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RADIAL GRADIENTS AND METALLICITIES IN THE GALACTIC DISK

W. J. Maciel

IAG/USP, São Paulo, Brasil

RESUMEN

Se combinan los gradientes radiales de O/H obtenidos a partir de regiones H II, estrellas calientes y nebulosas planetarias, con los gradientes de [Fe/H] obtenidos en cúmulos abiertos para determinar una relación independiente entre [O/Fe] y [Fe/H] para el disco galáctico. Una comparación de la relación obtenida con datos observacionales recientes y modelos teóricos sugiere que las abundancias de [O/Fe] no alcanzan valores mayores que [O/Fe] $\simeq 0.4$, por lo menos en el intervalo de metalicidades de las muestras consideradas.

ABSTRACT

Radial O/H abundance gradients derived from H II regions, hot stars and planetary nebulae are combined with [Fe/H] gradients from open cluster stars in order to derive an independent [O/Fe]–[Fe/H] relation for the Galactic disk. A comparison of the obtained relation with recent observational data and theoretical models suggests that the [O/Fe] ratio is not higher than [O/Fe] $\simeq 0.4$, at least within the metallicity range of the considered samples.

Key Words: **GALAXY: ABUNDANCES — H II REGIONS — ISM: ABUNDANCES — PLANETARY NEBULAE: GENERAL — STARS: ABUNDANCES**

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1. INTRODUCTION

The [O/Fe]–[Fe/H] relation is one of the basic relationships in the study of the chemical evolution of the Galaxy, as it links the main metallicity indicators and stresses the different contribution of Type II and Type I supernovae. Recently, some discrepancy has been observed between different sets of observational data and among theoretical models themselves regarding the [O/Fe] abundance ratio. Several of these results, which are generally based on studies of the [O I] forbidden line doublet at 6300,64 Å in metal-poor giants, lead to [O/Fe] $\simeq 0.5$ for [Fe/H] $\simeq -2$, showing a plateau in the [O/Fe] ratio at low metallicities (Barbuy & Erdelyi-Mendes 1989; Edvardsson et al. 1993; Fulbright & Kraft 1999, see Carretta, Gratton, & Sneden 2000 for additional references). Theoretical models such as those by Matteucci, Romano, & Molaro (1999) and Chiappini, Matteucci, & Gratton (1997) are successful in reproducing these abundances for metallicities down to [Fe/H] $\simeq -2$. On the other hand, oxygen abundances from the O I infrared lines and some recent studies based on ultraviolet OH bands in metal-poor subdwarfs reach a much higher ratio, [O/Fe] $\simeq 1$ at low metallicities (Israelian et al. 1998; Boesgaard et al. 1999), which can be reproduced by theoretical models by Ramaty et al. (2000).

Some authors find that the slope of the [O/Fe]–[Fe/H] relation is about -0.30 to -0.40, and essentially the same for the thin disk, thick disk and halo (Israelian et al. 1998; Boesgaard et al. 1999; Mishenina et al. 2000), so that any detailed investigation should include both metal rich and metal poor objects belonging to these Galactic subsystems.

A contribution to the understanding of this problem can be obtained by the analysis of radial abundance gradients in the Galactic disk. Such gradients can be observed both for the O/H ratio (and sometimes S/H, Ne/H and Ar/H as well) from H II regions, planetary nebulae and hot stars and also for the [Fe/H] metallicity, principally from open cluster stars (Maciel 1997; 2000). In this work, both sets of data are taken into account in order to derive an independent [O/Fe]–[Fe/H] relation appropriate to the Galactic disk, roughly at metallicities [Fe/H] ≥ -1.5. Such relation can be directly compared with recent observational data and with the predictions of detailed theoretical models, thus contributing to clarify the discrepancy in the [O/Fe] ratio at subsolar metallicities.

2. RADIAL ABUNDANCE GRADIENTS

2.1. *The* O/H *Gradient*

The best determinations of the O/H radial gradient are made on the basis of photoionized nebulae (H II regions and planetary nebulae) and hot stars. Earlier work on these nebulae already pointed to similar gradients, amounting roughly to

$d \log(\mathrm{O/H})/dR \simeq -0.06$ to -0.07 dex/kpc, as shown by Shaver et al. (1983) and Faúndez-Abans & Maciel (1986) for H II regions and planetary nebulae, respectively.

