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The radial abundance gradient of oxygen towards the Galactic anti-centre

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ABSTRACT

We present deep optical spectroscopy of eight H II regions located in the anti-centre of the Milky Way. The spectra were obtained at the 10.4 m GTC and 8.2 m VLT. We determined Te([N II]) for all objects and Te([O III]) for six of them. We also included in our analysis an additional sample of 13 inner-disc Galactic H II regions from the literature that have excellent Te determinations. We adopted the same methodology and atomic data set to determine the physical conditions and ionic abundances for both samples. We also detected the C II and O II optical recombination lines in Sh 2-100, which enables the determination of the abundance discrepancy factor for this object. We found that the slopes of the radial oxygen gradients defined by the H II regions from R25 (=11.5 kpc) to 17 kpc and those within R25 are similar within the uncertainties, indicating the absence of flattening in the radial oxygen gradient in the outer Milky Way. In general, we found that the scatter of the O/H ratios of H II regions is not substantially larger than the observational uncertainties. The largest possible local inhomogeneities of the oxygen abundances are of the order of 0.1 dex. We also found positive radial gradients in Te([O III]) and Te([N II]) across the Galactic disc. The shapes of these temperature gradients are similar and also consistent with the absence of flattening of the metallicity distribution in the outer Galactic disc.

Key words: ISM: abundances – H II regions – Galaxy: abundances – Galaxy: disc – Galaxy: evolution.

1 INTRODUCTION

The spatial distributions of abundances of chemical elements across galactic discs – the radial gradients – have been derived for many galaxies and are key to understanding the chemical evolution of galaxies. These gradients reflect the star formation history as well as the effects of gas flows in stellar systems. H II regions are fundamental probes to trace the present-day composition of the gas-phase interstellar medium. They have been widely used to determine the radial abundance gradients – especially for O, a proxy of metallicity in the analysis of ionized gaseous nebula – in the Milky Way and other spiral galaxies. Some authors have claimed – for example, Hawthorn & Freeman (2011) – that radial abundance gradients may flatten at the outer parts of the Milky Way. The spectra were obtained at the 10.4 m GTC and 8.2 m VLT. We determined Te([N II]) for all objects and Te([O III]) for six of them. We also included in our analysis an additional sample of 13 inner-disc Galactic H II regions from the literature that have excellent Te determinations. We adopted the same methodology and atomic data set to determine the physical conditions and ionic abundances for both samples. We also detected the C II and O II optical recombination lines in Sh 2-100, which enables the determination of the abundance discrepancy factor for this object. We found that the slopes of the radial oxygen gradients defined by the H II regions from R25 (=11.5 kpc) to 17 kpc and those within R25 are similar within the uncertainties, indicating the absence of flattening in the radial oxygen gradient in the outer Milky Way. In general, we found that the scatter of the O/H ratios of H II regions is not substantially larger than the observational uncertainties. The largest possible local inhomogeneities of the oxygen abundances are of the order of 0.1 dex. We also found positive radial gradients in Te([O III]) and Te([N II]) across the Galactic disc. The shapes of these temperature gradients are similar and also consistent with the absence of flattening of the metallicity distribution in the outer Galactic disc.

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region NGC 2579, which is located at a Galactocentric distance of 12.4 kpc, close to $R_{25}$, the best data ever taken for an H II region at the outer Galactic disc. They found that their O/H and C/H ratios are consistent with flattened geometries. Very recently, Fernández-Martín et al. (2017) presented the 4.2 m WHT spectroscopic observations of nine H II regions located at $R_{25} > 11$ kpc, but only detected the temperature-sensitive auroral lines in five of them. In addition, these authors re-analysed the data of other H II regions retrieved from the literature. The results of Fernández-Martín et al. (2017) do not confirm the presence of flattening at the Galactic anti-centre, and they point out the necessity of more observations of H II regions in the outer part of the Galaxy to establish the true shape of the metallicity gradient.

The paucity of accurate abundance determinations for H II regions in the anti-centre direction has been an enduring problem in the exploration of the shape of the O gradient in the Galactic disc. Those distant nebulae are usually faint and the number of such cases with direct determinations of electron temperature, $T_e$, is rather limited. A high-quality determination of $T_e$ is essential to obtain reliable O abundances. We have carried out a project to obtain very deep spectroscopy of a selected sample of H II regions located close to or beyond $R_{25}$ in order to increase the sample with reliable measurements of the O/H ratios in the direction of Galactic anti-centre. We have selected a sample of eight relatively bright objects with $R_0$ in the range 9.4–17.0 kpc that shows a high ionization degree, $I([\text{O} \text{III}] \lambda 5007)/I(\text{H} \beta) > 1.0$, for ensuring as much as possible the detection of the $[\text{O} \text{III}] \lambda 4363$ auroral line. These sample is complemented with some other outer-disc H II regions, NGC 2579 (Esteban et al. 2013), Sh 2-311 (García-Rojas et al. 2005) and NGC 7635 (Esteban et al. 2016b), which were previously observed and published by our group and for which we have excellent determinations of $T_e$.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Observations

Except Sh 2-298, observations of all objects were performed with the 10.4 m Gran Telescopio Canarias (GTC) at Observatorio del Roque de los Muchachos (ORM, La Palma, Spain). They were carried out in fourteen 1 h observing blocks distributed in several nights between September and November in 2015. The spectra were obtained with the OSIRIS (Optical System for Imaging and low-Intermediate-Resolution Integrated Spectroscopy) spectrograph (Cepa et al. 2000, 2003). OSIRIS consists of a mosaic of two Marconi CCD42-82 CCDs (CCD1+CCD2), each with 2048 × 4096 pixels, and a 74-pixel gap between them. Each pixel has a physical size of 15 μm. The standard readout mode of 2 × 2 pixel binning was adopted during observations, which gives a plate scale of 0.254 arcsec. The long-slit spectroscopy mode was used in our OSIRIS observations and all targets were located at the centre of CCD2. The slit length was 7.4 arcmin and its width was set at 0.8 arcsec, same as the typical seeing at ORM. Two OSIRIS grisms, R1000B and R2500V, were used for the spectroscopy. R1000B covers almost the whole optical wavelength range, from 3600 to 7750 Å, while R2500V covers from 4430 to 6020 Å but with higher spectral resolution for the wavelength region where the $T_e$-sensitive $[\text{O} \text{III}] \lambda 4363$ line lies. The effective spectral resolution (full width at half-maximum, FWHM) was 6.52 Å for the R1000B grism and 2.46 Å for R2500V. The long slit covers the brightest regions of the nebulae. Coordinates of the slit centre and the position angle (PA) of the long-slit are given in Table 1, where we also present the integration time of each object. In the two-dimensional (2D) spectrum of each object, we selected the brightest region along the slit to extract the highest signal-to-noise 1D spectrum. In Figs 1 and 2, we mark the slit position and aperture of spectral extraction for each object. The aperture size of extraction along the slit is indicated in the seventh column of Table 1. The OSIRIS spectra were wavelength calibrated using the HgAr, Ne and Xe arc lamps.

The observations of Sh 2-298 were made on 2003 November 14 and December 2 with the Ultraviolet Visual Echelle Spectrograph (UVES; D’Odorico et al. 2000), on the Very Large Telescope (VLT) Kueyen unit at Cerro Paranal Observatory (Chile). The adopted standard settings in both the red and blue arms of the spectrograph covered a broad region from 3100 to 10 400 Å. The wavelength intervals 5783–5830 and 8540–8650 Å were not observed due to a gap between the two CCDs used in the red arm. There are also five narrow gaps that were not observed, 9608–9612, 9761–9767, 9918–9927, 10 080–10 093 and 10 249–10 264 Å, because the five redmost orders did not fit completely within the CCD. The atmospheric dispersion corrector (ADC) was used to keep the same observed region within the slit regardless of the air mass value. The slit width was set to 3 arcsec and the slit length to 8 arcsec. The effective resolution at a given wavelength is approximately $\Delta \lambda \sim \lambda/8800$. Spectroscopic observations of the spectrophotometric standard star HD 49798 (Turnshek et al. 1990; Bohlin & Lindler 1992) were made for the flux calibration.

