SYMMETRIC AND ASYMMETRIC PLANETARY NEBULAE AND THE TIME VARIATION OF THE RADIAL ABUNDANCE GRADIENTS[1]

W. J. Maciel, R. D. D. Costa
IAG/USP

Planetary nebulae (PN) are excellent laboratories to study the chemical evolution of their host galaxies, especially concerning the radial abundance gradients and their time and spatial variations. Current chemical evolution models predict either some steepening or flattening of the abundance gradients with time, and PN can be useful in order to provide observational constraints on this issue. It is generally believed that asymmetrical nebulae, especially bipolars, are formed by younger, more massive progenitor stars, while symmetrical nebulae, such as the round and elliptical objects, are formed by older, less massive stars. As a consequence, if the abundance gradients change with time, some differences are expected between the gradients measured in symmetrical and asymmetrical nebulae. We have considered a large sample of well-studied galactic PN for which accurate abundances of O, S, Ne, and Ar are known, and for which a reliable morphological classification can be made. Average abundances and radial gradients of the ratios O/H, S/H, Ne/H and Ar/H were then determined for the main morphological classes, comprising B, E, R, and P nebulae. It is found that the average abundances of the younger objects are larger than those of the older nebulae, as expected on chemical evolution grounds, but the derived gradients are essentially the same within the uncertainties. It can then be concluded that the radial abundance gradients have not changed appreciably since the older progenitor stars were born, approximately 4 to 5 Gyr ago.

1. INTRODUCTION

Radial abundance gradients are one of the main constraints of chemical evolution models, especially in the case of the Milky Way, for which the gradients can be estimated for several elements in young and evolved objects (see for example Cescutti et al. 2007, Fu et al. 2009, Pedicelli et al. 2009, Luck et al. 2011, Spitoni & Matteucci 2011, Yong et al. 2012, Lemasle et al. 2013). Some recent work by our group (Maciel and Costa 2013a,b) based on different samples of planetary nebulae in the Galaxy and in M33 suggest that the O/H gradient derived for PN with central stars (CSPN) with different ages are very similar, which can be explained by (a) assuming that the gradient did not appreciably change in the last 3-5 Gyr, or (b) that radial migration may have erased part of the gradients of the older population.

It is generally believed that asymmetric planetary nebulae are formed by more massive, younger stars, while symmetric nebulae are originated from relatively older and less massive stars. It is therefore interesting to investigate whether or not the abundance gradients as measured by symmetric and asymmetric nebulae present some differences, which would indicate some time variation of the gradients during the CSPN lifetimes.

In this work we consider two independent galactic PN samples for which the distances, abundances and morphological characteristics have been determined, and estimate the gradients of the ratios O/H, S/H, Ne/H, and Ar/H along the galactic disk.

[1] Paper presented at the conference *Asymmetrical planetary nebulae VI* – Riviera Maya, Mexico, 4-8 November 2013

2. THE SAMPLES

We have taken into account two independent PN samples, namely Sample A and Sample B. The first sample is the same sample of 234 nebulae in the solar neighbourhood and galactic disk with galactocentric distances in the range 4 < R (kpc) < 14 considered in our previous work (Maciel et al. 2003, 2005, Maciel and Costa 2013a), for which accurate distances and chemical abundances have been obtained. The morphological classification of these objects assumes four basic types, namely round (R), elliptical (E), bipolar (B) and point symmetric (P) nebulae. (see Maciel and Costa 2011). The few bipolar center (BC) nebulae in the sample were put together with the bipolars. Table 1 shows the number of objects in each morphological class. The table also shows the unclassified (U) nebulae, the total of non-bipolar nebulae (NB), comprising the R, E, and P types, the symmetric objects (S), comprising R and E objects, and the asymmetric nebulae (A), comprising the B and P objects.

