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Invited Review

Galactic radial abundance gradients: cepheids and photoionized nebulae

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Abstract.
Radial abundance gradients are observed in the Galaxy and other galaxies as well, and include several chemical elements in different stellar systems. Possibly the most accurate gradients in the Galaxy are those determined from chepheid variable stars. These objects have very accurate abundances for many elements and are generally considered as standard candles, so that their galactocentric distances are very well determined. These stars are relatively young, with ages between the main types of photoionized nebulae, namely the younger HII regions and the older planetary nebulae. In this paper we consider the O/H and Fe/H gradients based on a large sample of galactic cepheids, and compare the results with recent determinations from photoionized nebulae.

Key words: galaxies: abundances — galaxies: ISM — stars: cepheids

1. Introduction

Radial abundance gradients are increasingly important as a constraint of chemical evolution models both for the Galaxy and other galaxies as well. They can be measured using a variety of objects, such as HII regions, cepheid variables, planetary nebulae, open clusters, etc. Since these objects comprise a large range of ages, from a few million years to several Gyr, the gradients can also give some information on the time variation of the abundances in several galactic systems. It is generally believed that the gradients derived from young objects, such as HII regions and cepheid stars are somewhat different from those measured in older systems, such as planetary nebulae and open clusters. However, the interpretation of the data is complex, in view of the different elements that can be studied and of the considerable uncertainties in assigning a definite age to each object, especially in the case of the older systems. Some references include Anders et al. (2017); Mollá et al. (2018); Mollá et al. (2019); Maciel & Costa (2014, 2013); Maciel et al. (2012); Cavichia et al. (2014, 2011). Some recent results obtained by our group suggest that the gradients have not appreciably changed in the past 3-5 Gyr, although these results are dependent on relatively uncertain age estimates (Maciel et al., 2012; Maciel & Costa, 2013).
Another source of uncertainties are possible space variations of the gradients, such as the proposed flattening at large galactocentric distances, the behaviour

of the gradients in the inner Galaxy, which can be affected by the presence of bars, and near the solar galactocentric distance, where a large amount of data is available. The simplest models assume a unique linear gradient throughout the galactic disk, but more complicated variations have also been considered, such as multiple linear gradients in different parts of the disk and non linear variations (see for example, Maciel et al., 2015; Davies et al., 2009; Ivezić et al., 2008; Esteban et al., 2017).

In this paper, we consider the O/H and Fe/H radial gradients in the galactic disk as measured by cepheid variable stars. There is a large amount of data for these stars, including the results of the group by S. Andrievsky and collaborators (Andrievsky et al., 2016, 2014, 2013, 2004, 2002b,a,c; Luck et al., 2013, 2011, 2006, 2003; Luck & Lambert, 2011; Korotin et al., 2014; Martin et al., 2015), as well as by other groups, (Genovali et al., 2015b,a, 2014, 2013; Lemasle et al., 2018, 2013, 2015; Pedicelli et al., 2009). Our goal is to consider the largest possible sample of reliable spectroscopic abundances as well as accurate galactocentric distances. It is expected that the use of a nearly complete sample may lead to an accurate determination of the gradients, so that the non-homogeneity of the data may be counterbalanced. We will analyze several possibilities of the abundance variations in the disk, such as a unique linear gradient, multiple gradients, and non-linear variations. The results can then be compared with the results from other young and older systems, such as HII regions, planetary nebulae and open clusters.

2. Cepheid gradients: O/H and Fe/H

2.1. The data

The basic sample comes from the work by Korotin et al. (2014), who have presented a NLTE analysis of the oxygen abundance distribution in the thin disk based on infrared data from two telescopes: the Hobby-Eberly Telescope (HET) and the Max Planck Gesellschaft Telescope (MPG). The lines used are the triplet 777.1 - 777.4 nm. The HET data are described by Luck & Lambert (2011), whereas the MPG data are from Luck et al. (2013) with atmospheric parameters from Luck et al. (2011). Fe/H data are also included from Luck & Lambert (2011) and Luck et al. (2013). The lowest uncertainties in the O/H abundances are in the range 0.05 to 0.08 dex, and an average uncertainty is 0.12. The data by Luck & Lambert (2011) include Fe abundances with errors and oxygen abundances, but not distances. The average uncertainties for the Fe/H data are 0.141 dex for FeI and 0.119 dex for FeII, with a standard deviation of 0.047 dex, considering all. We adopt the FeII data when possible, so that we can assume and average uncertainty of 0.12 dex for the Fe/H abundances, which is the same as the O/H uncertainties in the data by Korotin et al. (2014). The distances and galactocentric distances of the objects in the sample by Luck & Lambert (2011) are given in Luck et al. (2013).