2.2 Data reduction

The GTC OSIRIS long-slit spectra were reduced using IRAF1 v2.16. Data reduction followed the standard procedure for long-slit spectra. We first removed cosmic rays by combining the raw spectrograms of each H II region and then subtracted the bias and corrected for the flat-field. We then carried out wavelength calibration using the arc-line spectroscopy. According to the coverage of arc lines across the wavelength range of the grism, we used the HgAr arc lines for the calibration of the R1000B spectra and HgAr+Ne+Xe for the R2500V spectra. The geometry distortion of emission lines along the long slit exists for extended sources. During the wavelength calibration, this geometry distortion was also rectified by fitting the arc lines with sixth- or seventh-order polynomial functions in the 2D spectrogram. We then applied the resolution derived from fitting of the arc-line spectrogram to the target spectrum. Through this procedure, all nebular emission lines (also the sky emission lines) in a 2D spectrum were ‘straightened’ along the long slit.

Particular care was taken in the background subtraction because the sky background emission is inhomogeneous along the GTC OSIRIS long slit (Fang et al. 2015). The emission profiles of the sky background along the slit direction were first fitted with polynomial functions and then subtracted from the spectrogram. Since our targets are all extended sources, low-order polynomial functions were adopted for the profile fitting so that the true nebular emission was not removed due to a possible over-subtraction. The BACKGROUND package in IRAF was used in the background subtraction. This procedure produced a cleaned spectrogram for each target, which was then flux-calibrated (and also corrected for the atmospheric extinction) using the spectrum of a spectrophotometric standard star.

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1 IRAF, the Image Reduction and Analysis Facility, is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy under cooperative agreement with the National Science Foundation.
Table 1. Journal of observations.

| H II region | R.A.\(^a\) (J2000) | Decl.\(^a\) (J2000) | \(R_b^a\) (kpc) | Telescope/PA | PA (°) | Extracted area (arcsec\(^2\)) | Grating or configuration | Exposure time (s) |
|-------------|----------------------|----------------------|-----------------|--------------|-------|-------------------------------|------------------------|-----------------|
| Sh 2-83     | 19:24:52.55          | +20:47:24.4          | 15.3 ± 0.1      | GTC/OSIRIS   | 90    | 38.1 × 0.8                    | R1000B                 | 3 × 882         |
|             |                      |                     |                 |              |       |                               | R2500V                 |                 |
| Sh 2-100    | 20:02:00.69          | +33:29:23.9          | 9.4 ± 0.3       | GTC/OSIRIS   | −55   | 28.5 × 0.8                    | R1000B                 | 3 × 882         |
|             |                      |                     |                 |              |       |                               | R2500V                 |                 |
| Sh 2-127    | 21:28:40.95          | +54:42:13.9          | 14.2 ± 1.0      | GTC/OSIRIS   | 1     | 6.9 × 0.8                     | R1000B                 | 3 × 882         |
|             |                      |                     |                 |              |       |                               | R2500V                 |                 |
| Sh 2-128    | 21:32:49.86          | +55:53:16.2          | 12.5 ± 0.4      | GTC/OSIRIS   | 86    | 24.1 × 0.8                    | R1000B                 | 3 × 882         |
|             |                      |                     |                 |              |       |                               | R2500V                 |                 |
| Sh 2-209    | 04:11:25.69          | +51:14:33.8          | 17.0 ± 0.7      | GTC/OSIRIS   | 35    | 45.7 × 0.8                    | R1000B                 | 3 × 882         |
|             |                      |                     |                 |              |       |                               | R2500V                 |                 |
| Sh 2-212    | 04:40:56.13          | +50:26:53.1          | 14.6 ± 1.4      | GTC/OSIRIS   | −70   | 38.1 × 0.8                    | R1000B                 | 3 × 882         |
|             |                      |                     |                 |              |       |                               | R2500V                 |                 |
| Sh 2-288    | 07:08:48.90          | +07:08:48.9          | 14.1 ± 0.4      | GTC/OSIRIS   | −32   | 28.5 × 0.8                    | R1000B                 | 3 × 882         |
|             |                      |                     |                 |              |       |                               | R2500V                 |                 |
| Sh 2-298    | 07:18:28.10          | −13:17:19.7          | 11.9 ± 0.7      | VLT/UVES     | 90    | 8 × 3                         | DIC1(346+580)          | 3 × 540         |
|             |                      |                     |                 |              |       |                               | DIC2(437+860)          |                 |

*Notes.* \(^a\)Coordinates of the slit centre.

\(^b\)Galactocentric distances assuming the Sun at 8 kpc.

Figure 1. The GTC \(g\)-band acquisition images of Sh 2-83, Sh 2-100, Sh 2-127 and Sh 2-128. The position and length of the aperture extracted for each object are indicated.
Finally, we extracted 1D spectrum from the cleaned, fully calibrated 2D frame for each H II region, using the slit aperture indicated in Figs 1 and 2. As an example, Fig. 3 shows the extracted 1D spectra for Sh 2-100. The temperature-sensitive [O III] λ4363 and [N II] λ5755 auroral lines are well detected. In the sections below, we will also analyse the optical recombination lines of C II and O II that were also observed in the deep spectra of this target. It is worth mentioning that the second-order contamination exists in the red part (>6300 Å) of the OSIRIS R1000B grism. We corrected for this effect by fitting the overall shape of the derived R1000B efficiency curve with a fifth-order polynomial function. This correction has proved to be reliable (Fang et al. 2015).

The VLT UVES echelle spectra of Sh 2-298 were reduced using the ECHELLE reduction package in IRAF, following the standard procedure of bias subtraction, aperture extraction, flat-fielding, wavelength calibration and then flux calibration.

### 3 LINE INTENSITY MEASUREMENTS

Emission line fluxes of the spectra of the eight H II regions included in Table 1 were measured with the SPLOT routine of IRAF by integrating over the emission line profile between two given limits and over the average local continuum. All line fluxes of a given spectrum have been normalized to Hβ = 100. In the wavelength range between 4430 and 6020 Å of the GTC spectra, the emission line fluxes measured from the R2500V spectrum were used instead of those measured from the R1000B spectrum, although our flux calibration was reliable and the spectral-line measurements obtained with the two OSIRIS grisms agree well with each other. The S/Ns of faint emission lines are higher in the spectra taken with the grism R2500V. In the case of line blending, we applied double- or multiple-Gaussian profile fit using the SPLOT routine of IRAF to measure the individual line intensities. Identification of emission lines were made following our previous works on the spectroscopy of bright Galactic H II regions (see García-Rojas & Esteban 2007, and references therein).

The logarithmic reddening coefficient, $c(H\beta)$, was derived by comparing the observed flux ratios of the brightest H I Balmer lines (Hα, Hγ and Hδ) with the Case B theoretical calculations of Storey & Hummer (1995). The theoretical ratios of the H I lines were calculated for the nebular physical conditions diagnosed for each H II region, and $T_e$ and $N_e$ were determined following an iterative process (see Section 6.1 for details). We have used the reddening function, $f(\lambda)$, normalized to $H\beta$ derived by Cardelli, Clayton & Mathis (1989) and assumed $R_V = 3.1$.

In Tables 2–4, we present emission line measurements of the eight H II regions: the emission line identifications are given in the first three columns; the reddening function, $f(\lambda)$, is in the fourth column; the dereddened and normalized (with respect to $H\beta = 100$) line intensities are presented in the rest columns. The quoted
Figure 3. The GTC OSIRIS long-slit 1D spectra of Sh 2-100 obtained with the R1000B (top panel) and R2500V (bottom panel) grisms. Spectra have been fully calibrated, but the interstellar extinction has not been corrected for.

