Chemical abundances in Seyfert galaxies – VI. Empirical abundance calibration

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ABSTRACT
We derived a bi-dimensional calibration between the emission line ratios \( R_{23} = (\text{[O II]} \lambda 3726 + \lambda 3729 + \text{[O III]} \lambda 4959 + \lambda 5007)/\text{H}β \), \( P = \left( \text{[O III]} \lambda 4959 + \lambda 5007 \right)/R_{23} \) and the oxygen abundance relative to hydrogen (O/H) in the gas phase of Seyferts 1 and 2 nuclei. In view of this, emission-line intensity ratios for a sample of objects taken from the Sloan Digital Sky Survey Data Release 7 (SDSS-DR7) measured by the MPA/JHU group and direct estimates of O/H based on \( T_e \)-method, adapted for AGNs, are considered. We find no variation of \( R_{23} \) observed along the radii of AGNs which shows that this line ratio is a good oxygen abundance (O/H) indicator for the class of objects considered in this work. The derived O/H = \( f(R_{23}, P) \) relation produces O/H values similar to estimations via \( T_e \)-method in a wide range of metallicities (8.0 \( \lesssim \) 12 + log(O/H) \( \lesssim \) 9.2). Conversely to star-forming regions in the high metallicity regime, \( R_{23} \) shows a positive correlation trend with O/H in AGNs. This indicates that the hardness of ionizing radiation is not affected by the metallicities in these objects or Narrow Line Regions (NLRs) are not significantly modified by changes in the Spectral Energy Distribution due to metallicity variations.

Key words: galaxies: Seyfert – galaxies: active – galaxies: abundances –ISM: abundances –galaxies: evolution –galaxies: nuclei

1 INTRODUCTION
Active Galactic Nuclei (AGNs) and Star-forming regions (SFs) present in their spectra strong metal and hydrogen emission lines, whose relative intensities can be used to derive the metallicity and/or the abundances of heavy elements. These features make these objects essential for studying the chemical evolution of galaxies.

It is widely known that the most dependable approach for determining the chemical abundance of heavy elements (e.g., O, N, S) in galaxies is the gas phase of SFs and Planetary Nebulae is primarily based on direct measurements of the electron temperature (\( T_e \)), which is commonly referred to as the \( T_e \)-method (for a review, see Peimbert et al. 2017; Pérez-Montero 2017; Maiolino & Mannucci 2019). Basically, this method consists of determining the \( T_e \) of the gas phase through emission-line intensity ratios emitted by a given ion and originated in transitions from two levels with considerable different excitation energies. For example, the \( T_e \) for the gas regions where the \( O^+ \), \( O^{2+} \) and \( N^+ \) ions are located can be determined through the [O II] \( \lambda \lambda 3726+\lambda 3729/\lambda 7319+\lambda 7330 \), [O III] \( \lambda \lambda 4959+\lambda 5007/\lambda 4363 \) and [N I] \( \lambda \lambda 6548+\lambda 6584/\lambda 5755 \) line ratios, respectively (e.g., Hägele et al. 2008). However, for most extragalactic objects where the \( T_e \)-method can be applied, which has only the [O II] \( \lambda \lambda 4959+\lambda 5007/\lambda 4363 \) line ratio measured, it is only possible to estimate the temperature for the high ionization zone (e.g., van Zee et al. 1998). In these cases, temperatures for the low ionization zones are obtained from empirical (e.g., Kennicutt et al. 2003; Pilyugin et al. 2006; Pilyugin 2007; Esteban et al. 2009; Berg et al. 2015; Croxall et al. 2016; Yates et al. 2020) or from photoionization models (e.g., Campbell et al. 1986; Pagel et al. 1992; Garnett 1992; Izotov et al. 1997; Deharveng et al. 2000; Pérez-Montero & Contini 2009; Pérez-Montero 2014) relations, which can introduce some uncertainty in the abundance determinations (e.g., Arellano-Córdova & Rodríguez 2020).

The reliability of the \( T_e \)-method is supported by the agreement between oxygen abundance relative to hydrogen (O/H) estimates in H II regions located in the solar neighborhood and those derived through the weak interstellar O I \( \lambda 1356 \) line towards the stars (see Pilyugin 2003 and references therein). Moreover, a consonance has been found between oxygen abundances obtained for SFs and B-type stars in the Milky Way and other nearby galaxies (see Toribio San Cipriano et al. 2017 and references therein). However, determination of \( T_e \) requires measurements of auroral emission lines (e.g., [O II] \( \lambda 4363 \), [N II] \( \lambda 5755 \), [S II] \( \lambda 6312 \)), which are generally weak (about 100 times weaker than H β) in the spectrum of objects with high metallicity and/or low excitation (e.g., van Zee et al. 1998; Díaz et al. 2007; Dors et al. 2008). To circumvent this limitation of the \( T_e \)-method,
Pagel et al. (1979), following the original idea of Jensen et al. (1976), proposed the use of the $R_{23}=([\text{O} \text{~III}]+3726 + \lambda\lambda3729+\text{[O} \text{~II}]+4959+5007)/\text{H} \beta$ line ratio as $O/H$ abundance indicator for SFs. After the aforementioned pioneering work, several authors have proposed calibrations for SFs between $R_{23}$ and the $O/H$ abundance as well as considerations for other line ratios (for a review see Lopez-Sanchez & Esteban 2010). Basically, there are two ways to obtain a calibration between strong emission line ratios and $O/H$ (a metallicity tracer), i.e., assuming predictions from photoionization models (e.g., McEachern 1991; Kewley & Dopita 2002) and by using observational emission lines and $O/H$ abundance values derived from $T_e$-method (e.g., Storchi-Bergmann et al. 1994; Pilyugin 2000, 2001; Yin et al. 2007; Marino et al. 2013; Jiang et al. 2019). This method of utilizing calibration to estimate elemental abundances is known as strong-line method. It has been established that, for SFs, the majority of the strong-line methods based on theoretical models overestimate the $O/H$ abundance as compared to the results obtained from the $T_e$-method (e.g., Yin et al. 2007), where the discrepancies are in order of 0.2-0.3 dex (Lopez-Sanchez & Esteban 2010).