Type	Sample A	Sample B CKS	Sample B SSV
Round (R)	55	28	20
Elliptical (E)	74	34	31
Bipolar (B)	36	21	18
Point-Symmetric (P)	9	6	6
Unclassified (U)	60	35	26
Non-Bipolar (NB)	138	68	57
Symmetric (S)	129	62	51
Asymmetric (A)	45	27	24
Total Sample	234	124	101

Table 1 – Distribution of the PN morphological types for Samples A and B

The second sample, called Sample B, is the homogeneous sample analyzed by Henry et al. (2010), containing 124 objects. This sample is smaller than Sample A, but is more homogeneous, in the sense that all nebulae have been observed and analyzed by the same team, using the same techniques, especially concerning the determination of chemical abundances. The adopted distances are either from the catalogue of Cahn et al. (1992) (CKS) or from the more recent update by Stanghellini et al. (2008) (SSV). In this work, we have taken into account both distances scales, so that it can be assumed that the derived results are not very sensitive to the adopted distances. The number of objects in each class is also shown in Table 1.

3. RESULTS AND DISCUSSION

Sample A

The hypothesis that bipolar nebulae are relatively younger than non-bipolar objects can be examined using the Method 1 by Maciel et al. (2010), which includes enough data for a histogram of the stellar ages to be derived, as shown in Figure 1. It can be seen that bipolar nebulae are concentrated basically in ages lower than 3-4 Gyr, while non-bipolars extend to much older objects.

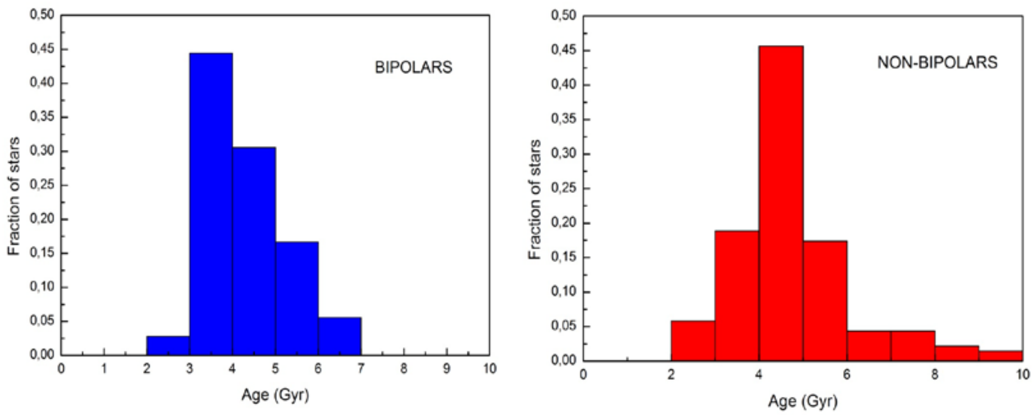

Figure 1 – Age distribution for bipolar and non-bipolar nebulae with ages obtained by Method 1 of Maciel et al. (2010)

The main results for Sample A are shown in Table 2 for the elements O, S, Ne, and Ar, where the first column shows the morphological type, the second column the number of objects in each case, the third column the average abundances with uncertainties, the fourth column the eestimated gradient (dex/kpc) also with uncertainties and the fifth column the correlation coefficient.

Considering the average abundances given in column 3 of Table 2, it can be seen that the bipolar nebulae have systematically higher abundances compared to the non-bipolars, or to the symmetric (round and elliptical) nebulae. The difference is however usually within the estimated uncertainties in the abundances. This is in agreement with the basic ideas of galactic chemical evolution, in the sense that the average interstellar metallicity increases as the Galaxy evolves, owing to the return of enriched gas by stellar deaths. In fact the average enrichment predicted by the age-metallicity relation is consistent with the differences between the young and old objects shown in Table 2, on the basis of some recent work on this relation for the galactic disk (see for example Rocha-Pinto et al. 2000, 2006, Feltzing et al. 2001, Bensby et al. 2004, and Marsakov et al. 2011).

