ON THE ABUNDANCE GRADIENT OF THE GALACTIC DISK

L. P. Martins and S. M. M. Viegas

Instituto Astronômico e Geofísico, São Paulo, Brazil

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 and 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, it 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: interstellar medium: abundances - 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 and 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 ($T_{Bal}$), and 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, respectively at the high- and low-ionization zones. 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, Torres-Peimbert and Peimbert (1998). Abundances derived from recombination lines are usually higher than those from collisionally excited lines.

Regarding the abundance gradient in the Galaxy, it 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 §2. The method used and the results are presented in §3. The conclusions appear in §4.
2. The PN sample

As proposed by Peimbert (1978), the PN of the galactic disk can be classified in 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 contrary, 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 have 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 galactic 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. Usually the gradient is obtained from abundance data available in the literature. In our case, we need a homogeneous sample, i.e., the elemental abundance must 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 line 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, respectively, by the [O III] and [N II] line ratios. 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 emission-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 equations 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 and Ferland (1995). The total helium abundance is the sum of the ions He^+ and He^{++} since the neutral helium in those objects is negligible.

\[
\frac{O}{H} = \frac{(O^+ + O^{++})}{H^+} \left( \frac{He^+}{He^+} \right).
\]

(1) (Peimbert & Torres-Peimbert 1977)

\[
\frac{N}{H} = \frac{(N^+)}{H^+} \left( \frac{O}{O^+} \right).
\]

(2) (Peimbert & Torres-Peimbert 1977)

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

(3) (Köppen et al. 1991)

\[
\frac{Ne}{H} = \frac{(Ne^{++})}{H^+} \left( \frac{O^+ + O^{++}}{O^{++}} \right).
\]

(4) (Peimbert 1990)

The calculated elemental abundances are listed in Table 1. These values are used to derive the standard abundance gradient, \( \alpha_0 \), 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 ics 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 previous papers this correction is 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...
Table 1. Results of density, temperatures and abundances

| Nebulae | Ref[\textsuperscript{a}] | n_e | $T_{NII}$ | $T_{OIII}$ | O/H | N/H | S/H | Ne/H | R(Kpc)[\textsuperscript{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 | 8.84 |
| NGC 5882 | 6 | 4994 | 9897 | 8979  | 8.76 | 7.86 | 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 | 11267 | 8.84 | 8.35 | 7.92 | 8.50 | 6.51 |
| NGC 6543 | 2 | 4329 | 10040 | 8249  | 8.70 | 8.05 | 7.54 | 7.79 | 8.59 |
| NGC 6563 | 6 | 5210 | 11174 | 12032 | 8.76 | 8.35 | 7.92 | 7.80 | 6.62 |
| NGC 6565 | 4 | 2426 | 9710 | 10383 | 8.82 | 8.63 | 7.73 | 7.80 | 7.01 |
| NGC 6572 | 2 | 10276 | 6074 | 9802  | 8.91 | 8.10 | 7.55 | 8.20 | 7.87 |
| NGC 6578 | 3 | 5438 | 11059 | 8371  | 8.76 | 7.95 | –   | 7.21 | 8.45 |
| NGC 6720 | 7 | 825 | 9780 | 11120 | 8.69 | 8.49 | 7.25 | 8.05 | 8.22 |
| NGC 6790 | 2 | 3468 | 19110 | 11638 | 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 | 6 | 5210 | 11174 | 12032 | 8.43 | 8.54 | 6.93 | 7.48 | 7.80 |
| NGC 6884 | 2 | 7282 | 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 7626 | 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 | 12482 | 10994 | 8.98 | 8.67 | 7.26 | –   | 7.97 |
| IC 4776 | 2 | 16561 | 15865 | 8564  | 8.79 | 8.02 | 7.53 | 8.03 | 5.29 |
| IC 5217 | 6 | 12965 | 12186 | 11230 | 8.57 | 8.00 | 7.35 | 7.85 | 9.42 |
| He-2-37 | 8 | 370 | 10169 | 12824 | 9.05 | 8.05 | 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 | 15017 | 8.78 | 8.31 | 6.89 | –   | 6.40 |
| Hii-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 | 4 | 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 |

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\textsuperscript{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.