In comparison with SFs, there are few abundance estimates for AGNs derived from the $T_e$-method in the literature. In fact, it appears that most complete abundance determinations for AGNs derived from the $R_{23}$ and the $O/H$ abundance as well as considerations for other line ratios (for a review see Lopez-Sanchez & Esteban 2010). Basically, there are two ways to obtain a calibration between strong emission line ratios and $O/H$ (a metallicity tracer), i.e., assuming predictions from photoionization models (e.g., McEachern 1991; Kewley & Dopita 2002) and by using observational emission lines and $O/H$ abundance values derived from $T_e$-method (e.g., Storchi-Bergmann et al. 1994; Pilyugin 2000, 2001; Yin et al. 2007; Marino et al. 2013; Jiang et al. 2019). This method of utilizing calibration to estimate elemental abundances is known as strong-line method. It has been established that, for SFs, the majority of the strong-line methods based on theoretical models overestimate the $O/H$ abundance as compared to the results obtained from the $T_e$-method (e.g., Yin et al. 2007), where the discrepancies are in order of 0.2-0.3 dex (Lopez-Sanchez & Esteban 2010).

In comparison with SFs, there are few abundance estimates for AGNs derived from the $T_e$-method in the literature. In fact, it appears that most complete abundance determinations for AGNs based on $T_e$-method were carried out by Osterbrock & Miller (1975), who derived the He, O, N, Ne, and Fe abundances, in relation to the hydrogen, in the gas phase of 3C 405 (Cygnus A). The majority of the other studies (e.g., Dors et al. 2015, 2020b; Izotov & Thuan 2008) have been focused on determining only the $O/H$ abundance and a few for the $N/H$ (e.g., Flury & Moran 2020). Furthermore, for the strong-line method based on narrow optical lines of AGNs, there are only theoretical calibrations proposed by Storchi-Bergmann et al. (1998) as well as semi-empirical calibrations proposed by Castro et al. (2017), Carvalho et al. (2020) and Dors et al. (2021). These calibrations are primarily based on photoionization models, which may have some uncertainties. Firstly, the foregoing AGN calibrations consider lines emitted by oxygen and nitrogen, so it is important to assume a correct relation between $O$ and $N$ in the models (Pérez-Montero & Contini 2009). However, the $N/H$ abundance is barely known in AGNs. In fact, Dors et al. (2017b), who used detailed photoionization models to reproduce narrow optical (3000 < $\lambda$ (Å) < 7000) emission lines of a sample of AGNs, presented the first quantitative nitrogen abundance determination for a small sample of 44 Seyfert 2 nuclei in the local universe ($z$ < 0.1; see also Hamann et al. 2002; Contini 2017; Pérez-Montero et al. 2019; Flury & Moran 2020). Secondly, photoionization models are subject to intrinsic uncertainties, e.g., all relevant physical processes are not treated correctly, inaccurate atomic data use, spherical geometry consideration, etc. (see Netzer & Ferland 1984; Viegas 2002; Kennicutt et al. 2003).

Recently, Dors et al. (2020b) investigated the discrepancy between $O/H$ abundance estimations for narrow-line regions (NLRs) of Seyferts 2 derived by using $T_e$-method and those derived from photoionization models. These authors found that the derived discrepancies are mainly due to the inappropriate use of the relations between temperatures of the low ($T_2$) and high ($T_3$) ionization gas zones derived for $\text{H} \text{~II}$ regions in AGN chemical abundance studies. In addition, Dors et al. (2020b), using a photoionization model grid, derived a new expression for the $t_2-t_3$ relation valid for Seyfert 2 nuclei which reduces the $O/H$ discrepancies between the abundances obtained from strong-line methods and those derived from $T_e$-method by $\sim$0.4 dex. This new methodology, combined with the very large sample of spectroscopic data made available by the Sloan Digital Sky Survey (SDSS, York et al. 2000), will help to build an empirical calibration for AGNs, which is not available in the literature reviewed thus far.