More recent work has firmly established the presence of such gradients, not only for the O/H ratio but also for other elements such as S/H, Ne/H and Ar/H (see for example Maciel 1997 and Maciel 2000). H II region data have been discussed by Simpson et al. (1995), Esteban & Peimbert (1995), Vílchez & Esteban (1996) and Deharveng et al. (2000). Studies of planetary nebulae (Maciel & Köppen 1994; Maciel & Quireza 1999) go as far as to investigate possible space and time variations within the Galactic disk, with important consequences for theoretical models.

Stellar data based on O and B stars apparently told a different story. Several investigations up to 1997 presented controversial results, with the general conclusion that no gradients were present or were restricted to the inner parts of the disk (Fitzsimmons et al. 1990; Kaufer et al. 1994; Kilian-Montenbruck et al. 1994). Since these stars were expected to have intermediate ages between H II regions and the planetary nebula central stars, it was difficult to conciliate these different sets of data. However, since the work of Smartt & Rolleston (1997) and Gummersbach et al. (1998) these contradictions have been settled out and a clear gradient of the same order as the one derived from the photoionized nebulae has been obtained. This work was based on medium to high-resolution spectra of a relatively large sample of main sequence B stars in clusters and associations, spanning about 12 kpc in galactocentric distances. The O/H gradient from the above mentioned sources can be written as

$$\log(\mathrm{O/H}) + 12 = a + bR, \tag{1}$$

where R is the galactocentric distance in kpc. Most determinations of the gradients assume different distances of the LSR to the Galactic center, ranging from 7 kpc to 8.5 kpc. For the sake of uniformity, we have adopted a recent value $R_0 = 7.6$ kpc (Maciel 1993; Reid 1989), so that the values of the gradients given here refer to this value.

The constants a and b have slightly different values depending on the nature of the objects considered, namely H II regions, planetary nebulae and hot stars. Generally speaking, H II regions and hot stars have very similar gradients, while most planetary nebulae show a slightly flatter gradient. An average gradient of the former, derived from the sources above and referring thus to the younger population, is characterized by the values $a = 9.34 \pm 0.14$ and $b = -0.070 \pm 0.014$ dex/kpc.

2.2. *The* [Fe/H] *Gradient*

A large amount of work has been done on the [Fe/H] gradient in the Galaxy, on the basis of data on open cluster stars (Janes 1995, Friel 1995, Janes 2000). Most of these determinations indicate a steeper [Fe/H] gradient as compared with the O/H gradient derived from H II regions, hot stars and planetary nebulae. Results by Friel, Janes and coworkers (Friel 1995; Janes 2000; Phelps 2000) suggest gradients of the order of -0.07 to -0.09 dex/kpc, which is in agreement with recent determinations by Twarog et al. (1998) and Carraro et al. (1998). The [Fe/H] gradient can be written as

$$[\mathrm{Fe/H}] = c + dR \tag{2}$$

and average values of the constants are $c = 0.50 \pm 0.05$ and $d = -0.085 \pm 0.008$ dex/kpc, again correcting for $R_0 = 7.6$ kpc.

2.3. *The Time Variation of the Gradients*

The time variation of the radial gradients is not well known, and in fact some theoretical models predict a time steepening of the gradients (Chiappini et al. 1997; Hensler 1999), while others predict just the opposite behavior (Allen et al. 1998; Mollá et al. 1997). The main difficulty in approaching this problem is that objects with rather different ages should be considered, which introduces some difficulty in understanding the measured gradients. Probably the best group of objects to study this problem is the planetary nebulae, since these objects include both relatively old objects (the so-called type III nebulae, see Peimbert 1978 and Maciel 1989) and relatively young ones (the type I and type II nebulae).

