Highlights on Spanish Astrophysics X, Proceedings of the XIII Scientific Meeting of the Spanish Astronomical Society held on July 16 – 20, 2018, in Salamanca, Spain. B. Montesinos, A. Asensio Ramos, F. Buitrago, R. Schödel, E. Villaver, S. Pérez-Hoyos, I. Ordóñez-Etxeberria (eds.), 2019

The shape of the Galactic abundance gradient of oxygen from deep spectra of H II regions.

C. Esteban[1,2]

[1] Instituto de Astrofísica de Canarias, E-38200, La Laguna, Tenerife, Spain
[2] Departamento de Astrofísica, Universidad de La Laguna, E-38206, La Laguna, Tenerife, Spain

Abstract

We present results of an ongoing project dedicated to reassess the shape of the radial abundance gradient of O in the Milky Way based on deep spectroscopy of H II regions. Most of he data have been obtained with spectrographs attached to 8-10 m telescopes. The actual sample comprises 35 objects located at Galactocentric distances, R_{G}, from 5.1 to 17 kpc, covering a substantial fraction of the Galactic disc. We determine T_{e} from the direct method for all of the objects, implying that the abundance determinations are very reliable. We confirm the absence of flattening of the O gradient in the outer Milky Way beyond R_{25}, at least up to $R_{\mathrm{G}} \sim 17$ kpc. We report the presence of a flattening or drop of the O abundance in the inner part of the Galactic disc, at $R_{\mathrm{G}} <$ 7-8 kpc. Finally, we find that the scatter of the O abundances of H II regions with respect to the gradient fitting is not substantially larger than the observational uncertainties, indicating that O is well mixed in the interstellar gas along the observed section of the Galactic disc.

1 Introduction

The determination of radial gradients of chemical abundances in galactic discs is a powerful observational constraint for chemical evolution models. These gradients reflect the distribution of star formation history and the effects of gas flows and other processes over the chemical composition of the galaxies. H II regions trace the present-day composition of the interstellar medium and are used to determine the abundance of several elements, especially of O, the proxy of metallicity in the analysis of ionised nebula. In these objects, the O abundance can be derived adding the ionic abundances of O^{+} and O^{2+}, that can be obtained from the intensity of bright optical collisionally excited lines (hereafter CELs).

Oxygen is produced mostly by massive, short-lived stars. There are numerous determinations of the radial abundance gradient of O of the Milky Way based on H II regions observations (e.g. [25], [5], [23] or [2], among others). Although the recent determinations agree on that the gradient slope is between -0.040 and -0.060 dex kpc^{-1}, its exact shape has been debated. Based on H II regions and planetary nebulae data, some authors have claimed that the gradients flatten out at the outer parts of the Galactic disc (e. g. [10], [26], [17]), while others do not find evidences of such flattening (e.g. [4], [14]). On the other hand, certain works on metallicity gradients based on Cepheids and red giants observations find indications of a flattening of the gradients in the inner Galactic disc, at $R_{\rm G} < 5$-6 kpc ([12], [18], [1]). However, no evidences of a inner flatter slope has been reported from observations of ionized nebulae.

The paucity of accurate abundance determinations for H II regions in both extremes of the Galactic disc – central zones and anticentre – has been an enduring problem in the exploration of the shape of the Galactic O gradient. Those distant nebulae are usually faint, heavily reddened and the number of them with direct determinations of $T_{\rm e}$ – essential for determining reliable abundances – is rather limited (e.g. [19], [9]). Several of the most cited papers on the Galactic O abundance gradient (e.g. [25] or [5]) use optical spectra of H II regions and $T_{\rm e}$ determinations from radio observations. Optical and radio measurements are not cospatial and the aperture sizes of both kinds of data are very different. In addition, radial abundance gradient studies based on FIR observations (e.g. [23]) combine measurements of CELs from FIR spectra and $T_{\rm e}$ determined from radio observations with also different apertures.