Line intensity errors include the uncertainties in the flux measurements and the error propagation of the reddening coefficient. The reddening coefficient $c$(H$\beta$) and the observed H$\beta$ line flux $F$(H$\beta$), as measured from the extracted 1D spectrum, of each H II region are presented in the final two rows of each table. In the case of Sh 2-298 (Table 4), we give two decimals for the laboratory wavelength of the lines because of the much higher spectral resolution of the VLT UVES observations.
Table 2. Dereddened line intensity ratios with respect to $\lambda(H\beta) = 100$ for Sh 2-100, Sh 2-128, Sh 2-288 and Sh 2-127.

| $\lambda_0$ (Å) | Ion | ID  | $f(\lambda)$ | $H(\lambda)/H(\beta)$ |
|-----------------|-----|-----|--------------|------------------------|
| 3704            | H$^+$| H16 | 0.260        | 0.99 ± 0.22            |
| 3705            | He$^+$| 25  | –            | –                      |
| 3712            | H$^+$| H15 | 0.259        | 0.67 ± 0.23            |
| 3723            | [OII] | 1F  | 0.257        | 68.0 ± 4.4             |
| 3724            | [OII] | 1F  | –            | –                      |
| 3750            | H$^+$| H12 | 0.253        | 2.25 ± 0.26            |
| 3771            | H$^+$| H11 | 0.249        | 3.36 ± 0.44            |
| 3782            | He$^+$| 22  | 0.240        | 1.02 ± 0.17            |
| 3835            | H$^+$| H9  | 0.237        | 7.00 ± 0.53            |
| 3867            | He$^+$| 20  | 0.231        | 20.6 ± 1.3             |
| 3889            | [Ne III] | 1F  | 0.227        | 14.93 ± 0.90           |
| 3889            | H$^+$| H8  | –            | –                      |
| 3967            | [Ne III] | 1F  | 0.211        | 23.3 ± 1.3             |
| 3970            | H$^+$| H7  | –            | 15.7 ± 1.1             |
| 4026            | He$^+$| 18  | 0.198        | 2.22 ± 0.17            |
| 4069            | [SII] | 1F  | 0.189        | 0.727 ± 0.051          |
| 4076            | [SII] | 1F  | 0.187        | 0.339 ± 0.024          |
| 4102            | He$^+$| H6  | 0.182        | 25.96 ± 1.23           |
| 4144            | He$^+$| 53  | 0.172        | 0.293 ± 0.069          |
| 4156            | Ne$^+$| 19  | 0.171        | 0.125 ± 0.043          |
| 4267            | Cu$^+$| 6   | 0.144        | 0.249 ± 0.049          |
| 4340            | H$^+$| H$^\gamma$ | 0.127 | 44.44 ± 1.60 |
| 4363            | [OIII] | 2F  | 0.121        | 1.145 ± 0.065          |
| 4388            | He$^+$| 51  | 0.115        | 0.529 ± 0.046          |
| 4471            | He$^+$| 14  | 0.096        | 4.85 ± 0.15            |
| 4607            | [FeII] | 3F  | 0.062        | –                      |
| 4639            | O$^+$| 1   | 0.055        | 0.217 ± 0.038          |
| 4642            | O$^+$| 1   | –            | –                      |
| 4643            | N$^+$| 5   | –            | –                      |
| 4649            | O$^+$| 1   | 0.052        | 0.183 ± 0.029          |
| 4651            | O$^+$| 1   | –            | –                      |
| 4658            | [FeII] | 3F  | 0.050        | 0.213 ± 0.019          |
| 4662            | O$^+$| 1   | 0.049        | 0.041 ± 0.008          |
| 4676            | O$^+$| 1   | 0.043        | 0.036 ± 0.009          |
| 4702            | [FeII] | 3F  | 0.039        | 0.072 ± 0.011          |
| 4711            | [ArI] | 1F  | 0.037        | 0.598 ± 0.035          |
| 4713            | He$^+$| 12  | 0.036        | –                      |
| 4734            | [FeII] | 3F  | 0.036        | 0.031 ± 0.013          |
| 4740            | [ArI] | 1F  | 0.030        | 0.090 ± 0.019          |
| 4755            | [FeII] | 3F  | 0.026        | –                      |
| 4770            | [FeII] | 3F  | 0.023        | –                      |
| 4778            | [FeII] | 3F  | 0.021        | –                      |
| 4789            | [FeII] | 1   | 0.018        | –                      |
| 4815            | [FeII] | 20F | 0.012        | –                      |
| 4861            | H$^+$| H$\beta$ | 0.000 | 100.0 ± 2.0 |
| 4881            | [FeII] | 2F  | –            | –                      |
| 4922            | He$^+$| 48  | –            | 1.323 ± 0.074          |
| 4959            | [OII] | 1F  | –            | 126.9 ± 2.6            |
| 5007            | [OII] | 1F  | –            | 341.9 ± 7.4            |
| 5016            | He$^+$| 4   | –            | 2.34 ± 0.30            |
| 5035            | [FeII] | 4F  | –            | –                      |
| 5048            | He$^+$| 47  | –            | 0.179 ± 0.029          |
| 5056            | Si$^+$| 5   | –            | 0.200 ± 0.010          |
| 5159            | [FeII] | 19F | –            | 0.037 ± 0.003          |
| 5192            | [ArIII] | 3F  | –            | 0.081 ± 0.007          |
| 5198            | N$^+$| 1F  | –            | 0.015 ± 0.002          |
| 5200            | N$^+$| 1F  | –            | –                      |
| 5262            | [FeII] | 19F | –            | –                      |
| 5270            | [FeII] | 1F  | –            | 0.099 ± 0.012          |
| 5518            | [ClIII] | 1F  | –            | 0.154 ± 0.025          |

Note: The values in the table are intensity ratios with respect to $\lambda(H\beta) = 100$. The uncertainties are given in the form of $n \pm m$. The table includes ions from H$^+$ to [ClIII] and covers wavelengths from 3704 Å to 5518 Å. The intensity ratios are given for each ion, with the intensity at $\lambda(H\beta)$ set to 100. The uncertainties are provided for each measurement.
WHT spectrograph. The observations of IC 5146, Sh 2-132 and Sh 2-156 were obtained with the same instrument for the observations of NGC 7635 were included in this paper. The data for M20, M16, M17, M8, NGC 3576, M42, NGC 3603, Sh 2-311 and NGC 2579 were observed with the UVES instrument. The references of their emission-line ratios used for analysis in this paper. The data for M20, M16, M17, M8, NGC 3576, M42, NGC 3603 and IC 5146 were retrieved from García-Rojas, Simón-Díaz & Esteban (2014).

4 THE ADDITIONAL SAMPLE

In addition to the Galactic H II regions observed in this paper, we have included the deep spectra of other Galactic objects available from the literature. Most of these nebulae are located at $R_G < 11.5$ kpc and only NGC 2579 lies beyond that distance. These objects were selected to compare the results of the anti-centre H II regions with those in the inner Galactic disc. Table 5 gives the most common designation of the additional sample of objects, their Galactocentric distances (see Section 5), their O abundances and the references of their emission-line ratios used for analysis in this paper.

The data for M20, M16, M17, M8, NGC 3576, M42, NGC 3603, Sh 2-311 and NGC 2579 were observed with the UVES spectrograph at the VLT, the same instrument configuration as used for the observations of Sh 2-298 included in this paper. The observations of NGC 7635 were obtained with the same instrument configuration as our observations obtained with the GTC OSIRIS spectrograph. The observations of IC 5146, Sh 2-132 and Sh 2-156 produced deep optical spectra obtained with the ISIS spectrograph at the 4.2m WHT. Sh 2-132 and Sh 2-156 have been selected from the sample of Galactic anti-centre H II regions observed by Fernández-Martín et al. (2017). We have not considered the rest of the objects observed by those authors because observations of three of them (Sh 2-83, Sh 2-212 and NGC 7635) were also reported by us in this or previous papers, and the rest do not show auroral lines for the determination of $T_e$ in their spectra. The emission line ratios of IC 5146 were retrieved from García-Rojas, Simón-Díaz & Esteban (2014).

