
The chemical gradient of oxygen in the Galaxy from planetary nebulae

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ABSTRACT

The chemical gradient of oxygen in the Galaxy from planetary nebulae (PNe) has been closely investigated using a recent extensive fully homogenous set of chemical determinations (up to end of 2001) and various distant scales. The found gradient is quite flatter than believed so far, amounting to about \(-0.016 \pm 0.008 \log(O/H) \text{kpc}^{-1}\) insensitive to the distance scales, when all PNe of types I, II, III of Peimbert are used. The value is \(-0.02 \pm 0.01\) if only type II PNe are considered, thus reducing the ambiguity introduced by the mixing up of progenitors coming from a large spread in mass.

A second control set made by the chemical oxygen abundances determined by all studies between 2002 and 2005, with a data base of some 200 objects, provides a similar result.

Since previous determinations do have a spread in the slope of the galactocentric oxygen gradient from PNe between \(-0.07\) and \(-0.01\), further work is required to assess the matter. If our low value will be confirmed, the suggestion arises that type II PNe, due to mixing processes, might have lost their ability to be good tracers of oxygen abundance in the interstellar medium at the time of formation of the progenitors.

Key words: planetary nebulae: general.

1 INTRODUCTION

The existence of chemical gradients of metals in spiral galaxies has been established long ago, both vertical, i.e. normal to the Galactic plane, and horizontal, i.e. across the Galactic plane or disc. The first type of gradients is commonly associated with the behaviour of stellar populations; both types are linked with the history of formation and evolution of the Galaxy.

Various kinds of objects can indeed serve to probe the metallicity across the Galaxy, at specific epochs with proper time resolutions.

Various useful categories of objects include metal-rich or perhaps super metal-rich stars (Spinrad & Taylor 1969), H II regions, Population I OB stars belonging to open clusters or associations, Cepheid variables, planetary nebulae (PNe), supergiants, giant stars, SNRs, G & K main sequence stars (cf. Shaver et al. 1983; Schields 1990; Rollenston et al. 2000). Each of them provides information on the metallicity of the interstellar medium at the epoch of their formation. Of course, the matter is complicated by the fact that some of the above categories of stars cover a significant spread in mass and then likely in time of formation (e.g. Maciel, Lago & Costa 2005).

The precise knowledge of these gradients is clearly of great importance to fix constraints to the chemical evolution history of spiral galaxies (cf. Rana 1991; McWilliam 1997) and consequently of cosmological relevance too.

Searle (1971) first interpreted observations of extragalactic H II regions belonging to the spiral galaxies M33 and M101, as providing evidence of a decrease of the abundance of O/H with the galactocentric distance in the disc.

Since then the existence of radial gradients of metals in spirals was found to be a general fact (cf. Shaver et al. 1983), with changes between early- and late-type spirals and/or with the physical properties of the spirals, as mass, luminosity and gas fraction (cf. the review by Schields 1990).

We are focusing in this paper the case of PNe in our Galaxy. We will see that the status of art is still far from being satisfactory, in spite of the numerous dedicated works by different authors along the years.

One must deal of course with chemical elements which did not suffer any appreciable modification from nucleosynthesis during the lifetime of the progenitors of PNe from their formation as progenitors out of the interstellar medium to the ejection of the nebula by the end of the asymptotic giant branch (AGB). The subsequent phase from the proto-PN to the presently observed PN phase is negligible in duration, and in any case the residual chemical burning does affect only a very minor layer of the nucleus with no inference at all to the chemistry of the nebula (cf. Iben & Renzini 1983).

To explore the status of art of metal gradients in the Galaxy from PNe, we concentrate on oxygen, because it is the best and more extensively studied heavy element in PNe (see Perinotto 1991).

We will see that a rather different slope of the gradient of O/H in the Galaxy has been determined by different authors along the years. It is then worthwhile to attempt to clarify the matter aiming to find out the most correct value of the gradient. This paper intends to bring a contribution in this direction. We start in Section 2 by
summarizing the so far derived radial gradients of O/H in various types of objects.