We are carrying out a project to obtain very deep spectroscopy of a selected sample of H II regions covering the largest possible fraction of the Galactic disc. By now, the observed sample covers 35 objects located at Galactocentric distances, $R_{\rm G}$, between 5.1 and 17.0 kpc. The main preliminary results concerning the O and N gradients have been published in [7] and [8]. Thirteen objects of the sample are located beyond the isophotal radius of the Milky Way, $R_{25} = 11.5$ kpc [6] and have been selected to investigate the behavior of the radial abundance gradients at the Galactic anticentre. Almost all the spectra have been taken with high or intermediate-resolution spectrographs attached to 8 - 10 m telescopes. In all the H II regions the $T_{\rm e}$-sensitive auroral [O III] 4363 Å and/or [N II] 5755 Å lines have been measured, assuring a direct and precise determination of the ionic abundances and avoiding uncertainties due to the combination of non-coespatial data used in previous abundance determinations.

We have taken special care in selecting appropriate values of $R_{\rm G}$ for the sample objects. For each one, we have assumed the mean values of the kinematic and stellar distances given in different published references (see [7] and [8] for details). We have associated an uncertainty for each distance, which corresponds to the standard deviation of the values considered for calculating the mean. In contrast to what is customary in many previous works, we include the errors in $R_{\rm G}$ when calculating the linear fits of the gradients. We have assumed the Sun located at $R_{\rm G} = 8.0$ kpc [21].

We have derived $n_{\rm e}$ and $T_{\rm e}$ using the density and temperature-sensitive emission line ratios of the CELs observed in each spectrum. Using the line intensities of available CELs, we have derived ionic and total abundances of several elements as N, O, S, Cl, Ne, Ar and Fe. We have used the same methodology and atomic dataset for the calculation of physical conditions and abundances in all the objects. In the case of O, we do not need to assume an ionising correction factor, so the total O abundance is simply the sum of the O^+/H^+ and

O^{2+}/H^{+} ratios determined from the observed line ratios and physical conditions. Several of the objects included in [8] are of very low ionisation degree, for which the [O III] lines at 4959 and 5007 Å are not detected. In these cases, we applied the assumption $O/H \approx O^{+}/H^{+}$.

2 The shape of the Galactic abundance gradient of oxygen

The spatial distribution of the O abundances for the H II regions of our sample is shown in Fig. 1. The data represented in this figure were firstly published in [8]. The least-squares linear fit to the $R_{\rm G}$ and the O/H ratios, gives the following radial O abundance gradient (continuous line in Fig. 1):

$$12 + \log(\mathrm{O/H}) = 8.80(\pm 0.09) - 0.041(\pm 0.006) R_{\rm G}; \tag{1}$$

valid for $R_{\rm G}$ from 5.1 to 17.0 kpc. As it is evident in Fig. 1 and was reported by [7], the slope of the radial abundance gradient of O does not change for objects located beyond or inside R_{25} whereas $R_{\rm G} > 8$ kpc. This fact demonstrate the absence of flattening of the O gradient in the outer Milky Way, at least up to $R_{\rm G} \sim 17$ kpc.

Fig. 1 also shows that the O/H ratio of H II regions located at $R_{\rm G} < 8$ kpc seem to break the general distribution of the rest of the objects. In fact, this zone shows an inner drop or flattening of the O gradient. As a simple exercise, we have made a double linear fit of the spatial distribution of the O abundances. Firstly, we made a least-squares linear fit to the $R_{\rm G}$ and the O/H ratios but only including objects with $R_{\rm G} > 8$ kpc. In this case, the resulting radial O abundance gradient is:

$$12 + \log(\mathrm{O/H}) = 8.90(\pm 0.11) - 0.050(\pm 0.010) R_{\rm G}; \tag{2}$$

which is somewhat stepper than the fit we obtain for the whole sample (Eq. 1) but still consistent within the errors. The linear fit given in Eq. 2 is shown by a dashed line in Fig. 1. We have performed a final least-squares linear fit including the objects with $R_{\rm G} < 8$ kpc, and we obtain a positive slope:

$$12 + \log(\mathrm{O/H}) = 8.35(\pm 0.13) + 0.023(\pm 0.019) R_{\rm G}. \tag{3}$$