\textsuperscript{b} Distances: Maciel & Köppen 1984
Fig. 1. 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.

atures, 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 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 (Figure 1a,b,c and d). The results are listed in Table 2.

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

| Table 2. Coefficients of the linear fits[a] |
|-------------------------------------------|
| O  | N  | S  | Ne |
|-------------------------------------------|
| $\alpha$ | -0.054 | -0.084 | -0.064 | -0.069 |
| $\sigma(\alpha)$ | 0.018 | 0.084 | 0.035 | 0.034 |
| $\beta$ | 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 = $\alpha_0 R + \beta$; r is the correlation coefficient and N is the number of data points used.
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 works. However our value for the gradient is barely in agreement with the Maciel and Quireza (1999) result. The PN sample used by these authors include 4 PN with distance from the galactic center 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 and 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 were 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, Viegas and Gruenwald (1997). For each PN, we assume that the $T_{OIII}$ is overestimated by $\Delta T$ chosen from a distribution ranging from zero to $\Delta T_{max}$, following a probability $P(\Delta T)$, which can be constant, linear increasing or linear decreasing. Thus, if a constant $P(\Delta T)$ is assumed for each object, any value of $\Delta T$ between 0 and $\Delta T_{max}$ has the same probability to be randomly chosen. On the other hand, if a linear increasing (or decreasing) probability is assumed, higher (or lower) $\Delta T$ values are favored.

Once the type of probability and $\Delta T_{max}$ are chosen, the chemical abundances are recalculated for each PN in the sample using $T = T_{OIII} - \Delta T$ for the high ionization zone, as described in §2.1. A new value of the elemental abundance gradient, $\alpha$, is then obtained by linear fit for each element, as well as the difference $\Delta \alpha = \alpha - \alpha_0$. 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 analyzed. There is no reason to adopt the same change $\Delta T$ 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.

![Fig. 2. Plot of the temperatures $T_{NII}$ versus $T_{OIII}$. Figure shows that exists no correlation between these two temperatures. The correlation coefficient is 0.21](image)
4.2. Systematic error

The PN sample observed by Liu & Danziger (1993) shows that the difference between \( T_{\text{OIII}} \) and \( T_{\text{Bal}} \) can reach up to 6000 K, although most objects show a difference 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 Table 4 and 5, for \( \Delta T_{\text{max}} \) equal to 4000 K and 2000 K, respectively. In both cases, the results obtained with a lower \( T_{\text{OIII}} \) is to steepen 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 inner region to the outer region of the Galaxy, we expect that the increase of the abundance, due to a decreasing of \( T_{\text{OIII}} \), 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 \( T_{\text{OIII}} \) (as O and Ne abundances are), steeper gradients are also obtained. It is a second order effect, because a decrease of \( T_{\text{OIII}} \) induces a change in the icf of N and S.

Table 4. Results of the Monte Carlo with \( \Delta T_{\text{max}} = 4000\text{K} \)

| \( \Delta \alpha \) | \( \text{P constant} \) | \( \text{P crescent} \) | \( \text{P decrescent} \) |
|----------------------|------------------|-------------------|------------------|
| 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 \( \Delta T_{\text{max}} = 2000\text{K} \)

| \( \Delta \alpha \) | \( \text{P constant} \) | \( \text{P crescent} \) | \( \text{P decrescent} \) |
|----------------------|------------------|-------------------|------------------|
| 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 Carlo simulations, where the decrease in the gas temperature for each PN in the sample is chosen randomly between zero and \( \Delta T_{\text{max}} \). 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, Guumersbach 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 \( T_{\text{OIII}} \) 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 \( T_{\text{OIII}} \) 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 behavior 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. She 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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References

