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On the abundance gradient of the galactic disk

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Abstract. Estimates of the gas temperature in planetary nebulae obtained from the [O III] emission line ratio and from the Balmer discontinuity indicate differences reaching up to 6000 K (Liu & Danziger 1993). The [O III] temperature is commonly used to obtain the ionic fractions of highly ionized ions, particularly the O^{++} and Ne^{++} ions when using the empirical method to calculate the elemental abundances of photoionized gas from the observed emission line intensities. However, if the gas temperature is overestimated the elemental abundances may be underestimated. In particular this may lead to an incorrect elemental abundance gradient for the Galaxy, usually used as a constraint for the chemical evolution models. Using Monte Carlo simulations, we calculate the systematic error introduced in the abundance gradient obtained from planetary nebulae by an overestimation of the gas temperature. The results indicate that the abundance gradient in the Galaxy should be steeper than previously assumed.

Key words: ISM: abundances – ISM: planetary nebulae: general – Galaxy: abundances

1. Introduction

Since the seminal paper by Peimbert & Costero (1969) discussing the empirical methods to obtain the chemical abundances, planetary nebulae (PN) observations have been used to derive the chemical composition of the interstellar gas in the Galaxy (for example, Peimbert & Torres-Peimbert 1971), as well as in nearby galaxies (for example, Ford et al. 1973). The results have been used for different purposes including PN classification (Peimbert 1978, 1990, Faúndez-Abans & Maciel 1987a) and abundance gradient determination (Faúndez-Abans & Maciel 1986, 1987b).

The empirical method used to derive the elemental chemical abundance from emission lines depends on the gas temperature and electron density (McCall 1984). The temperature is obtained from the observed [O III] line ratio (T_{OIII}), from the [N II] line ratio (T_{NII}), or from the Balmer discontinuity (T_{Bal}), which usually give different values. On the one hand, the difference between T_{OIII} and T_{NII} is probably due to the fact that O^{++} and N^{+} are in different regions, at the high- and low-ionization zones respectively. On the other hand, a T_{OIII} higher than T_{Bal} is generally explained by the presence of temperature fluctuations (Peimbert 1967). Very accurate data for a large sample of PN show that the difference between T_{Bal} and T_{OIII} can reach up to 6000 K (Liu & Danziger 1993). As discussed by the authors, such a value can not be reproduced by photoionization models of un-clumped gas. On the other hand, the presence of unresolved condensations could solve the problem (Viegas & Clegg 1994), indicating that T_{Bal} is probably a better indicator of the gas temperature. In this case, the elemental abundances must be derived assuming T_{Bal} instead of T_{OIII}.

Ionic abundances derived from both collisionally excited and recombination lines of C and O may also indicate the presence of temperature and/or density fluctuations in planetary nebulae, as recently discussed by Mathis et al. (1998). Abundances derived from recombination lines are usually higher than those from collisionally excited lines.

The abundance gradient in the Galaxy indicates that the abundances are higher closer to the galactic center. Since the oxygen lines are the main coolants, the gas temperature of the PN must be lower closer to the galactic center. In addition, the forbidden line emissivities increase rapidly with the gas temperature reaching a plateau for $T \geq 5 \times 10^4$ K. Thus, a change in the gas temperature from T_{OIII} to T_{Bal} must induce a bigger change in the abundance of the PN closer to the center, and, consequently, a change of the abundance gradient of the Galaxy.

In this paper, we quantify the systematic error in the abundance gradient due to an overestimation of the gas temperature, using a Monte Carlo method. The data sample is discussed in Sect. 2. The method used and the results are presented in Sect. 3. The conclusions appear in Sect. 4.

2. The PN sample

As proposed by Peimbert (1978), the PN of the galactic disk can be classified as type I, II and III. However, our sample includes only type II PN, which are probably more representative of the galactic chemical evolution. In fact, they are relatively young, produced by intermediate mass stars and participate in the galactic rotation (Maciel & Dutra 1992). On the other hand,

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type I PN are probably very young and their chemical abundance would correspond to the present interstellar abundance (Maciel & Köppen 1994), while type III PN probably originated from old less massive stars and could be displaced from their birthplace (Maciel & Dutra 1992).