To determine galactic gradients, one needs courses of good determinations of chemical abundances and of distances. In Section 3, we present two comprehensive sets of abundances of PNe on which the present work is based.

In Section 4, we summarize the status of art with distances of galactic PNe and select some distance scales which we adopt for the present study. In Section 5, we derive new galactocentric gradients of oxygen using these data. At this stage, we consider together PNe of types I, II, III of Peimbert (1978) in order to have a better statistics.

With these data, we obtain a gradient lower than found in most previous studies. In Section 6, the analysis is pursued by separating PNe of different types. Results are presented in Section 7. Conclusions follow in Section 8.

2 OXYGEN GALACTOCENTRIC GRADIENT IN THE GALAXY

Table 1 reports the slope of the oxygen galactocentric radial gradient log (O/H) kpc$^{-1}$ from PNe, derived by various authors.

The distance of the Sun from the Galactic Centre was always assumed to be close to 8 kpc. Small differences in this quantity are of minor importance.

Values between $-0.072$ and $-0.014$ have been determined. We consider then worthwhile to examine closely the matter, using new data.

It is worth recalling the analogous information from young objects, as OB stars and H II regions. This is shown in Table 2. Most results concentrate on a gradient slope of $-0.07$, except for the determination by Deharveng et al. equal to $-0.04$. It is out of the purpose of this paper to examine in any detail why this last gradient deviates from the others. Conservatively, we accept as relatively well established for young objects a gradient slope log (O/H) kpc$^{-1}$ of $-0.06 \pm 0.02$ in the usual units.

3 CHEMICAL ABUNDANCES IN PNe

Chemical abundances in PNe have recently been reviewed by Perinotto, Morbidelli & Scatazari (2004). These authors have reanalysed all existing determinations of abundances (up to the end of 2001) going back to the originally observed emission-line fluxes satisfying some criteria of quality, and reprocessing all the data in a fully homogeneous way concerning: the reddening extinction correction, the procedure used to interpret the observations in terms of a proper model nebula and the needed atomic data. Observations made in different positions across the image of the nebula were not mixed up; chemical abundances pertaining to individual positions were calculated. An effort was dedicated to estimate in an objective way the accuracy associated with each elemental abundance, by propagating the observational errors of individual line fluxes across the whole procedure. Weighted averages were then made to evaluate the final abundances in each nebula, considering that different abundances in different positions across the nebulae could not be claimed to represent real variations except for very few objects (see Perinotto & Corradi 1998). These do not enter in our sample.

This work required to examine some 416 papers with original determinations of line emission fluxes between the mid-seventies of last century up to the end of 2001. Final abundances refer to some 131 galactic PNe.

We claim that these abundances represent a quite reliable homogeneous extensive set of PNe abundances.

This is our set A.

We also consider a further set (set B) as a control sample. It contains all the PNe abundances determined in the papers appeared between 2002 and 2005 (about 200 objects). The sources of these abundances are listed in Table 3.

From both sets A and B, the halo PNe (type IV of Peimbert), identified as those in table 3 of Peimbert (1992), have been excluded because of their particular nature.

We must comment on the problem of ionic abundances of heavy elements derived from the strong collisionally excited forbidden lines (CEL) versus those obtained by the faint, temperature insensitive, radiative recombination lines (RRL) (Liu et al. 1995, 2000, 2001; Liu 1998; Luo, Liu & Barlow 2001).

The latter are found to be larger than the first by factors between 1.5 and 20 or more with no clear dependence on any nebular or stellar parameter. The understanding of this discrepancy is still matter of debate. It is accepted that abundances from RRL lines refer to a cold phase representing few per cent of the mass of the nebula. It is then justified to neglect them. Indeed all abundances we are using in the present paper are of the classical CEL type.