SAMPLE	N	AVERAGE O/H	GRADIENT	CORR. COEFF.
TOTAL	234	8.63 ± 0.26	-0.04 ± 0.01	-0.35
B	36	8.73 ± 0.23	-0.04 ± 0.02	-0.33
R	55	8.54 ± 0.29	-0.03 ± 0.02	-0.26
E	74	8.63 ± 0.22	-0.03 ± 0.01	-0.30
P	9	8.74 ± 0.20	0.00 ± 0.03	0.01
U	60	8.64 ± 0.28	-0.05 ± 0.01	-0.48
NON-B	138	8.60 ± 0.26	-0.03 ± 0.01	-0.27
S	129	8.59 ± 0.26	-0.03 ± 0.01	-0.28
A	45	8.73 ± 0.22	-0.03 ± 0.02	-0.25

SAMPLE	N	AVERAGE S/H	GRADIENT	CORR. COEFF.
TOTAL	203	6.87 ± 0.35	-0.07 ± 0.01	-0.44
B	32	6.99 ± 0.40	-0.06 ± 0.04	-0.28
R	49	6.76 ± 0.33	-0.07 ± 0.02	-0.47
E	64	6.84 ± 0.26	-0.06 ± 0.01	-0.47
P	9	7.04 ± 0.19	-0.04 ± 0.02	-0.58
U	49	6.92 ± 0.41	-0.07 ± 0.02	-0.47
NON-B	122	6.82 ± 0.29	-0.06 ± 0.01	-0.47
S	113	6.80 ± 0.29	-0.06 ± 0.01	-0.47
A	41	7.00 ± 0.36	-0.06 ± 0.03	-0.30

SAMPLE	N	AVERAGE Ne/H	GRADIENT	CORR. COEFF.
TOTAL	163	7.97 ± 0.26	-0.02 ± 0.01	-0.18
B	28	8.08 ± 0.29	-0.01 ± 0.03	-0.08
R	39	7.93 ± 0.26	-0.01 ± 0.02	-0.06
E	51	7.97 ± 0.22	-0.04 ± 0.01	-0.41
P	8	7.97 ± 0.15	-0.05 ± 0.02	0.68
U	37	7.90 ± 0.30	-0.01 ± 0.02	-0.07
NON-B	98	7.96 ± 0.23	-0.03 ± 0.01	-0.25
S	90	7.96 ± 0.24	-0.02 ± 0.01	-0.23
A	36	8.06 ± 0.27	-0.02 ± 0.02	-0.12

SAMPLE	N	AVERAGE Ar/H	GRADIENT	CORR. COEFF.
TOTAL	194	6.38 ± 0.31	-0.05 ± 0.01	-0.35
B	32	6.55 ± 0.31	-0.02 ± 0.03	-0.09
R	48	6.28 ± 0.31	-0.05 ± 0.02	-0.35
E	61	6.37 ± 0.27	-0.05 ± 0.02	-0.40
P	9	6.48 ± 0.31	0.03 ± 0.05	0.19
U	44	6.37 ± 0.34	-0.06 ± 0.02	-0.49
NON-B	118	6.34 ± 0.29	-0.04 ± 0.01	-0.33
S	109	6.33 ± 0.29	-0.05 ± 0.01	-0.37
A	41	6.53 ± 0.30	-0.00 ± 0.03	-0.02

Table 2 – Results for Sample A

Considering now the radial gradients, it is clear that for all elements considered there are no significant differences among the gradients of the younger bipolar nebulae and the older objects (non-bipolars) within the uncertainties. Also, comparing the symmetric and asymmetric objects, essentially the same gradients are obtained. The most reliable result is probably for oxygen, since the sample is larger and the average uncertainties smaller. In this case, bipolar and non-bipolar nebulae display the same gradients, which is also the case for symmetric and asymmetric nebulae. The point symmetric sample is always very small, so that their apparent flat gradients probably have no statistical significance.