Martin et al. (2015) presented chemical abundances for a sample of galactic cepheids, including also the elements O/H and Fe/H. The galactocentric distances range mostly from 5 to 7 kpc, adopting $R_0 = 7.9\,$kpc for the solar galactocentric distance, that is, the objects are generally closer to the galactic centre than in the previous samples. A combination of the previous data with the present results suggests a plateau in the chemical abundances closer to the galactic centre. The observations were secured with the 3.6 CFHT telescope, the VLT, and the MPG telescope as in Korotin et al. (2014). Stellar atmosphere parameters are presented, as in the previous samples. Fe abundances are from LTE analysis, while for O/H NLTE is used. The uncertainties in the abundances are small, similar or lower than in Korotin et al. (2014). A value of 0.12 dex can be estimated both for O/H and Fe/H, being usually an upper limit.

More recently, Andrievsky et al. (2016) presented a detailed study of a cepheid variable star located closer to the galactic bulge than the previous samples. It is the object ASAS 181024-2049.6, for which they derive $R_G = 2.53$ kpc, ϵ(O) = 9.17 and ϵ(Fe) = 7.94, corresponding to [O/H] = 0.46 and [Fe/H] = 0.44. The data were obtained with the CFHT telescope and a selection of 4 candidate stars was considered in the literature, one of which satisfied the usual criteria to distinguish Cepheid variables from W Vir stars. Andrievsky et al. (2016) included this object in order to obtain a more complete sample than the one by Martin et al. (2015). This sample emphasized the objects closer to the galactic centre in order to investigate an apparent flattening in the gradients in this region, possibly as a consequence of the existence of a bar. Such a suggestion had already been made in the literature based on theoretical models and planetary nebula data (see for example Cavichia et al., 2014, 2011). In the paper, Andrievsky et al. consider a large number of elements such as Mg, Si, S, Ca, and Ti, all of which share the same characteristics.

Genovali et al. (2015b,a) presented Fe/H abundances of a sample of galactic cepheids with data analyzed by Genovali et al. (2014). Some of the stars in their sample are also presented in the previous samples, so that they have not been considered. The data are based on high-resolution UVES spectra collected at ESO VLT (Cerro Paranal, Chile). The abundances are based essentially on the equivalent widths of FeI and FeII lines. The galactocentric distances are based on NIR photometry together with reddening-free Period-Wesenheit relations, with $R_0 = 7.94$ kpc. Some results by Lemasle et al. (2018) have also been taken into account (see also Lemasle et al., 2013, 2015). This work includes double-mode cepheids from the Gaia Data Release (DR2). The metallicity is derived from the ratio of the first overtone and fundamental periods by Gaia DR2 and the parallaxes are used to determine the Galactocentric distances of the stars. The derived abundances are then used to investigate the effects on the galactic [Fe/H] gradient.

2.2. Results

We have analyzed a large sample of galactic cepheids with accurate abundances and distances. In this paper we report some results for a total sample of 361 independent stars with Fe/H abundances, and 331 stars with O/H abundances. The main results are shown in Figures 1ab, 2ab, 3ab, and 4ab, and in Tables 1 and 2. We adopt an average uncertainty of 0.12 dex both for O/H and Fe/H. From the discussion by Groenewegen (2013) the uncertainty in the galactocentric distances is very small, as cepheids are considered as standard candles. The average uncertainty in the distance for the 128 galactic cepheids of Groenewegen (2013) is about 5.38%, and in the case of the galactocentric distance R_G it is 0.79%. Very few stars have uncertainties higher than 1%, so that we adopted

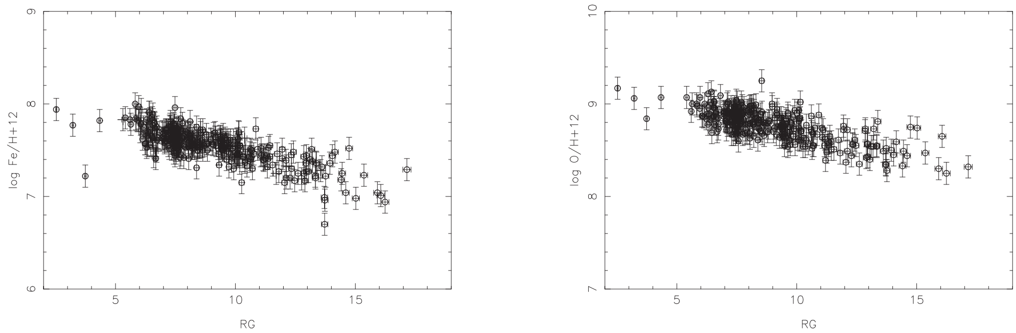

Figure 1. Fe/H and O/H abundances functions of the galactocentric distance for galactic cepehids with the adopted error bars.

