Helium abundances and its radial gradient from the spectra of H\textsc{ii} regions and ring nebulae of the Milky Way

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ABSTRACT

We determine the radial abundance gradient of helium in the disc of the Galaxy from published spectra of 19 H\textsc{ii} regions and ring nebulae surrounding massive O stars. We revise the Galactocentric distances of the objects considering Gaia DR2 parallaxes and determine the physical conditions and the ionic abundance of He\textsuperscript{+} in a homogeneous way, using between 3 and 10 He\textsuperscript{1} recombination lines in each object. We estimate the total He abundance of the nebulae and its radial abundance gradient using four different ICF(He) schemes. The slope of the gradient is always negative and weakly dependent on the ICF(He) scheme, especially when only the objects with log(\eta) < 0.9 are considered. The slope values go from −0.0078 to −0.0044 dex kpc\textsuperscript{−1}, consistent with the predictions of chemical evolution models of the Milky Way and chemodynamical simulations of disc galaxies. Finally, we estimate the abundance deviations of He, O and N in a sample of ring nebulae around Galactic WR stars, finding a quite similar He overabundance of about +0.24 ± 0.11 dex in three stellar ejecta ring nebulae.

Key words: ISM: abundances – H\textsc{ii} regions – Galaxy: abundances – Galaxy: disc – Galaxy: evolution – ISM: bubbles – stars: massive – stars: Wolf-Rayet

1 INTRODUCTION

Although rare on Earth, helium is the second most abundant element in the Universe and constitutes about 24-25% of its baryonic mass. The vast majority of the cosmic helium was produced during the primordial nucleosynthesis phase just after the Big Bang. The fraction of primordial mass in helium, \(Y_p\), has been determined following three different techniques. The results of Wilkinson Microwave Anisotropy Probe (WMAP) and Planck satellites devoted to the study of the Cosmic Microwave Background (CMB) anisotropies have obtained values between 0.245 and 0.247 assuming the Standard Big Bang Nucleosynthesis (Coc et al. 2005; Planck Collaboration et al. 2018). Studies of intergalactic clouds near pristine absorption systems along the line of sight of bright distant quasars determine upper limits of \(Y_p\) in the range 0.225 and 0.283 (Cooke & Fumagalli 2018). The last technique, based on the analysis of spectra of H\textsc{ii} regions of metal-poor galaxies gives values of \(Y_p\) between 0.238 and 0.257 in the most recent works (Izotov et al. 2014; Aver et al. 2015; Peimbert et al. 2016; Fernández et al. 2018; Valerdi et al. 2019).

After the Big Bang, helium is produced by hydrostatic nucleosynthesis in the interior of stars of all initial masses. Low-mass stars produce this element through the proton-proton chain while intermediate mass and massive ones via the CNO cycle. Helium can be also efficiently destroyed in stellar interiors by the triple-alpha process. The amount of this element that is actually ejected by a given star and enrich the ISM depends on its initial mass and the importance of stellar winds.

The analysis of Galactic H\textsc{ii} region spectra indicates the presence of radial gradients of the abundances of heavy elements – such as O, N, Ne, S, Ar or Cl – along the disc of the Milky Way (e.g. Shaver et al. 1983; Deharveng et al. 2000; Rudolph et al. 2006; Balser et al. 2011; Esteban & García-Rojas 2018). The form of such gradients reflects the action of stellar nucleosynthesis, the distribution and history of star formation and gas flows in the chemical evolution of the Galaxy. Although the helium abund-

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dance should increase with the metallicity, there is not a clear evidence of the presence of a radial gradient of this element in the Milky Way. Some authors (e.g. Peimbert et al. 1978; Talent & Dufour 1979) find a slight or marginal evidence of a negative gradient but others find a flat distribution of the helium abundance along the Galactic disc (e.g. Shaver et al. 1983; Fernández-Martín et al. 2017, see §4 for further discussion).

There are several sources of uncertainty in the determination of the total abundance of helium. The most important one is related to the ionization structure of the nebulae. The spectrum of normal H II regions only shows recombination lines of He\(^+\). Since the ionization potential of He\(^0\) is 24.6 eV, we expect the presence of neutral helium in the H II region, but it cannot be observed. To determine the total helium abundance from the measured He\(^+\)/H\(^+\) ratio, we have to rely on an ionization correction factor, ICF. In the absence of a tailored photoionization model for the object, we have to assume a particular ICF scheme based on the results of grids of photoionization models or on the similarity of ionization potentials of other particular ions. All ICF schemes are parameterized by the ionization degree measured in the nebular spectrum. There are several ICF schemes for helium available in the literature and based on different ionic ratios (e.g. Peimbert & Torres-Peimbert 1977; Peimbert et al. 1992; Kunth & Sargent 1983; Zhang & Liu 2003).

There are two more additional sources of uncertainty in the determination of the total abundance of helium and they are related to deviations from the pure recombination spectrum of He I. The He I atom has two different level states depending on its total spin quantum number, singlets and triplets. While – in principle – the intensity ratios of singlet lines should follow the predictions of recombination theory, the triplet spectrum is affected by the metastability of the lowest triplet level, the 2S\(^+\) (Osterbrock & Ferland 2006). This metastable level produces important collisional and self-absorption effects. Collisions with free electrons may pump electrons from 2S\(^+\) to upper levels, enhancing the intensities of the lines coming from those excited levels with respect to the predictions of recombination theory. Although triplet lines are the most affected, some singlet lines can be also enhanced (Sawey & Berrington 1993; Kingdom & Ferland 1995). Photons of transitions ending on 2S\(^+\) can be reabsorbed and, eventually, emitted as other He I lines. This self-absorption process increases or decreases line intensities of triplet lines with respect to recombination according to the line considered. The strength of collisional effects on the He I spectrum depends on the electron density and temperature of the ionized gas, being higher in denser and hotter nebulae. The calculations of the recombination spectrum of He I performed by Porter et al. (2012) include the collisional effects in the level populations of He\(^0\). Self-absorption effects depend mostly on density, and are not expected to be very important in H II regions (Benjamin et al. 2002).

The aim of this paper is to explore the existence of a radial gradient of helium in the Milky Way using the best dataset of deep spectra of H II regions available to date and considering revised distances for the nebulae. The selection gives priority to deep spectra that have been treated homogeneously in their reduction process. The structure of this paper is as follows. In §2 we describe the sample of H II region spectra used and the determination of the revised distances. In §3 we present the values of physical conditions, electron density and temperature – \(n_e\) and \(T_e\) – adopted for each object; the He\(^+\) and He abundance recalculations, as well as discuss the different ICF’s used. In §4 we discuss the results pertaining to the Galactic He radial gradients. In §5 we compute and discuss the abundance deviations of He, O and N with respect to the radial abundance gradients shown by a sample of Galactic ring nebulae around WR stars. Finally, in §6 we summarize our main conclusions.

2 OBSERVATIONAL DATA AND REVISED DISTANCES

We have used reddening-corrected intensity ratios of several emission lines of 39 spectra corresponding to 24 Galactic H II regions and ring nebulae around massive stars (Wolf-Rayet, WR or O-type stars). The data have been obtained, reduced and analyzed by our group and published in Esteban et al. (2004, 2013, 2016, 2017), Esteban & García-Rojas (2018) and García-Rojas et al. (2004, 2005, 2006, 2007). We will refer this group of publications as the “set of source papers”. The spectra were obtained with the Ultraviolet Visual Echelle Spectrograph (UVES, D’Odorico et al. 2000) at the Very Large Telescope (VLT); the OSIRIS (Optical System for Imaging and low-Intermediate-Resolution Integrated Spectroscopy) spectrograph (Cepa et al. 2000, 2003) at the 10.4 m Gran Telescopio Canarias (GTC) and the Magellan Echellette (MagE) spectrograph at the 6.5m Clay Telescope (Marshall et al. 2008). The details of the observations and the instrument configurations used are described in the set of source papers.

In the set of source papers the assumed distance of the Sun to the Galactic Centre was \(R_G = 8.0\) kpc (Reid 1993). Most of the recent determinations do not provide substantially different values of this parameter, but the precision has increased considerably. Bland-Hawthorn & Gerhard (2016) present a compilation of direct (primary), model-based and secondary determinations, proposing a best estimate for the distance to the Galactic Center of 8.2 ± 0.1 kpc. We adopt this value and its uncertainty for all our calculations of the Galactocentric distance (\(R_G\)) of the objects. The GRAVITY collaboration has published a very recent geometric distance determination of the Galactic centre black hole with 0.3% uncertainty (Gravity Collaboration et al. 2019), which is entirely consistent with 8.2 kpc.

The set of source papers give the Galactocentric distances, \(R_G\), for each object. In the case of the H II regions, Esteban et al. (2017) and Esteban & García-Rojas (2018) adopted the mean values of kinematic and stellar distances given in different published references and an uncertainty corresponding to their standard deviation. In order to obtain an improved set of \(R_G\) values, we have made a revision taking into account new distance measurements based on Gaia parallaxes of the second data release (DR2). For M8, M16, M17, M20, M42 and NGC 3576 we have adopted the distances derived by Binder & Povich (2018) from Gaia parallaxes, with typical uncertainties in the range 0.1-0.3 kpc. For the rest of the objects we have searched the distances of the ionizing and/or associated star (or stars) inferred by Bailer-Jones et al. (2018) from Gaia DR2 data.
and a distance prior that varies smoothly as a function of the Galactic coordinates of the objects according to a Galaxy model. In general, we find that distances based on Gaia parallaxes are very similar to those assumed previously in Esteban et al. (2017) and Esteban & García-Rojas (2018). The mean difference for the 23 objects for which the two kinds of determinations can be compared is about 9% (the median is 5%). The uncertainties in the distance of the Gaia parallaxes tend to be larger than about 1 kpc and larger than those quoted by Esteban et al. (2017) and Esteban & García-Rojas (2018) for objects at heliocentric distances about or larger than 5 kpc. The largest differences correspond to the the most external object of the sample (Sh 2-209, 38%), but also for the objects located at $R_G \lesssim 7$ kpc, with a mean difference of about 16%.

In the case of the ring nebulae (G2.4+1.4, NGC 6888, NGC 7535, RCW 52, RCW 58, Sh 2-289 and Sh 2-308), all of them are ionized by a single well identified WR or O star and are located at heliocentric distances smaller than 5 kpc. Their distances have been taken directly from the database of Bailer-Jones et al. (2018). For the rest of the objects – for which we do not have a single ionized source or lack information about their ionizing sources – we compare the distances obtained from Gaia DR2 data (Bailer-Jones et al. 2018) with those adopted by Esteban et al. (2017) or Esteban & García-Rojas (2018), assuming one or the other depending on which determination gives the smallest uncertainties. We describe the details for each object below.

