Planetary Nebulae in our Galaxy and Beyond
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Planetary nebulae as probes for galactic chemical evolution

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Abstract. The role of planetary nebulae as probes of galactic chemical evolution is reviewed. Their abundances throughout the Galaxy are discussed for key elements, in particular oxygen and other alpha elements. The abundance distribution derived from planetary nebulae leads to the establishment of radial abundance gradients in the galactic disk that are important constraints to model the chemical evolution of the Galaxy. The radial gradient, well determined for the solar neighborhood, is examined for distinct regions. For the galactic anticenter in particular, the observational data confirm results from galactic evolution models that point to a decrease in the gradient slope at large galactocentric distances. The possible time evolution of the radial gradient is also examined comparing samples of planetary nebulae of different ages, and the results indicate that a flattening in the gradient occurred, which is confirmed by some galactic evolution models. The galactic bulge is another important region whose modeling can be constrained by observational results obtained from planetary nebulae. Results derived in the last few years indicate that bulge nebulae have an abundance distribution similar to that of disk objects, however with a larger dispersion.

Keywords. Planetary nebulae: general, Galaxy: abundances, Galaxy: evolution

1. Introduction

Planetary nebulae (PN) constitute an important tool for the study of the chemical evolution of the Galaxy, being present in the disk, bulge and halo populations. By providing accurate abundance determinations of several chemical elements, these nebulae offer the possibility of studying both the light elements produced in low mass stars, such as helium, carbon and nitrogen, and also heavier elements, such as oxygen, sulfur and neon, which result from the nucleosynthesis of massive stars. The first group has abundances modified by the evolution of the PN progenitor stars, while the second reflects the conditions of the interstellar medium at the time the progenitors were formed.

Abundances derived for PN samples from different structures of the Galaxy can and should be used as constraints to galactic evolution models in order to reproduce their chemical evolution. In the last few years new samples from the bulge, disk and halo have been made available in the literature. Together they constitute a set of abundances that can be used to investigate the chemical evolution of the intermediate mass population in each galactic substructure.

Examining their chemical composition, important constraints for the modeling of the chemical evolution of the Galaxy can be derived, such as the abundance distribution in each galactic substructure, the radial gradient of abundances found in the disk, as well as its variation with galactocentric radius and with time.

In this paper we review some of the work done since the last IAU PN Symposium concerning the applicability of PN as probes for chemical evolution of the Galaxy. For

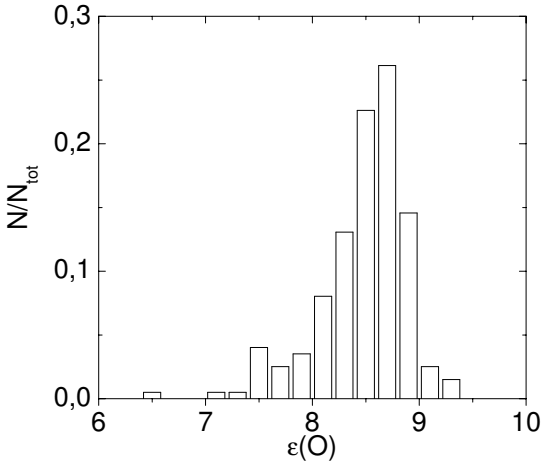


Figure 1. Distribution of oxygen abundances for bulge PN. (Escudero *et al.* 2004)

some interesting discussions of PN as a chemical evolution tool for other galaxies, the reader is referred to the recent volume edited by Stanghellini, Walsh & Douglas (2006).

2. The galactic bulge

From the observational point of view, it should be pointed out that although many new objects with accurate positions have been found in the bulge region (see for example Jacoby & van de Steene (2004)), the total number of bulge PN with accurate abundances is still small. Furthermore, a correlation between the chemical abundances and bulge kinematics is still to be determined, in contrast with the observed properties of the galactic disk. Besides, due to the nature and short lifetimes of PN, the presently available observational results are strongly biased since they are focused on brighter and younger objects.

In the past few years, many papers have been published dealing with the kinematics and abundances of the galactic bulge. Most of them are concerned with heavy elements produced by supernovae, so that light elements such as helium and nitrogen have had a smaller share of attention. In this context, PN constitute an important tool in the study of the bulge chemical evolution, providing accurate determinations of the abundances of light elements produced by progenitor stars of different masses, as well as heavier elements which result from the nucleosynthesis of high mass stars.