The actual magnitude of the gradients varies in the approximate range

$0.02 < |dX/dR|$ (dex/kpc) < 0.07

with an average $dX/dR \approx 0.04$ dex/kpc. Since the actual magnitudes of the gradients are small, the correlation coefficients are usually also small. Judging from the correlation coefficients, the best determined gradients are for O/H, S/H and Ar/H, implying a narrower range of

$0.03 < |dX/dR|$ (dex/kpc) < 0.06 .

The shallower gradients for Ne/H are affected both by a smaller sample and by the lack of objects at large galactocentric distances. Some examples of the derived O/H gradients are shown in Figure 2, and Figures 3, 4, and 5 present some results for S, Ne, and Ar, both for the bipolar and non-bipolar nebulae.

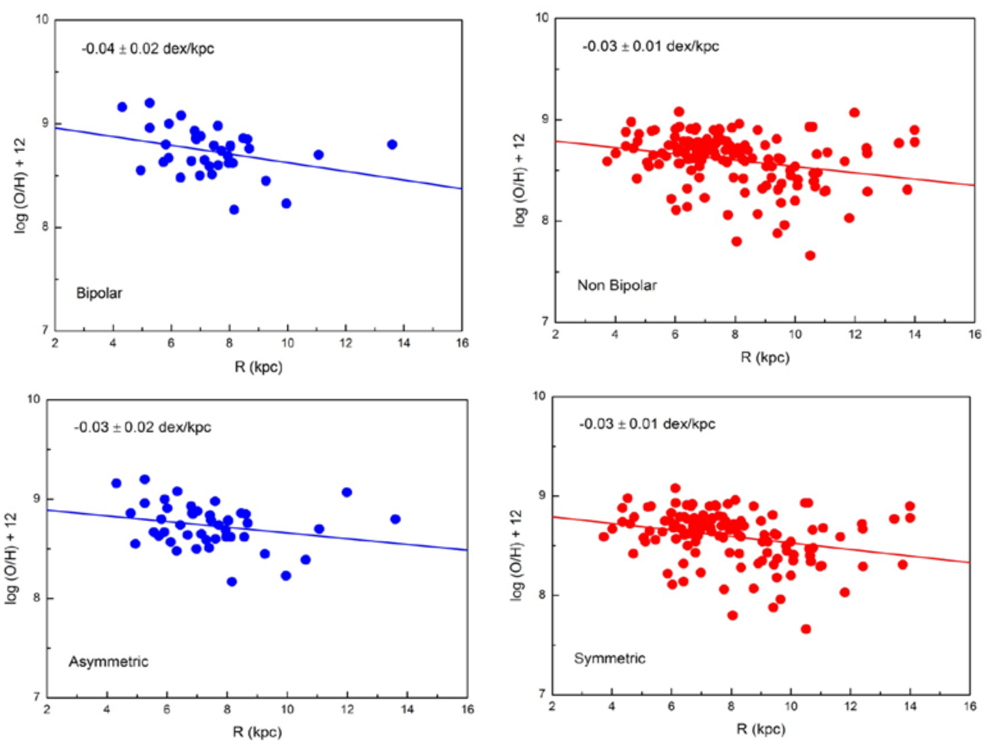

Figure 2 – O/H gradients for Sample A for different PN morphologies.