Previous gradient determinations were obtained using the abundance values provided by different authors. Some of them included objects for which the T_{OIII} or the electron density could not be calculated, so the abundances were derived assuming a given value for these quantities. In order to estimate the systematic error in the galatic abundance gradient induced by an overestimation of the temperature, we need a homogeneous sample of abundance data. Since the data available in the literature come from different observations and authors, it was necessary to recalculate the empirical abundances for all the objects in the sample from the observed emission-line intensities. For this, the optical line intensities necessary to calculate the temperature from the [O III] and [N II] line ratios, the density from the [S II] line ratio, as well as the ionic fractional of the ions present in the gas, are needed. Therefore, among all the type II PN data in the literature, only those with those line intensities available, as well as the galactocentric distance, were selected. These criteria reduced the sample to 43 objects listed in Table 1 with the corresponding references. The adopted distances come from Maciel & Köppen (1994).

3. Empirical abundances

We are interested in analysing systematic errors in the elemental abundance gradient derived from PN. The gradient is usually obtained from abundance data available in the literature. In our case, we needed a homogeneous sample, i.e., the elemental abundance had to be derived by the same method, in particular using the same equations for the ionic fractions and ionization corrections.

Following Peimbert & Costero (1969), the empirical method used to derive the chemical abundances is based on the observed optical lines and depends on the temperature and electron density of the emitting region. Here the emission lines used are: [O II]λ 3727, [O II]λ 7327, [O III]λ 4363, [O III]λ 4959+5007, [N II]λ 6548+6584, [Ne III]λ 3868 + 3967, [S II]λ 6717, [S II]λ 6730, [S III]λ 6312, He I λ 5876, He II λ 4686 and Hβ. It is usually assumed that the temperature of the high and low ionization regions are given by the [O III] and [N II] line ratios respectively. Because the dispersion of most of the observations is not enough to separate the [O II] doublet, the electron density is obtained from the [S II] line ratio. Once the physical conditions of the emitting regions are obtained, the ionic abundances, relative to H^+, are calculated from the observed emision-line intensities corrected for reddening.

The ionic abundances for O^+, O^{++}, N^+, Ne^{++}, S^+ and S^{++} have been obtained using the emission line coefficients from McCall (1984). However, since there are unobserved ions present in the gas, ionization correction factors are adopted in order to obtain the elemental abundances, as shown in Eqs. (1) to (4) below. The ionic abundances of He^+ and He^{++} have been obtained from Brocklehurst (1972) and the corrections for collisional de-excitation of He^+ adopted from Kingdon & Ferland (1995). The total helium abundance is the sum of the ions He^+ and He^{++} since the neutral helium in these objects is negligible.

$$\frac{O}{H} = \frac{(O^+ + O^{++})}{H^+}\left(\frac{He}{He^+}\right). \qquad (1)$$

(Peimbert & Torres- Peimbert 1977)

$$\frac{N}{H} = \frac{(N^+)}{H^+}\left(\frac{O}{O^+}\right). \qquad (2)$$

(Peimbert & Torres- Peimbert 1977)

$$\frac{S}{H} = \frac{(S^+ + S^{++})}{H^+}\left[1.43 + 0.196\left(\frac{O^{++}}{O^+}\right)^{1.29}\right]. \qquad (3)$$

(Köppen et al. 1991)

$$\frac{Ne}{H} = \left(\frac{Ne^{++}}{H^+}\right)\frac{O^+ + O^{++}}{O^{++}}. \qquad (4)$$

(Peimbert 1990)

The calculated elemental abundances are listed in Table 1. These values are used to derive the standard abundance gradient, α_0, in the absence of temperature fluctuations.

Notice that some values may differ from those given in the literature. The reason for the different results are mainly due to the collisional term included in the estimate of the He^+ fractional abundance and in the icf value used for S/H.