**NGC 2579.** We analyzed the Gaia DR2 data for stars located within 1 arcmin around the center of the H\textsc{ii} region. The parallaxes of the stars give a large and rather uncertain heliocentric distance for the object ($5.31 \pm 1.01$ kpc), that corresponds to an average $R_G$ of about $10.88 \pm 0.78$ kpc. Copetti et al. (2007) carried out a detailed study of spectroscopic parallaxes of the possible ionizing stars of the nebula, finding a somewhat larger distance of $R_G = 12.40 \pm 0.50$ kpc. This value is consistent with the kinematic distance derived by those authors from the $H\alpha$ velocity field as well as the previous photometrical and kinematical determinations by Russell et al. (2007). We assume the distance determined by Copetti et al. (2007) for this object.

**Sh 2-83.** There are not specific studies investigating the ionizing sources of this nebula. The only studies that give the distance of Sh 2-83 are those by Caplan et al. (2000) and Anderson et al. (2015) based on kinematic data of the nebular gas, and both give the same heliocentric distance of 18.4 kpc, the largest value of the whole sample. If the object is at such large distance, its parallax would be too small to be well measured in Gaia DR2. Therefore, it is not surprising that we do not find stars at so large distances in our analysis for stars located within 1 arcmin around the center of the H\textsc{ii} region. We adopted the distance obtained by Caplan et al. (2000) and Anderson et al. (2015), that was the one assumed by Esteban et al. (2017) for this object.

**Sh 2-209.** Chini & Wink (1984) identified 3 ionizing stars for this nebula, indicating their position in a photograph. We have searched for those stars in the Gaia DR2 database obtaining $R_G$ about 10.5 kpc for all of them. These values are very much lower than the 17.00 $\pm$ 0.70 kpc adopted by Esteban et al. (2017) based on several different but consistent kinematical and spectrophotometrical determinations. This is a serious drawback. The rather low O/H ratio of Sh 2-209 is more consistent with the larger value of the distance considering the predictions of the latest determinations of the Galactic O/H gradient (e.g. Esteban et al. 2017, see their Figure 11) for $R_G \sim 10.5$ kpc. Conversely, if we accept that the object is at $R_G = 17$ kpc, it would imply a heliocentric distance of about 9 kpc, but we do not find stars located at such large distances within 3 arcmin around the centre of the H\textsc{ii} region in Gaia DR2. Such a high heliocentric distance may imply a parallax too small to be measured in Gaia DR2 and this may be the explanation of not finding suitable distant stars in the catalogue. We finally adopt the distance of 17.00 $\pm$ 0.70 kpc given by Esteban et al. (2017) for this object.

**Sh 2-311.** This H\textsc{ii} region is ionized by a single star: HD 64315, but it is a multiple stellar system (Lorenzo et al. 2017) and its Gaia parallax is negative. We obtained and represented the parallaxes and proper motions of all stars located within 5 arcmin around HD 64315 (1810 stars) finding 3 defined peaks in the distribution. We calculated the distance corresponding to the center of each peak and the uncertainty corresponding to 1σ. We assumed the distance of 11.22 $\pm$ 0.22 kpc corresponding to the peak of the most distant distribution of stars, which is very similar to that of 11.1 $\pm$ 0.4 kpc assumed by Esteban et al. (2017). We assume the value determined from the Gaia data for this object.

The rest of the sample objects are located at heliocentric distances about or larger than 5 kpc and their Gaia DR2 parallaxes give rather uncertain distances. We have finally assumed the distance adopted by Esteban et al. (2017) or Esteban & García-Rojas (2018) for all these nebulae. As it has been said before, this distance corresponds to the mean of several independent photometrical and kinematical determinations (obtained mainly from Caplan et al. 2000; Russell 2003; Russell et al. 2007; Quireza et al. 2006; Balser et al. 2011; Foster & Brunt 2015) that provide a standard deviation lower than the distance uncertainty obtained from the Gaia parallaxes.

**NGC 3603.** This distant object has been cited as a Galactic giant H\textsc{ii} region and compared with 30 Doradus in the Large Magellanic Cloud. Drew et al. (2019) compiled a list of almost 300 candidate O stars of the associated cluster and estimate an heliocentric distance of 7.0 $\pm$ 1.0 kpc from the Gaia DR2 data, that implies a $R_G = 8.6 \pm 1.0$ kpc, in complete agreement with the distance of 8.6 $\pm$ 0.4 kpc adopted by Esteban et al. (2017).

**Sh 2-100.** Samal et al. (2010) found that Sh 2-100 is in a molecular complex containing 7 H\textsc{ii} regions. Those authors identify several ionizing stars inside the complex. We have obtained their Gaia parallaxes that give a very large heliocentric distance of 9.5$^{+2.4}_{-1.7}$ kpc for the object, corresponding to $R_G = 10.2^{+2.4}_{-1.7}$ kpc, which is consistent with the value adopted by Esteban et al. (2017) but much more uncertain.

**Sh 2-127.** Rudolph et al. (1996) conclude that this H\textsc{ii} region is ionized by two O-type stars. Only one of them is visible in the optical, that seems to be associated to the Gaia DR2 source 217611164377605888. The parallax of this source is very uncertain and gives a very large heliocentric distance of 9.5$^{+2.4}_{-1.7}$ kpc, that corresponds to $R_G = 13.2^{+2.1}_{-1.6}$ kpc. This value is consistent with the distance of 14.2 $\pm$ 1.0 kpc quoted by Esteban et al. (2017) within the errors.
3 RESULTS

Although the set of source papers present calculations of physical conditions – electron temperature, $T_e$, and density, $n_e$ – and ionic and total abundances of several elements – including helium in some cases – for the nebulae, we decided to re-calculate all the relevant quantities in order to have a homogeneous set of values using the same methodology and updated atomic data.

3.1 Physical Conditions

The values of $n_e$ and $T_e$ used for the calculation of the ionic abundances of the H II regions have been taken from Arellano-Córdova et al. (2020). In the case of the ring nebulae – G2.4+1.4, NGC 6888, NGC 7635, RCW52, RCW58, Sh 2-298 and Sh 2-308 –, we re-calculate their $n_e$ and $T_e$ using the same methodology and atomic data as for the rest of the objects. Following Arellano-Córdova et al. (2020), we use the version 1.0.26 of PYNES (Luridiana et al. 2015) in combination with the atomic data for collisionally excited lines listed in Table 2 and the reddening corrected line-intensity ratios published in the source papers. The $n_e$ was calculated using the ratio [S II] 6717/6731 or its average with [O II] $\lambda\lambda$3729/3727 when both density diagnostcs were available. We obtain low densities for most of the objects, and assumed the value $n_e = 100$ cm$^{-3}$ (Osterbrock & Ferland 2006) to determine $T_e$ and ionic abundances when $n_e < 100$ cm$^{-3}$. We used a two-zone scheme characterized by $T_e([N II])$ and $T_e([O III])$ derived from the line intensity ratios [N II] $\lambda\lambda$6548+6584/\lambda5755 and [O III] $\lambda\lambda$4959+5007/\lambda4363, respectively. Although the intensity of the [N II] $\lambda$5755 auroral line may have some small contribution due to recombination, we have not considered such effect in our calculations. We have estimated the contribution due to recombination using the formulae given by Liu et al. (2000) finding that it is almost negligible and always smaller than the uncertainties. We have used the temperature relation proposed by Esteban et al. (2009, their equation 3) – calibrated with normal and giant H II regions – to estimate $T_e([N II])$ or $T_e([O III])$ in those objects where one of these temperature indicators was not available. We have used Monte Carlo calculations to estimate the uncertainties associated to each value of $n_e$ and $T_e$. We generated 500 random values for each diagnostic line ratio assuming a Gaussian distribution with a standard deviation equal to the associated uncertainty of the line intensities involved in the diagnostic. With these distributions, we calculated new simulated values of $n_e$ and $T_e$. Their associated errors correspond to a deviation of 68 percent – equivalent to one standard deviation – centred in the mode of the distribution. The final results for $n_e$, $T_e([N II])$ and $T_e([O III])$ and their associated uncertainties are included in Table 3.

3.2 He$^+$ abundances

All the spectra of our sample show several He I recombination lines. Although the set of source papers present calculations of the He$^+$/H$^+$ and He/H ratios of some of the nebulae, we have re-calcualted them using the physical conditions indicated in Section 3.1. For each object, we use all or several of the following list of He I lines: $\lambda\lambda$3614, 3689, 3965, 4026, 4121, 4338, 4438, 4447, 4473, 4992, 5016, 5048, 5076, 5096, 47281 and 4946. The He$^+$ abundance has been determined using PYNES, the aforementioned line intensity ratios taken from the set of source papers, the values of $n_e$ and $T_e([O III])$ given in Table 3 and the effective recombination coefficient computations by Porter et al. (2012,
Table 1. Sample of objects which spectroscopical data are used in this paper.

| Object       | Type* | $R_0$ (kpc) | Telescope | Instrument | Reference                      |
|--------------|-------|-------------|-----------|------------|--------------------------------|
| G2.4+1.4     | WR-RN | 5.53$^{+0.32}_{-0.29}$ | GTC       | OSIRIS     | Esteban et al. (2016)          |
| M8           | H ii   | 7.04 ± 0.20 | VLT       | UVES       | García-Rojas et al. (2007)     |
| M16          | H ii   | 6.58 ± 0.25 | VLT       | UVES       | García-Rojas et al. (2006)     |
| M17          | H ii   | 6.46 ± 0.26 | VLT       | UVES       | García-Rojas et al. (2007)     |
| M20          | H ii   | 6.64 ± 0.31 | VLT       | UVES       | García-Rojas et al. (2006)     |
| M42          | H ii   | 8.54 ± 0.11 | VLT       | UVES       | Esteban et al. (2004)          |
| NGC 2579     | H ii   | 12.40±0.50 | VLT       | UVES       | Esteban et al. (2013)          |
| NGC 3576     | H ii   | 7.64 ± 0.30 | VLT       | UVES       | García-Rojas et al. (2004)     |
| NGC 3603     | H ii   | 8.60 ± 0.40 | VLT       | UVES       | García-Rojas et al. (2006)     |
| NGC 6888     | WR-RN | 7.94 ± 0.18 | GTC       | OSIRIS     | Esteban et al. (2016)          |
| NGC 7635     | O-RN   | 9.43$^{+0.21}_{-0.18}$ | GTC       | OSIRIS     | Esteban et al. (2016)          |
| RCW 52       | O-RN   | 7.83$^{+0.20}_{-0.18}$ | MTC       | MagE       | Esteban et al. (2016)          |
| RCW 58       | WR-RN | 7.63$^{+0.30}_{-0.28}$ | MTC       | MagE       | Esteban et al. (2016)          |
| Sh 2-83      | H ii   | 15.30±0.16 | GTC       | OSIRIS     | Esteban et al. (2017)          |
| Sh 2-100     | H ii   | 9.40±0.30  | GTC       | OSIRIS     | Esteban et al. (2017)          |
| Sh 2-127     | H ii   | 14.2±1.0   | GTC       | OSIRIS     | Esteban et al. (2017)          |
| Sh 2-128     | H ii   | 12.50±0.40 | GTC       | OSIRIS     | Esteban et al. (2017)          |
| Sh 2-152     | H ii   | 10.3±1.0   | GTC       | OSIRIS     | Esteban & García-Rojas (2018)  |
| Sh 2-209     | H ii   | 17.0±0.70  | GTC       | OSIRIS     | Esteban et al. (2017)          |
| Sh 2-212     | H ii   | 14.6±1.4   | GTC       | OSIRIS     | Esteban et al. (2017)          |
| Sh 2-288     | H ii   | 14.10±0.40 | GTC       | OSIRIS     | Esteban et al. (2017)          |
| Sh 2-298     | WR-RN | 11.56$^{+0.87}_{-0.89}$ | VLT       | UVES       | Esteban et al. (2017)          |
| Sh 2-308     | WR-RN | 9.67$^{+0.48}_{-0.47}$ | MTC       | MagE       | Esteban et al. (2016)          |
| Sh 2-311     | H ii   | 11.22 ± 0.22 | VLT       | UVES       | García-Rojas et al. (2005)     |

* H ii: H ii region; WR-RN: Wolf-Rayet ring nebula; O-RN: ring nebula around O-type star.

b Distance determined from Gaia DR2 parallaxes (see text for details).

