

# On the central abundances of Active Galactic Nuclei and Star-forming Galaxies

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## ABSTRACT

We examine the relation between oxygen abundances in the narrow-line regions (NLRs) of active galactic nuclei (AGNs) estimated from the optical emission lines through the strong-line method (the theoretical calibration of Storchi-Bergmann et al. 1998), via the direct  $T_e$ -method, and the central intersect abundances in the host galaxies determined from the radial abundance gradients. We found that the  $T_e$ -method underestimates the oxygen abundances by up to  $\sim 2$  dex (with average value of  $\sim 0.8$  dex) compared to the abundances derived through the strong-line method. This confirms the existence of the so-called “temperature problem” in AGNs. We also found that the abundances in the centres of galaxies obtained from their spectra through the strong-line method are close to or slightly lower than the central intersect abundances estimated from the radial abundance gradient both in AGNs and Star-forming galaxies. The oxygen abundance of the NLR is usually lower than the maximum attainable abundance in galaxies ( $\sim 2$  times the solar value). This suggests that there is no extraordinary chemical enrichment of the NLRs of AGNs.

**Key words:** galaxies: general – galaxies: evolution – galaxies: abundances – galaxies: formation – galaxies: ISM

## 1 INTRODUCTION

Active galactic nuclei (AGNs) and star-forming regions show prominent emission lines of heavy elements that can be easily measured, even for objects at large redshifts. The intensity of these emission lines depends on the metallicity, which makes them convenient tracers of the chemical evolution of the Universe.

The abundance of a given element in AGNs and in star-forming regions can be derived from measurements of the relative strengths of the emission lines of its ions and of the electron temperature and density of the gas (Osterbrock & Ferland 2006). Oxygen has been generally used as tracer of the metallicity ( $Z$ ) of star-forming regions (e.g., Tremonti et al. 2004; Thuan et al. 2010; Nagao et al. 2006a) and of AGNs (Izotov et al. 2010; Groves et al.

2006, among others). Methods for the abundance determinations in star-forming regions have been discussed in many papers (e.g., Stasińska 2004). The consensus is that *bona-fide* determinations of  $Z$  are only obtained by using the  $T_e$ -method (Hägele et al. 2006; Hägele et al. 2008). This method is based on the determination of the electron temperature ( $T_e$ ) from the ratios between intensities of two emission lines originating in transitions from two levels with different excitation energies of a same ion, such as the ratios  $[\text{O III}](\lambda 4959 + \lambda 5007)/\lambda 4363$ ,  $[\text{S III}](\lambda 9069 + \lambda 9532)/\lambda 6312$ , and  $[\text{N II}](\lambda 6548 + \lambda 6584)/\lambda 5755$  (see Osterbrock & Ferland 2006.) Unfortunately, these line ratios cannot easily be measured in distant objects and/or in objects with low excitation (e.g., Bresolin et al. 2005), preventing the use of the  $T_e$ -method.

Therefore, the oxygen abundances in H II regions are usually estimated using the strong-line method pioneered by Pagel et al. (1979) and Alloin et al. (1979). The princi-

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pal idea of the strong-line method is to establish the relation between the (oxygen) abundance in an H II region and some combination of the intensities of strong emission lines in its spectrum, i.e., the position of the objects in the strong-line diagram is calibrated in terms of abundance. Therefore such a relation is often called a “calibration”. The calibrations of strong emission lines in terms of the oxygen abundances can be accomplished by three methods: (i) theoretical calibrations based on photoionization models (e.g., Kewley & Dopita 2002; Dors et al. 2011; Dors & Copetti 2005), (ii) empirical calibrations based on H II regions with abundances derived through the  $T_e$ -method (Pilyugin 2000, 2001; Pilyugin & Thuan 2005; Pérez-Montero & Contini 2009, among others), and (iii) hybrid calibrations where both photoionization models and H II regions with  $T_e$ -based abundances are used as calibration data points (Pettini & Pagel 2004). The metallicity scales produced by these different methods may differ from each other by up to 0.7 dex (Kewley & Ellison 2008).

Here we use the metallicity scale in H II regions defined by the abundances determined through the classical  $T_e$ -method. This is because in the  $T_e$  method the physical conditions in the nebulae, which are essential ingredients in order to calculate the abundance, are derived directly from observations. Otherwise, if the physical conditions and consequently the abundances are derived by models they will be less certain. This is because of the parameters of the model such as the ionizing source, geometry, etc., tend not to be sufficiently realistic (see Dors & Copetti 2005; Kennicutt et al. 2003; Viegas 2002).

