disk. Therefore, figure 1 suggests that the gas is homogeneously distributed in the azimuthal direction. This can be confirmed by plotting the O/H abundances of PN in a concentric ring of width  $\Delta R$  around the galactic centre as a function of the longitude. No correlations are observed, even if relatively wide rings ( $\Delta R \simeq 1 - 2$  kpc) are considered. On the other hand, according to Wielen et al. (1996) the gradients are not much affected by orbital diffusion provided the surface density of stars falls off exponentially with the galactocentric distance  $R$ , and both the gradient and the diffusion coefficient do not appreciably change with  $R$ .

Radial variations of the gradients of O/H, S/H, Ne/H and Ar/H have been studied by Maciel and Quireza (1999). As an example, figure 2 shows the O/H gradient, where some recent data for planetary nebulae in the outer galactic disk from Costa et al. (1997) have been included. The dots are disk PN; the straight line gives a linear fit corresponding to  $-0.058$  dex/kpc; the curve is a second-order polynomial fit corresponding to a gradient of  $-0.058$  dex/kpc at the sun, where  $R_0 = 7.6$  kpc, and the step function has

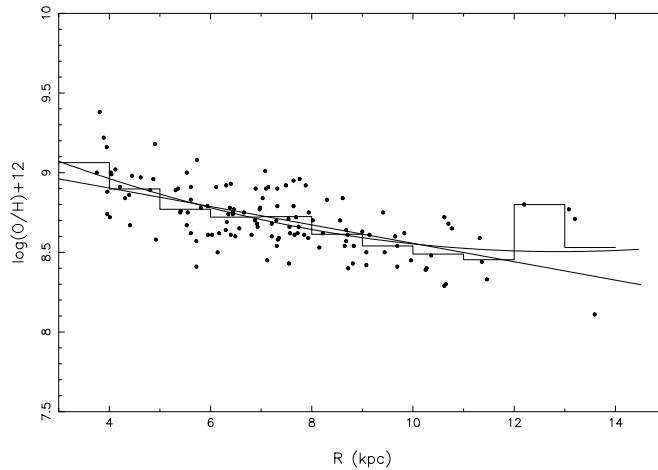


Figure 2. O/H gradient from disk PN (Maciel and Quireza 1999).

been fitted with 1 kpc bins. A flattening at large radial distances can be observed, in agreement with some recent work on HII regions (Vílchez and Esteban 1996).

The time variation of the abundance gradients is not as well defined, basically due to the fact that the ages attributed to PN are not sufficiently well known and the age difference between HII regions and B stars is relatively small. Type III PN are generally older and show flatter gradients, but part of this may be due to orbital diffusion. Including HII regions, B stars and the different types of PN, the present results are consistent with some steepening of the gradients, in agreement with earlier suggestions by Maciel and Köppen (1994), Golovaty and Malkov (1997) and Maciel and Quireza (1999). The latter obtained a rough estimate of the average steepening rate as  $-0.004 \text{ dex kpc}^{-1} \text{ Gyr}^{-1}$ . Despite the large uncertainty of this result, it clearly shows that any time variation in the gradients is probably small, so that the possibility of a constant gradient cannot be ruled out.

Radial gradients and their variations are extremely important as constraints to chemical evolution models. Recent classical models predict similar gradients as observed in the framework of an inside-out scenario, showing some flattening near the outer Galaxy and a time steepening (Chiappini et al. 1997, Matteucci and Chiappini 1999). Chemodynamical models (Samland et al. 1997, Hensler 1999) also predict some flattening at large  $R$ , and time steepening gradients are predicted by theoretical models by Götz and Köppen (1992) and Tosi (1988). On the other hand, multiphase models (Ferrini et al. 1994, Mollá et al. 1997) suggest just the opposite behaviour,

as also models developed by Prantzos and Silk (1998), Boissier and Prantzos (1999) and Allen et al. (1998), so that new independent observations and estimates of the gradients are needed to settle this question.

### 3. The halo

Only an handful of halo PN are known, and in some cases it is not clear whether the nebula is a true halo object or belongs to the thick disk. These PN have very low metal abundances as can be seen in Table 1, which shows very clearly halo–disk variations ranging from 0.10 dex to an order of magnitude, therefore much higher than the expected abundance uncertainties. A recent analysis of the halo object DDDM1 (Kwitter and Henry 1998) shows that the He, N, C, O, and Ne abundances are similar to those of type IV PN in Table 1. These abundances suggest that type IV PN reflect the metal poor conditions in the halo at the time of the formation of their progenitor stars, displaying a halo–disk vertical gradient, as found years ago by Faúndez-Abans and Maciel (1988) and confirmed by Cuisinier (1993), in contrast with an essentially flat vertical gradient for disk PN (Faúndez-Abans and Maciel 1988, Pasquali and Perinotto 1993, Cuisinier 1993).

From the second set of abundances of Table 1, it can be seen that halo PN have much lower S/O, Ne/O and Ar/O ratios than the remaining types, apart from being more metal-poor. According to Henry and Worthey (1999), these discrepancies could be caused by local abundance fluctuations due to unmixed ejecta from recent supernova events.

An additional problem is that several of the PN associated with the halo and thick disk (types III and IV) have probably low mass progenitors with strong stellar winds (Maciel et al. 1990, Maciel 1993). In fact, some of these nebulae apparently have central stars with masses under  $0.55 M_{\odot}$ , in contradiction with most evolutionary tracks for intermediate mass stars.

### 4. The bulge

Many bulge, or type V PN (Maciel 1989) are known (see for example Beaulieu et al. 1999), but only recently accurate abundances have been obtained (Ratag et al. 1997, Costa et al. 1996b). Recent work by Cuisinier et al. (1999) and Costa and Maciel (1999) has led to He, O, N, Ar and S abundances to about 40 bulge PN, with an uncertainty comparable to disk objects. However, van Hoof and van de Steene (1999) have found a larger scatter among the recent determinations for a sample of 5 bulge PN, which was attributed to uncertainties in the electron temperature.