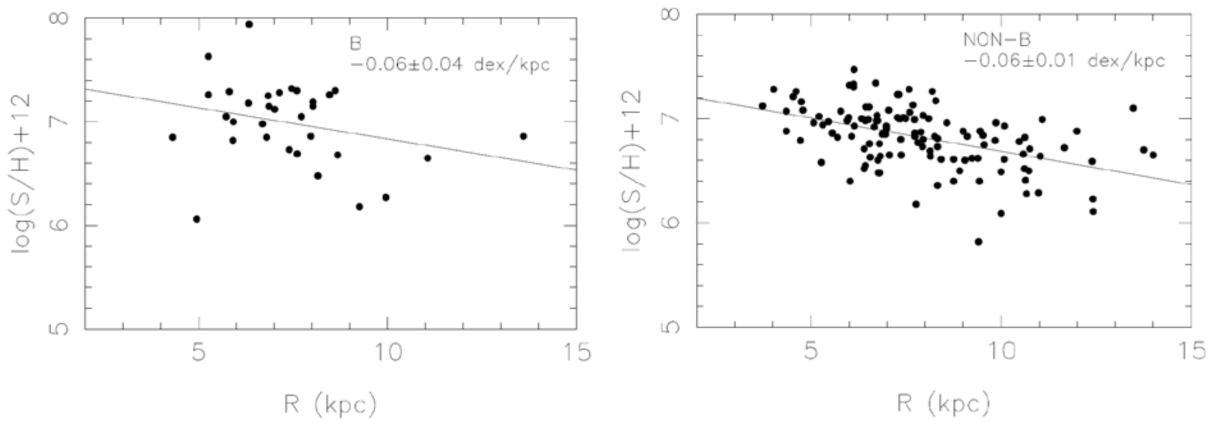

Figure 3 – S/H gradients for bipolar and non-bipolar nebulae for Sample A

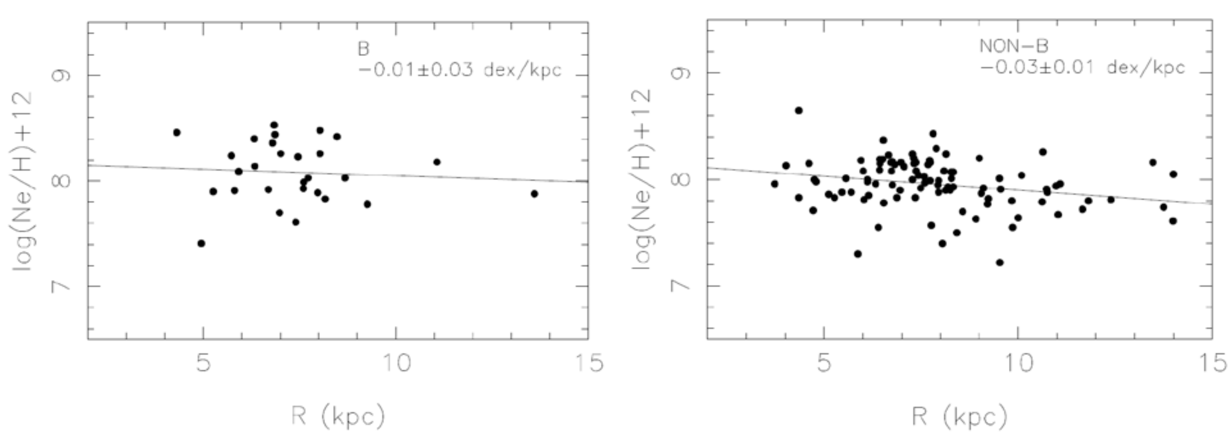

Figure 4 – Ne/H gradients for bipolar and non-bipolar nebulae for Sample A

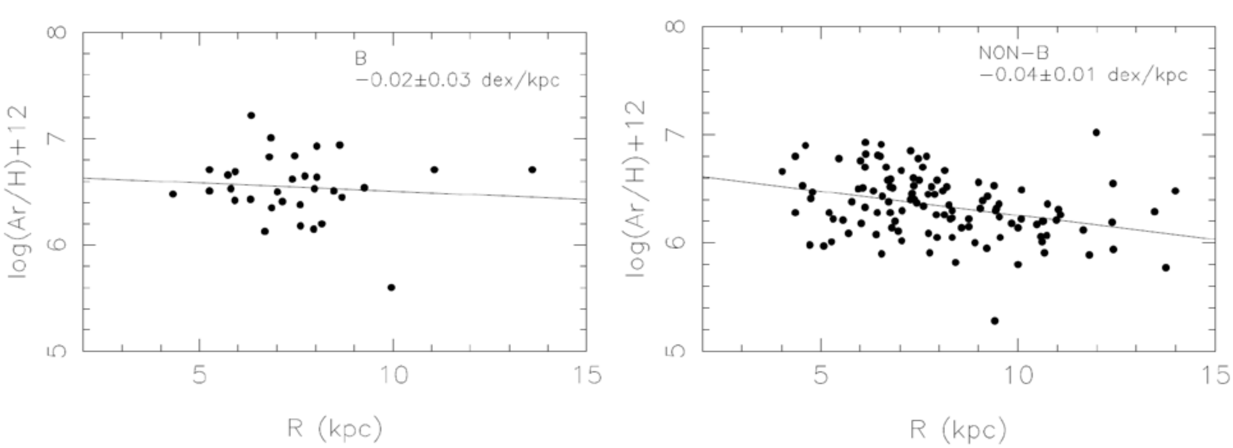

Figure 5 – Ar/H gradients for bipolar and non-bipolar nebulae for Sample A

Sample B

Results for Sample B (Henry et al. 2010) are similar to those of Sample A in the sense that all gradients are similar within the uncertainties, as shown in Table 3 and Figure 6. In fact, both for the CKS and SSV distances we get for oxygen

$0.02 < \left| dX/dR \right|$ (dex/kpc) < 0.04

OXYGEN - CKS

SAMPLE	N	AVERAGE Ne/H	GRADIENT	CORR. COEFF.
TOTAL	124	8.59 ± 0.21	-0.04 ± 0.01	-0.53
B	21	8.55 ± 0.27	-0.04 ± 0.02	-0.39
R	28	8.60 ± 0.15	-0.04 ± 0.01	-0.61
E	34	8.64 ± 0.17	-0.02 ± 0.01	-0.32
P	6	8.69 ± 0.05	0.01 ± 0.01	0.26
U	35	8.53 ± 0.26	-0.04 ± 0.01	-0.66
NON-B	68	8.63 ± 0.16	-0.03 ± 0.01	-0.42