AGN metallicities are usually estimated through strong-line theoretical calibrations (e.g., Storchi-Bergmann et al. 1998). Even solar or supersolar abundances have been found. Richardson et al. (2014) established a sequence of photoionization models to reproduce the narrow-line regions (NLRs) of AGN spectra and found that models with a metallicity of  $1.4 Z_\odot$  provide the best agreement with the observational data. Groves et al. (2006) used the photoionization models to analyse the emission lines in the spectra of the NLRs from the Sloan Digital Sky Survey (see Tremonti et al. 2004) and found supersolar metallicities for typical Seyfert galaxies (see also Batra & Baldwin 2014; Du et al. 2014; Wang et al. 2011; Dhanda et al. 2007; Baldwin et al. 2003; Hamann et al. 2002; Storchi-Bergmann et al. 1998; Ferland et al. 1996; Hamann & Ferland 1993, 1992). High metallicities at the centres of spiral galaxies are also obtained by the extrapolation of radial abundance gradients to the central regions (Vila-Costas & Edmunds 1992; Zaritsky et al. 1994; van Zee et al. 1998; Pilyugin et al. 2004, 2007; Gusev et al. 2012, among others).

In contrast, low metallicities in AGNs have been obtained when the  $T_e$  method was used (e.g., Zhang et al. 2013). The disagreement between the abundances obtained through the strong-line methods and through the  $T_e$ -method is the so-called “temperature problem”. On the other hand, Izotov & Thuan (2008) determined the abundances through the  $T_e$ -method in the AGNs in four dwarf galaxies and found metallicities between 0.05 and 0.2 of the solar value, which is a typical abundance of those galaxies. Alloin et al. (1992), also using the  $T_e$ -method, estimated the abundance in the Seyfert 2 nucleus of the galaxy ESO 138 G1 classified as E/S0

(Laubert 1982) and found  $Z \approx 0.4 Z_\odot$ . Thus, the  $T_e$  method seems to produce realistic abundance estimations in the low metallicity range, i.e., the temperature problem seems to disappear at low metallicities. Finding the correct method for the determination of AGN metallicities and establishing a relation between the AGN metallicity and the metallicity of the host galaxy are very important challenges. It should be noted that the AGN metallicity is sometimes adopted as a surrogate metallicity of the host galaxy, mainly at high redshifts (e.g., Dors et al. 2014; Matsuoka et al. 2009; Nagao et al. 2006b).

Nowadays, a large number of measured intensities of emission lines sensitive to the electron temperature are available for AGNs in the literature. This also holds for determinations of oxygen gradients in a large sample of spiral galaxies. This provides the possibility for an analysis of the metallicity determinations in AGNs. The main goals of the current study are: (i) To investigate the discrepancy between AGN abundances derived through the strong-line methods and through the  $T_e$  method. The magnitude of this discrepancy is well known for star-forming regions (Pilyugin 2003; Kewley & Ellison 2008; López-Sánchez & Esteban 2010, among others), however, this problem has received less attention in the case of the NLRs of AGNs. (ii) To compare the abundances of the NLRs of AGNs and nuclear star-forming regions estimated from their spectra and central oxygen abundances of the host galaxies derived from the radial abundance gradients. Differences between these values could be evidence in favour of the existence of gas infall onto the center of a galaxy or extraordinary chemical enrichment of these objects.

The present study is organised as follows. In Section 2 we compare the NLR abundances determined through the  $T_e$ -method and the strong emission-line relations of Storchi-Bergmann et al. (1998, hereafter SB98). We examine the relation between the abundances in the NLRs estimated from their optical emission-line spectra and the central intersect abundances in the host galaxies determined from the radial abundance gradients in Section 3. The conclusions are given in Section 4.

## 2 ABUNDANCE DETERMINATIONS IN NLRs: $T_E$ -METHOD VS. RELATIONS BY SB98

### 2.1 AGN sample

Intensities of narrow emission lines of AGNs were compiled from the literature. Our selection criterion was the presence of flux measurements of the narrow optical emission lines [O II] $\lambda$ 3727, [O II] $\lambda$ 4363, H $\beta$ , [O III] $\lambda$ 5007, H $\alpha$ , [N II] $\lambda$ 6584, and [S II] $\lambda$ 6717,6731. We only considered galaxies whose nuclei were classified as Seyfert 2 (Sy2) and Sy1.9. Sequences of photoionization models, not including the shock gas but only a power law radiation of the ionizing source, are able to reproduce measurements of strong narrow emission lines of Sy2 and Sy1.9 for a large spectral range (e.g., Riffel et al. 2013a; Dors et al. 2012; Groves et al. 2006). Hence, the selection of these AGN types minimises the effects of shock gas excitations and ionizations, which are not considered in our abundance determinations.

We list in Table 1 the identification of the objects, the emission-line intensities (relative to  $H\beta=1.0$ ), the spectral classification taken from the NED<sup>1</sup>, and bibliographic references from which the data were taken. The sample consists of 47 local AGNs (redshift  $z < 0.1$ ) observed with long-slit spectroscopy. In the cases where the reddening correction was not performed in the original works (indicated in Table. 1), we dereddened the emission-lines comparing the observed  $H\alpha/H\beta$  ratio with the theoretical value of 2.86 (Hummer & Storey 1997), obtained for an electron temperature of 10 000 K and an electron density of  $100 \text{ cm}^{-3}$ .