Galactic bulge PN provide accurate abundances of several elements that are difficult to study in stars (see for example Escudero & Costa (2001), Escudero, Costa & Maciel (2006), Exter, Barlow & Walton (2004), Górny *et al.* (2004) for some recent studies). These data on bulge PN can also be used in order to establish observational constraints to the [O/Fe] x [Fe/H] relation for the galactic bulge, which is important to derive the bulge evolution, as described by Maciel (1999). The results derived from different samples are similar. They have an abundance distribution similar to the disk with, perhaps, a larger dispersion. However, neither very poor nor super-metal-rich objects are found. Figure 1 shows the the oxygen abundance distribution for bulge PN as given by Escudero, Costa & Maciel (2004). In this figure and hereafter the notation ε(X)=log(X/H)+12 was adopted.

Figure 2 illustrates the typical distance-independent correlations between abundances. Dots represent the sample of Escudero, Costa & Maciel (2004) and crosses other data

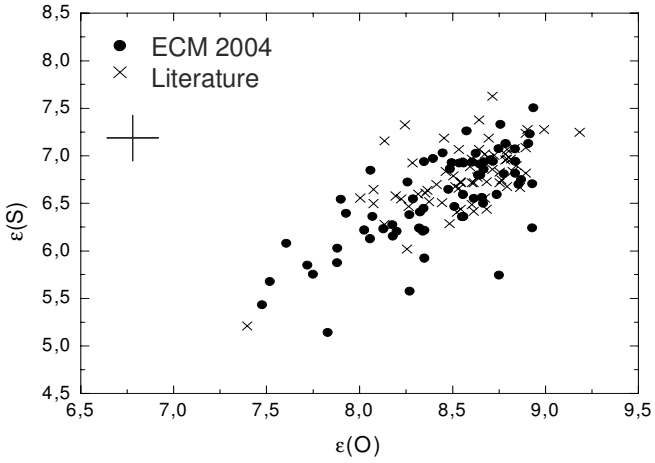


Figure 2. Sulfur abundance vs. oxygen abundance for bulge PN. Dots represent the sample of Escudero, Costa & Maciel (2004) and crosses the sample of Exter, Barlow & Walton (2004). It can be seen that both samples have similar distributions. (adapted from Escudero *et al.* 2004)

from the literature, mainly from Exter, Barlow & Walton (2004). The average error bar for the abundances is displayed at the upper left corner. The figure correlates the sulfur and oxygen abundances, which reflect the chemical abundances in the interstellar medium at the progenitor formation epoch. It can be seen that both samples have quite similar distributions. In this kind of diagram, high, intermediate and low mass objects are distributed sequentially, with higher mass objects located near the upper right corner of the figure while lower mass objects are at the lower left corner.

Additional results can be found investigating a special subsample of bulge PN: those with Wolf-Rayet central stars. Górny *et al.* (2004) investigate 164 PN toward the bulge, merging data from the literature with new observations, finding 18 objects with WR central stars and 24 other central stars with weak emission lines. Investigating these objects they found no difference between the oxygen abundances of normal PN and those with WR central stars, which implies that the oxygen abundances in WR are not significantly affected by nucleosynthesis or mixing in these objects.

As representatives of the intermediate age population of the bulge, PN can be used as constraints for chemical evolution models of this region. As an example, in figure 3 two samples of bulge PN are compared to different outputs of a multizone, double-infall chemical evolution model of the bulge, from Escudero, Costa & Maciel (2006). Continuous lines represent the central region of the bulge and dashed lines correspond to the first ring 1.5 kpc away. Thick and thin lines represent model outputs using different yields for low mass stars. It can be seen that the intermediate mass population described by the model fits reasonably well the observational data derived from PN. A small group of objects with low nitrogen and high oxygen abundances appears in both samples. Its presence can be understood if they are produced by a second infall episode, when material previously enriched by type-II supernovae ejecta falls onto the disk.

3. The radial gradient

The existence of a radial gradient of abundances in spiral galaxies has been known for a long time. Studying disks of spiral galaxies, Searle (1971) pointed out that abundance gradients should not be confined to the inner regions of galaxies but extend right across