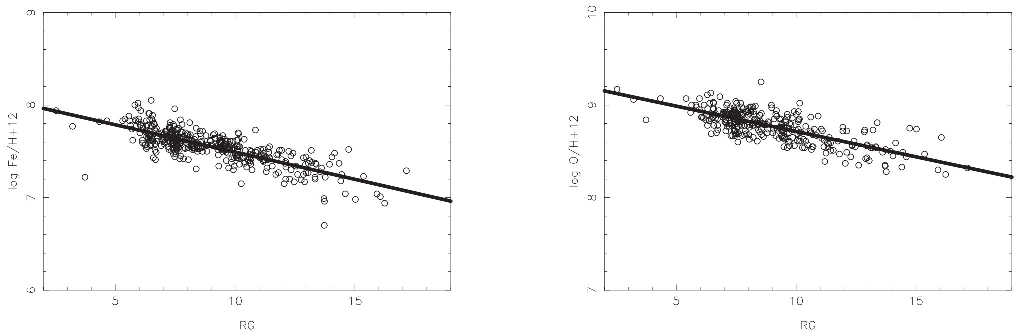

Figure 2. Same as Figure 1 including the linear fits.

here an average uncertainty of 1%. Figure 1a and 1b show the data with error bars for Fe/H and O/H, respectively. Figure 2ab includes linear fits, and the corresponding coefficients are given in Table 1, where we have

$$\log \mathrm{X/H} + 12 = A + B\ R_G \tag{1}$$

We notice that the O/H slope is very similar to the gradient found by Korotin et al. (2014), namely -0.058 dex/kpc, although we have used a larger sample. It can also be seen that both the Fe/H and O/H gradients are essentially the same within the uncertainties. From Figure 1ab there is some indication of a flattening in the inner Galaxy, where $R \leq 5\,$kpc, but the number of stars in this range is very small. Furthermore, the star with the lowest abundances at $R \simeq 3.6\,$kpc is probably a W Vir star, so that this possibility should be viewed with caution.

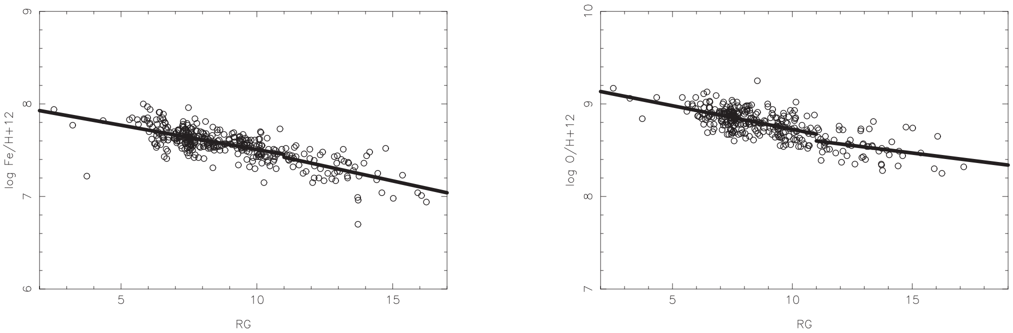

Figure 3. Same as Figure 1 including double linear fits.

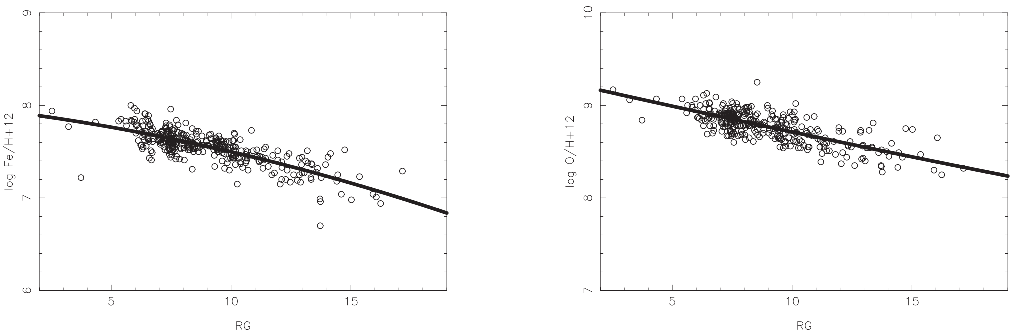

Figure 4. Same as Figure 1 including quadratic polynomial fits.