Following from above, the emission-line intensities of the SDSS-DR7 (Abazajian et al. 2009) measured by the MPA-JHU group$^1$ and the methodology proposed by Dors et al. (2020b) are used in this study to calculate the $O/H$ abundance for a sample of Seyfert 1 and 2 nuclei. Thereafter, following the methodology considered by Pilyugin (2000, 2001) and the same supposition for SFs – the strong oxygen lines $[\text{O} \text{~II}]+3726$, 3729 Å, $[\text{O} \text{~III}]+4959, 5007$, $\lambda \lambda 3726, 3729$, and $[\text{O} \text{~III}]$, contain the necessary information required to accurately derive the $O/H$ abundance (McGaugh 1991) – we obtain a bi-dimensional empirical calibration between the $R_{23}$ and $P=(O \text{~III}]+4959 + 5007/H \beta)/R_{23}$ line ratios and $O/H$ abundance, valid for AGNs. The present study is organized as follows. In Section 2, the observational data and the methodology used to estimate the oxygen abundance are presented. The resulting calibration and the discussion are presented in Sects. 3 and 4, respectively. Finally, the conclusion of the outcome is given in Sect. 5.

2 METHODOLOGY

To obtain a calibration between strong oxygen emission lines and the $O/H$ abundance for AGNs, we selected from the SDSS DR7 spectroscopic data of confirmed sample of types 1 and 2 Seyfert nuclei. These data were used to calculate the $O/H$ abundance through the $T_e$-method and, afterwards, an empirical calibration was derived. In what follows, each one of the procedures mentioned above is described.

2.1 Observational data

We used optical emission-line intensities of Seyferts 1 and 2 nuclei taken from the Sloan Digital Sky Survey (SDSS, Abazajian et al. 2009) DR7 and presented in Dors et al. (2020a) (hereafter Paper I). From these data, we considered only the intensities (in relation to $\text{H} \beta$) of the emission lines $[\text{O} \text{~II}], [\text{O} \text{~III}], [\text{N} \text{~II}], [\text{S} \text{~II}]$, $\lambda \lambda 6584, 6716$, and $\lambda \lambda 6731, 6716$. The lines measurements were carried out by the MPA/JHU group and they are reddening corrected (see Paper I).

The Seyferts 1 and 2 classifications were obtained by cross-correlation between the identification of each object in the SDSS data and in a catalogue provided by NED/IPAC$^2$ (NASA/IPAC Extragalactic Database). Here, we only considered objects for which the $[\text{O} \text{~III}]$ intensity line has a measurement error of less than 50% of its intensity. Thereafter, to minimize the contribution of SF emission to the observed AGN fluxes, we only considered objects which are more than

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used spectroscopic data of AGNs (a higher excitation than Seyfert 2 nuclei. Zhang et al. (2008) ties of distinct Seyfert classes, found that Seyfert 1 nuclei have Schmitt (1998), who compared optical emission line intensities effects on metallicity/abundance estimation.

Black lines, taken from Kewley et al. (2001) and represented by Eqs. 1 and 2, separate objects ionized by massive stars from those ionized by AGN-like mechanism. Error bar, in the left panel, represents the typical uncertainty (0.1 dex) in AGN emission-line ratio measurements (e.g., Kraemer et al. 1994).

0.1 dex (see Kewley et al. 2006) above the demarcation lines proposed by Kewley et al. (2001) to separate AGNs from SFs, where objects with

\[
\log([O\text{iii}]\lambda5007/H\beta) > \frac{0.61}{\log([Ni\text{ii}]\lambda6584/H\alpha) - 0.47} + 1.19
\]

and

\[
\log([O\text{iii}]\lambda5007/H\beta) > \frac{0.61}{\log([Si\text{ii}]\lambda6725/H\alpha) - 0.32} + 1.30
\]

are classified as AGNs. The [Si\text{ii}]\lambda6725 Å line represents the sum of the [Si\text{ii}]\lambda6717 Å and [Si\text{ii}]\lambda6731 Å lines. This procedure resulted in a sample of 91 objects (35 Sy2 and 56 Sy1) with redshifts \(z \lesssim 0.4\). The reader is referred to Paper I for a complete description about the observational data and aperture effects on metallicity/abundance estimation.

In contrast to previous studies (Carvalho et al. 2020; Dors et al. 2020a,b, 2021), Seyfert 1 nuclei are considered in the present work. According to the unification scheme, the continuum source and the Broad Line Region (BLR) are blocked by a dusty torus in Seyfert 2 (Antonucci 1993). However, it is not clear if the torus effects extend to NLRs. For instance, Schmitt (1998), who compared optical emission line intensities of distinct Seyfert classes, found that Seyfert 1 nuclei have a higher excitation than Seyfert 2 nuclei. Zhang et al. (2008) used spectroscopic data of AGNs (\(z < 0.3\)) from the SDSS DR4 (Blanton et al. 2017) and found that Seyferts 1 and 2 have different distributions in the BPT (Baldwin et al. 1981) [O\text{iii}]\lambda5007/H\beta versus [Ni\text{ii}]\lambda6584/H\alpha diagram. If Seyferts 1 and 2 of our sample show this difference in diagnostic diagrams some potential biases could be introduced in the calibrations based on emission line intensities from both kinds of AGNs. In order to verify this, the diagnostic diagrams [O\text{iii}]\lambda5007/H\beta (ordinate) versus [Ni\text{ii}]\lambda6584/H\alpha (abscissa) and [Si\text{ii}]\lambda6716 + \lambda6731/H\alpha (abscissa) containing our sample of objects as well as the criteria to separate SFSs from AGNs proposed by Kewley et al. (2001), i.e., Equations 1 and 2, are shown in Figure 1. In this figure, the line ratios of Seyferts 1 and 2 are indicated by different colours. It can be seen in Fig. 1 that Seyferts 1 and 2 occupy the same regions in both diagrams. Since the position of an object in diagnostic diagrams is driven by some physical parameters of the gas phase (e.g., Feltre et al. 2016), probably, these objects have similar ionization degree and metallicity. This result is apparently in disagreement with the findings obtained by Zhang et al. (2008), however, it is worthwhile to note that these authors considered a sample of objects with wider range of ionization, while we selected only objects which have the [O\text{iii}]\lambda4363 Å line measured, i.e., objects with high excitation degree (see also Flury & Moran 2020).