The presence of a drop or flattening of the O/H ratio in the inner zones of the Galactic disc is a striking result that may have important implications for chemical evolution models of the Galaxy. There are indications of such a change in previous works on the abundance distribution of O, Fe and α-elements in Cepheids in the inner Galactic disc ([18], [1]). Metallicity gradients derived from SDSS-III/APOGEE observations of red giants by [12] also indicate an apparent flattening at $R_{\rm G} < 6$ kpc, especially important for low-$[\alpha/Z]$ stars. The flattening found with Cepheids or red giants begins at somewhat smaller distances (at $R_{\rm G} \sim$ 5-6 kpc) than suggested by H II region observations, but the results seem to be qualitatively consistent considering the uncertainties. [1] proposed that this change of slope could be due to a decrease or quenching of the star formation rate produced by gas flows towards the Galactic

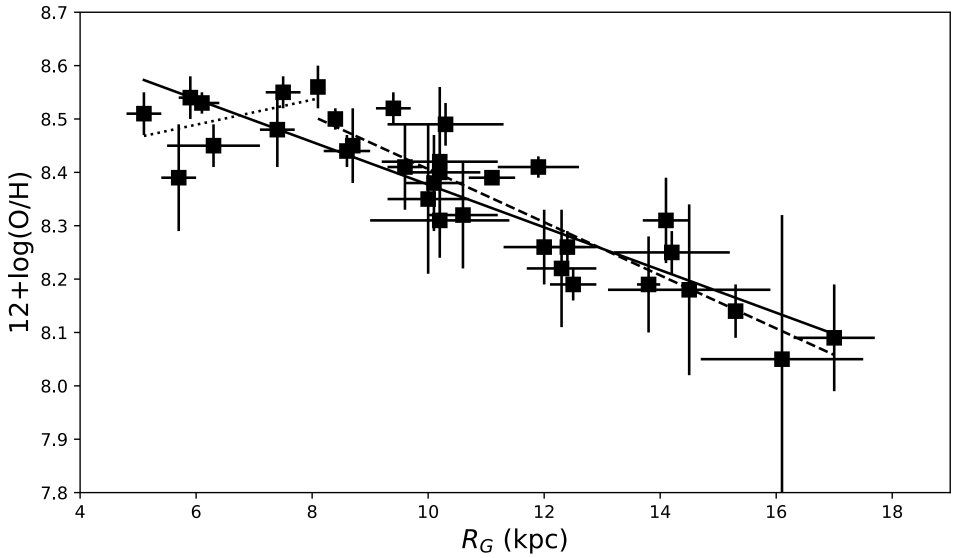

Figure 1: Radial distribution of the O abundance – in units of 12+log(O/H) – as a function of the Galactocentric distance, $R_{\rm G}$, for our sample of Galactic H II regions. The solid line represents the least-squares fit to all objects. The dashed line corresponds to the least-squares fit to the H II regions located at $R_{\rm G} > 8$ kpc and the dotted line to those with $R_{\rm G} < 8$ kpc.

Centre induced by the presence of the Galactic bar. On the other hand, [13] and [15] propose that the star formation quenching may be produced by the increasing of turbulence in the gas due to the stellar bar. The higher turbulence would prevent the gas from collapsing and producing a decrease of the star formation efficiency within the corotation radius of the bar.

The different estimations of the corotation radius of the Galactic bar go from 3.4 to 7 kpc [11]. Some dynamical models (e.g. [20], [16]) that reproduce recent density and kinematic data from red giants in the Galactic bulge/bar region require a corotation radius located at large distances for the Galactic Centre, $R_{\rm G} \sim$ 6-7 kpc. In this context, large a corotation radius is in reasonable agreement with our results for H II regions that suggest the inner drop or flattening at $R_{\rm G}$ of about 7-8 kpc.

Inner drops in the radial O abundance distributions have been already found in several spiral galaxies (e.g. [3], [22], [24]). In all the cases, these features have been obtained from abundance analysis based on strong-line methods and not on direct determinations of $T_{\rm e}$ of the H II regions. [24] have found that about 35% of the objects of their sample – about 100 – show an inner drop located about half of the effective radius, $R_{\rm e}$, of the galaxy. Considering that $R_{\rm e}$ is between 4-5 kpc in the Milky Way [6], the position of our change of slope is located at a considerably larger distance than expected if the behavior found by [24] is extrapolated to our Galaxy.

