THE OXYGEN ABUNDANCE IN THE SOLAR NEIGHBORHOOD

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ABSTRACT

We present a homogeneous analysis of the oxygen abundance in five H II regions and eight planetary nebulae (PNe) located at distances lower than 2 kpc and with available spectra of high quality. We find that both the collisionally excited lines (CELs) and recombination lines imply that the PNe are overabundant in oxygen by about 0.2 dex. An explanation that reconciles the oxygen abundances derived with CELs for H II regions and PNe with the values found for B stars, the Sun, and the diffuse interstellar medium (ISM) requires the presence in H II regions of an organic refractory dust component that is not present in PNe. This dust component has already been invoked to explain the depletion of oxygen in molecular clouds and in the diffuse ISM.

Key words: dust, extinction – H II regions – ISM: abundances – planetary nebulae: general

Online-only material: color figure

1. INTRODUCTION

The ionized gas that surrounds young stars in H II regions and evolved stars in planetary nebulae (PNe) is subjected to very similar processes, but the gas in H II regions samples the present interstellar medium (ISM), while the gas in PNe samples the ISM of several gigayears ago, when the progenitor stars formed. Hence, if we choose an element whose abundance in the PN has not changed significantly from the original one, like oxygen at near-solar metallicities (e.g. Karakas 2010), we can calculate its abundance in H II regions and PNe using the same procedure, and compare the differences with those predicted by galactic chemical evolution.

This potential is somewhat marred by the existing discrepancy between the abundances derived using collisionally excited lines (CELs) and those implied by recombination lines (RLs) of the same elements (Peimbert et al. 1993). In all the ionized nebulae studied so far, RLs imply abundances higher than those implied by CELs by factors around two in most cases, with some PNe showing much higher discrepancies (Liu 2006). The emissivities of CELs have a stronger dependence on temperature than those of RLs, and most of the proposed explanations of the difference rely on the production of temperature fluctuations by some mechanism in the observed nebulae. The exception would be those explanations that consider uncertainties in the recombination coefficients of the heavy elements. The different explanations of the discrepancy imply that the real abundances will be either close to the values implied by CELs, closer to the abundances derived with RLs, or intermediate between them (Torres-Peimbert & Peimbert 2003; Rodríguez & García-Rojas 2010, and references therein). Therefore, a meaningful comparison between the abundances derived for H II regions and PNe must not only take into account the results provided by both CELs and RLs, but also the fact that the explanation can be different for the two kinds of objects.

A further issue to consider is that the ionizing radiation fields can be very different in H II regions and PNe. This implies that the corrections for the contribution of unobserved ions to the total abundance, generally based on the relative abundances of two ions of another element, are likely to introduce a different bias in each kind of object. Hence, the best option is to perform the comparison using an element whose dominant ionization states are all observed. In H II regions and low-ionization PNe, this happens with oxygen. Besides, the required [O II] and [O III] lines can be observed in the optical region of the spectrum along with the other H I and diagnostic lines needed for the analysis. This reduces the uncertainties introduced when comparing the relative intensities of lines measured at widely separated wavelengths, with mismatched apertures, and with different telescopes.

In this Letter, we present a comparative analysis of the oxygen abundance in five H II regions and eight low-ionization PNe of the solar neighborhood. The solar neighborhood is defined here as a region around the Sun with a radius of 2 kpc. This allows us to secure a representative number of objects whose abundances should not be much affected by the Galactic abundance gradient. The analysis follows the same method and uses the same atomic data for all the objects. We use the best-available spectra and provide results for both CELs and RLs. The derived oxygen abundances are compared with those implied by nearby young stars and those based on absorption lines in the diffuse ISM.

2. THE SAMPLE

The sample objects were selected from the compilation in Delgado-Inglada et al. (2009) of Galactic H II regions and low-ionization PNe with available deep optical spectra. There are around 100–800 detected lines in each object and the spectral resolution in the blue is better than 1.5 Å. All the objects have individual distance determinations locating them at distances below 2 kpc (see Section 3 below). The distance to NGC 6884 could be larger, but at a Galactic longitude of 82 deg, the effect of the Galactic radial abundance gradient should be small.