Another concern in our analysis is about the electron density (\(N_e\)) of Seyfert 1, because the gas phase in this object class can reach high \(N_e\) values and some lines emitted by transitions between levels with low critical density \(N_c\), such as [O\text{ii}]\lambda3726 Å, \(\lambda3729\) Å (\(N_c = 10^{3.7}\) cm\(^{-3}\), Vaona et al. 2012) can suffer collisional de-excitation, resulting in incorrect abundance estimates. To verify the range of electron density of our sample, the \(N_e\) value for each object was derived through the relation between this parameter with the [S\text{ii}]\lambda6717/[S\text{ii}]\lambda6731 line ratio by using the IRAF code (Tody 1986; De Robertis et al. 1987; Shaw & Dufour 1995) and assuming an electron temperature value of 10000 K. In Fig. 2, left panel, the \(N_e\) distribution and the average value for our

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{figure1}
\caption{Diagnostic diagrams \(\log([O\text{iii}]\lambda5007/H\beta)\) versus \(\log([Ni\text{ii}]\lambda6584/H\alpha)\) and versus \(\log([Si\text{ii}]\lambda6725/H\alpha)\). Points represent objects of our sample (see Sect. 2.1), where objects classified as Seyfert 1 and 2 are represented by different colours, as indicated. Black lines, taken from Kewley et al. (2001) and represented by Eqs. 1 and 2, separate objects ionized by massive stars from those ionized by AGN-like mechanism. Error bar, in the left panel, represents the typical uncertainty (0.1 dex) in AGN emission-line ratio measurements (e.g., Kraemer et al. 1994).}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{figure2}
\caption{Histogram containing the distributions of electron density \(N_e\) (left panel) and reddening correction \(C(H\beta)\) (right panel) for our sample of objects (see Sect. 2.1). \(N_e\) is calculated through the emission line ratio \([Si\text{ii}]\lambda6717/[Si\text{ii}]\lambda6731\).}
\end{figure}
sample of Seyferts 1 and 2 are shown. It can be seen that both Seyfert types present similar distributions and average values of $N_e$. The maximum $N_e$ value (2250 cm$^{-3}$), derived for a Seyfert 1 object, is a factor of $\sim 2$ lower than the lowest critical density of the lines considered in the present analysis. Also in Fig. 2, right panel, the reddening correction $C$(H$\beta$) distributions and the average values of these for our sample of objects are shown. We notice very similar distributions and average values for both Seyferts 1 and 2. From the analysis above, one can assume that the emission lines considered in this work are emitted in the gas phase of Seyferts 1 and 2 with similar physical conditions.

Typical uncertainty in AGN emission lines measurements considered in the present analysis is in order of 0.1 dex (e.g., Kraemer et al. 1994).

2.2 O/H derivation

To calculate the abundance of oxygen in relation to hydrogen (O/H) through the $T_e$-method, we follow the same methodology developed by Dors et al. (2020b) for AGNs. This method is an adaptation of the $T_e$-method for H II regions but differing only in the $t_2$-$t_3$ assumed relation. Thus, hereafter referred to as $T_e$-method (AGN).

Firstly, using the observational data for each object, the temperature for the high $t_3$(obs.) ionization gas zone, i.e., for the nebular region where O$^{2+}$ and ions with similar ionization potentials (e.g., Ne$^{2+}$, S$^{2+}$) are located, is derived from the expression:

$$t_3(\text{obs.}) = 0.8254 - 0.0002415 \times R_{\text{O3}} + 47.77 \times \frac{1}{R_{\text{O3}}} ,$$

where $R_{\text{O3}} = \lambda \text{[O III]} (5007 \, \text{Å}) / \lambda \text{[N II]} (6583 \, \text{Å})$ and $t_3(\text{obs.})$ is in units of 10$^4$ K. The $t_3$($\text{obs.}$) – $R_{\text{O3}}$ relation depends on the atomic data used to derive the emissivities of the emission lines involved and it suffers some uncertainties. In fact, different $t_3(\text{obs.})$ – $R_{\text{O3}}$ relations have been proposed by several authors along the years (e.g., Pagel et al. 1992; Izotov et al. 2006; Hägele et al. 2008; Pérez-Montero 2014) and different temperature values in order of some hundreds, for a given $R_{\text{O3}}$ value, have been derived when distinct relations are considered. The Eq. 3 is valid for the range $30 \lesssim R_{\text{O3}} \lesssim 700$ with correspondingly temperature range of $0.70 \lesssim t_3(\text{obs.}) \lesssim 2.3$. In this study, only objects with $t_3(\text{obs.})$ in this range of values were considered.