The He^+ fractional abundance is used as the icf correction for the O abundance (Eq. 1), and an incorrect value may affect all the results derived from it. The main problem comes from collisional correction of He^+. In some of the earlier papers this correction was not accounted for (Freitas Pacheco et al. 1992), leading to an overabundance of the He^+ fractional abundance, and consequently, of the He abundance. Other authors accounted for the collisional correction (Köppen et al. 1991) as proposed by Clegg (1987) which may overcorrect He^+/He (Kingdon & Ferland 1995), leading to an underestimate of the He abundance. However, for the objects listed in Table 1, the results using Clegg's correction or Kingdom and Ferland correction for He I λ5876 differ by less than 3%.

Regarding the S abundance, the icf used by different authors has changed over the years leading to different results. Two decades ago, an icf similar to the icf for N was assumed (Barker 1978), followed by a more precise value (Barker 1983). However, several authors (for example Freitas Pacheco et al. 1991 and references therein) used the icf value suggested by Dennefeld & Stasinska (1983), based on photoionization models for HII regions. Because the HII region ionizing stars have lower temperatures, the high ionization zone of HII regions is smaller than in planetary nebulae, leading to a smaller ionization correction factor due to the presence of highly ionized ions. Thus, when the icf derived for HII regions is applied to PN it

Table 1. Results of density, temperatures and abundances

Nebulae	Ref^a	n_e	T_{NII}	T_{OIII}	O/H	N/H	S/H	Ne/H	$R(Kpc)^b$
NGC 2371	2	3114	9638	15919	8.60	8.31	7.42	7.53	9.90
NGC 2392	2	4469	7316	13676	8.82	8.63	7.73	7.80	10.33
NGC 2867	8	3474	9981	11181	8.82	8.27	7.31	7.97	8.42
NGC 3918	1	7320	9351	12065	8.78	8.52	7.64	7.70	7.84
NGC 5882	6	4994	9897	8979	8.76	7.78	7.47	–	7.22
NGC 6210	7	3557	12290	9918	8.50	7.88	7.45	7.87	7.78
NGC 6309	2	4828	10151	11267	8.84	8.35	7.92	7.80	6.51
NGC 6439	6	6295	8767	8909	9.11	8.62	7.27	8.50	4.84
NGC 6543	2	4329	10040	8249	8.70	8.05	7.54	8.99	8.59
NGC 6563	6	5210	11174	12032	8.43	8.35	–	–	6.62
NGC 6565	4	2246	9710	10383	8.84	8.52	7.24	8.20	7.01
NGC 6572	2	12076	6074	9802	8.91	8.10	7.55	8.20	7.87
NGC 6578	3	5438	11059	8371	8.76	7.95	–	8.21	6.45
NGC 6720	7	825	9780	11120	8.69	8.49	7.25	8.05	8.22
NGC 6790	2	13468	19110	11683	8.58	7.93	7.32	7.76	7.38
NGC 6818	2	1742	11677	12841	8.95	8.54	7.67	7.66	7.24
NGC 6826	2	2903	12594	10569	8.37	7.28	6.81	6.89	8.45
NGC 6879	4	6967	14640	10129	8.62	7.75	7.47	7.96	7.21
NGC 6884	2	7928	12507	10859	8.71	7.99	7.27	7.90	8.44
NGC 6886	2	13446	11022	11850	8.86	8.31	6.95	8.02	7.80
NGC 6894	3	383	14815	8219	8.79	8.53	7.39	8.29	8.10
NGC 7026	2	11664	9990	9003	8.80	8.46	7.38	8.29	8.53
NGC 7662	2	3623	10113	13591	8.62	8.00	7.80	7.49	8.75
IC 418	6	13058	8456	13121	8.60	7.83	6.53	–	9.73
IC 1297	4	3478	8924	10098	8.88	8.73	7.98	8.07	5.71
IC 2003	2	8517	16316	11593	8.64	8.13	7.19	7.65	10.72
IC 2149	5	4754	9103	9727	8.93	7.10	–	8.11	9.55
IC 2165	2	5587	12023	14067	8.61	8.03	6.93	7.48	9.97
IC 2501	6	40972	9451	9516	8.73	8.16	6.89	–	8.38
IC 2621	6	18979	12428	10994	8.98	8.67	7.26	–	7.97
IC 4776	2	14651	15865	8564	8.79	8.02	7.53	8.03	5.29
IC 5217	2	12965	12186	11230	8.57	8.00	7.35	7.85	9.42
He2-37	8	270	10169	12824	9.05	8.59	7.13	8.01	8.62
He 2-48	8	196	11235	11820	8.57	8.05	7.00	7.89	8.87
He 2-115	6	21032	12650	12384	8.13	7.52	6.30	–	7.05
He 2-141	6	2916	10761	15015	8.78	8.31	6.89	–	6.40
Hu 1-1	2	2012	10278	12883	8.62	8.06	6.95	7.93	11.55
J 320	2	4816	12158	12456	8.39	7.66	7.29	7.75	12.36
J 900	2	4521	11054	12167	8.65	8.02	6.88	7.69	10.55
M 1-4	4	6975	11002	12077	8.43	7.61	7.25	7.76	9.97
M 1-5	5	2121	12251	15493	7.96	7.40	6.32	–	10.59
M 1-54	5	2074	9023	9541	8.90	8.69	7.34	–	5.51
Th 2-a	8	1466	12435	11840	8.89	8.50	–	8.02	7.30