As a second possibility, we have considered a double linear fit, in the ranges 4-11 kpc and 11-19 kpc, respectively, in agreement with the discussion by Korotin et al. (2014). The adoption of different ranges leads to slightly different results. The results of the fits are also given in Table 1 and Figures 3a and 3b. It can be seen that the correlation becomes less accurate for both segments, in view of the lower correlation coefficients r. For O/H there seems to exist some flattening in the outer galaxy, while for Fe/H the inner gradient is slightly flatter, but the difference is small, so that the gradient can be considered as essentially constant. As a third possibility, we have considered a quadratic polynomial fit, which in principle could take into account any detailed space variations of the gradients, especially in the outer galaxy. The equation used is

$$\log \mathrm{X/H} + 12 = A + B\ R_G + C\ R_G^2 \qquad (2)$$

The results are shown in Figures 4ab, and are essentially indistinguishable from the unique gradient shown in Figures 2ab. For example, at $R_G = 7.9\,\mathrm{kpc}$ we have $-0.056\,\mathrm{dex/kpc}$ and $-0.054\,\mathrm{dex/kpc}$ for the O/H and Fe/H gradients, respectively. The coefficients are given in Table 2. Again the correlations seem less accurate. For O/H the gradient is essentially constant, with maybe a slight flattening at large distances. For Fe/H there is a slight steepening in the outer galaxy, but again the difference is small. It should be mentioned that the results for the samples containing all variability phases and only one phase are similar, since the abundances in different phases are essentially the same.

Table 1 - Linear fits of O/H and Fe/H gradients for galactic cepheids.

element	n	A	B	r
Single linear fits				
O/H	331	9.26 ± 0.02	-0.055 ± 0.003	-0.75 ± 0.11
Fe/H	361	8.09 ± 0.02	-0.060 ± 0.003	-0.77 ± 0.11
Double linear fits				
O/H: $R_G < 11$ kpc	273	9.24 ± 0.04	-0.051 ± 0.005	-0.56 ± 0.10
O/H: $R_G > 11$ kpc	58	8.96 ± 0.15	-0.033 ± 0.011	-0.35 ± 0.13
Fe/H: $R_G < 11$ kpc	298	8.03 ± 0.04	-0.053 ± 0.004	-0.58 ± 0.11
Fe/H: $R_G > 11$ kpc	63	8.13 ± 0.17	-0.064 ± 0.013	-0.53 ± 0.15

Table 2 - Quadratic fit of O/H and Fe/H gradients for galactic cepheids.

element	n	A	B	C	χ^2
O/H	331	9.281	-0.05889	-0.0002061	0.0122
Fe/H	361	7.957	-0.03114	-0.001462	0.0130

3. Gradients of photoionized nebulae

Photoionized nebulae, namely HII regions and planetary nebulae are favourite objects to study radial gradients, especially for element ratios such as O/H, Ne/H, Ar/H and S/H, which are usually more difficult to determine in stars. On the other hand, Fe/H abundances are hardly measured in the nebulae, since most Fe is probably condensed in solid grains, so that the interpretation of the iron lines is more complex.

3.1. HII regions

Since the study by Shaver et al. (1983), many papers have dealt with the determination of radial gradients from HII regions, especially for O/H, on the basis of optical or infrared data (see for example Esteban & García-Rojas, 2018; García-Rojas, 2018; Esteban et al., 2017; Balser et al., 2011; Rudolph et al., 2006; Quireza et al., 2006; Deharveng et al., 2000). These papers are based on rather small samples compared with the cepheid samples. Recent work suggests a constant gradient of about −0.04 to −0.05 dex/kpc for O/H and no flattening at large galactocentric distances (Esteban & García-Rojas, 2018). The data are based on a sample with 35 objects with 10.4 GTC observations, for which electron temperatures have been measured. An inverse temperature gradient is also apparent. Some flattening has been pointed out in the inner Galaxy ($R_G \leq 5\,\mathrm{kpc}$), a result also suggested on the basis of planetary nebulae (see for example Gutenkunst et al., 2008; Cavichia et al., 2011). This feature is also observed in our data, as mentioned in section 2.2. A compilation of recent determinations from photoionized nebulae can be found in Mollá et al. (2019).