Since it is not possible to estimate the temperature for the low $t_2$(obs.) ionization gas zone, i.e., for the nebular region where O$^+$ and ions with similar ionization potentials (e.g., S$^+$, N$^+$) are located, due to the absence of the [N II]$\lambda 5755$ and [O II]$\lambda 7330$ observational line intensities, the following theoretical relation between $t_2$-$t_3$ has been adopted:

$$t_2 = (a \times t_3^2) + (b \times t_3) + (c \times t_3) + d,$$

where $a = 0.17$, $b = -1.07$, $c = 2.07$, and $d = -0.33$ and $t_2$ is in units of 10$^4$ K. This $t_2$-$t_3$ relation was derived by Dors et al. (2020b) based on the photoionization model results built by Carvalho et al. (2020). This grid of models takes into account a wide range of nebular parameters, which are summarized below:

(i) Spectral Energy Distribution (SED): It is made up of two parts that are added together. The first is a Big Bump component that peaks at $\approx 1$ Ryd and is parametrized by the temperature of the bump, which is assumed to be $5 \times 10^5$ K. The second component is an X-ray power law with spectral index $\alpha_{\text{ox}} = -1$ which is only added for energies greater than 0.1 Ryd to prevent it from extending into the infrared region. The $\alpha_{\text{ox}}$ spectral index defined as the slope of a power law between 2 keV and 2500 Å was assumed to vary from $-0.8$ to $-1.4$ (see Krabbe et al. 2021 for a detailed description of this SED).

(ii) Metallicity: Values for the metallicity in relation to the solar ($Z/Z_\odot$) = 0.2, 0.5, 0.75, 1.0, 1.5 and 2.0 were assumed in the models. All the abundances for the heavy metals were linearly scaled with the solar abundance$^3$ with the exception of nitrogen where we adopted the relation $\log(N/O) = 1.29 \times [12 + \log(O/H)] - 11.84$.

(iii) Electron density ($N_e$): The $N_e$ was considered to be constant along the radius of AGN and the values 100, 500 and 3000 cm$^{-3}$ were assumed.

(iv) Ionization parameter: The range of the logarithm of the ionization parameter was considered to be $-4.0 \leq \log U \leq -0.5$, with a step of 0.5 dex.

The $t_2$ and $t_3$ values predicted by the models correspond to the mean temperature for O$^+$ and O$^{2+}$ over the nebular AGN radius times the electron density. Therefore, the $t_2$(obs.) and $t_3$(obs.) temperatures, calculated through integrated measurements of the flux of observational emission lines, could differ from those predicted by the models. In Riffel et al. (2021), the relation $t_2$-$t_3$ (Eq. 4) was compared with direct estimations of electron temperatures, calculated from observational auroral emission lines, for a small sample of AGNs (11 objects) and a good agreement was found between them. However, these authors showed that when outflowing gas is present in AGNs, a large deviation of direct electron temperature values from those derived through Eq. 4 is obtained.

Additionally, the O$^{2+}$/H$^+$ and O$^+$/H$^+$ ionic abundances were estimated using the following relations:

$$12 + \log \left( \frac{\text{O}^{2+}}{\text{H}^+} \right) = \log \left( \frac{1.33 \times I(5007)}{I(\text{H}\beta)} \right) + 6.144$$

or

$$12 + \log \left( \frac{\text{O}^+}{\text{H}^+} \right) = \log \left( \frac{I(3727)}{I(\text{H}\beta)} \right) + 5.992$$

where $n_e$ is the electron density $N_e$ in units of 10$^4$ cm$^{-3}$. For each object, the value of $t_3$(obs.) is obtained by using the Eq. 3. The value of $t_2$ is derived by applying $t_3$(obs.) in the theoretical relation represented by Eq. 4. The same procedure is usually carried out in H II region abundance studies in scenarios where $t_2$(obs.) can not be derived (e.g. Garnett 1992; Kennicutt et al. 2003.)

Finally, the total oxygen abundance (O/H) was derived.

$^3$ The solar composition assumed in the Cloudy code is listed in http://web.physics.ucsb.edu/~phys203/w2014/hazy1_15.pdf.
assuming

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

(7)

where ICF(O) is the Ionization Correction Factor for oxygen which takes into account the contribution of unobserved oxygen ions (e.g., O\textsuperscript{+}). To derive ICF(O) it is necessary to have the He\textsuperscript{2+}/H\textsuperscript{+} and He\textsuperscript{+}/H\textsuperscript{+} abundances (e.g., Torres-Peimbert & Peimbert 1977; Izotov et al. 2006), which it is not possible to derive because the helium recombination line \(\lambda 4686\ \text{Å}\) is not available in our data sample. Therefore, we assume for all objects an average value of 1.20 for ICF(O), which translates into an abundance correction of 0.1 dex, i.e., in order of the uncertainty derived in \(T_e\)-method estimates (e.g., Kennicutt et al. 2003; Hägele et al. 2008). This value represents the average for the values derived by Dors et al. (2020a), who found ICF(O) values ranging from 1.00 to 1.80 for a sample of local Seyfert 2.