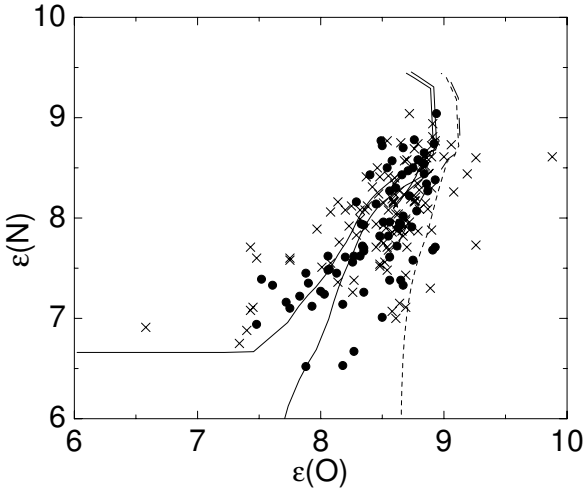


Figure 3. Two samples of bulge PN used as constraints for a bulge chemical evolution model. Continuous and dashed lines correspond to different zones in the bulge and thick and thin lines correspond to different yields for low mass stars. (Escudero *et al.* 2006)

galactic disks. As in other spirals, many results report the existence of a radial gradient in the solar neighborhood, see Maciel & Costa (2003) or Henry & Worthey (1999) for previous reviews. These results can also be examined within a more general framework for the chemical evolution of galaxies, e.g. that of Pagel (1997).

In the last years several works appeared in the literature, defining the radial gradient from different objects. Some of the recent works include Daflon & Cunha (2004) (using OB stars), Deharveng *et al.* (2000) and Carigi *et al.* (2005) (using H II regions), Andrievsky *et al.* (2004) (using Cepheids), Friel *et al.* (2002) (using open clusters) and Maciel, Lago & Costa (2005a) (using PN). In these works the derived slope for the gradient typically varies between -0.03 and -0.07 dex/kpc, as can be seen in the compilation by Stasińska (2004), which includes works from different authors, using PN and H II regions to derive the radial gradient from several elements. Using a homogeneous sample of PN, Henry, Kwitter & Balick (2004) find slopes between -0.03 and -0.05 dex/kpc for different elements.

For PN in particular, some key problems arise in the derivation of gradients. Their distances are usually derived from statistical methods, and errors are within a factor of two or even more. There are different distance scales available in the literature but, despite the fact that the computed slope in principle depend on the adopted distance for each object, the choice between different statistical distances does not significantly affect the magnitude of the gradient. Other important points that have to be taken into account when deriving gradients are the homogeneity of the samples and the relationship between nebular abundances and stellar nucleosynthesis for those elements whose abundances are changed during the progenitor evolution.

3.1. *The anticenter*

Most of the results concerning the radial gradient of abundances consider samples of objects with galactocentric distances between 3 and 10 kpc. Generally there is a considerable under-sampling of objects with distances larger than 10 kpc, and when the outer part of the disk is considered, results derived from PN indicate a flattening in the gradient around 10 kpc, as shown by Costa, Uchida & Maciel (2004). This result is also supported by data derived from Cepheids, however there are contradictory results when

H II regions and OB stars are used. Theoretical models for the evolution of spiral galaxies, e.g. Chiappini, Romano & Matteucci (2003) or Mollá & Díaz (2005), also support the existence of a flattening in the radial gradient of abundances around 10 kpc.

At present, it is not possible to know what happens to the gradient *beyond* 10 kpc. Data from PN and Cepheids indicate that there is a flattening indeed, but beyond this point the samples are too small to clearly define either a slope or a constant value. When examining chemical evolution models for the galactic disk, many of them predict a flattening in the abundances; however a different result appears when chemical and dynamical evolution of the galactic disk are combined. As described by Mishurov, Lépine & Acharova (2002), a chemo-dynamical model indicates a possible minimum of abundances around 8-9 kpc from the galactic center, followed not by a flattening but by an inversion in the gradient slope, with abundances increasing again outward. This effect could be explained by the presence of the co-rotation radius of the Milky Way nearly 8.5 kpc from the center. At this position there would be no compression of the spiral pattern onto the disk, causing a minimum in the star formation and then a minimum in the radial abundance distribution. Clearly this hypothesis deserves further attention, and new, larger samples of abundances at large galactocentric distances are required to better verify this hypothesis.

The flattening of the abundance gradient beyond 10 kpc probably reflects a lower star formation rate in the outer part of the disk compared to the regions closer to the galactic center. This is apparent from distinct PN data samples but less apparent, or even nonexistent, from O,B stars and H II regions, which implies a possible correlation between flattening and the time variation of the gradient.

3.2. *The time variation of the radial gradient*

As demonstrated by Maciel, Costa & Uchida (2003), if a sample of disk PN is divided into groups according to the approximate ages of their progenitor stars and the radial gradient is derived for each group, younger objects will always tend to have a flatter gradient, no matter how the age limits between the groups are defined. Based on a sample of PN in the galactic disk, they concluded that the O/H gradient flattens out from -0.11 to -0.06 dex/kpc during the last 9 Gyr, or from -0.08 to -0.06 dex/kpc in the last 5 Gyr. Later, Maciel, Lago & Costa (2005a) extended this analysis including S/H data and deriving the [Fe/H] gradient based on [Fe/H] $\times$ [O/H] and [Fe/H] $\times$ [S/H] calibrations, confirming the previous results. A detailed analysis of the errors involved in the determination of the gradients has been given by Maciel, Lago & Costa (2005b).