3.2. Planetary Nebulae

Planetary nebulae can be compared with HII regions, taking into account their different ages and also the fact that some elements have their abundances changed by the evolution of the progenitor stars, such as He and N. The determination of PN ages is a very difficult problem, which certainly affects the interpretation of the gradients (see for example Stanghellini & Haywood, 2018; Maciel et al., 2011, 2010, for some recent discussions on the age problem).

Recent determinations of the abundance gradients include mainly the ratios O/H, Ne/H, S/H and Ar/H, with particular emphasis on the possible variations along the galactocentric distance and also relative to the distance from the galactic plane (see for example Stanghellini & Haywood, 2018; Pagomenos et al., 2018; Maciel et al., 2015; Maciel & Costa, 2013). A detailed study of distance-independent abundance correlations between Ne/H, S/H and Ar/H with O/H has been recently presented by Maciel et al. (2017) for photoionized nebulae of the Local Group, showing that these elements are well correlated in HII regions and also in PN, albeit with a larger dispersion. The O/H radial gradients of PN are usually in the range −0.02 to −0.05 dex/kpc, and most recent papers favour the lowest gradients. However, the interpretation of these results is complex for a variety of reasons. First, the PN distances are not as well known as in the case of cepheids and even HII regions. Second, the (in)famous discrepancy between the results of forbidden lines and recombination lines is still largely unresolved, affecting both PN and HII regions (cf. Carigi et al., 2018). Third, PN central stars have different ages, which are poorly known, especially for those objects older than about 4 Gyr. Fourth, radial migration has been recently found to be an important factor (see for example Minchev et al., 2018; Jia et al., 2018), which probably acts in order to flatten the gradients. This may explain some of the shallow gradients found in the literature, affecting the comparison between the gradients derived from young and old objects. Therefore the uncertainties of the average gradients are probably higher than generally assumed, and any spatial and temporal variations of the gradients based on PN should be viewed with care.

4. Some Conclusions

• The radial gradients from cepheids are reasonably well represented by a unique gradient of about -0.05 dex/kpc, which is essentially the same both for Fe/H and O/H. This is probably the best estimate of the radial gradient at the present time. A double linear fit does not seem likely, although some flattening in the outer galaxy can be observed for O/H. The data are consistent with some flattening in the inner Galaxy, but this region is clearly not well covered in the present sample, since very few stars have galactocentric distances lower than about 5 kpc.

• O/H gradients from HII regions and cepheids are similar within the uncertainties. HII region abundances of O, Ne, S, and Ar show good correlations, and Ne, S, and Ar vary in lockstep with O, so that similar gradients can be expected for these elements.

• PN apparently have slightly flattened gradients of about -0.03 dex/kpc for O/H and Ne/H, but most samples probably include objects with different ages. The uncertainties in the age determination of the PN progenitor stars (and their distances) are very large for the older objects, with ages higher than about 5 Gyr. Radial migration makes things even more difficult, especially for older objects. These facts may explain the lower PN gradients compared with cepheids and HII regions.

• A comparison of the gradients derived from cepheids and photoionized nebulae shows as a first approximation that the gradients are similar, taking into account the uncertainties in the abundances, distances and, especially, the age determinations of PN. There are apparently no important temporal variations in the gradients in the last 3 to 5 Gyr for O/H. The distance-independent correlations for photoionized nebulae studied by Maciel et al. (2017) and stars (see for example Ramírez et al., 2007) suggest that the Fe/H gradients are only marginally different from the O/H gradients.

• Recent theoretical models are able to explain the average gradients based on a inside out formation scenario for the Galaxy. Some models can account for the inner flattening of the gradients, or predict some steepening at galactocentric distances larger than R_0 (see for example Mollá et al., 2019; Stanghellini & Haywood, 2018; Grisoni et al., 2018). These models consider the time variation of the gradients and the results are often conflicting. The idea of a nearly constant gradient in the last few Gyr is supported by several models, but the behaviour of the gradients at earlier epochs is largely controversial. More recently, studies of the variation of the gradients with redshift are also consistent with approximately constant gradients for $z \leq 2$, but again the behaviour at earlier epochs is not clear, and a steeper gradient for $z > 3$ cannot be ruled out (see for example Mollá et al., 2019; Stanghellini & Haywood, 2018).

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