S	62	8.62 ± 0.16	-0.03 ± 0.01	-0.44
A	27	8.58 ± 0.25	-0.03 ± 0.02	-0.35

OXYGEN - SSV

SAMPLE	N	AVERAGE Ar/H	GRADIENT	CORR. COEFF.
TOTAL	101	8.60 ± 0.26	-0.04 ± 0.01	-0.35
B	18	8.59 ± 0.27	-0.03 ± 0.02	-0.32
R	20	8.61 ± 0.17	-0.03 ± 0.01	-0.72
E	31	8.65 ± 0.16	-0.02 ± 0.01	-0.31
P	6	8.69 ± 0.05	0.01 ± 0.01	0.32
U	26	8.52 ± 0.28	-0.03 ± 0.01	-0.64
NON-B	57	8.64 ± 0.16	-0.02 ± 0.01	-0.49
S	51	8.63 ± 0.17	-0.02 ± 0.01	-0.51
A	24	8.61 ± 0.24	-0.02 ± 0.02	-0.30

Table 3 – Results for Sample B

so that the distance scales apparently do not affect the result. In particular, bipolar and non-bipolar nebulae present the same gradients, which is particularly interesting since the Henry et al. (2010) sample is very homogeneous. Combining the O/H gradients from Table 3 with those of Sample A in Table 2 we see that there is also an agreement between the absolute magnitude of the gradients, but the correlation coefficients for Sample B are larger.