5 DISTANCES

In the studies of Galactic abundance gradients, the distances to H II regions are highly uncertain. However, these uncertainties are usually not taken into account when calculating the radial gradients. The adopted galactocentric distances, $R_G$, of the objects are presented in Tables 1 and 5. These distances are estimated as the mean values of kinematic and stellar distances given in different published references. Their associated uncertainties correspond to the standard deviation of the values considered for the average. In our distance calculations, we assumed that the Sun is located at $R_G = 8.0$ kpc (Reid 1993). To derive the mean value and standard deviation of $R_G$ for each object, we used the kinematic distances determined by Quireza et al. (2006) and Balser et al. (2011), the stellar ones calculated by Foster & Brunt (2015) and the kinematic and stellar distances calculated or compiled by Russell (2003) and Caplan et al. (2000). In addition, we have also considered other calculations of the average distance values of NGC 2579, M20, NGC 3576, NGC 3603 and IC 5146. In the case of NGC 2579, we have included the consistent stellar and kinematic distances obtained by Copetti et al. (2007). For M20, we adopted the distance derived from a detailed 3D extinction map by Cambrésy et al. (2011). For IC 5146,
García-Rojas et al. (2014) obtained an accurate stellar distance based on their spectroscopic analysis of the ionizing star of the nebula. For NGC 3576 and NGC 3603, we have included the kinematic distances determined by de Pree, Nysewander & Goss (1999). In general, these additional distance determinations are fairly consistent with the stellar and kinematic distances given by Russell (2003) for each object. Finally, for M42, we adopted the distance obtained from trigonometric parallax (Menten et al. 2007). We have not considered other sources of distances for this last object. From Tables 1 and 5, we can see that the whole sample includes 21 H II regions with direct determinations of $T_e$ that covers a range of Galactocentric distances from 5.1 to 17 kpc, 8 objects with $R_G > R_{25}$ and 13 with $R_G < R_{25}$.

### 6 RESULTS

For the eight objects in the observed sample, we carried out plasma diagnostics to determine the physical conditions ($T_e$, $N_e$) and the ionic abundances based on the line-intensity ratios given in Tables 2–4, using the program PYNEB v1.0.26 (Luridiana, Morisset & Shaw 2015). The atomic data listed in Table 6 are adopted in our spectral analysis. The physical conditions and the ionic and
Oxygen gradient at the Galactic anti-centre

We have adopted the [S ii] λ6717/λ6731 and [Cl iii] λ5581/λ5538 density-diagnostic line ratios for all the objects and also added the [O ii] λ3726/λ3729 ratio for Sh 2-298. The electron density, N_e, derived from the [S ii] line ratio, N_e([S ii]), was assumed for all the apertures and objects and it is always below 1000 cm^{-1} (see Tables 7 and 8). For the singly ionized species, we derived T_e using the [N ii] (λ6548+λ6584)/λ5755 nebular-to-auroral line ratio for all objects (see Fig. 4) and the [O iii] (λλ7319+λ7330)/(λ3726+λ3729) and [S ii] (λλ4068+λ4076)/(λ6717+λ6731) ratios for some of them. Intensities of the [O ii] λλ7319, 7330 and [N ii] λ5755 auroral lines have been corrected for the possible contribution due to the recombination process using the formulae derived by Liu et al. (2000). This contribution is between 0.2 and 13 per cent in the case of the [O ii] lines and between 0.07 and 5 per cent for [N ii] λ5755. For the doubly ionized species, we have derived T_e using the [O iii] λλ4959+λ5007/λ4363 line ratio for all objects except Sh 2-127 and Sh 2-209, where the [O ii] λλ4363 auroral line was undetected (see Fig. 5). For these two H II regions, we estimated T_e([O iii]) using T_e([N ii]) and the empirical relation between the two temperatures given in the equation 3 of Esteban et al. (2009). The [S ii] (λλ9069+λ9532)/λ6312 line ratio was also measured in Sh 2-298 because the spectrum of this object extends to the near-infrared region. The physical conditions of the H II regions in our observed sample are presented in Tables 7 and 8.

The physical conditions of M20, M16, M17, M8, NGC 3576, M42, NGC 3603, Sh 2-311 and NGC 2579 are presented in Table 3 of Esteban et al. (2015), and the physical conditions adopted for the rest of the objects in the additional sample (IC 5146, Sh 2-132, NGC 7635 and Sh 2-156) are given in Table 9. For NGC 7635, the mean values obtained for apertures 2, 3, 4, 5 and 6 observed by Esteban et al. (2016b) were adopted. For IC 5146, we present the average value from apertures 2, 3 and 4 observed by García-Rojas et al. (2014) but recalculated it following the above mentioned procedure and using the atomic data set indicated in Table 6. T_e([O iii]) is not quoted for IC 5146 because the [O iii] lines were not well detected in its spectrum and its O^3/He^+ ratio was negligible. In the case of Sh 2-132 and Sh 2-156, we recalculated their N_e([S ii]), T_e([N ii]) and...
particular, we derived abundances of \( N^+ \) and \( T \) the calculations of ionic abundances. We adopted combination lines (hereafter RLs). We assumed a two-zone scheme for lowed us to obtain very deep spectra where the temperature-sensitive The use of large-aperture telescopes, such as the GTC and VLT, al-

### 6.2 Abundances

The use of large-aperture telescopes, such as the GTC and VLT, allowed us to obtain very deep spectra where the temperature-sensitive faint auroral lines have been well detected in all the objects, which is especially important in the case of the relatively faint \( \text{H}\alpha \) regions in the Galactic anti-centre. With these data, we have determined ionic abundances from the collisionally excited lines (hereafter CELs). In particular, we derived abundances of \( \text{N}^+ \), \( \text{O}^+ \), \( \text{O}^+ \), \( \text{S}^+ \), \( \text{S}^+ \), \( \text{Cl}^+ \) and \( \text{Ar}^+ \) for all the objects in our observed sample; the \( \text{Ne}^+ / \text{H}^+ \) ratio was derived for all nebulae except \( \text{Sh} \ 2-288, \text{Sh} \ 2-127 \) and \( \text{Sh} \ 2-209; \) the \( \text{Ar}^+ \) abundance was derived only in \( \text{Sh} \ 2-127 \) and \( \text{Sh} \ 2-128, \text{Sh} \ 2-288, \text{Sh} \ 2-127 \) and \( \text{Sh} \ 2-212, \text{Sh} \ 2-212 \). We have also determined the \( \text{He}^+/\text{H}^+ \) ratio for all the objects using the relative intensities of recombi-

### Table 5. Additional sample of \( \text{H}\alpha \) regions.

| \( \text{H}\alpha \) region | \( R_G^0 \) (kpc) | 12 + log(\( \text{O}/\text{H} \)) | Reference |
|--------------------------|----------------|-----------------|-----------|
| M20                      | 5.1 ± 0.3      | 8.51 ± 0.04     | García-Rojas et al. (2006) |
| M16                      | 5.9 ± 0.2      | 8.54 ± 0.04     | García-Rojas, Peña & Peimbert (2009) |
| M17                      | 6.1 ± 0.2      | 8.54 ± 0.04     | García-Rojas et al. (2007) |
| M8                       | 6.3 ± 0.8      | 8.45 ± 0.04     | García-Rojas et al. (2007) |
| NGC 3576                 | 7.5 ± 0.3      | 8.55 ± 0.04     | García-Rojas et al. (2004) |
| IC 5146                  | 8.10 ± 0.02    | 8.56 ± 0.04     | García-Rojas et al. (2014) |
| M42                      | 8.34 ± 0.02    | 8.50 ± 0.04     | Esteban et al. (2004) |
| NGC 3603                 | 8.6 ± 0.4      | 8.44 ± 0.03     | García-Rojas et al. (2006) |
| Sh 2-132                 | 10.0 ± 0.7     | 8.35 ± 0.14     | Fernández-Martín et al. (2017) |
| NGC 7635                 | 10.2 ± 0.7     | 8.40 ± 0.08     | Esteban et al. (2016b) |
| Sh 2-156                 | 10.6 ± 0.6     | 8.32 ± 0.10     | Fernández-Martín et al. (2017) |
| Sh 2-311                 | 11.1 ± 0.4     | 8.39 ± 0.01     | García-Rojas et al. (2005) |
| NGC 2579                 | 12.4 ± 0.5     | 8.26 ± 0.03     | Esteban et al. (2013) |