The emission-line flux errors are reported in the original works for only 4 out of the 47 objects of our sample. Therefore the errors are not given in Table 1. Typical errors of the emission-line intensities are about 10 to 20 per cent (e.g., Kraemer et al. 1994), which yield uncertainties in the oxygen abundance estimations of about 0.1 to 0.2 dex (e.g., Rosa et al. 2014; Hägele et al. 2008; Dors et al. 2011; Kennicutt et al. 2003). Hereafter we will assume that the oxygen estimations from the  $T_e$ -method and the relations by SB98 have an uncertainty of 0.15 dex, an average of the values above. For the objects which the flux of the line  $[O \text{ III}]\lambda 4959$  is not available, this was calculated from the theoretical relation  $I[O \text{ III}]\lambda 4959 = I[O \text{ III}]\lambda 5007/3.0$ .

## 2.2 Relations of SB98

SB98 carried out NLR model calculations using the photoionization code CLOUDY (Ferland et al. 1996) and suggested two relations for the abundance determinations in the NLRs of AGNs. The first one is

$$\begin{aligned} (O/H)_{\text{SB98,1}} &= 8.34 + (0.212x) - (0.012x^2) - (0.02y) \\ &+ (0.007xy) - (0.002x^2y) + (6.52 \times 10^{-4}y^2) \\ &+ (2.27 \times 10^{-4}xy^2) + (8.87 \times 10^{-5}x^2y^2), \end{aligned}$$

where  $x = [N \text{ II}]\lambda\lambda 6548,6584/H\alpha$  and  $y = [O \text{ III}]\lambda\lambda 4959,5007/H\beta$ . The second relation of SB98 is

$$\begin{aligned} (O/H)_{\text{SB98,2}} &= 8.643 - 0.275u + 0.164u^2 \\ &+ 0.655v - 0.154uv - 0.021u^2v \\ &+ 0.288v^2 + 0.162uv^2 + 0.0353u^2v^2, \end{aligned} \quad (2)$$

where  $u = \log([O \text{ II}]\lambda\lambda 3727,3729/[O \text{ III}]\lambda\lambda 4959,5007)$  and  $v = \log([N \text{ II}]\lambda\lambda 6548,6584/H\alpha)$ . Both calibrations are valid for  $8.4 \leq 12 + \log(O/H) \leq 9.4$ .

The dependence of these relations on the density should be taken into account. This dependence is given by the expression considered by SB98

$$(O/H)_{\text{final}} = O/H - 0.1 \log(N_e/300), \quad (3)$$

where  $N_e$  is the electron density in  $\text{cm}^{-3}$  and the correction is valid for  $100 \text{ cm}^{-3} \lesssim N_e \lesssim 10^4 \text{ cm}^{-3}$ . It should be noted that the value of this correction exceeds 0.1 dex for high-density objects only, i.e., for objects with electron densities  $N_e \gtrsim 3 \times 10^3 \text{ cm}^{-3}$ .

## 2.3 $T_e$ -method

We use the emission-line intensities listed in Table 1 to determine the oxygen abundances  $(O/H)_{T_e}$  of the narrow-line regions through the classic  $T_e$ -method. We will follow the methodology described in Dors et al. (2013) based on the equations given by Pérez-Montero & Contini (2009), Hägele et al. (2008), Pérez-Montero et al. (2007), and Pérez-Montero & Díaz (2003).

The electron temperature in the high ionization zone (referred to as  $t_3$ ) for each object was obtained from the observed line-intensity ratio  $R_{O3} = [O \text{ III}](\lambda 4959 + \lambda 5007)/\lambda 4363$  using the expression

$$t_3 = 0.8254 - 0.0002415R_{O3} + \frac{47.77}{R_{O3}}, \quad (4)$$

with  $t_3$  in units of  $10^4 \text{ K}$ . The electron temperature of the low ionization zone (referred to as  $t_2$ ) was derived from the theoretical relation:

$$t_2^{-1} = 0.693 t_3^{-1} + 0.281. \quad (5)$$

The  $O^{++}$  and  $O^+$  ionic abundances were computed through the relations:

$$\begin{aligned} 12 + \log\left(\frac{O^{++}}{H^+}\right) &= \log\left(\frac{I(4959) + I(5007)}{I(H\beta)}\right) + 6.144 \\ &+ \frac{1.251}{t_3} - 0.55 \log t_3. \end{aligned} \quad (6)$$

and

$$\begin{aligned} 12 + \log\left(\frac{O^+}{H^+}\right) &= \log\left(\frac{I(3727)}{I(H\beta)}\right) + 5.992 \\ &+ \frac{1.583}{t_2} - 0.681 \log t_2 + \log(1 + 2.3n_e). \end{aligned} \quad (7)$$

(1) Finally, we assumed

$$\frac{O}{H} = \frac{O^+}{H^+} + \frac{O^{++}}{H^+}. \quad (8)$$

for the determination of the total abundance.