This approach is illustrated in figure 4. Group I (empty circles) is younger, with ages lower than the age limit shown, and Group II (filled circles) is older, with ages higher than the limit. The age limit that separates the groups varied from 3 to 6 Gyr. For each age limit, in steps of 0.25 Gyr, the gradient was calculated for both groups. The result indicates that the younger group always has a flatter gradient.

More recently, Maciel, Lago & Costa (2006) extended this discussion with data for oxygen, sulfur, argon and neon, and compared four distinct PN samples, including both highly homogeneous samples and compilations. Examining them it was possible to verify that the derived results are essentially the same, in the sense that younger objects show a flatter gradient, no matter what is the source of the abundances. This result is illustrated in figure 5, where four different samples of PN were used, showing basically the same result, in spite of some fluctuation that can be attributed mainly to under-sampling. The average error bar for the oxygen abundances is displayed at the lower right corner. The four samples used to derive these results are discussed in detail in the paper above mentioned, where similar plots for other elements are also presented.

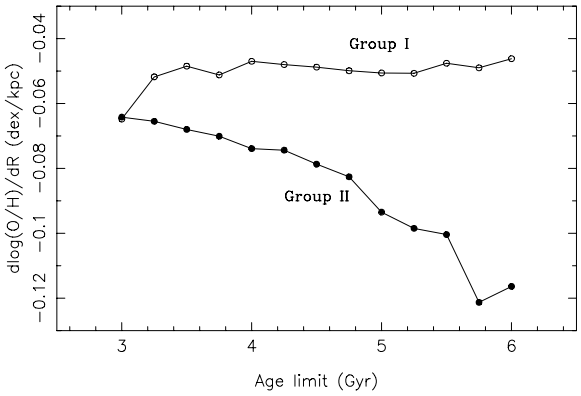


Figure 4. Time variation of the O/H gradient from planetary nebulae. The PN sample was divided into two age groups, Group I ('younger'), with ages lower than the age limit, and Group II ('older'), with ages higher than the limit. The plot shows the O/H gradient (in dex/kpc) of each group as a function of the age limit separating the groups. It can be seen that the gradients of the younger Group I are always flatter than those of the older Group II. (Maciel *et al.* 2005a)

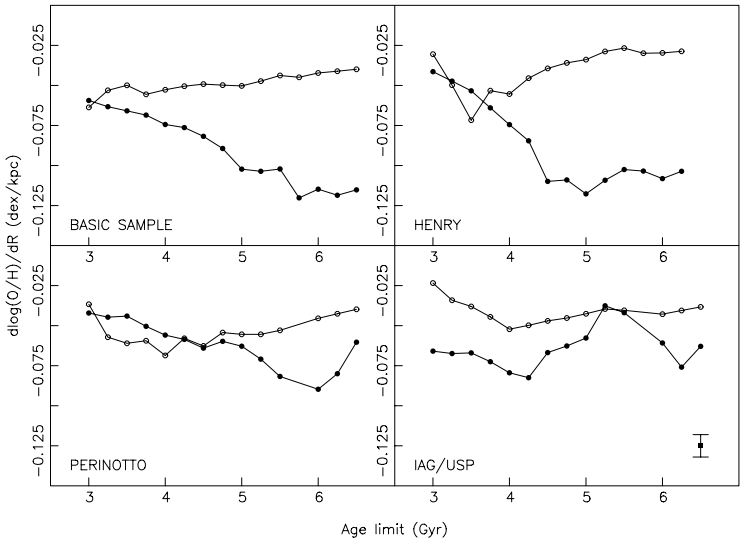


Figure 5. Time variation of the O/H gradient displayed for four PN samples. As in figure 4, the samples were divided in two age groups. The age limit between the groups varies from 3 to 6 Gyr. (Maciel *et al.* 2006)

Figure 6, from Maciel, Lago & Costa (2006) summarizes the conclusions on the temporal variation of the radial gradient. It displays the magnitude of the radial [Fe/H] gradient derived from different objects, reflecting the abundances of the interstellar medium at distinct epochs. Data for PN are divided into 'young' and 'old' groups, and combined with additional data from open clusters, Cepheids, OB stars and H II regions. The result indicates that older objects display gradients with larger slopes than those derived from H II regions or OB stars, which reflect the present abundances of the galactic disk. In the same figure chemical evolution models for the Galaxy by Chiappini, Matteucci & Romano (2001) and Hou, Prantzos & Boissier (2000) are also shown as illustrations. It can be seen that the latter, which predicts a time flattening of the radial gradient, fits well the observational data.