a References: (1) Torres-Peimbert & Peimbert 1977; (2) Aller & Czyzak 1983; (3) Aller & Keyes 1987; (4) Kaller et al. 1997;(5) Barker 1978; (6) Freitas-Pacheco et al. 1992; (7) French 1981; (8) Kingsburgh & Barlow 1992.
b Distances: Maciel & Köppen 1984

systematically gives lower S abundances than those obtained using the icf proposed by Köppen et al. (1991), obtained from an extensive grid of density bounded photoionization models for planetary nebulae.

4. Abundance gradients

For each element (O, N, Ne and S), the radial gradient is obtained from a linear fit of the elemental abundance versus distance (Fig. 1a,b,c and d). The results are listed in Table 2.

Table 2. Coefficients of the linear fits[a]

	O	N	S	Ne
α_0	-0.054	-0.084	-0.064	-0.069
$\sigma(\alpha_0)$	0.018	0.084	0.035	0.034
β	9.16	8.86	7.83	8.51
$\sigma(\beta)$	0.16	0.29	0.30	0.30
r	-0.42	-0.39	-0.31	-0.34
N	43	43	39	34

a Log(X/H)+12 $=\alpha_0$R + β; r is the correlation coefficient and N is the number of data points used.

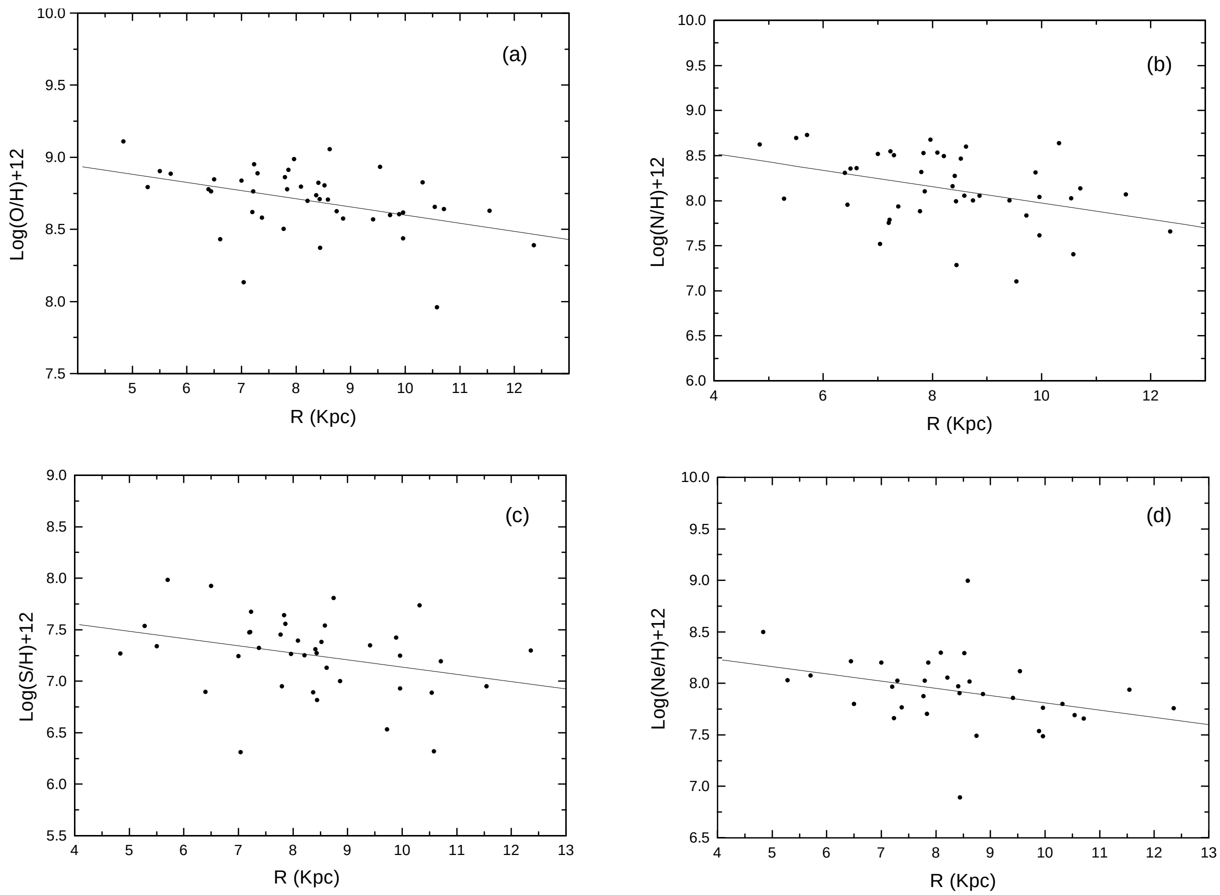

Fig. 1a–d. Radial abundance gradients: **a** O/H, **b** N/H, **c** S/H and **d** Ne/H. The solid line corresponds to the linear fit to the data.

Table 3. Comparation between the gradients of this paper and those found in the literature [a]

	This study	MK94	FM86	PP93	MQ99
α_O	-0.054 ± 0.019	-0.069 ± 0.006	-0.072 ± 0.012	-0.03 ± 0.01	-0.058 ± 0.007
α_N	-0.084 ± 0.034	–	-0.072 ± 0.028	-0.05 ± 0.01	–
α_S	-0.064 ± 0.035	-0.067 ± 0.006	-0.098 ± 0.022	–	-0.077 ± 0.011