The PNe have been classified as type II of Peimbert (Peimbert 1978), though NGC 6210 could be of type III (Quireza et al. 2007). Quireza et al. estimate that the thin disk progenitors of type II PNe have ages around 4–6 Gyr and initial masses 1.2–2.4 M⊙.

3. ANALYSIS AND RESULTS

We used the same set of lines for the analysis of all the sample objects. The lines were measured with the same telescope and aperture for each object. The physical conditions and ionic
abundances were calculated with the nebular package in IRAF.\footnote{IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.}

In order to check the effect of the atomic data on the calculations, we performed two sets of calculations. The first set is based on the atomic data compiled in IRAF and the second one on the atomic data used in the photoionization code Cloudy (version 08.00, last described by Ferland et al. 1998). Below we present the results of the second set and comment on the differences found with the first one.

The adopted electron densities, \(n_e\), are weighted averages of the values implied by the diagnostics \([\text{S~II}]\) \(\lambda\lambda 6716/6731\), \([\text{Cl~III}]\) \(\lambda\lambda 5517/5537\), and \([\text{Ar~IV}]\) \(\lambda\lambda 4711/4740\). For \(n_e\) and the lower ionization objects we do not use the last diagnostic. In \(\text{M17}\), the intensity of \([\text{Ar~IV}]\) \(\lambda 4740\) was not measured; in \(\text{IC~418}\), the ratio of line \([\text{O~II}]\) \(\lambda 3727\) and \([\text{Ar~IV}]\) \(\lambda 4740\) is very uncertain and the intensity ratio \(\lambda 4711/\lambda 4740\) is out of bounds; in \(\text{M16}\) and \(\text{M20}\), \([\text{Ar~IV}]\) \(\lambda 4740\) was not measured; in \(\text{IC~418}\), the \([\text{Ar~IV}]\) line ratio implies \(n_e = 4800\) cm\(^{-3}\), in disagreement with the other diagnostics, based on lines whose intensities in this object are larger by factors \(\geq 50\). We derive two values for the electron temperature, \(T_e\), one for the high-ionization regions in the nebula, \(T_e([\text{O~III}])\), based on the ratio of line intensities \((\lambda 4959 + \lambda 5007)/\lambda 4363\), and another for the low-ionization regions, \(T_e([\text{N~II}])\), based on \((\lambda 6548 + \lambda 6583)/\lambda 5755\). We list in Table 1 the physical conditions derived for each object. We also give the observational uncertainties, i.e., those derived from the propagation of errors in the line intensities.

The \(O^+/	ext{H}^+\) abundance ratio was calculated using the values found for \(n_e\), \(T_e([\text{N~II}])\), and \(I(\text{O~II})/I(\text{H}\beta)\); for the \(O^+/\text{H}^+\) ratio we used \(n_e\), \(T_e([\text{O~III}])\), and \(I(\text{O~III})/I(\text{H}\beta)\).