**Note.** aGalactocentric distances assuming the Sun is at 8 kpc.

### Table 6. Atomic data set used for collisionally excited lines.

| Ion              | Transition probabilities and energy levels | Collisional strengths |
|------------------|--------------------------------------------|-----------------------|
| \( \text{N}^+ \) | Froese Fischer & Tachiev (2004)             | Teyal (2011)          |
| \( \text{O}^+ \) | Froese Fischer & Tachiev (2004)             | Kisielius et al. (2009) |
| \( \text{O}^+ \) | Froese Fischer & Tachiev (2004); Storey & Zeippen (2000) | Storey, Sochi & Badnell (2014) |
| \( \text{Ne}^+ \) | Galavís, Mendoza & Zeippen (1997)          | McLaughlin & Bell (2006) |
| \( \text{S}^+ \) | Podobedova, Kettle & Wiese (2009)          | Teyal & Zatsarinny (2010) |
| \( \text{S}^+ \) | Podobedova et al. (2009)                   | Teyal & Gupta (1999)   |
| \( \text{Cl}^+ \) | Mendoza (1983)                             | Butler & Zeippen (1989) |
| \( \text{Ar}^+ \) | Mendoza (1983); Kaufman & Sugar (1986)     | Galavís, Mendoza & Zeippen (1995) |
| \( \text{Fe}^+ \) | Mendoza & Zeippen (1982); Kaufman & Sugar (1986) | Zeippen, Butler & Le Bourlot (1987) |
| \( \text{Fe}^+ \) | Quinet (1996); Johansson et al. (2000)     | Zhang (1996)           |

The \( \text{He}^+/\text{H}^+ \) abundance ratio was determined using **PYNEB**. Here, the effective recombination coefficients for the \( \text{He}^+ \) recombination lines calculated by Porter et al. (2012, 2013), who considered the effects of collisional contribution and the optical depth in the triplet transitions, were adopted. The final adopted \( \text{He}^+/\text{H}^+ \) ratio is a weighted average of the ratios derived from several bright \( \text{He}^+ \) lines.

We have detected in the spectrum of \( \text{Sh} \ 2-100 \) several RLs of heavy-element ions excited by the pure recombination (see Fig. 6). We derived the \( \text{C}^+/\text{H}^+ \) abundance ratio using the measured flux of the \( \text{C} \ \lambda 4267 \) line, \( T_e(\text{O} \ \text{iii}) \) and the Case B \( \text{C}^+ \) effective recombination coefficients calculated by Davey, Storey & Kisielius (2000). We have determined the \( \text{O}^+/\text{H}^+ \) ratio from the intensity of the \( \text{O} \ \text{iii} \) Multiplet 1 pure RLs. Here, the \( \text{O} \ \text{iii} \) effective recombination coefficients were adopted from the Case B, LS-coupling calculations of Storey (1994) and the \( T_e(\text{O} \ \text{iii}) \) was assumed. Under typical physical conditions of photoionized nebulae (\( N_e \sim 10^2–10^4 \)), the relative intensities of individual fine-structure lines within the \( \text{O} \ \text{iii} \) M1 multiplet are not constant but varies as a function of the electron density (e.g. Fang & Liu 2013). This is due to the fact that the relative populations of the ground fine-structure levels of the recombinig ion (e.g. \( \text{O}^+ \) in the case of \( \text{O} \ \text{ii} \) deviate from the local thermodynamical equilibrium (LTE), which was seldom considered in previous atomic calculations. We considered this deviation from the LTE by adopting the prescriptions of Peimbert & Peimbert (2005) to apply appropriate correction of the relative strengths of the \( \text{O} \ \text{iii} \) Multiplet 1 lines at densities \( N_e < 10^4 \) cm\(^{-3}\). The derived ionic abundances

\( T_e(\text{O} \ \text{iii}) \) using the aforementioned procedure and atomic data set. The \( T_e \) and \( N_e \) values derived for the two last nebulae are consistent with those obtained by Fernández-Martín et al. (2017) within the errors.
Table 7. Physical conditions and abundances for Sh 2-100, Sh 2-128, Sh 2-288, Sh 2-127 and Sh 2-212.

|          | Sh 2-100   | Sh 2-128   | Sh 2-288   | Sh 2-127   | Sh 2-212   |
|----------|------------|------------|------------|------------|------------|
|          | \( r^2 = 0.0 \) | \( r^2 = 0.010 \) | \( r^2 = 0.0 \) | \( r^2 = 0.0 \) | \( r^2 = 0.0 \) |

Physical conditions

- \( N_e([\text{S} \text{ii}]) \): \( 430 \pm 210 \)
- \( N_e([\text{Cl} \text{m}]) \): \( 660 \pm 350 \)
- \( T_e([\text{N} \text{ii}]) \): \( 8950 \pm 320 \)
- \( T_e([\text{O} \text{ii}]) \): \( 10 \ 010 \pm 560 \)
- \( T_e([\text{S} \text{ii}]) \): \( 19 \ 780 \pm 2450 \)
- \( T_e([\text{O} \text{iii}]) \): \( 8140 \pm 120 \)

Notes: \( aN_e \) in cm\(^{-3}\); \( T_e \) in K.

Table 8. Physical conditions and abundances for Sh 2-83, Sh 2-209 and Sh 2-298.

|          | Sh 2-83   | Sh 2-209   | Sh 2-298   |
|----------|------------|------------|------------|
|          | \( r^2 = 0.0 \) | \( r^2 = 0.010 \) | \( r^2 = 0.0 \) |

Physical conditions

- \( N_e([\text{S} \text{ii}]) \): \( 300 \pm 100 \)
- \( N_e([\text{O} \text{ii}]) \): \( ... \)
- \( N_e([\text{Cl} \text{m}]) \): \( <100 \)
- \( T_e([\text{N} \text{ii}]) \): \( 12840 \pm 660 \)
- \( T_e([\text{O} \text{ii}]) \): \( 13670 \pm 890 \)
- \( T_e([\text{S} \text{ii}]) \): \( ... \)
- \( T_e([\text{O} \text{iii}]) \): \( 11490 \pm 490 \)
- \( T_e([\text{S} \text{ii}]) \): \( ... \)

Ionic abundances and O/H* ratio

- He\(^+\): \( 10.94 \pm 0.01 \)
- N\(^+\): \( 6.24 \pm 0.04 \)
- O\(^+\): \( 7.05 \pm 0.12 \)
- O\(^{2+}\): \( 8.10 \pm 0.05 \)
- N\(^{2+}\): \( 7.45 \pm 0.12 \)
- S\(^+\): \( 5.14 \pm 0.05 \)
- S\(^{2+}\): \( 6.31 \pm 0.10 \)
- Cl\(^{2+}\): \( 4.63 \pm 0.06 \)
- Ar\(^{2+}\): \( 5.69 \pm 0.05 \)
- Ar\(^{3+}\): \( ... \)
- O: \( 8.14 \pm 0.05 \)

Notes: \( aN_e \) in cm\(^{-3}\); \( T_e \) in K.

As we can see in Table 7, the O\(^{2+}\)/H\(^+\) abundance ratio derived from the RLSs for Sh 2-100 is higher than the abundances determined from the CELs. This is a common observational fact in all HII regions where the O\(^{2+}\)/H\(^+\) and C\(^{2+}\)/H\(^+\) ratios can be determined using both CELs and RLSs. This is called the abundance discrepancy problem and its origin is still under debate (e.g. García-Rojas &
Figure 4. Section of the spectrum of Sh 2-83, Sh 2-100, Sh 2-127, Sh 2-128, Sh 2-209, Sh 2-212, Sh 2-288 and Sh 2-298 showing the [N II] $\lambda$5755 auroral line.