α_{Ne}	-0.069 ± 0.034	-0.056 ± 0.007	–	-0.05 ± 0.02	-0.036 ± 0.010

[a] (MK94) Maciel & Köppen 1994; (FM86) Faùndez-Abans & Maciel 1986; (PP93) Pasquali & Perinoto 1993; (MQ99) Maciel & Quireza 1999

The values obtained for the elemental abundance gradients are compared to those from previous works in Table 3. Our results have a larger statistical error because of the smaller number of objects used in this paper. Notice, however, that the results obtained by other authors come from a non-homogeneous sample of elemental abundance data, where collisional correction for He may or may not be included and the icf for S may differ from one object to another. Thus a small statistical error due to a larger number of objects included in their sample may be misleading and hide a larger uncertainty.

In the case of neon, the icf is usually the same in all studies. However our value for the gradient is barely in agreement with the Maciel & Quireza (1999) result. The PN sample used by these authors include 4 PN with a distance from the galactic center which is larger than 12 kpc, whereas all the PN in our sample are closer than 12 kpc. Three of these distant PN are usually classified as type I planetary. However, they were reclassified as type II by Maciel & Quireza (1999) and included in their sample. Since they have high Ne abundance, their Ne abundance gradient is flatter. Without these PN in the sample, the Ne gradient is -0.042 ± 0.014 (Quireza 1999), which is in agreement with our result (Table 3) within the errors.