* Distance taken from Esteban et al. (2017) or Esteban & García-Rojas (2018).

Table 2. Atomic dataset used for collisionally excited lines of selected heavy-element ions.

| Ion           | Transition probabilities and energy levels | Collision strengths |
|---------------|--------------------------------------------|---------------------|
| N+            | Froese Fischer & Tachiev (2004)             | Tayal (2011)        |
| O+            | Froese Fischer & Tachiev (2004)             | Kisielius et al. (2009) |
| O2+           | Wiese et al. (1996); Storey & Zeippen (2000) | Storey et al. (2014) |
| S+            | Podobedova et al. (2009)                    | Tayal & Zatsarinmy (2010) |
| S2+           | Podobedova et al. (2009)                    | Grieve et al. (2014) |

2013) for He i lines and Storey & Hummer (1995) for H i lines. The calculations by Porter et al. (2012) include collisional effects in the level populations of He i. A Monte Carlo simulation similar to the one described in Section 3.1 – including random distributions of $n_e$, $T_e$ and the line intensities – was applied to estimate the uncertainty of the He i/H i ratios derived for each individual line of each spectrum. The He i/H i ratios obtained for each of the He i lines of the spectra of the sample objects are shown in Table A1. Lines with intensity uncertainties greater than 40% and those affected by blending with telluric lines or other spectral features were not considered for abundance determinations. Moreover, the He i/H i ratios calculated from the bright He i 43889 and 47065 lines are not included in Table A1. Both lines are the most affected, with great difference, by optical depth effects of the 2 $^3P$ level on the predicted recombination spectrum of He i (Benjamin et al. 2002), that only affect noticeably to triplet lines. Moreover, He i 43888.64 is blended with the also bright H i 43889.05 line even in our highest spectral resolution spectra.

We have calculated the weighted mean of the individual He i/H i ratios of each spectrum. The weight of each line has been taken as the inverse of the square of the error associated with its He i/H i value. For a given spectrum, we have calculated means taking all possible combinations of the individual lines without repetition, leaving at least 3 lines to average (for those spectra with more than 3 He i lines). Once this is done, of all the means, we consider those within the 5th percentile of uncertainty and, from this subset, we finally select the mean for which more He i lines have been used for its calculation. This method excludes the most discrepant individual lines but maintain the largest possible number of them giving consistent values. The finally adopted mean He i/H i ratio of each spectrum is also included in Table A1. The uncertainty associated to that mean corresponds to the weighted standard deviation. In Table A2, we give the list
of individual He I lines used to derive the average value of the He\(^+\)/H\(^+\) ratio adopted for each spectrum.

The usual methodology for calculating chemical abundances in H II regions is to consider a zone of high and low ionization and adopt a representative \(T_e\) for each zone. However, this may be inappropriate for several ions, because they can emit radiation in an intermediate zone or in both ionization zones. This is the case of He\(^+\), since it can emit in the high and low ionization zone. To calculate He\(^+\) optimally, the characteristic temperature of the ion – \(T_e\) (He I) in this case – should be used or the precise geometry of the different ionization zones of each nebula should be known. However, the difference of He\(^+\)/H\(^+\) considering \(T_e\) (He I) and \(T_e\) (O III)](\(7.99 \pm 0.13\)) \(7.67 \pm 0.12\) \(7.91 \pm 0.17\) \(5.16 \pm 0.18\) \(5.94 \pm 0.23\) \(7.99 \pm 0.13\) \(7.67 \pm 0.12\) \(7.91 \pm 0.17\) \(5.16 \pm 0.18\) \(5.94 \pm 0.23\) 

\(\text{NGC 3576}\) & 1490 \pm 280 & 8440 \pm 60 & 8760 \pm 200 & 8.04 \pm 0.07 & 8.37 \pm 0.02 & 5.79 \pm 0.05 & 6.88 \pm 0.04 & 
\(\text{NGC 3603}\) & 2760 \pm 910 & 9020 \pm 140 & 11190 \pm 550 & 7.35 \pm 0.13 & 8.44 \pm 0.04 & 5.07 \pm 0.10 & 6.88 \pm 0.04 & 
\(\text{NGC 6888}\) & 100 \pm 100 & 19040 \pm 1130 & 7700 \pm 700 & 5.81 \pm 0.28 & 7.64 \pm 0.05 & 6.26 \pm 0.11 & - & 
\(\text{RCW 52}\) & 230 \pm 40 & 5910 \pm 620\(^b\) & 7190 \pm 430 & 8.87 \pm 0.23 & 8.12 \pm 0.17 & 6.64 \pm 0.14 & 7.36 \pm 0.20 & 
\(\text{RCW 58}\) & 100 \pm 100 & 4770 \pm 250\(^b\) & 6390 \pm 180 & 8.36 \pm 0.11 & 8.23 \pm 0.23 & 6.28 \pm 0.06 & 7.49 \pm 0.14 & 8.43 \pm 0.05 

\(\text{Sh 2-83} & 300 \pm 90 & 10370 \pm 3770 & 11960 \pm 640 & 7.15 \pm 0.12 & 8.25 \pm 0.07 & 5.20 \pm 0.07 & 6.51 \pm 0.10 & 
\(\text{Sh 2-100} & 420 \pm 240 & 8250 \pm 150 & 8610 \pm 250 & 7.73 \pm 0.10 & 8.41 \pm 0.04 & 5.53 \pm 0.07 & 6.96 \pm 0.06 & 
\(\text{Sh 2-127} & 600 \pm 100 & 9660 \pm 2200\(^b\) & 9810 \pm 150 & 8.20 \pm 0.05 & 7.88 \pm 0.21 & 5.91 \pm 0.03 & 6.72 \pm 0.07 & 
\(\text{Sh 2-128} & 480 \pm 100 & 9970 \pm 340 & 10550 \pm 240 & 7.84 \pm 0.06 & 7.98 \pm 0.07 & 5.62 \pm 0.04 & 6.56 \pm 0.09 & 
\(\text{Sh 2-152} & 750 \pm 80 & 7360 \pm 120 & 8200 \pm 70 & 8.46 \pm 0.03 & 7.70 \pm 0.05 & 6.15 \pm 0.02 & 7.18 \pm 0.06 & 
\(\text{Sh 2-209} & 300 \pm 290 & 10760 \pm 1140\(^b\) & 10580 \pm 860 & 7.67 \pm 0.31 & 7.88 \pm 0.21 & 5.51 \pm 0.11 & 6.29 \pm 0.29 & 
\(\text{Sh 2-212} & 100 \pm 100 & 11250 \pm 970 & 8350 \pm 770 & 8.16 \pm 0.31 & 7.81 \pm 0.17 & 5.16 \pm 0.18 & 5.94 \pm 0.23 & 
\(\text{Sh 2-288} & 410 \pm 270 & 9200 \pm 530 & 9430 \pm 340 & 8.20 \pm 0.11 & 7.75 \pm 0.15 & 5.93 \pm 0.07 & 6.67 \pm 0.19 & 
\(\text{Sh 2-298} & 100 \pm 100 & 11720 \pm 210 & 11650 \pm 490 & 8.15 \pm 0.10 & 8.10 \pm 0.04 & 6.48 \pm 0.06 & 6.50 \pm 0.03 & 7.32 \pm 0.04 
\(\text{Sh 2-308} & 100 \pm 100 & 16600 \pm 2470 & 14300 \pm 2910 & 6.92 \pm 0.42 & 7.84 \pm 0.24 & 5.32 \pm 0.26 & 6.53 \pm 0.16 & 7.08 \pm 0.18 
\(\text{Sh 2-311} & 290 \pm 80 & 8940 \pm 110 & 9270 \pm 180 & 8.28 \pm 0.06 & 7.83 \pm 0.03 & 6.21 \pm 0.04 & 6.70 \pm 0.03 & 

\(^a\) In units of 12 + \log(\text{X(H)/H}).
\(^b\) \(T_e\) (O I) estimated from \(T_e\) (N II) using equation 3 of Esteban et al. (2009).
\(^c\) \(T_e\) (O II) estimated from \(T_e\) (O III) using equation 3 of Esteban et al. (2009).
Helium abundances and gradient in Galactic nebulae

(2012). The code uses the effective recombination coefficients of Storey & Hummer (1995) for H İ, and Porter et al. (2007) for He İ, the collisional contribution of He İ lines calculated by Sawey & Berrington (1993) and the optical depth effects in the triplets estimated by Kingdon & Ferland (1995). He-lilo14 calculates the most likely values for $n_0$(He İ), $\tau(2S)$ and the He İ/H İ ratio from the theoretical He İ/H İ ratios using as input a set of parameters, atomic data, and up to 20 He İ/H İ line intensity ratios along with their uncertainties. Then, it compares the observed ratios to the theoretical ones minimising $\chi^2$:

$$\chi^2 = \sum_{i} \frac{[I(\lambda_i)_{\text{obs}} - I(\lambda_i)_{\text{theo}}]^2}{\sigma_I(\lambda_i)^2}.$$  

(1)

Where $\sigma_I(\lambda)$ is the uncertainty in the intensity of $\lambda$. The comparison of Figure 2 shows that all the objects are entirely consistent with the 1:1 relation. The nebulae with the largest deviations with respect to the 1:1 line are RCW 52, Sh 2-209 and Sh 2-308, although the values agree with such relation within the uncertainties. These three objects are among the ones with fewer He İ lines in their spectra: 4, 4 and 2, respectively, so the determination of the abundance of He İ is very sensitive to the variations of the fitted parameters in the minimisation of $\chi^2$. Helio14 determines the available parameter space within $\chi^2_{\text{min}} < \chi^2 < \chi^2_{\text{min}} + 1$ to estimate the 1σ error bars. In any case, from these 3 objects, just RWC 52 was taken into account in the determination of radial He İ gradients. The rest are ring nebula associated Wolf-Rayet stars and they present an overabundance of helium. This is discussed in greater detail in §5. The general deviation between the values of He İ/H İ ratios obtained with Helio14 and those obtained following the procedure described in this section is less than 0.008 dex even including the 3 objects showing the largest differences.