\begin{table}
\centering
\begin{tabular}{llllllllll}
\hline
Object & \(n_e([\text{S~II}])\) & \(n_e([\text{Cl~III}])\) & \(n_e([\text{Ar~IV}])\) & \(n_e(\text{adopted})\) & \(T_e([\text{N~II}])\) & \(T_e([\text{O~III}])\) & Reference \\
\hline
\text{H~II regions} & & & & & & & & & \\
\hline
M8 & 1500 & 2000 & 2000 & 1600 & 8500 & 8000 & 1 \\
M16 & 1300 & 1300 & \cdots & 1300 & 8500 & 7600 & 2 \\
M17 & 500 & 200 & \cdots & 400 & 9200 & 7900 & 1 \\
M20 & 300 & \cdots & 300 & \cdots & 8500 & 7700 & 2 \\
M42 & 5400 & 8000 & 4900 & 7000 & 10100 & 8250 & 3 \\
\hline
\text{Planetary nebulae} & & & & & & & & & \\
IC 418 & 16400 & 13400 & \cdots & 13900 & 8900 & 8700 & 4 \\
NGC 3132 & 500 & 800 & 300 & 500 & 9700 & 9400 & 5 \\
NGC 3242 & 2100 & 1300 & 2100 & 1800 & 12400 & 11600 & 5 \\
NGC 6210 & 3700 & 4100 & 6200 & 4600 & 11200 & 9500 & 6 \\
NGC 6543 & 5800 & 6400 & 3100 & 3700 & 10300 & 7800 & 7 \\
NGC 6572 & 16000 & 20100 & 15100 & 16400 & 12000 & 10200 & 6 \\
NGC 6720 & 500 & 500 & 500 & 500 & 10600 & 10400 & 6 \\
NGC 6884 & 6700 & 6800 & 9700 & 7900 & 11600 & 10900 & 6 \\
\hline
\end{tabular}
\caption{Physical Conditions}
\end{table}

\begin{itemize}
\item Table 1 also lists the results implied by RLs. The \(O^+\) abundances were derived using the \(\text{O~II}\) RLs of multiplet 1 (the only one measured in all the objects) and the recombination coefficients of Storey (1994). The multiplet intensity was calculated correcting for the unobserved lines, when necessary, using the prescriptions given by Peimbert et al. (2005). A comparison with the results obtained in the original references, which use all reliable multiplets, shows small differences in most cases, with a maximum difference of 0.14 dex. We estimated the total oxygen abundance implied by RLs, \(O(\text{H})_{\text{RLs}}\), by assuming the same ionization fractions found with CELs.

The total oxygen abundances derived using the atomic data compiled in IRAF differ from those shown in Table 2 by a maximum of 0.05 dex with one exception, IC 418. For this nebula, the value implied by IRAF is \(\sim 0.2\) dex higher. This large difference arises because the nebula has a high density and because its oxygen abundance is dominated by \(O^+\). When the electron density is high, the absolute uncertainties in \(T_e([\text{N~II}])\) and \(n_e\) are large, and since the estimated \(O^+\) abundance is very sensitive to the physical conditions, its value is subject to large fluctuations.

In fact, as pointed out by the referee, the values of \(T_e([\text{N~II}])\) are usually affected by many uncertainties, and this could be critical for our purposes. The \([\text{N~II}]\) diagnostic ratio is very susceptible to errors in the flux calibration and reddening correction, and can be altered by a contribution from recombination to \([\text{N~II}]\) \(\lambda 5755\) (Rubin 1986), or by contamination from high-density objects included in the slit, such as cometary knots, globules, proplyds, or Herbig-Haro objects (e.g., Mesa-Delgado et al. 2008). The recombination contribution can be large for objects with high densities of ionization, but for these objects \(O^+\) makes a small contribution to the total abundance, which is then barely affected. On the other hand, the contamination by high-density objects could be a problem for the sample PNe, since most of them were observed using a long-slit scanning all of their volume. Our sample \(\text{H~II}\) regions are less likely to be contaminated.
Since they were observed using small slits (≈ 3′′ × 10′′), and include nebulae like M42, the Orion Nebula, where proplyds and Herbig-Haro objects are easily resolved and identified. The uncertainties in \( T_e([\text{N}\,\text{II}]) \) have prompted some authors to use only \( T_e([\text{O}\,\text{III}]) \) to calculate all the ionic abundances. If we did this, the oxygen abundances would be higher by up to 0.03 dex in our PNe, and by significant amounts, 0.07–0.20 dex, in the H II regions: \( 12 + \log(O/H)_{\text{CELs}} = 8.55, 8.73, 8.61, 8.68, \) and 8.64 for M8, M16, M17, M20, and M42, respectively. However, we consider that the evidence for the values of \( T_e([\text{N}\,\text{II}]) \) shown in Table 1 is strong, in particular for the H II regions. Temperature values similar to those presented here and also satisfying \( T_e([\text{N}\,\text{II}]) > T_e([\text{O}\,\text{III}]) \) are generally found at different positions within the bright areas of our sample H II regions (e.g., Rodríguez 1999; Mesa-Delgado et al. 2008). These temperature gradients are also predicted by photoionization models (Stasińska 1978). Furthermore, the temperatures and temperature ratios measured for the sample H II regions from the same spectra we are using here have been shown to be consistent with the predictions of photoionization models (Rodríguez & García-Rojas 2010). We conclude that the available evidence indicates that our values of \( T_e([\text{N}\,\text{II}]) \) are reliable, but problems with this temperature could be a possible source of bias when comparing abundances in H II regions and PNe.