4.1. Effect of the gas temperature

If the Balmer temperature was available for most of the type II PN, a new value for the galactic abundance gradient could easily be obtained by recalculating the chemical abundances for each object assuming T_{Bal} as the gas temperature. As shown by Viegas & Clegg (1994), if the difference between T_{OIII} and T_{Bal} is due to density fluctuations, the oxygen and neon abundance may increase up to 50%. This would resolve the discrepancy between the elemental abundances derived from permitted lines and from forbidden lines.

The value of T_{Bal} is not available for most of the PN of our sample, thus the estimation of the systematic error, introduced into the abundance gradient by an uncertainty in the gas temperature, is obtained by Monte Carlo simulations. The method is similar to that used by Steigman et al. (1997). For each PN, we assume that the T_{OIII} is overestimated by ΔT chosen from a distribution ranging from zero to Δ T_{max}, following a probability P(ΔT), which can be constant, linear increasing or linear decreasing. Thus, if a constant P(ΔT) is assumed for each object, any value of ΔT between 0 and Δ T_{max} has the same probability to be randomly chosen. On the other hand, if a linear increasing (or deacreasing) probability is assumed, higher (or lower) ΔT values are favoured.

Once the type of probability and Δ T_{max} are chosen, the chemical abundances are recalculated for each PN in the sample using T = T_{OIII} - ΔT for the high ionization zone, as described in Sect. 2.1. A new value of the elemental abundance gradient, α, is then obtained by linear fit for each element, as well as the difference $\Delta\alpha$=α - α_0. The procedure is repeated 15,000 times and the $\Delta\alpha$ average value gives the estimate of the systematic error in the gradient due to an overestimation of the gas temperature.

Since the difference between T_{OIII} and T_{Bal} is not easily explained, a possible overestimation of T_{NII} must be also analysed. There is no reason to adopt the same change ΔT for T_{OIII} and T_{NII}. In fact, no correlation was found between these two temperatures (Fig. 2). In addition, for most of the PN, T_{NII} is close to T_{Bal}. Thus, when calculating the systematic error in the abundance gradient, only a decrease in T_{OIII} is accounted for; T_{NII} remaining constant.

4.2. Systematic error

The PN sample observed by Liu & Danziger (1993) shows that the difference between T_{OIII} and T_{Bal} can reach up to 6000 K, although most objects show a difference of less than 4000 K. This value will be assumed as the maximum in our calculations.

The results of the Monte Carlo simulations are shown in Tables 4 and 5, for ΔT_{max} equal to 4000 K and 2000 K, respectively. In both cases, the results obtained with a lower T_{OIII} steepens the gradients.

Because of the rapid increase of the line emissivity with the gas temperature and of the expected increase of the PN gas temperature from the inner region to the outer region of the Galaxy, we expect that the increase of the abundance, due to a decreasing of T_{OIII}, is stronger for the PN closer to the center, leading to a steeper gradient.

This effect is found for all elements. Although the N and S abundances are not directly dependent on T_{OIII} (as O and Ne abundances are), steeper gradients are also obtained. This is a second order effect, because a decrease of T_{OIII} induces a change in the icf of N and S.

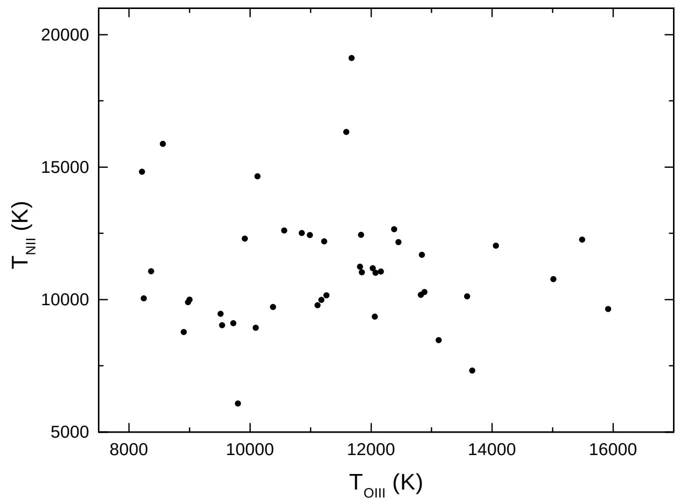

Fig. 2. Plot of the temperatures T_{NII} versus T_{OIII}. This figure shows that no correlation exists between these two temperatures. The correlation coefficient is 0.21