We assume the typical uncertainty in the O/H estimates to be in the order of 0.1 dex, as estimated in Flury & Moran (2020).

3 O/H CALIBRATION

To calibrate a certain line ratio with the abundance, initially, it is necessary to analyse if the line ratio being considered has a secondary dependence on other physical parameters, usually, on the ionization degree of the gas. In the case of the \(R_{23}\) line ratio, McGaugh (1991) suggested that its use as O/H indicator for SFs must be conciliated with the effective temperature of the hottest ionizing stars of SFs (see dependence on the ionization degree of the gas and/or on the parameters, usually, on the ionization parameter \((U)\) of the gas \([U \propto Q(H)]\). Following Pilyugin (2001), we adopt the line ratio defined as

\[
P = \frac{[(O\text{\textsc{iii}})\lambda 4959 + 5007]}{H\beta} / R_{23}
\]

(8)
as an indicator of the hardness of the ionizing radiation. In order to verify the dependence of \(R_{23}\) on the hardness of the ionizing radiation by using our data, in Fig. 3, the oxygen abundance derived through the \(T_e\)-method (AGN) for each object of our data sample versus the corresponding \(R_{23}\) value is shown. In this figure, the colour bars indicate objects with different P values while objects classified as Seyferts 1 and 2 are represented by different symbols. We notice the following:

(i) Seyferts 1 and 2 show similar O/H abundances and P values, and

(ii) the O/H-\(R_{23}\) relation for AGNs is dependent on P, hence objects with lower P values are located at the top-left region in Fig. 3.

The fact that O/H-\(R_{23}\) relation is dependent on P indicates that a bi-parametric calibration \(O/H=f(R_{23}, P)\) is more accurate for AGNs instead of \(O/H=f(R_{23})\). In view of this, the \(R_{23}, P\) and 12+\log(O/H) values are shown in Fig. 4. A fit to the points, by using the least square method, results in the following expression

\[
Z = (-1.00 \pm 0.09)P + (0.036 \pm 0.003)R_{23} + (8.80 \pm 0.06),
\]

(9)

where \(Z \equiv 12 + \log(O/H)\). We refer to this approach as the D-method.
4 DISCUSSION

The estimation of O/H abundance through strong emission lines was first proposed by Jensen et al. (1976). Based on the behaviour of the intensity of optical emission line ratios across the disk of some nearby spiral galaxies, mainly caused by radial abundance gradients as originally proposed by Searle (1971), Jensen et al. (1976) suggested that the \([\text{O} \text{II}]/\text{H} \beta\) and \([\text{N} \text{II}]/\text{H} \alpha\) line ratios can be chemical enrichment indicators. Between these two line ratios, these authors posited that \([\text{O} \text{II}]/\text{H} \beta\) shows some advantages over \([\text{N} \text{II}]/\text{O} \text{II}\), however, any calibration between these line ratios and O/H can be obtained. Thereafter, Pagel et al. (1979) introduced the \(R_{23}\) line ratio as an O/H abundance indicator. These authors, by using O/H estimates based on the \(T_e\)-method for the disk of H II regions and predictions from theoretical models built by Sarazin (1976), Shields & Searle (1978) and Stasińska (1978), proposed the first calibration between strong line ratios and O/H abundance for SFs (for other pioneering papers see, for instance, Alloin et al. 1979; Stasińska et al. 1981; Shaver et al. 1983; Edmunds & Pagel 1984). The first empirical calibration between strong emission lines and O/H abundances derived through the \(T_e\)-method seems to have been proposed by Storchi-Bergmann et al. (1994)\(^4\), who presented a SF calibration using the \(\text{N}2/([\text{N} \text{II}]/\text{H} \alpha)\) line ratio as abundance indicator (see also Pettini & Pagel 2004; Shi et al. 2007; Yin et al. 2007; Liang et al. 2007; Pilyugin et al. 2012; Marino et al. 2013; Morales-Luis et al. 2014; Jones et al. 2015; Sanders et al. 2016; Brown et al. 2016; Pilyugin & Grebel 2016; Bian et al. 2018; Jiang et al. 2019; Gburek et al. 2019).

In regard to AGNs, the first strong emission line calibrations were proposed by Storchi-Bergmann et al. (1998), who by using photoionization model results, proposed two bi-dimensional calibrations among \(\text{N}2/\text{[O} \text{II}]/\text{H} \beta\), \(\text{N}2/\text{[O} \text{I}]/\text{H} \beta\) narrow line ratios and O/H abundance. Thereafter, theoretical (e.g., Dors et al. 2014, 2015) and semiempirical (e.g., Castro et al. 2017; Carvalho et al. 2020; Dors et al. 2021) calibrations as well as bayesian-like approach to derive AGNs chemical abundances (e.g., Thomas et al. 2018; Mignoli et al. 2019; Pérez-Montero et al. 2019) have been proposed. Recently, Flury & Moran (2020) developed an approach for estimating abundances of heavy elements, which involves a reverse-engineering of the \(T_e\)-method and considering the \([\text{O} \text{II}]/\text{H} \beta\) versus \([\text{N} \text{II}]/\text{H} \alpha\) diagnostic diagram. This methodology, which is only based on strong emission lines, consistently recovers O/H and N/H abundance values calculated through the \(T_e\)-method with an uncertainty of about 0.2 dex. The method proposed by Flury & Moran (2020), although has been classified by them as semiempirical calibration, it is the first AGN calibration which takes into account O/H as reference values derived through the \(T_e\)-method instead of photoionization models.