If we now compare our results with those derived by other authors from the same spectra (see Tsamis et al. 2004 and Liu et al. 2004b, in addition to the references listed in Table 1), the differences are larger, since besides using different atomic data, they apply other tools. The differences are all \( \leq 0.1 \) dex with three exceptions: Sharpee et al. (2004) find \( O/H\) CELs \( 0.21 \) dex below our value in IC 418, whereas Tsamis et al. (2003) and Wesson & Liu (2004) find \( O/H\) CELs \( 0.17 \) and \( 0.21 \) dex above our derived values for NGC 3132 and NGC 6543, respectively.

Finally, we note the importance of using spectra of relatively high spectral resolution in order to obtain the best estimates for the oxygen abundance, even when using strong CELs. If the spectral resolution is poor, \( [\text{O}\,\text{III}] \lambda 4363 \) can be blended with several lines, such as \([\text{Fe} \,\text{II}] \lambda 4359, \lambda 4368, \) and \( [\text{O} \,\text{I}] \lambda 4369, \lambda 4370, \) and \( [\text{O} \,\text{I}] \lambda 4368. \) In the sample H II regions, these blends would lead to values of \( T_e([\text{O}\,\text{III}]) \) up to 1000 K higher and final oxygen abundances up to 0.05 dex lower. In our sample PNe the effects are smaller: up to 300 K higher \( T_e([\text{O}\,\text{III}]) \) and oxygen abundances up to 0.02 dex lower.

### 4. DISCUSSION

Figure 1 shows the total oxygen abundances implied by CELs and RLs for the H II regions and PNe as a function of \( O^+\)/\( O^++ \). All the H II regions show similar abundances, with \( 12 + \log(O/H)_{\text{CELs}} \) H II = 8.52 and \( 12 + \log(O/H)_{\text{RLs}} \) H II = 8.80, suggesting that the ISM in the solar neighborhood is homogeneous. The PNe results show more dispersion, but can be seen to be higher by about 0.2 dex: \( 12 + \log(O/H)_{\text{CELs}} \) PNe = 8.70 and \( 12 + \log(O/H)_{\text{RLs}} \) PNe = 8.98. We expect to find the real oxygen abundances of the nebulae somewhere in the ranges defined by CELs and RLs, with the different explanations of the discrepancy favoring values at different positions along these ranges. There are some indications that the explanations might differ in H II regions and PNe, like the fact that all the H II regions studied so far show moderate discrepancies, whereas PNe can show huge discrepancies, like NGC 1501, where Ercolano et al. (2004) find \( 12 + \log(O/H)_{\text{CELs}} = 8.52 \) and \( 12 + \log(O/H)_{\text{RLs}} = 10.09 \). However, at least three of the