Aller, L. H. & Czyzak, S. J. 1983, 51, 211
Aller, L. H. & Keyes, C. D., 1987, ApJS, 65, 405
Barker, T. 1978, ApJ, 219, 914
Barker, T. 1983, ApJ, 267, 630
Brocklehurst, M. 1972, MNRAS, 157, 211
Clegg, R. E. S. 1987, MNRAS, 229, 31
Chiappini, C. 1998, PhD thesis, IAGUSP, Brazil
Deharveng, L., Peña, M. Caplan, J. & Costero, R. 1999, MNRAS, 311, 329
Dennefeld, M. & Satsinska, G. 1983, A & Am 118, 234
Fatínez-Abans, M. & Maciel, W. J. 1986, A&A 158, 228
Fatínez-Abans, M. & Maciel, W. J. 1987a, A&A 183, 324
Fatínez-Abans, M. & Maciel, W. J. 1987b, Astrophys. Sp. Sci 129, 353
Ford, H. C., Jenner, D. C., Epps, H. W. 1973, ApJ, 183, 73
French, H. B. 1981, ApJ, 246, 434
Freitas-Pacheco, J. A., Maciel, W. J., Costa, R. D. D. 1992, A&A, 261, 579
Freitas-Pacheco, J. A., Maciel, W. J., Costa, R. D. D., Barbuy, B. 1991, A&A, 250, 159
Friel, E. D. 1995 ARAA 33, 381
Friel, E. D. 1999, A&SS, 265, 271
Gummersbach, C. A., Kaufer, A., Schaefer, D. R., Szeifert, T. & Wolf, B. 1998, A&A 338, 896
Kaler, J. B., Shaw, R. A., Browning, L. 1997, PASP, 109, 289
Kingdon, J. & Ferland, G. J. 1995, 442, 714
Kingsburgh, R. L., Barlow, M. J. 1992, MNRAS, 257, 317
Köppen, J., Acker, A., Stenholm, B., 1991, A&A, 248, 197
Liu, X. & Danziger, J. 1993, MNRAS 263, 236
McCall, M. L. 1984, MNRAS 208, 253
Maciel, W. J., 1984, A&AS, 52, 253
Maciel, W. J. & Dutra, C. M. 1992, A&A 262, 271
Maciel, W. J. & Köggen, J. 1994, A&A 282, 436
Maciel, W. J. & Quireza, C. 1999 A&A 345, 629
Mathis, J. S., Torres-Peimbert, S. & Peimbert, M. 1998, ApJ 495, 328
Pasquali, A. & Perinoto, M., 1993, A&A 280, 581
Peimbert, M. 1967, ApJ 150, 825
Peimbert, M. 1978, IAU Symp. 76, ed. Y. Terzian (Reidel: Dordrecht) p. 215.
Peimbert, M. 1990, Rep. Prog. Phys. 53, 1559
Peimbert, M. & Costero, R. 1969, Bol. Obs. Tonantzintla y Tacubaya 5, 3
Peimbert, M. & Torres-Peimbert, S. 1971, ApJ, 168, 413
Peimbert, M. & Torres-Peimbert, S. 1977, MNRAS, 179, 217
Quireza, C. 1999, PhD thesis, IAGUSP, Brazil
Shaver, P. A., McGee, R. X., Newton, L. M., Danks, A. C., Pottash, S. R. 1983, MNRAS 204, 53
Smartt, S. J. & Rolleston, W. R. J. 1997, ApJ 481, 147
Steigmann, G., Viegas, S. M., Gruenwald, R., 1997, ApJ, 490, 187
Torres-Peimbert, S., Peimbert, M. 1977, Rev. Mex. AA, 2, 181
Viegas, S. M. & Clegg, R. E. S. 1994, MNRAS 271, 993