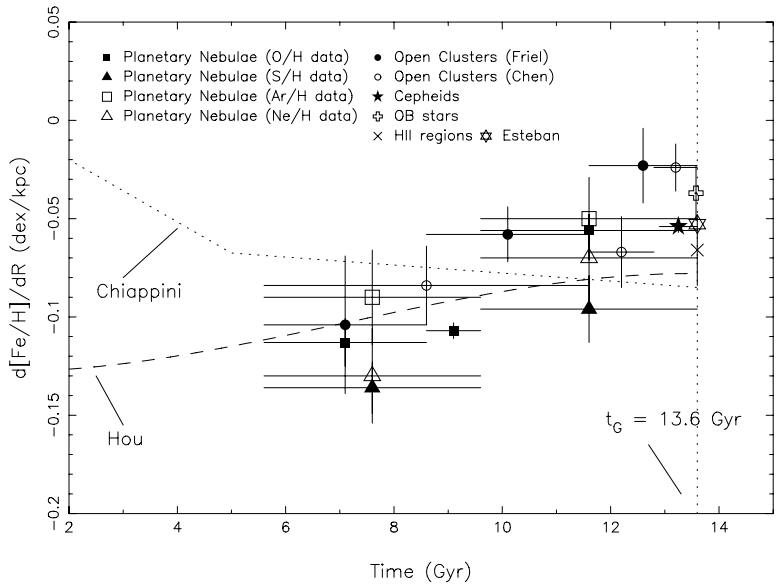


Figure 6. The magnitude of the radial [Fe/H] gradient derived from different objects, reflecting the abundances of the interstellar medium at distinct epochs. Gradients from PN are combined with data from open clusters, Cepheids, OB stars and H II regions, and the result indicates that older objects have gradients with larger slopes than those derived from H II regions or OB stars. The outputs of two chemical evolution models are also shown, and the adopted age for the galactic disk is indicated at the lower right corner. (Maciel *et al.* 2006)

The origin of the time variation of the radial gradient is related to the evolution of the galactic disk. It can be understood considering that the flattening in the gradient, initially located near the outer border of the galactic disk, spreads inward as the galactic chemical evolution proceeds, resulting in a flatter gradient. Gradients that flatten out in time with a decreasing flattening rate in the last few Gyr are supported by models proposed by Hou, Prantzos & Boissier (2000) or Mollá & Díaz (2005). In particular, different timescales for star formation and infall rates can account for the detected time variation of the radial gradient. In fact, models such as those by Hou, Prantzos & Boissier (2000) or Chiappini, Matteucci & Romano (2001) can predict either flattening or steepening of the gradient, depending on the star formation and infall timescales.

4. The halo

Halo PN belong to the old, metal poor halo population, and therefore can be used to probe the chemical evolution of its intermediate mass population, in the same way PN of types I, II, III are used to infer the disk chemical evolution. However, the available sample of halo PN is very small. Collecting data up to the end of 2001, Stasińska (2004) mentions a total of 20 objects. Howard, Henry & McCartney (1997) derived the chemical composition for nine halo PN, finding subsolar O/H abundances for the whole sample, with ε(O)=7.61 for K648, the most metal poor object of their sample. They also found that the spreads in Ne/O, S/O and Ar/O were consistent with the scatter found for halo stars, suggesting that accretion of extragalactic material occurred during the formation of the halo.

In the last few years some additional objects had their abundances reported. One of them deserves particular attention: PN G 135.9+55.9 was studied by Richer *et al.* (2002),

who found extremely low oxygen abundances, $5.8 < \varepsilon(\mathrm{O}) < 6.5$, with $\mathrm{H}\alpha/\mathrm{H}\beta$ unusually low, and found to be variable between different runs and even among individual spectra, suggesting the presence of some sort of accretion disk. Later Péquignot & Tsamis (2005) examined more accurately the atomic physics involved in the chemical diagnosis and concluded that the oxygen abundance is around 1/30 solar, which is the lowest oxygen abundance for a planetary nebula. They concluded that this is an extreme Population II object, reinforcing the idea of an endogenous origin of part of the oxygen.

Acknowledgements

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