### Table 2

| Object | \( l \) (°) | \( b \) (°) | \( d \) (kpc) | Reference | \( [\text{O}^+]/[\text{H}^+] \) CELs | \( [\text{O}^+]/[\text{H}^+] \) CELs | ICF | \( [\text{O}]/[\text{H}] \) CELs | \( [\text{O}^+]/[\text{H}] \) CELs | \( [\text{O}]/[\text{H}] \) CELs |
|--------|------|------|--------|-----------|----------------|----------------|---|---------------|----------------|---------------|
| M8     | 6    | -1   | 1.322  | 1         | 8.50 ± 0.04 | 7.90 ± 0.02 | 1.00 | 8.45 ± 0.03 | 8.24 ± 0.03 | 8.24 ± 0.03 |
| M16    | 17   | +1   | 1.719  | 1         | 8.41 ± 0.03 | 7.93 ± 0.05 | 1.00 | 8.53 ± 0.04 | 8.31 ± 0.04 | 8.91 ± 0.04 |
| M17    | 15   | -1   | 1.814  | 1         | 7.70 ± 0.05 | 8.47 ± 0.03 | 1.00 | 8.54 ± 0.02 | 8.73 ± 0.02 | 8.82 ± 0.02 |
| M20    | 7    | 0    | 0.816  | 1         | 8.40 ± 0.03 | 7.76 ± 0.05 | 1.00 | 8.49 ± 0.04 | 8.08 ± 0.04 | 8.82 ± 0.04 |
| M42    | 209  | -19  | 0.399  | 1         | 7.77 ± 0.06 | 8.45 ± 0.01 | 1.00 | 8.53 ± 0.01 | 8.61 ± 0.01 | 8.68 ± 0.01 |

**References.** (1) Kharchenko et al. 2005; (2) Guzmán et al. 2009; (3) Ciardullo et al. 1999; (4) Mellema 2004; (5) Hajian et al. 1995; (6) Harris et al. 2007; (7) Palen et al. 2002.
PNe show CEL abundances similar to the RL abundances of the H II regions. This implies that even if the explanation of the abundance discrepancy is very different in each kind of object, these PNe will still show similar or larger oxygen abundances than the H II regions. This is contrary to our expectations from simple models of galactic chemical evolution. The difference could arise from extensive stellar migration from the inner parts of the Galaxy, or gas flows or infall (e.g., Schönrich & Binney 2009). We also show the protosolar abundance (the symbol for Asplund et al. 2009), the abundance of nearby B stars (star; Przybilla et al. 2008), and the range of abundances found for the ISM (rectangle; Jenkins 2009).

(A color version of this figure is available in the online journal.)

Figure 1. Oxygen abundances derived using CELs (filled circles and squares) and RLs (empty circles and squares) for our sample H II regions (squares) and PNe (circles) as a function of the values of O\(^+\)/O\(^{++}\). From left to right, the objects are: NGC 3242, NGC 6543, NGC 6210, NGC 6884, NGC 6572, M17, M42, NGC 6720, NGC 3132, M8, IC 418, M16, and M20. We also show the protosolar abundance (the symbol for Asplund et al. 2009), the abundance of nearby B stars (star; Przybilla et al. 2008), and the range of abundances found for the ISM (rectangle; Jenkins 2009).

5. CONCLUSIONS

We have selected a sample of five H II regions and eight low-ionization PNe that have available spectra of high quality, all of them located at distances lower than 2 kpc. A homogeneous analysis of their oxygen abundances based on CELs and RLs shows that the PNe are, on average, overabundant by 0.18 dex.
If we take at face value the results implied by B stars, the Sun, and the diffuse ISM, along with the almost flat age–metallicity relation implied by F and G stars, we find that for the PNe, the abundances implied by CELs agree with the expected values, whereas the abundances implied by RLs are too high. For the H$_\text{ii}$ regions, the abundances implied by CELs are similar to the lower values found by Jenkins (2009) in the ISM, which are explained by Whittet (2010) as due to depletion in organic refractory dust grains. If we assume that these grains are also present in H$_\text{ii}$ regions, their CEL abundances agree with all the other results. We can thus explain the overabundance of oxygen in PNe through the presence of different dust components in H$_\text{ii}$ regions and PNe.

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