4 DISTANCES OF GALACTIC PNe

To derive distances of PNe, one can use either direct methods or statistical methods. The last are based on the assumed constancy of a basic nebular or stellar parameter.

Table 1. Oxygen galactocentric gradient from PNe.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Gradient (dex kpc$^{-1}$)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>D’Odorico, Peimbert &amp; Sabbadin (1976)</td>
<td>$-0.062^a$</td>
<td>$\pm 0.033$</td>
</tr>
<tr>
<td>Torres-Peimbert &amp; Peimbert (1977)</td>
<td>$-0.06$</td>
<td>$\pm 0.02$</td>
</tr>
<tr>
<td>Faundez-Abas &amp; Maciel (1987)</td>
<td>$-0.072$</td>
<td>$\pm 0.10$</td>
</tr>
<tr>
<td>Koeppen, Acker &amp; Stenhof (1991)</td>
<td>$-0.014$</td>
<td>$\pm 0.016$</td>
</tr>
<tr>
<td>Samland et al. (1992)</td>
<td>$-0.031$</td>
<td>$\pm 0.020$</td>
</tr>
<tr>
<td>Amue1 (1993)</td>
<td>$-0.030$</td>
<td>$\pm 0.010$</td>
</tr>
<tr>
<td>Pasquali &amp; Perinotto (1993)</td>
<td>$-0.03$</td>
<td>$\pm 0.01$</td>
</tr>
<tr>
<td>Maciel &amp; Koeppen (1994)</td>
<td>$-0.06$</td>
<td>No error given</td>
</tr>
<tr>
<td>Maciel &amp; Quireza (1999)</td>
<td>$-0.058$</td>
<td>$\pm 0.007$</td>
</tr>
<tr>
<td>Martins &amp; Viegas (2000)</td>
<td>$-0.054$</td>
<td>$\pm 0.019$</td>
</tr>
<tr>
<td>Henry, Kwitter &amp; Balick (2004)</td>
<td>$-0.037$</td>
<td>$\pm 0.008$</td>
</tr>
<tr>
<td>Costa, Uchida &amp; Maciel (2004)</td>
<td>$-0.05$</td>
<td>No error given</td>
</tr>
</tbody>
</table>

$^a$ Derived by us using their data, because they do not present this quantity.
Statistical determinations of distances of galactic PNe go back to the early thirties of last century, when assumption of the constancy of a basic PN parameter was made. This can be a nebular or stellar parameter or a combination of them. Examples are: the absolute photographic nebular magnitude $M_N$ (Zanstra 1931); the mass of the nebular shell (Minkowski & Aller 1954; Shklovskij 1956); the difference between $M_N$ and the bolometric absolute magnitude of the central star $M_{bol}$ (Kohoutek 1961).

Distances to individual objects could be obtained using a variety of methods (cf. Acker 1978; Sabbadin 1986, hereafter S86). For example, these methods were used to find the distances of 81 PNe by S86.

Individual distances were used as ‘calibrators’ to construct statistical distance ‘scale’ by various authors across the years. Noteworthy are those by O’Dell (1962, 1963), Seaton (1966, 1968), Cahn & Kaler (1971), Milne & Aller (1975), Cahn (1976) and Khromov (1979).

It became later clear that evolutionary effects enter the subject, so that they must be considered in the procedure. The first suggestion in this direction was, to our knowledge, made by Kohoutek (1961). Other significant works in the field are e.g. by Maciel & Pottash in this direction was, to our knowledge, made by Kohoutek (1961).


We concentrate in the following on P2002, Z95 and CKS92.

To these, we add the distances compiled by S86, although he has quite less PNe than the above three authors, because his distances are all from direct methods and thus conceivably rather precise. From him, we do use only PNe which he declares accurate to within a factor of 1.5 or better.

5 NEW ESTIMATES OF CHEMICAL GRADIENTS FROM PNe

New estimates of chemical gradients have been made using sets A and B of chemical abundances and the distance scales by P2002, Z95 and CKS92, as well as those compiled by S86.