A comparison of He/H and N/O abundances in the bulge and in the disk shows that objects with higher ratios are less present in the bulge,

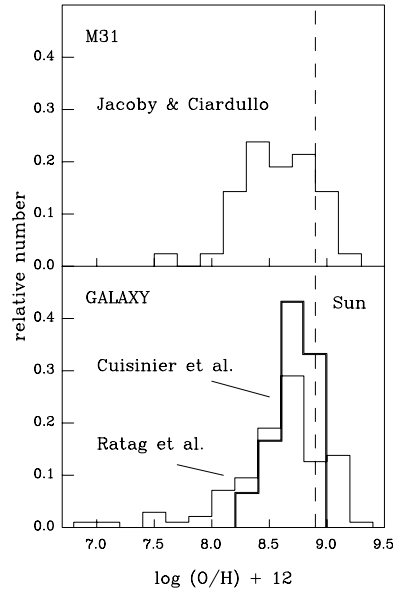


Figure 3. O/H distributions of bulge PN in the Galaxy and in M31.

suggesting that it contains an excess of older progenitor stars, since younger, massive objects are generally overabundant in these elements. On the other hand, the bulge metal abundances are generally comparable with those of the disk, and the O/H, Ar/H and S/H ratios can be higher than the disk counterparts even though very metal rich PN are missing in the bulge. Since underabundant nebulae are also present, these results suggest that the bulge contains a mixed population, so that star formation in the bulge probably spans a wide time interval.

Chemical abundances of PN in the bulge of M31 have been recently studied by Jacoby and Ciardullo (1999), who have included in their analysis some results by Stasińska et al. (1998) and Richer et al. (1999). Figure 3 shows a comparison of this sample (top panel) with the galactic bulge objects from Ratag et al. (1997) (lower panel, thin line) and Cuisinier et al. (1999) (lower panel, thick line). It can be seen that the O/H abundance distributions are very similar, peaking around 8.7 dex, and showing very few if any super metal rich objects with supersolar abundances.

This fact has been interpreted by Jacoby and Ciardullo (1999) as an inability of metal rich stars to produce sufficiently bright PN and to a possible gradient in the bulge of M31. Coupled with the He/H and N/O abundances, it would suggest again that the youngest and most metal rich PN are less frequent in the bulge.



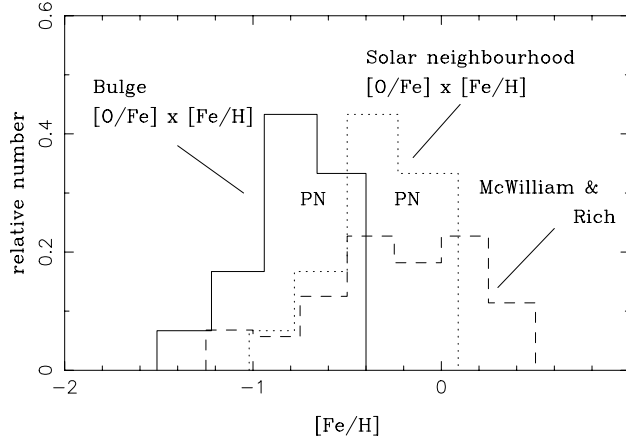


Figure 4. Metallicity distribution of bulge PN and K giants.

It is interesting to compare the PN metallicity distribution with the  $[\text{Fe}/\text{H}]$  distribution of stars in the bulge. A direct comparison depends on the adopted  $[\text{O}/\text{Fe}] \times [\text{Fe}/\text{H}]$  relationship, as Fe abundances are known for a limited sample of PN only. Adopting the  $[\text{O}/\text{Fe}] \times [\text{Fe}/\text{H}]$  relation for the *solar neighbourhood* (Matteucci et al. 1999), it can be seen from figure 4 that the observed peak in the PN metallicity distribution for the bulge (dotted line) looks similar to the distribution of K giants in Baade’s Window (McWilliam and Rich 1994, dashed line), but depleted of the very metal rich objects. In this case, the peak of the distribution occurs for  $[\text{Fe}/\text{H}]$  close to zero, which is also similar to the Mira variables metallicity distribution shown by Feast (this conference). Taking into account the predicted relationship of Matteucci et al. (1999) for the *bulge*, which assumes a faster evolution of the bulge compared to the halo, the observed peak of the PN metallicity distribution is displaced by about 0.5 dex towards lower metallicities (solid line), as in this case a given  $[\text{Fe}/\text{H}]$  metallicity implies a larger  $[\text{O}/\text{Fe}]$  ratio. As a result, the derived distribution shows an even stronger depletion of the very metal rich objects.

Several reasons can be considered to explain the differences in the metallicity distributions of figure 4, namely (i) systematic errors in the PN abundances, (ii) ON cycling in the PN progenitor stars, (iii) statistical uncertainties, and (iv) uncertainties in the adopted  $[\text{O}/\text{Fe}] \times [\text{Fe}/\text{H}]$  relationships. As discussed by Maciel (1999), the first three are probably not important enough to account for a 0.5 dex discrepancy as shown in figure 4, so that we suggest that the main reason is an excess of oxygen enhancement relative to iron in the bulge  $[\text{O}/\text{Fe}] \times [\text{Fe}/\text{H}]$  relation from Matteucci et al. (1999). This is supported by recent results by Barbuy (1999) for the bulge globular

cluster NGC 6528 and for the six giants in the McWilliam and Rich (1994) sample for which [OI] lines have been measured.

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