Esteban 2007; Esteban, Toribio San Cipriano & García-Rojas 2016a). For Sh 2-100, the ratio of the two $O^{2+}/H^+$ abundances determined from RLs and CELs, defined as the abundance discrepancy factor (ADF), is 0.07 dex, which is one of the lowest values ever found in H II regions. This is also slightly lower than the ADF found in the Orion nebula (see Esteban et al. 2016a). Assuming that the abundance discrepancy is due to the presence of fluctuations in the spatial distribution of $T_e$ inside the nebula (Torres-Peimbert, Peimbert & Daltabuit 1980), we can estimate the temperature fluctuation parameter $\tau^2$, which was first defined by Peimbert (1967) to reconcile the $O^{2+}/H^+$ abundance ratios determined from RLs and CELs. The $\tau^2$ value we obtained for Sh 2-100 is 0.010 $\pm$ 0.010. We considered two sets of abundances for this object, one for the case of $\tau^2 = 0$ and the other for $\tau^2 = 0.010 \pm 0.010$. We could not derive $\tau^2$ for the other H II regions in our sample. Therefore, their abundances were only calculated for $\tau^2 = 0$.

Since the aim of this paper is to explore the slope of the Galactic radial gradient of oxygen in the anti-centre direction, we limit our study to determine the total abundances of oxygen. In H II regions, O is the only element for which no ionization correction factor
Figure 5. Section of the spectrum of Sh 2-83, Sh 2-100, Sh 2-128, Sh 2-212, Sh 2-288 and Sh 2-298 showing the [O III] $\lambda$4363 auroral line (indicated by an arrow).

(hereafter ICF) is needed to derive its total abundance; therefore its calculation is more accurate than for other elements. The total O abundance is simply the sum of the $O^+/H^+$ and $O^{2+}/H^+$ ratios. We could also estimate the total abundances of He, N, Ne, S, Cl, Ar and Fe for our objects, but we need ICFs, which are empirically derived based on the similarity of ionization potentials of different ionic species or estimated from photoionization models. We plan to study the gradients of these elements in a future paper where we will carry out a critical analysis of the best ICFs for each element, including additional observations for the nebulae with accurate determinations of the N abundance. As it has been said before, we detect the very faint C II $\lambda$4267 RL in the spectrum of Sh 2-100, and this is a remarkable result considering the paucity of determinations of C abundance in Galactic H II regions. As for the rest of the elements – apart from O – we will present the C abundance of this object as well as a reassessment of the Galactic gradient of C/H in a future paper.

In Table 9, we present the recalculated values of the O abundances for IC 5146, Sh 2-132, NGC 7635 and Sh 2-156. The O/H ratios of M20, M16, M17, M8, NGC 3576, M42, NGC 3603, Sh 2-311 and NGC 2579 are presented in table 7 of Esteban et al. (2015).

7 THE O GRADIENT AT THE ANTI-CENTRE

As indicated in Section 1, Fernández-Martín et al. (2017) recently studied the chemical composition of a sample of H II regions in the Galactic anti-centre. We developed the observational program prior to the publication of that paper. Fernández-Martín et al. (2017) detected auroral lines to derive $T_e$ in five objects of their sample. Of those five objects, two are included in our current sample, Sh 2-83 and Sh 2-212, and a third one, Sh 2-162, corresponds to our NGC 7635, for which we recalculated $T_e$ and the O/H ratio from the emission line ratios measured by Esteban et al. (2016b) in their
Table 9. \(T_e, N_e\) and abundances recalculated for IC 5146, Sh 2-132, NGC 7635 and Sh 2-156.

|          | IC 5146a | Sh 2-132 | NGC 7635b | Sh 2-156 |
|----------|----------|----------|------------|----------|
| \(N_e([\text{S} \text{II}])\) (cm\(^{-3}\)) | <100 | 260 ± 10 | 160 ± 100 | 900 ± 25 |
| \(T_e([\text{N} \text{II}])\) (K) | 7140 ± 120 | 9350 ± 460 | 8390 ± 390 | 9460 ± 400 |
| \(T_e([\text{O} \text{III}])\) (K) | ... | 8870 ± 460 | 8190 ± 510 | 9010 ± 350 |
| \(12+\log(O/H)\) | 8.56 ± 0.04 | 8.35 ± 0.14 | 8.40 ± 0.08 | 8.32 ± 0.10 |

Notes: aMean of the values of apertures 2, 3 and 4 observed by García-Rojas et al. (2014).
bMean of the values of apertures 2, 3, 4, 5 and 6 observed by Esteban et al. (2016b).
cEstimated from \(T_e([\text{N} \text{II}])\) and equation 3 of Esteban et al. (2009).

deeper spectra taken at the GTC. The other two objects for which Fernández-Martín et al. (2017) determined \(T_e\) are Sh 2-132 and Sh 2-156. The authors collected spectra of additional \(\text{H} \text{II}\) regions taken from the literature and all of them correspond to observations obtained at 2–4 m telescopes and published between 1979 and 2000. When describing the procedure of data collection from the literature, Fernández-Martín et al. (2017) stated that they carried out an exhaustive bibliographical review of spectroscopical results of \(\text{H} \text{II}\) regions located at \(R_G > 11\) kpc. It is surprising that they overlooked the deepest observations of this kind of objects published prior to 2016: the VLT spectroscopy of Sh 2-311 and NGC 2579 published by García-Rojas et al. (2005) and Esteban et al. (2013), respectively. Moreover, for Sh 2-311, Fernández-Martín et al. (2017) instead of using the far much better quality data by García-Rojas et al. (2005) adopted the emission line ratios obtained by Shaver et al. (1983) with the 3.6 m telescope and the 3.9 m AAT at La Silla and Siding Spring, respectively. We consider that the new data presented in this paper in combination with (a) the compilation of deep spectroscopy from the literature (all of them except one obtained from 8-10 m telescopes) and (b) the recalculations of the abundances in a homogeneous way are a substantial improvement in the exploration of the true shape of the O abundance gradient at the Galactic anti-centre.

We performed a least-squares linear fit to the oxygen abundance as a function of \(R_G\) for the whole sample, including objects in the Galactic anti-centre and the inner disc, i.e. all the objects included in Tables 7–9 which cover \(R_G\) of 5.1–17 kpc. The fits give the following radial O abundance gradient:

\[
12 + \log(O/H) = 8.79(±0.05) - 0.040(±0.005)R_G, \tag{1}
\]

where the uncertainties are estimated through Monte Carlo simulations. We generated \(10^6\) random values of \(R_G\) and the O abundance for each observational data point assuming a Gaussian distribution with a sigma equal to the measurement uncertainty of each quantity. We performed a least-squares linear fit to each of these \(10^6\) random distributions. The uncertainties associated with the slope and intercept correspond to the standard deviation of the values of these two quantities obtained from the fits. The spatial distribution of the O abundances and the gradient are shown in Fig. 7. Using a similar methodology, Esteban et al. (2015) determined a slope of \(-0.043\) dex kpc\(^{-1}\) for the O gradient defined by a subset of our sample of \(\text{H} \text{II}\) regions restricted to \(R_G \leq 12.4\) kpc. The most recent determinations of the Galactic gradient of oxygen for the whole disc available in the literature show consistent slopes: Deharveng et al. (2000) obtained a slope of \(-0.040(±0.005)\) dex kpc\(^{-1}\); Queiroz et al. (2006) derived \(-0.043(±0.007)\) dex kpc\(^{-1}\); Rudolph et al. (2006) gave \(-0.060(±0.010)\) and \(-0.042(±0.013)\) dex kpc\(^{-1}\), when they used the optical and far-infrared lines, respectively; Balser et al. (2011) presented a slope of \(-0.045(±0.005)\) dex kpc\(^{-1}\). As we can see, these determinations are highly consistent, indicating that the slope of the radial abundance gradient of oxygen has been well established for the Milky Way.