We adopt 8.0 kpc for the distance of the Sun from the Galactic Centre, considering that there are determinations just above or below this value.

Results are shown in Fig. 1 for set A and Fig. 2 for set B using distances by P2002, Z95, CKS92 and S86 projected on the Galactic plane.

Linear least-squares fits to the data, taking into account the individual errors as provided by the authors, give for set A

$$12 + \log(O/H) = (8.73 \pm 0.020) - (0.016 \pm 0.010)Rg$$ (1)

$$12 + \log(O/H) = (8.74 \pm 0.013) - (0.015 \pm 0.007)Rg$$ (2)

$$12 + \log(O/H) = (8.75 \pm 0.015) - (0.017 \pm 0.008)Rg$$ (3)

$$12 + \log(O/H) = (8.93 \pm 0.066) - (0.029 \pm 0.035)Rg$$ (4)

with distances from P2002, Z95, CKS92 and S86 for equations (1), (2), (3) and (4), respectively.

Analogously for set B,

$$12 + \log(O/H) = (8.71 \pm 0.062) - (0.012 \pm 0.007)Rg$$ (5)

$$12 + \log(O/H) = (8.62 \pm 0.040) + (0.016 \pm 0.005)Rg$$ (6)

$$12 + \log(O/H) = (8.61 \pm 0.041) - (0.003 \pm 0.006)Rg$$ (7)

$$12 + \log(O/H) = (8.86 \pm 0.521) - (0.025 \pm 0.066)Rg$$ (8)

Note that in set A each point refers to one PN while in set B the same nebula can appear more than once, due to measurements of the oxygen abundance done in more than one paper.

The slopes of new gradients are summarized in Table 4.

It is interesting to see that set A of abundances yields a very similar slope of $-0.016 \pm 0.010$ for the four distance scales used. This behaviour with still lower slopes occurs also for set B.

Table 3. Sources for Oxygen abundances of set B.

<table>
<thead>
<tr>
<th>Reference</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Costa et al. (2004); Escudero, Costa &amp; Maciel (2004); Ercolano et al. (2004); Gorny et al. (2004); Hyung &amp; Feibelman (2004); Kwitter &amp; Henry (2001); Kwitter, Henry &amp; Milingo (2003); Liu et al. (2004); Milingo, Henry &amp; Kwitter (2002); Pottasch et al. (2004); Pottasch, Beintema &amp; Feibelman (2005); Pottasch &amp; Surendiranath (2005a); Pottasch &amp; Surendiranath (2005b); Tsamis et al. (2003); Tsamis et al. (2004); Wesson, Liu &amp; Barlow (2005)</td>
<td></td>
</tr>
</tbody>
</table>

Note the newly found slope of the oxygen gradient is quite lower than most found in the past (see Table 1) and indeed barely support the existence of a gradient.

To search the reason of the discrepancy, we note that both sets A and B refer to PNe of all Peimbert’s types, except type IV, while most of the studies reported in Table 1 refer to only type II PNe.
The reason of our choice, as said, was to improve the statistics.
On the other hand, it is known that PNe of different Peimbert's types are associated with progenitors of different mass, what might well hide physical effects linked to the age of the progenitors. We then pursue the analysis by considering the different PNe types.

6 NEW OXYGEN GRADIENTS AS FUNCTION OF THE PEIMBERT'S TYPE

We have separated PNe of sets A and B according to their Peimbert's type (Peimbert 1978; Peimbert & Torres-Peimbert 1983, hereafter PTP) as revised by Pasquali & Perinotto (1993). Accordingly, type I PNe have He/H $\geq 0.125$ and log(N/O) $> -0.3$. They are located in the galactic thin disc and are believed to be associated with massive progenitors (2.4–8.0) M$_\odot$; PTP; Calvet & Peimbert 1982). PNe not of type I have been separated in type II (radial velocity $|v|$ relative to LSR $< 60$ km s$^{-1}$) and type III (radial velocity $|v|$ relative to LSR $\geq 60$ km s$^{-1}$), using the comprehensive catalogue of PNe radial velocities by Schneider et al. (1983). Type II PNe are believed to be derived from intermediate mass progenitors (1.2–2.4) M$_\odot$. Type III PNe are considered being associated with lower mass progenitors (1–1.2) M$_\odot$.