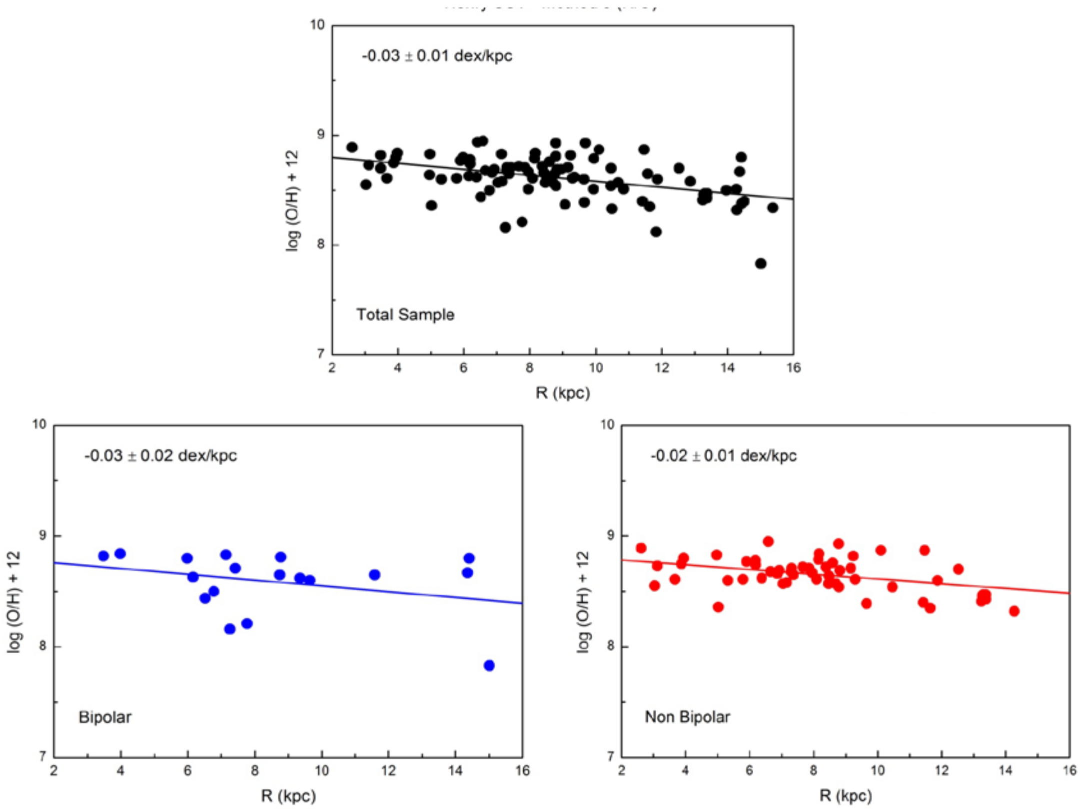

Figure 6 – O/H gradients for Sample B for different PN morphologies.

On the basis of the present results and also from our previous results based on the age estimates of the central stars, it is clear that the actual magnitude of the gradients are affected by the choice of the particular sample, especially since the samples themselves are usually small. This implies that only a magnitude range can be given as presented above, but our main goal with this work is unaffected, as we would like to find the differences – if any – between young and old nebulae.

The results shown in Tables 2 and 3 and Figures 2-6 are in agreement with the recent work by Maciel and Costa (2013a), where it was shown that the gradients derived from PN with younger central stars are essentially indistinguished from those obtained by PN with older progenitors. In that work, three different methods were employed to estimate the ages of the central stars, based either on the nebular abundances or on their kinematic properties. These results are also in agreement with some recent work by Pilkington et al. (2012) and Gibson et al. (2013), where it is concluded that the radial abundance gradients show essentially no time variations in the local universe, near zero redshift, while at higher z steepest gradients are observed, which is supported by some recent work based on gravitational lensing of galaxies with $z \approx 1.5 – 2.0$.

Therefore, the main conclusions of this paper are as follows:

1) The younger groups of planetary nebulae have slightly higher abundances compared with the older groups, as expected, although the differences are small.

2) The radial gradients for both groups are similar within the uncertainties. The average O/H gradient is in the range -0.03 to -0.07 dex/kpc in the local universe.

3) This reinforces the conclusion that the average gradient has remained approximately constant in the last 3-5 Gyr, which corresponds the ages of the older objects studied here. Radial migration and mixing may affect this conclusion. This age range corresponds roughly to redshifts up to about 0.5, while for higher redshifts there is some evidence of a steepening of the gradient.

Acknowledgements. This work was partially supported by FAPESP and CNPq.

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