Table 4. Results of the Monte Carlo with ΔT_{max} = 4000 K

	$\Delta\alpha$		
	P constant	P crescent	P decrescent
O	0.039 ± 0.021	0.056 ± 0.018	0.023 ± 0.016
N	0.036 ± 0.016	0.051 ± 0.014	0.022 ± 0.012
S	0.038 ± 0.016	0.055 ± 0.018	0.022 ± 0.015
Ne	0.052 ± 0.031	0.074 ± 0.028	0.030 ± 0.023

Table 5. Results of the Monte Carlo with ΔT_{max} = 2000 K

	$\Delta\alpha$		
	P constant	P crescent	P decrescent
O	0.015 ± 0.008	0.021 ± 0.007	0.009 ± 0.007
N	0.014 ± 0.007	0.020 ± 0.006	0.009 ± 0.005
S	0.013 ± 0.008	0.020 ± 0.007	0.008 ± 0.007
Ne	0.019 ± 0.012	0.026 ± 0.010	0.013 ± 0.010

5. Concluding remarks

The overestimation of the temperature in planetary nebulae, used to obtain the elemental abundances, may lead to a systematic uncertainty in the radial abundance gradient of the Galaxy. Because of the lack of observational data necessary to obtain the Balmer temperature, the systematic uncertainty was evaluated by Monte Carto simulations, where the decrease in the gas temperature for each PN in the sample is chosen randomly between zero and ΔT_{max}. The radial gradients tend to become steeper as long as the temperature fluctuations are taken into account.

Several estimations of the radial gradient of the Galaxy are available in the literature, obtained from objects other than the already discussed PN. The galactic HII regions indicate an oxygen gradient of about -0.07 dex Kpc^{-1} (Shaver et al. 1983), very close to that obtained from the PN data,which is also found from B type stars (Smartt & Rolleston 1997, Gummersbach et al. 1998). More recently, a new result of about -0.04 for the O abundance gradient was obtained from HII regions (Deharveng et al. 1999). The T_{OIII} temperature of these HII regions are close to the value obtained from radio recombination lines, indicating that temperature fluctuations may not be present. However, the value of the O gradient was obtained by a linear fit with a sample which includes O abundance data from Shaver et al. (1983), although assuming a low weight for them. We calculated the non-weighted O abundance gradient for the same sample and obtained -0.052, thus closer to our PN result. It is clear that new observations are needed to increase the number of objects for which a more precise T_{OIII} can be obtained.

On the other hand, for open clusters the Fe/H gradient was -0.095 dex Kpc^{-1} (Friel 1995), but recent results indicate a flatter gradient in agreement with the O/H gradient from the B stars (Friel 1999). The temperature effect discussed in this paper could also apply to HII regions, and we would expect that the corresponding abundance gradient would also be steeper, approaching the former value obtained from open clusters, although O and Fe are produced by different progenitors. However, two important issues are *how to explain the observed gradient and how constant it is during the galactic evolution*.

A value for the radial abundance gradients as precise as possible is of fundamental importance for the chemical evolution models of our Galaxy (e.g. Chiappini 1998) The abundance gradient is an important constraint on the models, since it is not restricted to the solar vicinity as are most of the other constraints. The temporal and spatial behaviour of the gradient depends on the star formation rate and on the gas density distribution in the disc. Regarding chemical evolution models, different authors adopt different prescriptions for the input parameters, and different solutions are obtained. Some constraints are satisfied by different models, however, the abundance gradient is one of the few that may really determine the model. The model discussed by Chiappini (1998) gives an O gradient of - 0.04 dex/Kpc for the inner part of the Galaxy, which is too flat. Chiappini suggests that if radial flows are included in the model the theoretical O gradient could become steeper. As shown in this paper, the real elemental abundance gradient may be steeper than previously assumed, and it may then imply that radial flows must really be accounted for in future models.

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