From all the spectra in our sample, we have deconvolved He İ $\lambda 3889.64$ from H İ $\lambda 3889.05$ by multiple Gaussian fitting in NGC 3576 and Sh 2-311. Among all the spectra, only Sh 2-152, NGC 3576, NGC 7635-A4, M16, M17, M20 and M42 have measurements of the intensity ratio of He İ $\lambda 3889.64$ or the blend of He İ $\lambda 3889.64$ and H İ $\lambda 3889.05$ with $\tau$ with uncertainties smaller than 3%. In these last cases, we study the possible effect of $\chi(3889)$ on the determination of the He İ/H İ ratios. A small uncertainty in the measurement of He İ $\lambda 3889.64$ is indispensable to avoid spreading uncontrolled errors in $\chi(3889)$ and consequently in the abundance of He İ/H İ.

In the nebulae where both lines cannot be deblended with multiple Gaussian fitting, the contribution of He İ $\lambda 3889.64$ to the total intensity was obtained after subtracting its theoretical ratio to H İ $\lambda 3889.05$ based on the work by Brocklehurst (1971). In Figure 3 we compare the values of the He İ/H İ ratios for Sh 2-152, NGC 3576, NGC 7635-A4, M16, M17, M20 and M42 using Helio14 with the same input parameters as in Figure 2 but taking into account $\chi(3889)$ and the results we obtain with our methodology. The general dispersion is smaller than 0.007 dex. From this comparison, we can conclude that our results can be considered virtually independent of the effects of $\tau(2S)$. In fact, this is minimised by averaging He İ/H İ ratios from a large number of emission lines, including several singlets, which intensities are practically independent of $\tau(2S)$.

Among the brightest He İ lines, 44922, $\lambda 5876$ and $\lambda 6678$ have been considered for calculating the weighted mean in more that 84% of the spectra in which they have been measured (most or all of them). Other well-behaved less intense He İ lines are $\lambda 43614$, $\lambda 43965$, $\lambda 44026$, $\lambda 44388$ and $\lambda 44438$, that have been taken for calculating the mean in more than 70% of the spectra in which they have been measured. Most of these lines (6) corresponds to singlets, and only 2 to triplets ($\lambda 4026$ and $\lambda 5876$). The He İ lines that have a greater tendency to provide less consistent values with respect to the average He İ/H İ ratio are: $\lambda 44121$, $\lambda 44713$, $\lambda 45048$, $\lambda 47281$ and $\lambda 49464$, that have been used in less than 50% of the objects in which they have been measured. Of these, 2 are singlets and 3 triplets. In the case of the 2 lines of redder wavelength, $\lambda 47281$ and $\lambda 49464$, their line intensity may be affected by contamination with telluric emission or absorption features. In fact, when these lines are observed with high-resolution echelle spectroscopy, the He İ abundances obtained from them are similar to those obtained from other more intense lines and they are considered to compute the average value of the He İ/H İ ratio. The He İ $\lambda 5007$ line is relatively bright but has not been considered in many spectra because it is blended with the [O III] $\lambda 5007$ line in the OSIRIS spectra and affected by a ghost emission feature in

Figure 2. General comparison of the average He İ/H İ ratios obtained for the sample objects using our methodology described in the text and using the Helio14 code (Peimbert et al. 2012). The continuous line indicates the 1:1 relation.

Figure 3. Comparison between He İ/H İ determinations after estimating the effects of optical depth ($\tau(3889)$) in 7 objects: Sh 2-152, NGC 3576, NGC 7635-A4, M16, M17, M20 and M42. The continuous line indicates the 1:1 relation.
the UVES ones. Another bright He I line is 4447 Å, but it is only used in 59% of the spectra. This is mainly because it provides He II/He I ratios lower than the mean in G2.4+1.4, NGC 6888 and NGC 7635, the objects with the largest number of spectra. The whole optical OSIRIS spectra of these objects were taken with two grisms, R1000B and R2500V. Since the He I 4447 Å line was the closest one to the blue edge of the spectra taken with in R2500V, some deviations at the border of the flux calibration curve may be affecting the flux measurement obtained by Esteban et al. (2016) for this line.

3.3 Total He abundances

The presence of He II inside the H II zone may be significant in low ionization nebulae. We need to assume an ICF(He) to determine the total helium abundance from the measured He II/He I ratio, in the form: He/He = ICF(He) \cdot He II/He I. However, the estimation of the ICF(He) is a controversial issue and there is no a consensus among the different authors. Traditional ICF(He) schemes involve abundance ratios of different heavy-element ions such as O+2, O+3, S+ and S+2. For the H II regions of our sample, we have used the values of O+2, O+3, S+ and S+2 abundances determined by Arellano-Córdova et al. (2020), who use PYNEB and the atomic data given in Table 2. In addition, we have re-calculated the N+ abundances of the WR ring nebulae using the same methodology, their N abundances will be discussed in §5. The line intensities used to derive the heavy-element ionic abundances have been - [O II] \lambda \lambda 3726, 3729, [O I] \lambda 4959, 5007, [S II] \lambda \lambda 6717, 6731, [S III] \lambda 6312 (we used also [S II] \lambda 6300, 6305 in several objects) and [N II] \lambda 6548, 6583. Their reddening-corrected values have been taken from the set of source papers. Arellano-Córdova et al. (2020) use T_e([N II]) as representative of the O+2, S+ and N+ emitting regions and T_e([O III]) as representative of the O+3 zone. Following the recommendation of Dominguez-Guzmán et al. (2019), Arellano-Córdova et al. (2020) adopt the mean value of T_e([N II]) and T_e([O III]) to calculate the S+3 abundance. In the sake of homogeneity and as we did for determining the physical conditions, we used the same methodology and atomic data as Arellano-Córdova et al. (2020) for deriving the O+2, O+3, S+ and S+2 or N+ abundances for the ring nebulae. The heavy-element ionic abundances determined for each spectrum and object are included in Table 3.

Photoionization models (e.g. Stasińska & Schaerer 1997) predict that helium is completely ionized inside the H II zone when the exciting star is hotter than about 39 000K (earlier than O6.5V), independently of the ionization parameter. Most of the ionizing stars of our sample are ionized by stars that should be colder, so one would expect a certain amount of He I in most of our nebulae. On the other hand, observations in different directions inside H II regions carried out by Deharveng et al. (2000) show that even an H II region excited by a star of spectral type earlier than O6.5 can contain a significant amount of He I. We have used different ICF(He) schemes because, as we have said before, there is not a standard method to correct for the fraction of He I, although all schemes consider that the higher the ionization degree the higher the He II/He ratio of the nebulae. ICF(He) schemes usually consider the similarity between the ionization potential of He I (23.33 eV) and/or O I (34.97 eV) assuming that the relation O I/O > He II/He > S I/S should be applicable but using different parameters proportional to the ionization degree of the nebula. One of the first ICF(He) schemes was proposed by Peimbert & Torres-Peimbert (1977) in their work on the chemical composition of the Orion Nebula that uses a linear combination of O I/O and S I/S ratios,

\[
\text{ICF(He)}_{\text{PTP77}} = \left[ 1 - \gamma \cdot \frac{O^+}{O} - (1 - \gamma) \cdot \frac{S^+}{S} \right]^{-1}.
\]

The value of \( \gamma \) depends on the density distribution (Peimbert et al. 1974). It can be determined when spectra at different positions covering different ionization conditions are available for the nebula, but this is not the case for most of our sample objects. The only objects with several slit positions are all ring nebulae and bubbles, that are better represented by relatively thin ionized shells rather than typical Strömgren spheres and, therefore, that method for estimating the parameter \( \gamma \) may not be appropriate.

Peimbert & Torres-Peimbert (1977) estimated \( \gamma = 0.35 \) in the case of the Orion Nebula and Peimbert et al. (1978) found \( \gamma = 0.20 \) for \( \eta \) Carina nebula. Those last authors assume the same value of 0.20 for other H II regions with \( n_e \) values similar to that of \( \eta \) Carina nebula (300-1000 cm \(^{-3} \)). Lequeux et al. (1979) use equation 2 for determining the He abundance for a sample of metal-poor H II galaxies with \( n_e \) in the 10-100 cm \(^{-3} \) range using \( \gamma = 0.15 \). In our case, following the prescriptions given in the cited works, we have used equation 2 using values of \( \gamma \) interpolating between 0.15 to 0.35 as a function of the \( n_e \) of the nebula.

Other ICF(He) schemes only use O I/O or S I/S ratios as indicators of the ionization degree of the nebulae. Kunth & Sargent (1983), in their study of a sample of metal-poor galaxies, proposed an ICF(He) dependent on the O I/O ratio deduced from Peimbert et al. (1974) empirical models,

\[
\text{ICF(He)}_{\text{KS83}} = \left[ 1 - 0.25 \cdot \frac{O^+}{O} \right]^{-1}.
\]

Peimbert et al. (1992) presented a detailed spectroscopical study of the highly-ionized Galactic H II region M17 and propose an ICF(He) parameterized only by the S+2/S ionization fraction. Zhang & Liu (2003) use a very similar scheme in their study of the relatively low excitation planetary nebula M 2-24 but depending on the S+2/S ratio, which – in contrast to S+2/S – is a parameter that can be obtained directly from optical spectra:

\[
\text{ICF(He)}_{\text{ZL03}} = 1 + \frac{S^+}{S^+}.
\]

Delgado-Inglada et al. (2014) do not recommend the use of traditional ICF(He) schemes – as those given in equations 3 and 4 – because the He I/He II ratio is more dependent on the effective temperature of the ionizing source, whereas heavy-element abundance ratios depend essentially on the ionization parameter. Vilchez (1989) proposed an ICF(He) scheme based on the radiation softness parameter defined as \( \eta = (O^+ / S^+) \cdot (S^+ / O^2+) \) (Vilchez & Pagel 1988), which is sensitive to the effective temperature of the ionizing source and a good indicator of the ionization structure of the nebula. Vilchez (1989) and Pagel et al. (1992) pointed out that for log(\( \eta \)) < 0.9 the amount of He I inside the H II zone is negligible for a large variety of models, but becomes very

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model dependent for \( \log(\eta) > 1 \). Izotov et al. (1994) and Bresolin et al. (2009) have obtained approximate analytical expressions of ICF(He) as a function of \( \eta \) parameter based on photoionization models. In our case, we have used the relation given by Bresolin et al. (2009) in their study of H\textsc{ii} regions in the spiral galaxy NGC 300 and based on the predictions of photoionization models by Stasińska et al. (2001).

\[ \text{ICF(He)}_{\text{B09}} = 1.585 + \log(\eta) \cdot \left[ 1.642 - \log(\eta) - 1.948 \right]. \]

In the case of the ring nebulae for which we have spectra at several slit positions and, therefore, several independent determinations of the He abundance, we have selected the representative He/H ratio of the nebula as a whole attending to different considerations in each object. In the case of G2.4+1.4, we only considered the spectra of zone A2, which has the highest signal-to-noise ratio and was observed with higher spectral resolution (MagE echelle spectrograph). In the case of NGC 6888, we take the weighted mean value of zones A3, A4, A5 and A6, which are located in the main body of the ionized nebula. Zones A1 and A2 correspond to high-ionization narrow peripheral arcs showing very high values of \( T_e \) and may be contaminated by shock excitation (see Esteban et al. 2016). For NGC 7635 we have taken the weighted mean value of zones A2, A3, A5 and A6, which correspond to the relatively highly-ionized gas of the expanding bubble. Zone A1 of NGC 7635 corresponds to one of the brightest knots of Sh 2-162, a large H\textsc{ii} region that encompasses the ring nebula NGC 7635. Sh 2-162 is ionized by the same O-type star but shows a lower ionization degree. Zone A4 covers the brightest of a group of several high-density cometary knots just at the southwest of the ionizing star that show rather higher densities and quite lower ionization degrees.