Available data, as discussed by Maciel & Köppen (1994) and Maciel & Quireza (1999) point to a mild steepening of the gradients, so that the H II region gradient is slightly steeper than that of the planetary nebulae. Also, some steepening is observed comparing the gradients of type III objects relative to the remaining, younger types, which supports this conclusion. On the other hand, the difference between the H II region and the stellar data is negligible, reflecting the similar ages of these objects or a constancy of the gradients at more recent times. In fact, recent models by Chiappini and collaborators (Chiappini et al. 1999 and private communication) predict a very slow steepening of the gradients during the last few Gyr, so that this assumption is probably correct. Therefore, we can consider the H II regions and open cluster stars as referring to essentially similar epochs, so that equations (1) and (2)

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and the given values of the constants a, b, c and d can be safely used as reflecting the present interstellar abundances of oxygen and iron in the Galactic disk, within the assumed uncertainties.

3. METALLICITIES IN THE GALACTIC DISK

Adopting the usual definition of the abundance ratios relative to the sun, $[X/Y] = \log(X/Y) - \log(X/Y)_\odot$, we have for the oxygen and iron abundances

$$[O/Fe] = \alpha + \beta\ [Fe/H], \tag{3}$$

where we have defined

$$\alpha = a - \frac{bc}{d} - [\log(O/H)_\odot + 12] \tag{4}$$

and

$$\beta = \frac{b}{d} - 1, \tag{5}$$

and have assumed that relations (1) and (2) hold throughout the disk. Equivalently, we may write $[O/H] = \alpha + (\beta + 1)\ [Fe/H]$. Another interesting relation can be written as

$$[Fe/H] = \gamma + \delta\ [\log(O/H) + 12], \tag{6}$$

with

$$\gamma = c - \frac{a\,d}{b} \tag{7}$$

and

$$\delta = \frac{d}{b}. \tag{8}$$

It is easy to show that $\delta = 1/(1+\beta)$ and $-\gamma/\delta = \alpha + [\log(O/H)_\odot + 12]$, so that the parameters γ and δ are not independent.

4. RESULTS AND DISCUSSION

In view of the previous discussion, adopting the given values of the constants a, b and c, we obtain the following parameters: $\alpha = 0.098$, $\beta = -0.176$, $\gamma = -10.841$ and $\delta = 1.214$, where we have used the solar abundances $\log(O/H)_\odot + 12 = 8.83$ (Grevesse & Sauval 1998).

The main results are shown in Figure 1, which includes two panels, the first showing the usual [O/Fe]–[Fe/H] relationship and the second showing the [Fe/H]–log(O/H) + 12 relationship. The solid lines show the predicted "theoretical" relationships taking into account the observed radial gradients. The dotted lines show results of theoretical models by Matteucci et al. (1999) and the dot-and-dashed lines represent models by Ramaty et al. (2000). Data from Matteucci et al. (1999) follow models by Chiappini et al. (1997), and are representative of models predicting a [O/Fe] plateau for metallicities under solar, without a significant increase in the [O/Fe] ratio above 0.5 dex for $[Fe/H] \leq -2$. On the other hand, models by Ramaty et al. (2000) have been selected to display higher [O/Fe] ratios at lower metallicities, adopting supernova yields from Woosley & Weaver (1995) and finite Fe and O mixing delay times. Figure 1 also includes some representative observational data by Barbuy & Erdelyi-Mendes (1989), asterisks; Boesgaard et al. (1999), filled squares; Edvardsson et al. (1993), crosses; Israelian et al. (1998), solid dots; Spiesman & Wallerstein (1991), open circles; Spite & Spite (1991), plus signs; Takada-Hidai et al. (2001), empty squares; Mishenina et al. (2000), open stars, and Cavallo et al. (1997), filled stars, as recomputed by Mishenina et al. (2000).

It can be seen that for metallicities close to and slightly lower than the solar value, all observational data and models show a reasonable agreement, while for lower metallicities the spread is considerably larger. Part of this scatter may be due to the use of different scales of stellar parameters such as effective temperatures, gravities and metallicities, to the adoption of different atomic parameters or the neglecting of NLTE effects. However, the spread is large enough so that two different regimes can be distinguished, namely, "low [O/Fe]" and "high [O/Fe]" at low metallicities. The data by Boesgaard et al. (1999) and Israelian et al. (1998) indicate higher [O/Fe] ratios, closer to the models by Ramaty et al. (2000). The remaining data do not show such large [O/Fe] abundances, in agreement with the models by Matteucci et al. (1999) and Chiappini et al. (1997).