The average difference between the oxygen abundances of the \(\text{H} \text{II}\) regions represented in Fig. 7 and those given by the linear fit at their corresponding galactocentric distances is \(±0.05\) dex, similar order of the average uncertainty of the abundance determinations. The maximum difference we find is \(±0.10\) dex. This is an upper limit of any local inhomogeneity of the O abundance that is consistent with our results.

In order to explore whether a change of the slope of the oxygen gradient is present in the outer disc, we carried out additional least-square fits separately to the \(\text{H} \text{II}\) regions within and beyond \(R_{25}\) (= 11.5 kpc). The radial O gradient we found for the objects within \(R_{25}\) is

\[
12 + \log(O/H) = 8.70(±0.07) - 0.029(±0.009)R_G \tag{2}
\]

and that for the external \(\text{H} \text{II}\) regions (\(R_G > R_{25}\)) is

\[
12 + \log(O/H) = 8.87(±0.23) - 0.046(±0.017)R_G. \tag{3}
\]

All these gradients are presented in Fig. 7. As we can see in the figure and ascertain by comparing the parameters of the gradients, their slopes are consistent within the uncertainties, indicating that the shape of the gradient does not change substantially across the Galactic disc. Therefore, our results confirm the absence of flattening in the radial O abundance gradient beyond \(R_{25}\), at least up to \(R_G \sim 17\) kpc or \(\sim 1.5 \times R_{25}\). As a conclusion, we can say that inside-out models of galaxy formation are also valid to explain the chemical composition of the outer parts of the Milky Way.

In Fig. 7, we also present the average O abundances of the Large and Small Magellanic Clouds (hereafter LMC and SMC) obtained by Toribio San Cipriano et al. (2017) and Domínguez-Guzmán et al. (2017) from deep echelle spectra of a sample of \(\text{H} \text{II}\) regions obtained with the VLT. We can see that the ionized gas-phase abundances of O in the outer regions (beyond \(R_{25}\)) of the Milky Way is between the values measured in the Magellanic Clouds. Abundances of the outermost \(\text{H} \text{II}\) regions are closer to the low value observed in the SMC. The slope of the oxygen gradient obtained by Fernández-Martín et al. (2017) for the \(R_G\) from 11 to 18 kpc is between \(-0.053\)
and $-0.061 \, \text{dex kpc}^{-1}$, consistent with our determinations for the outer disc within the uncertainties.

We have investigated O gradients – in the Milky Way and other nearby galaxies – in other papers of our group (Estevez et al. 2005, 2013; Toribio San Cipriano et al. 2016, 2017), always focusing on the gradient derived from O abundances determined from RLs. One question that we want to briefly address is the possible effect of the abundance discrepancy or the presence of temperature fluctuations in the abundance gradient derived in this paper. García-Rojas & Esteban (2007) and Esteban et al. (2016a) found that H II regions in the discs of spiral galaxies where the ADF has been calculated show quite similar values of such quantity. In fact, García-Rojas & Esteban (2007) found that the ADF seemed to be independent of some basic properties of H II regions, i.e. metallicity or $T_e$. Moreover, the O/H gradients determined from CELs and RLs are almost identical. Some indication of a possible correlation between the ADF and the O/H ratio determined from CELs has appeared with the latest results on low-metallicity objects obtained by Toribio San Cipriano et al. (2017). This correlation indicates that objects with a lower O/H ratio seem to show higher values of the ADF, but this is only apparent for objects with $12 + \log(O/H) \lesssim 8.1$. Taking into account that our objects show O/H ratios – determined from CELs – larger than that value, we do not consider that this effect may be affecting to the H II regions studied in this paper.

8 CONCLUSIONS

We present very deep optical spectra of eight H II regions located in the anti-centre of the Milky Way, with $R_G$ between 9.4 and 17 kpc. The data were obtained at the 10.4m GTC and the 8.2m VLT. We derived $T_e([\text{O} \, \text{iii}])$ for all the objects and $T_e([\text{O} \, \text{iii}])$ for six of them. This permits to use the direct-$T_e$ method based on the measurements of the temperature-sensitive auroral lines to derive chemical abundances. We also included an additional sample of 13 H II regions located in the inner and outer disc of the Milky Way, whose spectra were also obtained with large telescopes. Reliable electron temperatures were also determined for these additional objects. The physical conditions and ionic abundances of all objects were derived using the same methodology and atomic data set. We also detected the C II and O II optical recombination lines in Sh 2-100, for which we calculated the abundance discrepancy factor in $O^{+\text{II}}$. This factor is higher than unity but rather small.

We derived the oxygen abundances for all objects, thus allowing the determination of the radial abundance gradient over a wide range of $R_G$, from 5.1 to 17 kpc. Eight objects are located outside of $R_{25}$ and 13 inside $R_{25}$. A least-squares linear fit to the oxygen abundance gradient of the whole sample, including the H II regions in the outer and inner Galactic disc, gives a slope of $-0.040 \pm 0.005 \, \text{dex kpc}^{-1}$. Additional least-squares fits of the inner and outer disc objects, separated by $R_{25} = 11.5 \, \text{kpc}$, give similar slopes. In particular, the slope of the H II regions located beyond $R_{25}$ is $-0.046 \pm 0.017 \, \text{dex kpc}^{-1}$. This result indicates that there is no evidence of flattening in the radial O abundance gradient beyond $R_{25}$, at least up to 17 kpc ($\sim 1.5 \times R_{25}$). In general, we find that the scatter in the O/H ratios of H II regions across the Galactic disc is not substantially larger than the observational uncertainties, with the largest possible inhomogeneities of the order of 0.1 dex.

In an appendix, we explored the radial distribution of $T_e([\text{O} \, \text{iii}])$ and $T_e([\text{N} \, \text{ii}])$ across the Galactic disc and found gradients with similar positive slopes for both temperatures, with much larger scatter in $T_e([\text{N} \, \text{ii}])$. The shape of the $T_e$ gradients is consistent with

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**Figure 7.** Radial distribution of the oxygen abundance, in logarithm $12 + \log(O/H)$, as a function of the Galactocentric distance, $R_G$, for the whole sample of Galactic H II regions. Large filled squares represent the objects of our current sample and small filled triangles indicate the additional sample. The solid black line is a least-squares linear fit to all objects. The vertical grey line marks the position of the isophotal radius of the Milky Way, $R_{25} = 11.5 \, \text{kpc}$ (de Vaucouleurs & Pence 1978). The blue dotted line is a least-squares linear fit to the H II regions located at $R_G < R_{25}$ and the red dashed line is the fit to those at $R_G > R_{25}$. The figure graphically demonstrates that the slope of the gradient does not change significantly across the Galactic disc and the lack of flattening in the outer zone. The arrows indicate the average O abundances of H II regions in the LMC and SMC (Dominguez-Guzmán et al. 2017; Toribio San Cipriano et al. 2017).
the absence of flattening in the metallicity gradient in the outer Galactic disc.

The results of this work indicate that the inside-out models of galaxy formation are also valid to explain the chemical composition of the outer regions of the Milky Way.