The mean difference of the O abundance of the H II regions represented in Fig. 1 and the abundance given by Eq. 1 at their corresponding distance is ±0.05 dex, of the order of the typical uncertainties in the determination of individual abundances. This indicates that

O is well mixed in the interstellar gas along the observed section of the Galactic disc. This result contrast dramatically, for example, with the large scatter shown in figure 5 of [23]. The high quality of our data, the homogeneous analysis of a single set of observations and the cospatial direct determination of $T_{\rm e}$ for all the objects may be the reasons that explain these remarkably different results.

Acknowledgments

This work has been funded by the Spanish Ministerio de Ciencia, Innovación y Universidades under project AYA2015-65205-P. I thank the collaboration of J. García-Rojas, X. Fang and L. Toribio San Cipriano in different aspects of this project.

References

[1] Andrievsky, S. M., Martin, R. P., Kovtyukh, V. V., Korotin, S. A., & Lépine, J. R. D. 2016, MNRAS, 461, 4256

[2] Balser, D. S., Rood, R. T., Bania, T. M., & Anderson, L. D. 2011, ApJ, 738, 27

[3] Belley, J., & Roy, J.-R. 1992, ApJS, 78, 61

[4] Caplan, J., Deharveng, L., Peña, M., Costero, R., & Blondel, C., 2000, MNRAS, 311, 317

[5] Deharveng, L., Peña, M., Caplan, J., & Costero, R. 2000, MNRAS, 311, 329

[6] de Vaucouleurs, G., & Pence, W. D., 1978, AJ, 83, 1163

[7] Esteban, C., Fang, X., & García-Rojas, J. 2017, MNRAS, 471, 987

[8] Esteban, C., & García-Rojas, J. 2018, MNRAS, 478, 2315

[9] Esteban, C., García-Rojas, J., Peimbert, M., Peimbert, A., Ruiz, M. T., Rodríguez M., & Carigi, L. 2005, ApJ, 618, L95

[10] Fich, M., & Silkey, M. 1991, ApJ, 366, 107

[11] Gerhard, O. 2011, Mem. della Soc. Astron. Ital. Suppl., 18, 185

[12] Hayden, M. R. et al. 2014, AJ, 147, 116

[13] Haywood, M., Lehnert, M. D., Di Matteo, P., Snaith, O., Schultheis, M., Katz, D., & Gómez, A. 2016, A&A, 589, A66

[14] Henry, R. B. C., Kwitter, K. B., Jaskot, A. E., Balick, B., Morrison, M. A., & Milingo, J. B. 2010, ApJ, 724, 748

[15] Khoperskov, S., Haywood, M., Di Matteo, P., Lehnert, M. D., & Combes, F. 2018, A&A, 609, A60

[16] Li, Z., Gerhard, O., Shen, J., Portail, M., & Wegg, C. 2016, ApJ, 824, 13

[17] Maciel, W. J., Lago, L. G., & Costa, R. D. D. 2006, A&A, 453, 587

[18] Martin, R. P., Andrievsky, S. M., Kovtyukh, V. V., Korotin, S. A., Yegorova, I. A., & Saviane, I. 2015, MNRAS, 449, 4071

[19] Peimbert, M., Torres-Peimbert, S., & Rayo, J. F. 1978, ApJ, 220, 516

[20] Portail, M., Wegg C., Gerhard, O., & Martinez-Valpuesta, I. 2015, MNRAS, 448, 713

[21] Reid, M. J. 1993, ARA&A, 31, 345

[22] Rosales-Ortega, F. F., Díaz, A. I., Kennicutt, R. C., & Sánchez, S. F. 2011, MNRAS, 415, 2439

[23] Rudolph, A. L., Fich, M., Bell, G. R., Norsen, T., Simpson, J. P., Haas, M. R., & Erickson, E. F. 2006, ApJS, 162, 346

[24] Sánchez-Menguiano L., Sánchez, S. F., Pérez, I., Ruiz-Lara, T., et al. 2018, A&A, 609, A119

[25] Shaver, P. A., McGee, R. X., Newton, L. M., Danks, A. C., & Pottasch, S. R. 1983, MNRAS, 204, 53

[26] Vilchez, J. M., & Esteban, C. 1996, MNRAS, 280, 720