In the present work we proposed an empirical calibration for AGNs between \(R_{23}\) and P line ratios with the O/H abundance, which is represented by a simple bi-dimensional expression (Eq. 9). In what follows this approach (D-method) is a somewhat thoroughly discussions of its implications relative to other known methods in AGNs studies. First of all, there are some concerns on the abundance determinations in AGNs via \(T_e\)-method. For instance, Stasinska (1984) compared observational emission line ratio intensities of a sample of Seyfert 2 AGNs with those predicted by photoionization models. This author argued that the \([\text{O} \text{II}]/(\text{H} \lambda 4959+\text{H} \lambda 5003)/\text{H} \lambda 4363\) ratio is enhanced by gas emission with very high electron density which precludes any abundance estimations in AGNs via \(T_e\)-method (see also Nagao et al. 2001). In fact, direct estimates of O/H abundance based on the same methodology of the \(T_e\)-method for SFs applied to AGN studies produces unreal low (subsolr) O/H values (see Figure 6 of Paper I) for most part of objects. However, these low values are not due to electron density effects but as a consequence of inappropriate use of the relations between temperatures of the low and high ionization gas zones derived for SFs in AGN chemical abundance studies (see Dors et al. 2020b; Riffel et al. 2021). Therefore, our O/H estimates following the adaptation of the \(T_e\)-method for AGNs by Dors et al. (2020b), in principle, are correct and can be used to derive empirical calibrations based on strong emission lines of AGNs. In fact, by inspecting Fig. 3 carefully, it can be seen that most parts of the sample present O/H abundance values close to or over the solar abundance \([12+\log(O/H)] = 8.69\), Allende Prieto et al. (2002) and few objects present equally subsolar O/H values (see also Groves et al. 2006).

Another concern in that the value of an abundance indicator must not differ substantially across the area of the object type for which it will be considered in the estimation of abundances. Otherwise, the value of the abundance indicator measured from integrated flux might not be representative of the entire object. For SFs, Oey & Shields (2000) found no spatial variation of \(R_{23}\) across H II regions with distinct morphology (see also Oey & Shields 2000; Pilyugin 2001; Relaño et al. 2010; Mao et al. 2018). In order to verify this in our case, the logarithm of \(R_{23}\) as a function of the distance (in arcsec) from the centre of three AGN nuclei Mrk573, Mrk34 and Mrk78, whose data were taken from Revalski et al. (2018b), Revalski et al. (2018b) and Revalski et al. (2021), respectively, is shown in Fig. 5. Although a small decreasing of \(R_{23}\) is noted at external region (at distances larger than 2 arcsec or \(\sim 1.5\) kpc) from the centre of Mrk78, we notice that \(R_{23}\) is relatively constant within the three objects. Therefore, similar to H II regions, \(R_{23}\) is a robust oxygen abundance indicator for AGNs.

In Fig. 6, bottom panel, a comparison between oxygen abundance \([12+\log(O/H)]\) derived by using the D-method (Eq. 9) with estimations from the \(T_e\)-method (AGN) is performed. In Fig. 6, top panel the difference (D) between these two methods versus the \(T_e\)-method (AGN) estimates is shown. There is a good agreement between the estimates for a wide range of O/H abundances, with D being approximately zero. However, we notice that the D-method (over) underestimates the O/H for the very (low) high metallicity regimes. In spite of the above observations, more objects with low and high metallicities are necessary to obtain a better conclusion. A comparison between O/H estimates derived assuming a vast number of methods available in the literature is presented in Paper I and it is repeated here.

Finally, we proceed with a comparison between our AGN O/H calibration and that of SFs. Particularly, this comparison can provide important pieces information on the SED, physical processes in the gas phase of AGNs and how they

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\(^4\) For a review on empirical calibration for SFs and their limitations see Kewley et al. (2019).
Figure 5. Logarithm of $R_{23}$ as a function of distance (in arcsec) from the centre of three AGNs, as indicated. The data for Mrk 573, Mrk 34 and Mrk 78 were taken from Revalski et al. (2018a), Revalski et al. (2018b) and Revalski et al. (2021), respectively. For Mrk 573, Mrk 34 and Mrk 78 1 arcsec corresponds to 349.1, 1007.7 and 747.4 pc in the galactic plane of each object, respectively (Revalski et al. 2021).

Figure 6. Bottom panel: Comparison between oxygen abundances [in units of $12 + \log(O/H)$] computed using the observational data described in Sect. 2.1 obtained through the D-method (y-axis, Eq. 9) and $T_e$-method (AGN) (x-axis, see Sect. 2.2). Solid line represents the equality between the estimates. Top panel: Difference ($D = x - y$) between the estimations versus those via $T_e$-method. The dashed area indicates the uncertainty of $\pm 0.1$ assumed in the oxygen abundance estimations (e.g., Denicoló et al. 2002), whilst red line represents a linear regression to these differences whose slope is indicated. The average difference ($<D>$) is indicated.