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REFERENCES

Balser D. S., Rood R. T., Bania T. M., Anderson L. D., 2011, ApJ, 738, 27
Bohlin R. C., Lindler D., 1992, STScI Newsl., 9, 19
Balser D. S., Rood R. T., Bania T. M., Anderson L. D., 2011, ApJ, 738, 27

...
Shafter P. A., McGee R. X., Newton L. M., Danks A. C., Pottasch S. R., 1983, MNRAS, 204, 53
Storey P. J., 1994, A&A, 282, 999
Storey P. J., Hummer D. G., 1995, MNRAS, 272, 41
Storey P. J., Zeippen C. J., 2000, MNRAS, 312, 813
Storey P. J., Sochi T., Badnell N. R., 2014, MNRAS, 441, 3028
Tayal S. S., 2011, ApJS, 195, 12
Tayal S. S., Gupta G. P., 1999, ApJ, 526, 544
Tayal S. S., Zatsarinny O., 2010, ApJS, 188, 32
Toribio San Cipriano L., García-Rojas J., Esteban C., Bresolin F., Peimbert M., 2016, MNRAS, 458, 1866
Toribio San Cipriano L., Domínguez-Guzmán G., Esteban C., García-Rojas J., Mesa-Delgado A., Bresolin F., Rodríguez M., Simón-Díaz S., 2017, MNRAS, 467, 3759
Torres-Peimbert S., Peimbert M., Daltabuit E., 1980, ApJ, 238, 133
Turnshek D. A., Bohlin R. C., Williamson R. L., Lupie O. L., Koornneef J., Morgan D. H., 1990, AJ, 99, 1243
Vale Asari N., Stasińska G., Morisset C., Cid Fernandes R., 2016, MNRAS, 460, 1739
Vilchez J. M., Esteban C., 1996, MNRAS, 280, 720
Vlajic M., Bland-Hawthorn J., Freeman K. C., 2011, ApJ, 732, 7
Yong D., Carney B. W., Friel E. D., 2012, AJ, 144, 95
Zeippen C. J., Butler K., Le Bourlot J., 1987, A&A, 188, 251
Zhang H., 1996, A&AS, 119, 523

APPENDIX A: THE $T_e$ GRADIENT

The presence of a radial gradient of $T_e$ in the Milky Way is well established from the radio continuum emission observations (e.g. Churchwell & Walmsley 1975; Shafter et al. 1983; Quireza et al. 2006) and the optical [O II] emission line ratios (e.g. Peimbert, Torres-Peimbert & Rayo 1978; Deharveng et al. 2000). Heavy elements such as O or N are the main coolants of photoionized gas and therefore the $T_e$ of H II regions is related to its metallicity. Consequently, we expect to find $T_e$ gradients in the Milky Way and in other galaxies. In this paper, we have derived the $T_e$([O II]) and $T_e$([N II]) for a number of H II regions in the outer disc of the Galaxy and compiled/recalculated these temperatures for additional objects in the inner Galactic disc. In total, we obtained 17 determinations of the $T_e$([O II]) and 20 $T_e$([N II]), which are presented in Tables 7–9 in this paper and table 3 in Esteban et al. (2015).

In Fig. A1, we show the radial distribution of $T_e$([O II]) and $T_e$([N II]) of the H II regions of our complete sample. Our least-squares linear fit to the $T_e$([O II]) of the whole sample gives

\[ T_e([\text{O II}]) = 5900(\pm320) K + 320(\pm40) \times R_G; \]  

and our fit to the $T_e$([N II]) gives

\[ T_e([\text{N II}]) = 7110(\pm360) K + 240(\pm40) \times R_G. \]  

The derived slope of the $T_e$([O II]) radial gradient, 320 ± 40 K kpc$^{-1}$, is fairly close to the values of 372 ± 38 and 287 ± 46 K kpc$^{-1}$ determined by Deharveng et al. (2000) and Quireza et al. (2006), respectively. The average difference between the $T_e$([O II]) of the H II regions in Fig. A1 and the value derived from the linear fit at their corresponding distances is 530 K, not much larger than the average uncertainty (300 K) of the $T_e$([O II]) determinations. The maximum difference is 2040 K found in Sh 2-298, an H II region with the hottest ionizing star in our sample. The ionizing source of Sh 2-298 is the Wolf–Rayet (WR) star HD 56925, which has been classified as WN4, with $T_{\text{eff}} \sim 112$ 200 K (Hamann, Gräfener & Liermann 2006). Normal H II regions are usually ionized by OB stars with $T_{\text{eff}}$ between 30 000 and 45 000 K. We have recalculated the average difference between the observed and the fitted $T_e$([O II]) of the H II regions by removing the outlier (Sh 2-298) and we obtained 430 K, a value closer to a mean observational uncertainty of 300 K.

Fig. A1 shows, for the first time, that the $T_e$([N II]) of H II regions in the Milky Way also varies with the galactocentric distance. The slope in the $T_e$([N II]), 240 ± 40 K kpc$^{-1}$, is somewhat lower than that obtained for the $T_e$([O II]) although the scatter is considerably larger. The mean difference between the observed and the fitted $T_e$([N II]) of the H II regions presented in Fig. A1 is 810 K, higher than the average uncertainty (390 K) of all $T_e$([N II]) determinations. The exact origin of this scatter is difficult to explain. N$^+$ is usually located in the outer regions of the nebulae, and depending on the relative development of the Strömgren spheres of the high and low ionization species, the differences between $T_e$([N II]) and $T_e$([O II]) may vary among different objects. The maximum difference we find in the sample is 2160 K (Sh 2-298) and additional three objects show differences of about 2000 K: IC 5146, NGC 3603 and Sh 2-83. It is interesting to note that three out of these nebulae are ionized by stars with effective temperatures higher or lower than the usual $T_{\text{eff}}$ of O-type stars. IC 5146 is ionized by a B0.5 V star and shows the lowest ionization degree amongst the whole sample. NGC 3603 is the only optically visible, giant H II region in the Milky Way and contains several WR and hot O3-4 stars (Drissen 1999). As aforementioned in this section, Sh 2-298 is ionized by a WR star and also shows a large difference in $T_e$([O II]). Excluding the four objects showing very large differences (≥2000 K) between the observed and the fitted $T_e$([N II]), the average difference in the rest
of the H II regions goes down to 520 K, much closer to the typical uncertainty of 390 K.

As we can see in Fig. A1, the expected values of $T_e(\text{[O III]})$ and $T_e(\text{[N II]})$ in H II regions in the outer disc of the Milky Way ($R_d \sim 17$ kpc) are, as in the case of the O/H ratios (see Fig. 7), between the mean values found for the H II regions in the LMC and SMC (Domínguez-Guzmán et al. 2017; Toribio San Cipriano et al. 2017). Remarkably, Fig. A1 does not give any hint about a flattening of the $T_e$ gradient in the outer Galactic disc, reinforcing the conclusion drawn from Fig. 7.

In Fig. A2, we show the dependence of $T_e(\text{[O III]})$ and $T_e(\text{[N II]})$ with respect to the O/H ratio. In particular, the correlation between $T_e(\text{[O III]})$ and the O abundance is specially tight. As expected, the objects showing the largest differences with respect to the linear fit are the same as in Fig. A1.

The least-squares linear fit to the $T_e(\text{[O III]})$ versus O/H ratio relation gives

$$T_e(\text{[O III]}) = -15540(\pm 3800)K - 6820(\pm 1070) \times \log(O/H).$$

(A3)

In Fig. A3, we show the dependence of the $T_e(\text{[N II]})/T_e(\text{[O III]})$ ratio with respect to the O abundance. The least-squares linear fit of the data included in that figure gives

$$T_e(\text{[N II]})/T_e(\text{[O III]}) = 1.80(\pm 0.48) + 0.20(\pm 0.13) \times \log(O/H),$$

(A5)

which indicates a very small or almost absent correlation between both quantities.

Finally, we have obtained the relation between $T_e(\text{[N II]})$ and $T_e(\text{[O III]})$ in Fig. A4, finding a relatively tight correlation and the following least-squares linear fit:

$$T_e(\text{[N II]}) = 1780(\pm 1280)K + 0.88(\pm 0.15) \times T_e(\text{[O III]});$$

(A6)

the slope of the fit is consistent with a 1:1 relation considering the uncertainties. This fit is also very similar to the classical one obtained by Garnett (1992) using photoionization models and assuming $T_e(\text{[N II]}) = T_e(\text{[O II]})$:

$$T_e(\text{[N II]}) = T_e(\text{[O II]}) = 3000K + 0.7 \times T_e(\text{[O III]}).$$

(A7)

Our $T_e(\text{[N II]})-T_e(\text{[O III]})$ relation is also consistent with that obtained by Esteban et al. (2009) from deep spectra for a sample of Galactic and extragalactic H II regions and Vale Asari et al. (2016) from the results of an extensive grid of modern photoionization models (see their fig. A2).

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