It is clear that the gradient data support the lower [O/Fe] abundances predicted by the latter, at least for metallicities larger than $[Fe/H] \simeq -1.5$, which are appropriate for the oldest populations of the disk. The gradients themselves cover a smaller fraction of the metallicity range, as shown by the solid lines in figure 1, and already in this region it is apparent a better agreement with the model predictions of Matteucci et al. (1999). Extrapolating the solid lines towards lower metallicities, as shown by the broken lines, we obtain an upper limit for the [O/Fe] ratio of 0.4 dex, which is also closer to the low [O/Fe] regime.

Therefore, our data is consistent with a maximum $[O/Fe] \simeq 0.4$ for the Galactic disk, at least for metallicities as low as $[Fe/H] \simeq -1.5$, which are appropriate to the region where the abundance gradients are observed. This is also supported by recent observations of infrared OH lines in metal-poor stars (Meléndez et al. 2000) and by a recent anal-

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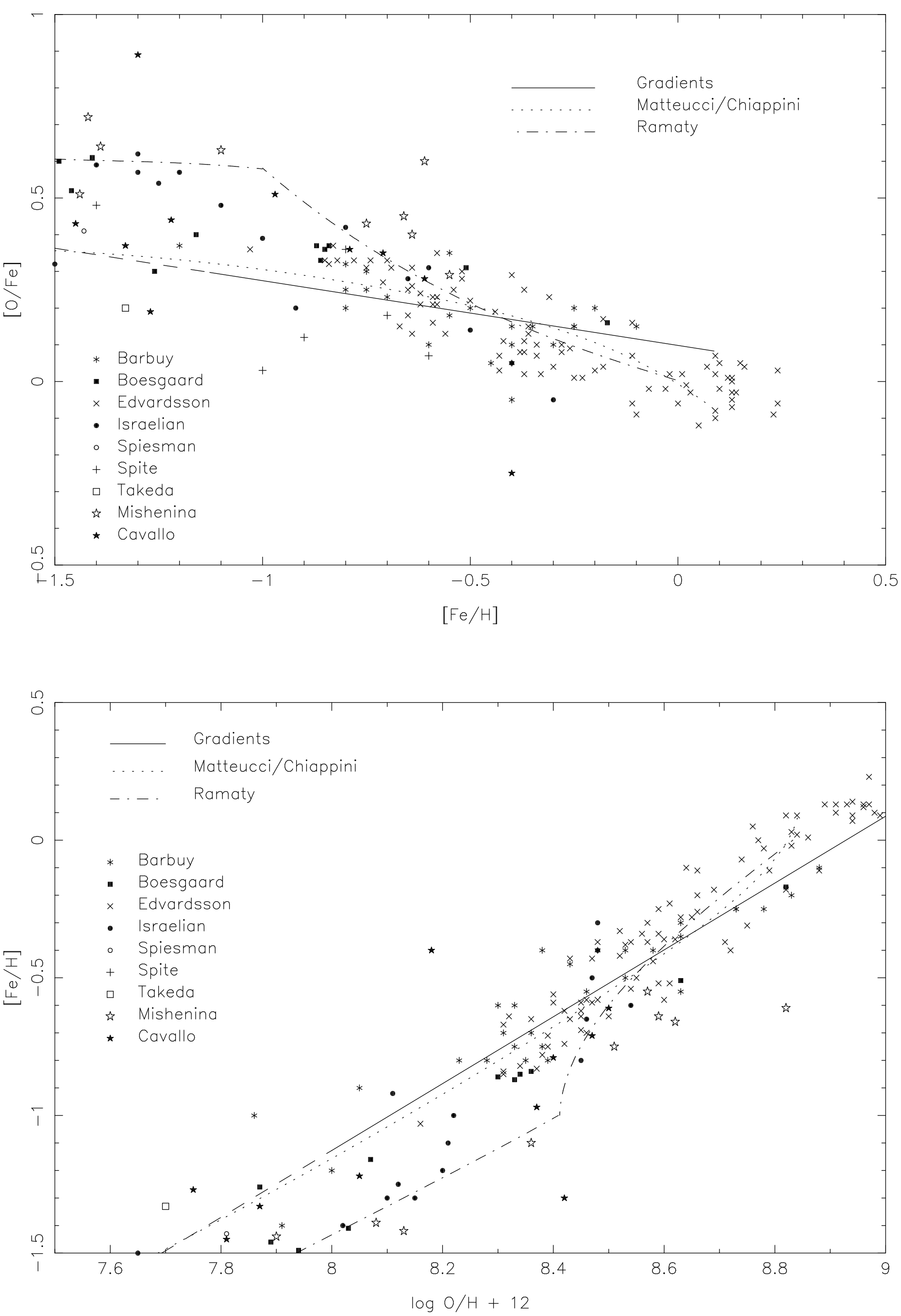