The empirical calibration

$$12 + \log(O/H) = \frac{R_{23} + 54.2 + 59.45P + 7.31P^2}{6.07 + 6.71P + 0.37P^2 + 0.243R_{23}}$$

(10)

for O/H determinations in SFs with moderately high metallicity [$12 + \log(O/H) \gtrsim 8.2$] proposed by Pilyugin (2001) are shown in Fig. 7. In both calibrations a fixed value of $P=0.70$ is assumed, which is the mean value for our sample of AGNs. Also in Fig. 7, the $R_{23}$ and O/H values derived via $T_e$-method (AGN) for our sample of objects, the semi-empirical calibration derived by Dors & Copetti (2005) and the theoretical calibration (assuming the ionizing parameter $q = 4 \times 10^7$ cm s$^{-1}$) proposed by Kewley & Dopita (2002) are shown. This $q$ value represents an average value from the range of values considered by Kewley & Dopita (2002). It can be seen from Fig. 7 that our calibration and the $T_e$-method (AGN) estimates have a different behaviour between O/H-$R_{23}$ relative to the calibrations for SFs, in the sense that $R_{23}$ increases with the increase in O/H. In SFs, for the metallicity regime considered in Fig. 7, the decrease in $R_{23}$ with the increase in O/H is mainly due to the decrease in the electron temperature and electrons with enough energy to excite the levels involved in producing the optical collisional excitation lines (CELs), in the case, $R_{23}$. Moreover, as increase in the metallicity occur, effects of line blanketing by metal lines in the atmosphere of the ionizing star(s) become more pronounced (e.g., Zastrow et al. 2013), resulting in softer SED in stars and, consequently, decreasing $R_{23}$. A decrease in the ionization parameters ($U$) with the increase of metallicity (or O/H) can also contribute to a decrease in $R_{23}$. However, the dependence relations between these parameters is controversial in the literature (see Zinchenko et al. 2019 and references therein).

For AGNs, probably, SEDs are not affected by line blanketing or the NLRs are not significantly modified by changes in the SED, producing a direct relation between O/H and $R_{23}$. Ludwig et al. (2012) presented spectroscopic observations of 27 AGNs with some of the lowest black hole (BH) masses known and compared the emission line ratios and SEDs of these objects with that of AGNs with higher-mass BHs. These authors found evidence for steeper far-UV spectral slopes in lower-mass systems in comparison with higher mass BHs. However, Ludwig et al. (2012) found similar NLR emission lines in objects with distinct BH masses. Also, Stern & Laor (2013) showed that parameters other than the ionizing continuum slope, such as metallicity, density and ionization parameter, dominate the scatter in the BPT diagrams. Regarding the $U$-O/H dependence for AGNs, Pérez-Montero et al. (2019), based on bayesian comparison between optical emission-line intensity ratios of a sample of AGNs and photoionization model results, found no correlation between these parameters. However, the sample considered by these authors consists of few objects (47 Seyfert 2), therefore, additional analysis is necessary to confirm this result.
The oxygen abundance estimates based on strong emission lines of Seyfert nuclei were investigated. Starting from the idea that the $\lambda\lambda$3726, 3729 and $\lambda$5007 emission lines contain the necessary information to estimate the oxygen abundance in Seyfert nuclei and the $T_e$-method for AGNs, yields reliable abundance values, an empirical abundance in Seyfert nuclei and the $T_e$-method (AGN) for our sample. Our calibration and the one by Pilyugin (2001) are shown for $P=0.7$.

5 CONCLUSIONS

The oxygen abundance estimates based on strong emission lines of Seyfert nuclei were investigated. Starting from the idea that the $[\text{O} \text{II}]\lambda\lambda3726, 3729$ and $[\text{O} \text{III}]\lambda5007$ emission lines contain the necessary information to estimate the oxygen abundance in Seyfert nuclei and the $T_e$-method, adapted for AGNs, yields reliable abundance values, an empirical abundance calibration among $R_{23}$, $P$ and O/H was derived for AGNs. This calibration has been derived by using intensities of emission line ratios from a sample of Seyferts 1 and 2 nuclei, whose data were taken from the SDSS DR7 and the lines measurements carried out by the MPA/JHU group. No variation of $R_{23}$ is observed inside AGNs, showing that this line ratio is a good O/H abundance indicator. The derived O/H=$f(R_{23}, P)$ relation produces, for a wide range of metallicities $[8.0 < 12 + \log(O/H) < 9.2]$, oxygen abundance values similar to those estimated via $T_e$-method (AGN). In contrast to star-forming regions, the $R_{23}$ line ratio increases with the increase of O/H in AGNs, indicating that the hardness of ionizing radiation is not affected by the metallicities in these kinds of objects or NLRs are not significantly modified by changes in the SED due to metallicity variations.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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Figure 7. Oxygen abundances [in units of $12 + \log(O/H)$] versus $R_{23}$. Red, cyan and pink lines represent SF calibrations proposed by Pilyugin (2001) (P-method, Eq. 10), Dors & Copetti (2005) (DC05) and Kewley & Dopita (2002) (KD02), respectively, as indicated. Blue line represents our calibration (Eq. 9). Points represent estimates via $T_e$-method (AGN) for our sample. Our calibration and the one by Pilyugin (2001) are shown for $P=0.7$. 