The WR ring nebulae G2.4+1.4 and NGC 6888 show He\textsc{ii} lines in their spectra (Esteban et al. 2016). G2.4+1.4 is a high ionization degree object ionized by a very hot WO2 star and the He\textsc{ii} \( \lambda 4686 \) line is very bright. We have determined the He\textsuperscript{2+} abundance using \( \lambda \)4959, \( \lambda \)\textsc{O}3(H\textsc{i}) and the effective recombination coefficient calculated by Storey & Hummer (1995), obtaining \( 12 + \log(\text{He}\textsuperscript{2+}/\text{H}^+) = 10.45 \pm 0.02 \) for the zone A2 of G2.4+1.4. In the case on NGC 6888 the He\textsuperscript{2+} abundances we determine for the different zones is very much lower, with values ranging from 8.14 to 8.51, which are clearly negligible in comparison to the He\textsuperscript{+}/H\textsuperscript{+} ratio determined in this object. We did not use an ICF(He) for G2.4+1.4 and NGC 6888 and their total He abundance was simply He\textsuperscript{+}/H\textsuperscript{+} + He\textsuperscript{2+}/H\textsuperscript{+}.

In Table 4 we show the He/H ratios obtained for each nebulae using the different ICF(He) schemes considered. In the case of the ICF(He)\texttextsuperscript{peimbert}, there is an explicit dependence of the S/H ratio, which has been derived from the sum of the S\textsuperscript{+} and S\textsuperscript{2+} abundances given in Table 3 and an appropriate ICF(S) using the relations:

\[ \frac{S}{H} = \text{ICF(S)} \cdot \left[ \frac{S^+}{H^+} + \frac{S^{2+}}{H^+} \right], \]

where

\[ \text{ICF(S)} = \left[ 1 - \left( \frac{1 - O^+}{O} \right)^{3.1/3} \right]. \]
which was proposed by Stasińska (1978). The uncertainty of the total He abundance has been determined propagating the errors of the He\(^+\)/H\(^+\) ratio and that of the ICF(He) and ICF(S) – used, which comes from the derivation of each equation of the ICF and the quoted errors of the ionic abundances given in Table 3.

4 THE GALACTIC RADIAL ABUNDANCE GRADIENT OF HELIUM

In Fig. 4 we show the radial distribution of the He abundances of the H\(\text{II}\) regions of our sample – a total of 19 objects – using the different ICF(He) schemes introduced in equations 2 to 5. We have also included the ring nebulae around O-type objects in this group because they do not contain chemically enriched material from the central star (see Esteban et al. 2016). In these diagrams we have separated the nebulae in two groups, those with log(\(\eta\)) < 0.9 – which are expected to contain a small fraction of He\(^0\) represented with full black squares and the rest of them (grey empty squares). This separation is made in order to explore the radial distribution of the He abundances minimizing the effect of the ICF(He) and maintaining a reasonable number of objects distributed along a significant part of the Galactic disc. The least-squares linear fit to the objects with log(\(\eta\)) < 0.9 (solid lines) and to all the objects included in each panel (dotted lines) are also included in each panel of Fig. 4. The parameters of the fits along with their associated uncertainties are shown in Table 5. The uncertainties of the slope and intercept of the linear fits are computed through Monte Carlo simulations. We generate 10,000 random values of \(R_G\) and the He/H ratios for each observational point assuming a Gaussian distribution with a sigma equal to the uncertainty of each quantity. We performed a least-squares linear fit to each of these random distributions. It is important to remark that the uncertainty of \(R_G\) has been considered in the fittings, which is not usually taken into account in most works except, for example, in Esteban et al. (2017) or Esteban & García-Rojas (2018). The uncertainties associated to the slope and intercept correspond to the standard deviation of the values of these two quantities obtained from the fits. From the radial gradients represented in Fig. 4 and their parameters collected in Table 5, we can see that although the uncertainties of the slopes are larger than the slope values in most cases, they show pretty similar values in all cases, especially when only the objects with log(\(\eta\)) < 0.9 are considered. More importantly, the gradients are always negative independently on the ICF(He) scheme used.

In Fig. 5 we show the radial distribution and the least-squares linear fit of the He abundances of the H\(\text{II}\) regions with log(\(\eta\)) < 0.9 assuming no ICF(He), i.e. He/H = He\(^+\)/H\(^+\). Each data point is represented with a colour proportional to its log(\(\eta\)), and the diagram indicates that the value of the \(\eta\) parameter does not seem to determine the behaviour of the gradient. In fact, the objects with the lowest values of log(\(\eta\)) (i.e. those with the lowest expected fraction of He\(^0\)) are precisely those located at larger \(R_G\) showing lower He\(^+\)/H\(^+\) ratios. In Fig. 6, we can compare the least-squares linear fits of the He abundances obtained for the H\(\text{II}\) regions with log(\(\eta\)) < 0.9 assuming different ICF(He) schemes or no ICF(He). In the figure we can see that the slopes are rather similar in all cases, going from −0.0078 to −0.0044 dex kpc\(^{-1}\), with a dispersion of values smaller than the typical uncertainty of each individual determination of the slope. The differences are larger when we compare the values of the He/H given by each fit for a given \(R_G\). The no-ICF(He) case gives the lowest values of the He/H ratio – as expected – and the ICF(He) by Peimbert & Torres-Peimbert (1977) gives the largest ones. It is interesting to note that the other ICF(He) schemes give He/H values that differ less than 0.02 dex. It is remarkable that the ICF scheme from Bresolin et al. (2009) is the most sensitive to the propagation of the errors. Its use requires very precise determinations of O\(^+\), S\(^+\), O\(^2\)\(^+\) and S\(^2\)\(^+\).

The presence of abundance gradients of heavy elements – such as O, N, Ne, S, Ar or Cl – along the disc of the galaxy is a well established fact from the observational point of view (e.g. Shaver et al. 1983; Deharveng et al. 2000; Rudolph et al. 2006; Balser et al. 2011; Esteban & García-Rojas 2018). However, although theoretical models predict its existence, this has not been the case for He. Very recent cosmological chemodynamical simulations for galaxy formation and evolution predict negative radial gradients of He/H due to the inside-out growth of galaxy discs as a function of time (Vincenzo et al. 2019). Previous chemical evolution models of the Milky Way disc by Matteucci & Chiappini (1999) and Chiappini et al. (2002) predicted He/H gradients with slopes between −0.0085 and −0.002 dex kpc\(^{-1}\) in the \(R_G\) range from 4 to 18 kpc. Kubryk et al. (2015) obtain a similar range of values (from about −0.007 to −0.003 dex kpc\(^{-1}\)) from models including radial motions of gas and stars in the Milky Way disc and different sets of stellar yields. These values are pretty consistent with our results given in Table 5. From the observational point of view, the evidence of a Galactic radial gradient of the He/H has been elusive. Peimbert et al. (1978) found a negative gradient of −0.02 ± 0.01 dex kpc\(^{-1}\) from the analysis of the abundance obtained from 3 He\(^i\) lines in a small sample of 5 Galactic H\(\text{II}\) regions. Talent & Dufour (1979) obtain a marginal evidence of a negative gradient, −0.008 ± 0.008 dex kpc\(^{-1}\) for a larger sample of objects based solely on the intensity of He\(^i\)\(\lambda 5876\) and \(\lambda 6678\) lines. Other works as Hawley (1978), Shaver et al. (1983), Deharveng et al. (2000) or Fernández-Martín et al. (2017) find a flat He abundance distribution along the Galactic disc from observations of a limited number of He\(^i\) lines in samples with different number of objects. In their work, Fernández-Martín et al. (2017) include some of the H\(\text{II}\) regions of our sample (Sh2-83, Sh2-212 and NGC 7635), whose data are based on other spectroscopic observations. The He\(^+\)/H\(^+\) ratios per line shown in their Table A.2. are consistent with our results, although there are slight differences attributable to the different recombination coefficients used. However, the methodology followed by Fernández-Martín et al. (2017) to adopt a final He\(^+\)/H\(^+\) value differs from ours, among other things, by the use of fewer He\(^i\) lines and the inclusion of He\(^i\)\(\lambda 47065\). Although their sample includes spectra of some Galactic H\(\text{II}\) regions not considered in the present paper, we decided not to include them for the sake of having a group of nebulae with a homogeneous data reduction process; furthermore, the \(R_G\) of those objects are well covered by the H\(\text{II}\) regions of our sample.

Other determinations of the radial He/H gradient in the Milky Way come from the analysis of the emission-line spec-
Early works such as those by Pasquali & Perinotto (1993) found slopes between $-0.03$ and $-0.02$ dex kpc$^{-1}$, while others reported negligible gradients (e.g. Pasquali & Perinotto 1993). At any rate, PNe are not confident probes of the abundances of the ISM because they are composed of stellar ejecta material and can be contaminated by the products of nucleosynthesis. Trying to alleviate this drawback, Maciel (2001) introduced corrections to the measured He abundance owing to the contamination from the progenitor star obtaining an essentially flat radial He/H gradient for a large sample of PNe.