7 RESULTS OF THE ANALYSIS

For both sets A and B, PNe of type I do not show any gradient out of the errors.

Set A, for both types II and III PNe, shows the presence of a very weak gradient. Type III sample is, however, statistically less significant. We are then brought to consider as meaningful only the gradient exhibited by type II PNe.

In set B, neither type II nor type III PNe show any significant gradient.

The slopes of the linear fit to the oxygen abundance versus galactocentric distances for both set A and B, together with their errors, are reported in Table 5.

Plots showing the results are presented in Figs 3 and 4 for set A, type II and type III, respectively. As usual, distances are from P2002, Z95, CKS92 and S86, projected on the Galactic plane.
The chemical gradient of oxygen in the Galaxy

Figure 2. Set B abundances versus galactocentric distances.

Table 4. New oxygen gradients from PNe.

<table>
<thead>
<tr>
<th>Distance method</th>
<th>Set A</th>
<th>Set B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slope (dex kpc$^{-1}$)</td>
<td>Error</td>
</tr>
<tr>
<td>P2002</td>
<td>-0.016</td>
<td>0.010</td>
</tr>
<tr>
<td>Z95</td>
<td>-0.015</td>
<td>0.007</td>
</tr>
<tr>
<td>CKS92</td>
<td>-0.017</td>
<td>0.008</td>
</tr>
<tr>
<td>S86</td>
<td>-0.029</td>
<td>0.035</td>
</tr>
</tbody>
</table>

Table 5. Oxygen gradients from PNe of types II and III – set A.

<table>
<thead>
<tr>
<th>Distance method</th>
<th>Type II</th>
<th>Type III</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slope (dex kpc$^{-1}$)</td>
<td>Error</td>
</tr>
<tr>
<td>P2002</td>
<td>-0.011</td>
<td>0.016</td>
</tr>
<tr>
<td>Z95</td>
<td>-0.018</td>
<td>0.011</td>
</tr>
<tr>
<td>CKS92</td>
<td>-0.025</td>
<td>0.012</td>
</tr>
<tr>
<td>S86</td>
<td>-0.029</td>
<td>0.034</td>
</tr>
</tbody>
</table>
8 CONCLUSIONS

A new analysis of the chemical gradient of oxygen from galactic PNe indicates a gradient much lower than accepted by most previous studies. When working with only Peimbert’s type II PNe, as done by most recent authors, we obtain a slope of $-0.02 \pm 0.01$

A control sample composed by all the determinations of oxygen abundance in galactic PNe from very recent works (2002–2005, excluding our 2004 paper) does not indicate a gradient out of the errors. This suggests that homogeneity is important to extract the information.

The found low slope differs from what accepted by most authors (see Table 1). The reason of this discrepancy has not been identified. On the other hand, quite a significant scatter in the oxygen galactocentric gradient is reported in the literature, something that in our opinion has not received enough attention so far.

Further work is certainly necessary in order to clarify the issue, which is of course of prime importance for the evolutionary history of the Galaxy.

If our result will be confirmed, one should conclude that while H II regions are good tracers of the present epoch metal gradients, PNe, whatever is the gradient at the moment of formation of the progenitors, having undergone two major processes of mixing in their envelopes (red giant branch and AGB), might have lost the ability to be good tracers of oxygen gradients in the interstellar medium at the time of formation of the progenitors.

ACKNOWLEDGMENT

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REFERENCES

Figure 4. Set A – PNe type III – abundances versus galactocentric distances.

Khromov G., 1979, Astrofizika, 15, 269