Fig. 1. Metallicities in the Galactic disk.

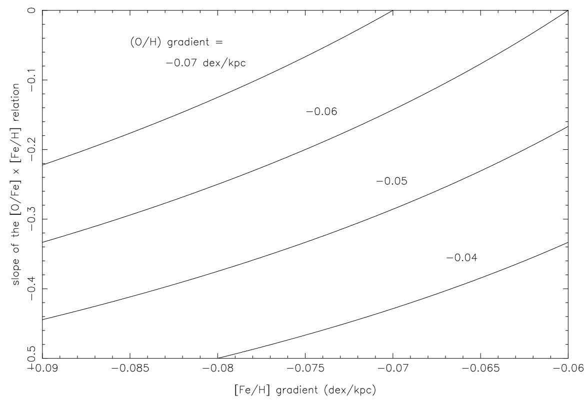

Fig. 2. Slope of the [O/Fe]–[Fe/H] relation in the Galactic disk.

ysis by Carretta et al. (2000), based on data for a selected sample of 19 stars. Their results support a moderate increase in the [O/Fe] ratio, pointing out that the higher [O/Fe] obtained by Boesgaard et al. (1999) derive mostly from OH abundances, which suffer from a difficulty in the location of the continuum levels, so that these abundances are probably not reliable. Also, the analysis of Fulbright & Kraft (1999) of some of the stars studied by Israelian et al. (1998) concludes that the [O/Fe] ratio is lower than derived earlier, and that it is premature that the oxygen abundances of metal-poor stars should be increased. Of course, the simplicity of the linear gradients does not allow to predict any change of slope or the presence of a plateau, so that the agreement between the solid lines of Figure 1, the metallicity data and theoretical models is only approximate. However, it is clear that no [O/Fe] ratio higher than about 0.4 dex can be expected for the metallicities considered. Furthermore, a small upward trend in [O/Fe] is also observed by Carretta et al. (2000), leading to maximum ratios close to the results shown in Figure 1.

The second panel in Figure 1 is particularly useful for photoionized nebulae such as H II regions and planetary nebulae, for which the [Fe/H] abundance cannot be usually obtained directly. In this case, an average relation such as shown by the solid straight line could be used to estimate the expected [Fe/H] for a given oxygen abundance. Also, if a determination of [Fe/H] is available, this line could be used to estimate the amount of iron that is condensed in solid grains.

The straight lines in Figure 1 should be considered as average relations, as no effort has been made to fit either the solar or the remaining data. For example, these lines could be slightly displaced vertically if we take into account the uncertainties in the intercepts a and c of equations (1) and (2), respectively. The effect of the uncertainties in the determination of the gradients can be observed in Figure 2, where we show the slope β of the [O/Fe]–[Fe/H] relation as a function of the [Fe/H] gradient for different values of the O/H gradient. It can be seen that the average slope is about $\beta \simeq -0.2$, and that steeper slopes would require either a very low O/H gradient, assuming that the [Fe/H] gradient is -0.085 dex/kpc, or a very steep [Fe/H] gradient, assuming that the O/H gradient is -0.07 dex/kpc. Since there is no observational evidence for these possibilities, it can be concluded that average slopes steeper than $\beta \simeq -0.2$ are not supported by the present data.

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W. J. Maciel: Instituto Astronômico e Geofísico da USP, Av. Miguel Stefano 4200, CEP 04301-904, São Paulo SP, Brazil (maciel@iagusp.usp.br).