5 ABUNDANCE DEVIATIONS IN WR RING NEBULAE

Ring nebulae are bubbles of gas swept-up by the mechanical action of the mass loss episodes experienced by their massive stellar progenitors. They are rather common around Wolf-Rayet (WR) stars and luminous blue variables (LBVs). There have been several spectroscopical works devoted to study the chemical composition of the ionized gas contained in ring nebulae around Galactic WR stars (e.g. Kwitter 1984; Esteban et al. 1992, 2016; Stock et al. 2011). Those works have found that some ring nebulae (NGC 6888, RCW 58, Sh 2-308 and M 1-67) show clear chemical enrichment patterns, in general they are He and N enriched and some of them show some O deficiency, indicating that they are composed by ejecta material that has suffered contamination by the CNO cycle. Esteban & Vilchez (1992) and Esteban et al. (1992) compared the abundance pattern of Galactic ejecta ring nebulae with the surface abundances predicted by evolutionary models of massive stars, finding that the He, N and O abundances of the nebulae are consistent with the expected surface composition of stars with initial masses between 25 and 40 M$_\odot$ at the red supergiant (RSG) phase, prior to the onset of the WR stage. Later studies by Mesa-Delgado et al. (2014) and Esteban et al. (2016) using stellar evolution models by Ekström et al. (2012) and Georgy et al. (2012) confirmed that non-rotational models of stars of initial masses between 25 and 40 M$_\odot$ seem to

Table 5. Radial He/H gradients using different combinations of H II regions and ICF schemes.

| ICF(He) | All H II regions | Only with log($\eta$) < 0.9 |
|---------|-----------------|---------------------------|
|         | Slope (dex kpc$^{-1}$) | Intercept | Slope (dex kpc$^{-1}$) | Intercept |
| PTP77   | $-0.0036 \pm 0.0069$ | 11.04 $\pm$ 0.07 | $-0.0046 \pm 0.0091$ | 11.04 $\pm$ 0.08 |
| ZL03    | $-0.0028 \pm 0.0043$ | 10.99 $\pm$ 0.04 | $-0.0044 \pm 0.0062$ | 11.02 $\pm$ 0.06 |
| KS83    | $-0.0025 \pm 0.0049$ | 10.99 $\pm$ 0.05 | $-0.0067 \pm 0.0060$ | 11.04 $\pm$ 0.06 |
| B09     | $-0.006 \pm 0.015$ | 11.09 $\pm$ 0.07 | $-0.0051 \pm 0.0077$ | 11.09 $\pm$ 0.15 |
| No ICF(He) | -- | -- | $-0.0078 \pm 0.0029$ | 11.03 $\pm$ 0.03 |

Figure 4. Radial distribution of the He abundances of the H II regions of our sample using different ICF(He) schemes. Upper left: using the ICF(He) proposed by Peimbert & Torres-Peimbert (1977, PTP77); upper right: ICF(He) by Zhang & Liu (2003, ZL03); lower left: ICF(He) by Kunth & Sargent (1983, KS83); lower right: ICF(He) by Bresolin et al. (2009, B09). Black full squares indicate H II regions with log($\eta$) < 0.9 and grey empty squares indicate H II regions with log($\eta$) ≥ 0.9. Solid lines represent the least-squares linear fits only to the objects with log($\eta$) < 0.9 and dot lines represent the linear least-squares fits to all the objects included in each panel.
These results confirm that and the classical. In Table (2015) Zhang & Liu we can see that G2.4 (17.5)12.5 (Bresolin et al. Kunth & Sargent 10.0 (Delgado-Inglada et al. Figure 5. Radial distribution of the He abundances of the H\textsc{ii} regions with log(\eta) < 0.9 assuming no ICF(He) (i.e. He/H = He\(^+\)/H\(^+\)). The colour of the squares indicates the value of log(\eta) of each object. The solid lines represent the least-squares linear fits to the data. Figure 6. Comparison of the least-squares linear fits of the He abundances obtained for the H\textsc{ii} regions with log(\eta) < 0.9 assuming different ICF(He) schemes or no ICF(He). Solid line: no ICF(He); dash line: ICF(He) by Peimbert & Torres-Peimbert (1977, PTP77); dot line: ICF(He) by Zhang & Liu (2003, ZL03); dash dot line: ICF(He) by Kunth & Sargent (1983, KS83); long-dash dash line: ICF(He) by Bresolin et al. (2009, B09).

reproduce the abundance patterns in most of the ejecta nebulae, being this range wider in the case of Sh 2-308, from 25 to 50 M\(_\odot\). Only rotational models of 25 M\(_\odot\) show agreement with the data for NGC 6888, RCW 58 and Sh 2-308.

The availability of new Gaia distances, the results of this paper and the recent reassessment of the Galactic radial gradients of O/H and N/H by Esteban & García-Rojas (2018), allow us to perform a better estimate of the chemical enrichment pattern in He, N and O of the WR ring nebulae observed by our group (Esteban et al. 2016). In Table 6 we give the total He/H, O/H and N/H ratios and the difference with the values expected from the radial abundance gradients for the sample of WR ring nebulae included in Table 1. The He abundances of each object have been taken from Table 4. In the case of RCW 58, Sh 2-298 and Sh 2-308, we have considered the mean and standard deviation of the 4 values obtained using the different ICF(He) schemes. The O abundances have been calculated simply adding the O\(^+\)/H\(^+\) and O\(^{2+}\)/H\(^+\) ratios given in Table 3, except in the case of G2.4+1.4, the only object where we find a substantial amount of He\(^{2+}\)/H\(^+\). In this case, we have considered the ICF(O) proposed by Delgado-Inglada et al. (2014) for determining the O/H ratio. The N/H ratio has been calculated using the N\(^+\) abundance given in Table 3 and the classical ICF(N) by Peimbert & Costero (1969), that assumes N/O = N\(^+\)/O\(^+\).

In Table 6 we can see that G2.4+1.4 and Sh 2-298 do not show He/H, O/H and N/H ratios significantly larger than the expected values from the radial gradients considering the abundance uncertainties. NGC 6888, RCW 58 and Sh 2-308 show clear overabundances of He/H and N/H, although the errors in the last nebula are rather large due to its highly uncertain O\(^+\)/H\(^+\) ratio. The overabundance of He/H is very similar in the three objects, of about +0.24 ± 0.11 dex. Only NGC 6888 and Sh 2-308 show some possible oxygen deficiency, a result that would indicate that ON-cycle of the CNO burning has been more effective than CN-cycle in the interior of the massive progenitors stars of the nebulae (Esteban et al. 2016). These results confirm that only NGC 6888, RCW 58 and Sh 2-308 should be considered ejecta nebulae.

6 CONCLUSIONS

We determine the radial abundance gradient of helium of the Milky Way from published spectra of H\textsc{ii} regions. The data set is the largest collection of deep spectra of Galactic H\textsc{ii} regions available. We also include data of similar quality for several ring nebulae surrounding massive O and WR stars. The total number of nebulae included in the sample is 24. We have revised the Galactocentric distances of the objects, \(R_G\), considering Gaia DR2 parallaxes and previous kinematic and spectroscopical determinations. We have determined the physical conditions \(n_e\) and \(T_e\) – and the ionic abundance of He\(^+\) and other selected ions in a homogeneous way and using the most recent atomic data sets. We have determined the He\(^+\) abundance using several He\(^+\) recombination lines. In the case of the H\textsc{ii} regions, we have used between 3 and 10 individual He\(^+\) lines depending on the object, selecting only those well-measured lines that are not affected by line-blending, telluric contamination or important self-absorption effects. The total He abundance of the objects have been estimated using four different ICF(He)
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DATA AVAILABILITY

This research is based on public data available in the references. The whole dataset can be obtained from the authors by request. All the results are available in the tables and in the appendix of this article.

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slopes are larger than the slope values obtained using several of the four ICF(He) schemes, they show consistent values in all cases, especially when only the objects with log(η) < 0.9 are considered. More importantly, the gradients are always negative independently on the ICF(He) scheme used. The slope values go from −0.0078 to −0.0044 dex kpc−1, consistent with the predictions of different chemical evolution models of the Milky Way and chemodynamical simulations of galactic discs. We have estimated the abundance deviations of He, O and N of the ring nebulae around WR stars included in our sample with respect to the radial gradients, finding that only NGC 6888, RCW 585 and Sh 2-308 can be considered ejecta nebulae. These objects show He and N overabundances. The degree of enrichment of He is very similar and about +0.24 ± 0.11 dex in the three objects. NGC 6888 and Sh 2-308 can show a possible O deficiency.

Helium abundances and gradient in Galactic nebulae

We thank the referee Ángeles I. Díaz for a constructive report. We acknowledge support from the State Research Agency (AEI) of the Spanish Ministry of Science, Innovation and Universities (MCIU) and the European Regional Development Fund (FEDER) under grant AYA2015-65205-P. JG-R acknowledges support from an Advanced Fellowship from the Severo Ochoa excellence program (SEV-2015-0548). The authors acknowledge support under grant P/308614 financed by funds transferred from the Spanish Ministry of Science, Innovation and Universities, charged to the General State Budgets and with funds transferred from the General Budgets of the Autonomous Community of the Canary Islands by the MCIU. KZA-C acknowledges support from Mexican CONACyT postdoctoral grant 364239. JEM-D thanks the Fundación Carolina for the support provided for his Master’s studies. JEM-D also thanks the support of the Instituto de Astrofísica de Canarias under the Astrophysicist Resident Program and acknowledges support from the Mexican CONACyT (grant CVU 602402). This work has made use of data from the European Space Agency (ESA) mission *Gaia* ([https://www.cosmos.esa.int/gaia](https://www.cosmos.esa.int/gaia)), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, [https://www.cosmos.esa.int/web/gaia/dpac/consortium](https://www.cosmos.esa.int/web/gaia/dpac/consortium)). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

This research is based on public data available in the references. The whole dataset can be obtained from the authors by request. All the results are available in the tables and in the appendix of this article.

MNRS 000, 1–15 (2015)
In this Appendix we include four tables. Table A1 shows the $\text{He}^+ / \text{H}^+$ ratio for each individual He line of the spectra analyzed in this work. In the second column we indicate the level state that produce each line, S for singlet and T for triplet. We also include the mean level state that produce each line.

In Table A2 we give the list of individual He lines analyzed in this work. In the second column we indicate the mean level state that produce each line.

In Table A4 we include the ICFs used in each total abundance estimated with the code HEPHAB.

In Table A5 we include the ICFs used in each total abundance estimated with the code HEPHAB.

APPENDIX A: IONIC ABUNDANCES FOR EACH INDIVIDUAL He LINE

In this Appendix we include four tables. Table A1 shows the $\text{He}^+ / \text{H}^+$ ratio for each individual He line of the spectra analyzed in this work. In the second column we indicate the level state that produce each line, S for singlet and T for triplet. We also include the mean $\text{He}^+ / \text{H}^+$ ratio for each spectrum. In Table A2 we give the list of individual He lines used to derive the mean value of the $\text{He}^+ / \text{H}^+$ ratio adopted for each spectrum. In table Table A3 we include the results of the abundances of $\text{He}^+ / \text{H}^+$ estimated with the code HEPHAB. In Table A4 we include the ICFs used in each total abundance calculation.


| Heλ line | Level | A1 | A2 | A3 | A4 | A5 |
|----------|-------|----|----|----|----|----|
| 4471 T   | -     | 10.865 ± 0.109 | -   | -  | -  | -  |
| 5876 T   | 10.808 ± 0.032 | 10.922 ± 0.029 | 10.817 ± 0.089 | 10.925 ± 0.025 | 11.003 ± 0.057 | -  |
| 6678 S   | 10.720 ± 0.118 | 10.896 ± 0.036 | -   | 10.867 ± 0.039 | 10.838 ± 0.093 | -  |
| Mean     | 10.800 ± 0.065 | 10.909 ± 0.016 | 10.817 ± 0.089 | 10.906 ± 0.031 | 10.937 ± 0.071 | -  |

| M8       | M16   | M17  | M20  | M42  |
|----------|-------|------|------|------|
| 43614 S  | 10.844 ± 0.052 | 10.919 ± 0.052 | 10.934 ± 0.108 | 10.868 ± 0.057 | 10.947 ± 0.031 | -  |
| 43965 S  | 10.849 ± 0.035 | 10.883 ± 0.017 | 10.938 ± 0.022 | 10.869 ± 0.017 | 10.925 ± 0.013 | -  |
| 44026 T  | -     | -    | -    | -    | -    | -  |
| 44121 T  | 10.859 ± 0.027 | 11.013 ± 0.044 | 11.068 ± 0.056 | 10.598 ± 0.110 | 11.051 ± 0.019 | -  |
| 44388 S  | 10.830 ± 0.013 | 10.886 ± 0.017 | 10.961 ± 0.026 | 10.826 ± 0.026 | 10.929 ± 0.009 | -  |
| 44438 S  | 10.880 ± 0.044 | 10.817 ± 0.103 | 10.979 ± 0.109 | 10.938 ± 0.109 | 10.946 ± 0.035 | -  |
| 44471 T  | 10.840 ± 0.013 | 10.893 ± 0.013 | 10.973 ± 0.013 | 10.850 ± 0.013 | 10.950 ± 0.005 | -  |
| 44713 T  | 10.839 ± 0.014 | 10.900 ± 0.019 | 11.013 ± 0.026 | 10.825 ± 0.027 | 11.109 ± 0.011 | -  |
| 44922 S  | 10.829 ± 0.013 | 10.883 ± 0.013 | 10.959 ± 0.013 | 10.862 ± 0.013 | 10.946 ± 0.005 | -  |
| 45016 S  | 10.810 ± 0.013 | 10.864 ± 0.013 | 10.926 ± 0.013 | 10.849 ± 0.013 | 10.900 ± 0.006 | -  |
| 45048 S  | 11.001 ± 0.018 | 11.057 ± 0.053 | 10.807 ± 0.048 | 10.925 ± 0.048 | 11.463 ± 0.011 | -  |
| 45876 T  | 10.838 ± 0.013 | 10.903 ± 0.013 | 10.974 ± 0.013 | 10.853 ± 0.014 | 10.990 ± 0.014 | -  |
| 46678 S  | 10.845 ± 0.013 | 10.895 ± 0.018 | 10.988 ± 0.017 | 10.862 ± 0.018 | 10.965 ± 0.026 | -  |
| 47281 S  | 10.808 ± 0.016 | 10.900 ± 0.023 | 10.928 ± 0.022 | 10.885 ± 0.022 | 10.872 ± 0.038 | -  |
| 49464 T  | 10.751 ± 0.022 | 10.690 ± 0.039 | -   | -   | 10.889 ± 0.065 | -  |
| Mean     | 10.838 ± 0.009 | 10.892 ± 0.009 | 10.967 ± 0.013 | 10.854 ± 0.009 | 10.946 ± 0.014 | -  |

| NGC 2579 | NGC 3576 | NGC 3603 | A1 | A2 |
|----------|----------|----------|----|----|
| 43614 S  | 10.730 ± 0.052 | 10.927 ± 0.039 | -  | -  |
| 43965 S  | 10.904 ± 0.026 | 10.925 ± 0.013 | 10.895 ± 0.048 | -  | -  |
| 44026 T  | 10.962 ± 0.022 | 10.951 ± 0.013 | -  | -  | -  |
| 44121 T  | 11.050 ± 0.048 | -   | 11.202 ± 0.086 | -  | -  | -  |
| 44388 S  | 10.961 ± 0.026 | 10.944 ± 0.013 | 11.025 ± 0.044 | -  | -  | -  |
| 44438 S  | 10.965 ± 0.070 | 11.003 ± 0.044 | -  | -  | -  | -  |
| 44471 T  | 10.964 ± 0.017 | 11.040 ± 0.009 | 11.021 ± 0.013 | -  | -  | -  | -  |
| 44713 T  | 11.062 ± 0.023 | 11.086 ± 0.010 | 11.106 ± 0.032 | -  | -  | -  | -  |
| 44922 S  | 10.915 ± 0.017 | 10.938 ± 0.009 | 10.971 ± 0.018 | -  | -  | -  | -  |
| 45016 S  | 10.898 ± 0.017 | 10.900 ± 0.009 | 10.876 ± 0.022 | 10.861 ± 0.122 | 11.080 ± 0.022 | -  |
| 45904 S  | -   | -   | -   | -   | -   | -   | -  |
| 45876 T  | 11.011 ± 0.018 | 10.900 ± 0.018 | 10.999 ± 0.018 | 11.049 ± 0.036 | 11.161 ± 0.014 | -  |
| 46678 S  | 10.943 ± 0.017 | 10.946 ± 0.026 | 10.974 ± 0.022 | 10.865 ± 0.073 | 11.151 ± 0.018 | -  |
| 47281 S  | -   | 10.953 ± 0.031 | 10.972 ± 0.029 | -  | -  | -  | -  |
| 49464 T  | 10.949 ± 0.018 | 11.031 ± 0.048 | 11.226 ± 0.040 | -  | -  | -  | -  |
| Mean     | 10.934 ± 0.026 | 10.941 ± 0.015 | 10.996 ± 0.027 | 10.977 ± 0.088 | 11.154 ± 0.014 | -  |

This paper has been typeset from a TeX/LaTeX file prepared by the author.
Table A1. continued

| He I line (Å) | Level state | RCW 52 | RCW 58 | Sh 2-83 | Sh 2-100 | Sh 2-127 |
|---------------|-------------|--------|--------|---------|----------|----------|
| 44026         | T           | 10.780 ± 0.137 | 10.811 ± 0.028 | 11.140 ± 0.131 | - | - |
| 44388         | S           | -       | 10.805 ± 0.039 | -       | -       | -       |
| 44471         | T           | 10.899 ± 0.026 | 10.914 ± 0.015 | 10.795 ± 0.010 | 10.887 ± 0.045 | 10.823 ± 0.025 |
| 44713         | T           | 10.893 ± 0.083 | 10.928 ± 0.057 | 10.834 ± 0.022 | - | - |
| 44922         | S           | 10.992 ± 0.036 | 10.997 ± 0.036 | 10.804 ± 0.011 | 10.884 ± 0.090 | 10.744 ± 0.097 |
| 45016         | S           | -       | -       | 10.771 ± 0.029 | 10.961 ± 0.025 | 10.933 ± 0.031 |
| 45048         | S           | 11.034 ± 0.131 | 10.918 ± 0.145 | 10.887 ± 0.025 | - | - |
| 45876         | T           | 11.040 ± 0.012 | 10.989 ± 0.014 | 10.853 ± 0.009 | 10.969 ± 0.019 | 10.933 ± 0.016 |
| 46678         | S           | 11.066 ± 0.016 | 10.993 ± 0.020 | 10.849 ± 0.010 | 10.946 ± 0.028 | 10.896 ± 0.029 |
| 47281         | S           | -       | 10.627 ± 0.139 | 10.798 ± 0.046 | 11.212 ± 0.119 | - |
| Mean          |             | 11.049 ± 0.013 | 10.987 ± 0.013 | 10.798 ± 0.009 | 10.959 ± 0.015 | 10.925 ± 0.015 |
|                | RCW 52      | 10.825 ± 0.009 | 11.217 ± 0.008 | 10.899 ± 0.007 | 10.984 ± 0.015 | 10.799 ± 0.008 |
|                | RCW 58      | -       | -       | -       | -       | -       |
|                | Sh 2-83     | -       | -       | -       | -       | -       |
|                | Sh 2-100    | -       | -       | -       | -       | -       |
|                | Sh 2-127    | -       | -       | -       | -       | -       |

| He I line (Å) | Level state | RCW 52 | RCW 58 | Sh 2-83 | Sh 2-100 | Sh 2-127 |
|---------------|-------------|--------|--------|---------|----------|----------|
| 49026         | T           | 10.817 ± 0.039 | -       | -       | 10.853 ± 0.047 |
| 44388         | S           | 10.751 ± 0.097 | -       | -       | -       |
| 44471         | T           | 10.924 ± 0.024 | 10.839 ± 0.011 | 10.975 ± 0.024 | 10.780 ± 0.022 |
| 44713         | T           | -       | 10.961 ± 0.052 | -       | -       | -       |
| 44922         | S           | 10.950 ± 0.032 | 10.807 ± 0.029 | -       | 11.036 ± 0.020 | 10.739 ± 0.024 |
| 45016         | S           | 10.913 ± 0.013 | 10.658 ± 0.019 | 10.709 ± 0.079 | 10.964 ± 0.039 | 10.798 ± 0.016 |
| 45048         | S           | 11.113 ± 0.078 | 10.792 ± 0.017 | -       | -       | 10.745 ± 0.096 |
| 45876         | T           | 10.970 ± 0.011 | 10.803 ± 0.009 | 10.923 ± 0.027 | 11.020 ± 0.014 | 10.798 ± 0.026 |
| 46678         | S           | 10.945 ± 0.015 | 10.790 ± 0.010 | 10.882 ± 0.044 | 10.765 ± 0.050 | 10.745 ± 0.040 |
| 47281         | S           | 10.847 ± 0.031 | 10.833 ± 0.066 | 10.780 ± 0.074 | -       | 10.683 ± 0.063 |
| Mean          |             | 10.928 ± 0.015 | 10.802 ± 0.007 | 10.893 ± 0.046 | 11.019 ± 0.019 | 10.792 ± 0.010 |
|                | Sh 2-83     | 10.885 ± 0.065 | -       | -       | -       |
|                | Sh 2-100    | 10.905 ± 0.018 | -       | -       | -       |
|                | Sh 2-127    | 10.915 ± 0.017 | -       | -       | -       |
|                | RCW 52      | -       | -       | -       | -       |
|                | RCW 58      | -       | -       | -       | -       |
|                | Sh 2-83     | 10.926 ± 0.039 | -       | -       |
|                | Sh 2-100    | 10.922 ± 0.017 | -       | -       |
|                | Sh 2-127    | 10.963 ± 0.065 | -       | -       |
|                | RCW 52      | -       | -       | -       |
|                | RCW 58      | -       | -       | -       |
|                | Sh 2-83     | 10.913 ± 0.013 | -       | -       |
|                | Sh 2-100    | 10.919 ± 0.018 | -       | -       |
|                | Sh 2-127    | 10.901 ± 0.017 | -       | -       |
|                | RCW 52      | -       | -       | -       |
|                | RCW 58      | -       | -       | -       |
|                | Sh 2-83     | 10.892 ± 0.013 | -       | -       |
|                | Sh 2-100    | 10.909 ± 0.022 | -       | -       |
|                | Sh 2-127    | 10.985 ± 0.035 | -       | -       |
| Mean          |             | 10.971 ± 0.017 | 11.200 ± 0.062 | 10.914 ± 0.006 |
Table A2. List of lines used for the calculation of the mean He$^+$/H$^+$ ratio for each spectra.

| Object     | Zone | Lines used                  |
|------------|------|-----------------------------|
| G2.4+1.4   | A1   | 5876, 6678                  |
|            | A2   | 4471, 5876, 6678            |
|            | A3   | 5876                        |
|            | A4   | 5876, 6678                  |
|            | A5   | 5876, 6678                  |
| M8         |      | 3614, 3965, 4121, 4388, 4438, 4471, 4713, 4922, 5876, 6678 |
| M16        |      | 3614, 3965, 4388, 4438, 4471, 4713, 4922, 5876, 6678, 7281 |
| M17        |      | 3614, 3965, 4388, 4438, 4471, 4922, 5876, 6678 |
| M20        |      | 3614, 3965, 4388, 4438, 4471, 4922, 5016, 5876, 6678 |
| M42        |      | 3614, 3965, 4388, 4438, 4471, 4922, 5876, 6678, 7281, 9464 |
| NGC 2579   |      | 3965, 4026, 4388, 4438, 4471, 4922, 5016, 5876, 6678, 9464 |
| NGC 3576   |      | 3614, 3965, 4026, 4388, 4438, 4922, 4922, 5876, 6678, 7281, 9464 |
| NGC 3603   |      | 4121, 4388, 4471, 4922, 5876, 6678, 7281 |
| NGC 6888   |      | 5016, 5876, 6678 |
|            | A2   | 4026, 4388, 4922, 5048, 5876, 6678 |
|            | A3   | 4026, 4388, 4922, 5876, 6678 |
|            | A4   | 4026, 4471, 4922, 5876, 6678 |
|            | A5   | 4026, 4471, 4922, 5876, 6678 |
|            | A6   | 4026, 4471, 4922, 5876, 6678 |
| RCW 52     |      | 4471, 5016, 5876 |
| RCW 58     |      | 4388, 4471, 4922, 5016, 5876 |
| NGC 7635   |      | 4026, 4388, 4713, 5016, 6678 |
|            | A2   | 5048, 5876, 6678 |
|            | A3   | 4713, 4922, 5048, 5876, 6678 |
|            | A4   | 4026, 4388, 4471, 4922, 5016, 7281 |
|            | A5   | 4922, 5016, 5876, 6678 |
|            | A6   | 5016, 5876, 6678 |
| Sh 2-83    |      | 4471, 4922, 5016, 6678 |
| Sh 2-100   |      | 4026, 4471, 4922, 5016, 5048, 6678 |
| Sh 2-127   |      | 4922, 5016, 6678 |
| Sh 2-128   |      | 4471, 4922, 5016, 6678 |
| Sh 2-152   |      | 4026, 4922, 5048, 5876, 7281 |
| Sh 2-209   |      | 5876, 6678, 7281 |
| Sh 2-212   |      | 4922, 5016, 5876 |
| Sh 2-288   |      | 4471, 5016, 5048, 5876 |
| Sh 2-298   |      | 4026, 4388, 4471, 4713, 4922, 5876 |
| Sh 2-308   |      | 5876, 6678 |
| Sh 2-311   |      | 3614, 3965, 4026, 4121, 4388, 4471, 4713, 4922, 5876, 6678, 7281 |
Table A3. Results of Helio14 code: He\(^+\)/H\(^+\) ratios, minimal \(\chi^2\) and \(T_e\) (OII+OIII).

| Object   | Zone | He\(^+\)/H\(^+\) | \(\chi^2\) | \(T_e\) (OII+OIII) (K) |
|----------|------|------------------|------------|------------------------|
| G2.4+1.4 | A1   | 10.800 \pm 0.132 | 0.4824     | 8300                   |
|          | A2   | 10.913 \pm 0.062 | 0.2778     | 9900                   |
|          | A3   | 10.823 \pm 0.025 | 0.0001     | 13200                  |
|          | A4   | 10.911 \pm 0.056 | 1.5670     | 10800                  |
|          | A5   | 10.955 \pm 0.104 | 2.1964     | 9400                   |
| M8       |      | 10.835 \pm 0.006 | 3.1286     | 8300                   |
| M16      |      | 10.892 \pm 0.005 | 1.8101     | 8200                   |
| M17      |      | 10.951 \pm 0.010 | 1.7033     | 8100                   |
| M20      |      | 10.849 \pm 0.006 | 5.6603     | 8200                   |
| M42      |      | 10.937 \pm 0.005 | 10.4708    | 8600                   |
| NGC 2579 |      | 10.932 \pm 0.007 | 9.9796     | 9100                   |
| NGC 3576 |      | 10.940 \pm 0.005 | 6.4027     | 8500                   |
| NGC 3603 |      | 10.997 \pm 0.008 | 11.1381    | 9200                   |
| NGC 6888 | A1   | 10.938 \pm 0.061 | 6.3886     | 9000                   |
|          | A2   | 11.135 \pm 0.010 | 3.6936     | 8100                   |
|          | A3   | 11.211 \pm 0.024 | 1.1789     | 8200                   |
|          | A4   | 11.248 \pm 0.017 | 1.1147     | 9800                   |
|          | A5   | 11.215 \pm 0.031 | 0.4958     | 9700                   |
|          | A6   | 11.222 \pm 0.029 | 1.1959     | 9300                   |
| RCW 52   |      | 10.797 \pm 0.135 | 0.1317     | 7000                   |
| RCW 58   |      | 11.218 \pm 0.011 | 0.5340     | 5700                   |
| NGC 7635 | A1   | 10.876 \pm 0.010 | 0.2989     | 7800                   |
|          | A2   | 11.049 \pm 0.061 | 3.73       | 8000                   |
|          | A3   | 10.979 \pm 0.036 | 0.20       | 7900                   |
|          | A4   | 10.794 \pm 0.009 | 1.4294     | 8900                   |
|          | A5   | 10.959 \pm 0.016 | 2.2715     | 7700                   |
|          | A6   | 10.926 \pm 0.016 | 1.4500     | 7500                   |
| Sh 2-83  |      | 10.894 \pm 0.026 | 0.0529     | 10500                  |
| Sh 2-100 |      | 10.969 \pm 0.019 | 0.9411     | 8300                   |
| Sh 2-127 |      | 10.804 \pm 0.010 | 0.3323     | 9800                   |
| Sh 2-128 |      | 10.927 \pm 0.010 | 0.4683     | 10200                  |
| Sh 2-152 |      | 10.794 \pm 0.008 | 0.9671     | 8100                   |
| Sh 2-209 |      | 10.855 \pm 0.034 | 0.7623     | 10700                  |
| Sh 2-212 |      | 11.003 \pm 0.017 | 1.8543     | 9200                   |
| Sh 2-288 |      | 10.792 \pm 0.011 | 0.8347     | 9400                   |
| Sh 2-298 |      | 10.967 \pm 0.016 | 2.5547     | 11700                  |
| Sh 2-308 |      | 11.177 \pm 0.056 | 0.0046     | 16300                  |
| Sh 2-311 |      | 10.909 \pm 0.006 | 0.9385     | 9200                   |
Table A4. ICF values.

| Object       | ICF(He) scheme |
|--------------|----------------|
|              | PTP77 | ZL03 | KS83 | B09   |
| G2.4+1.4     |       |      |      |       |
| M8           | 1.33 ± 0.09 | 1.15 ± 0.02 | 1.23 ± 0.07 | 1.82 ± 0.36 |
| M16          | 1.59 ± 0.21 | 1.38 ± 0.08 | 1.24 ± 0.07 | 1.23 ± 0.27 |
| M17          | 1.06 ± 0.02 | 1.04 ± 0.01 | 1.05 ± 0.01 | 1.05 ± 0.09 |
| M20          | 1.54 ± 0.16 | 1.30 ± 0.06 | 1.27 ± 0.07 | 1.74 ± 0.46 |
| M42          | 1.08 ± 0.04 | 1.04 ± 0.02 | 1.04 ± 0.02 | 1.02 ± 0.09 |
| NGC 2579     | 1.16 ± 0.05 | 1.09 ± 0.02 | 1.10 ± 0.04 | 1.10 ± 0.18 |
| NGC 3576     | 1.13 ± 0.04 | 1.08 ± 0.02 | 1.09 ± 0.02 | 1.05 ± 0.10 |
| NGC 3603     | 1.03 ± 0.01 | 1.02 ± 0.01 | 1.02 ± 0.01 | 1.03 ± 0.13 |
| RCW 52       | 1.39 ± 0.49 | 1.22 ± 0.17 | 1.27 ± 0.36 | 2.12 ± 2.47 |
| RCW 58       | 1.15 ± 0.10 | 1.06 ± 0.03 | 1.17 ± 0.12 | 1.94 ± 1.33 |
| Sh 2-83      | 1.04 ± 0.02 | 1.05 ± 0.02 | 1.02 ± 0.01 | 1.25 ± 0.45 |
| Sh 2-100     | 1.06 ± 0.02 | 1.04 ± 0.01 | 1.05 ± 0.01 | 1.04 ± 0.13 |
| Sh 2-127     | 1.39 ± 0.12 | 1.16 ± 0.04 | 1.28 ± 0.08 | 1.47 ± 0.63 |
| Sh 2-128     | 1.19 ± 0.07 | 1.12 ± 0.03 | 1.12 ± 0.03 | 1.07 ± 0.17 |
| Sh 2-132     | 1.31 ± 0.07 | 1.09 ± 0.02 | 1.27 ± 0.05 | 3.35 ± 0.64 |
| Sh 2-209     | 1.22 ± 0.30 | 1.17 ± 0.16 | 1.10 ± 0.14 | 1.01 ± 0.08 |
| Sh 2-212     | 1.28 ± 0.40 | 1.16 ± 0.15 | 1.20 ± 0.30 | 1.50 ± 1.60 |
| Sh 2-288     | 1.37 ± 0.25 | 1.18 ± 0.11 | 1.22 ± 0.12 | 1.60 ± 1.03 |
| Sh 2-298     | 1.91 ± 0.53 | 1.95 ± 0.20 | 1.15 ± 0.06 | 1.46 ± 0.40 |
| Sh 2-308     | 1.05 ± 0.08 | 1.06 ± 0.06 | 1.03 ± 0.04 | 1.16 ± 1.09 |
| Sh 2-311     | 1.47 ± 0.14 | 1.33 ± 0.05 | 1.23 ± 0.07 | 1.20 ± 0.18 |