## 2.4 Abundance results

Electron densities ( $N_e$ ),  $O \text{ III}$  electron temperatures ( $T_e$ ), and the oxygen abundances estimated using three different ways for the objects in our sample are reported in Table 2. The oxygen abundances of some objects can not be determined through the relations given by SB98 because for those objects the estimated abundances or electron densities are outside of the validity ranges considered by these authors, i.e., beyond of the range of values for which the relations are defined. The electron densities,  $N_e$ , for the objects in our sample were computed from the line intensity ratio  $[S \text{ II}]\lambda 6716/\lambda 6731$  using the TEMDEN routine of the nebular package of IRAF<sup>2</sup>. Most of our objects have values in the range  $0.01 < n_e < 0.12$ , where  $n_e = N_e/(10^4 \text{ cm}^{-3})$ . These values are somewhat higher than the ones derived for H II regions, which were found to be  $n_e < 0.06$  (see Krabbe et al. 2014; Copetti et al. 2000). However, they are sufficiently low so that one does not need to consider the contribution

<sup>1</sup> The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

<sup>2</sup> Image Reduction and Analysis Facility, distributed by NOAO, operated by AURA, Inc., under agreement with the NSF.

**Table 1.** Emission-line intensities of AGNs relative to  $H\beta=1.00$  compiled from the literature.

Object	[O II] $\lambda$ 3727	[O III] $\lambda$ 4363	[O III] $\lambda$ 4959	[O III] $\lambda$ 5007	H $\alpha$	[N II] $\lambda$ 6584	[S II] $\lambda$ 6717	[S II] $\lambda$ 6731	Type	Ref.
NGC 7674	1.29	0.12	3.94	12.55	3.70	3.68	0.54	0.64	Sy2	1
IZw 92	2.63	0.32	3.52	10.12	2.42	0.97	0.37	0.40	Sy2	1
NGC 3393 <sup>(a),(b)</sup>	2.41	0.14	5.47	16.42	2.78	4.50	0.64	0.89	Sy2	2
Mrk 176	3.54	0.32	4.69	14.36	2.81	2.99	0.56	0.54	Sy2	3
3c33	4.93	0.32	4.10	12.68	2.63	1.76	0.87	0.73	Sy2	3
Mrk 3	3.52	0.24	3.99	12.67	3.10	3.18	0.73	0.82	Sy2	3
NGC 1068	1.23	0.22	4.11	12.42	2.57	4.55	0.26	0.55	Sy2	3
Mrk 573	2.92	0.18	3.89	12.12	2.95	2.47	0.75	0.80	Sy2	3
Mrk 78	4.96	0.14	3.88	11.94	2.46	2.32	0.68	0.61	Sy2	3
Mrk 34	3.43	0.15	3.68	11.46	2.99	2.18	0.82	0.80	Sy2	3
Mrk 1	2.78	0.21	3.56	10.95	2.66	2.21	0.49	0.52	Sy2	3
3c433	6.17	0.41	3.27	9.44	3.38	5.13	1.58	1.13	Sy2	3
Mrk 270	5.64	0.28	2.96	8.71	3.14	2.93	1.21	1.39	Sy2	3
3c452	4.81	0.18	2.40	6.85	2.98	3.58	1.10	0.77	Sy2	3
Mrk 198	2.51	0.12	1.79	5.56	3.02	2.26	0.89	0.68	Sy2	3
Mrk 268	3.75	0.25	1.55	4.82	3.38	4.94	1.28	1.08	Sy2	3
Mrk 273	8.27	0.22	1.52	4.44	2.94	2.62	0.89	0.54	Sy2	3
NGC 3227 <sup>(b)</sup>	3.22	0.50	3.57	10.73	2.86	5.01	1.24	1.26	Sy2	4
Mrk 6	2.45	0.28	3.37	10.13	2.79	1.79	0.62	0.63	Sy2	4
ESO 138 G1	2.35	0.34	2.93	8.71	3.01	0.68	0.47	0.48	Sy2	5
NGC 5643 <sup>(a),(b)</sup>	5.55	0.54	4.20	12.61	2.66	2.90	0.91	0.71	Sy2	6
NGC 1667	11.50	0.59	2.78	9.20	2.80	6.96	1.37	1.17	Sy2	7
Mrk 423	8.00	0.40	2.80	6.20	2.90	3.60	1.20	1.00	Sy1.9	8
Mrk 609	1.80	0.50	1.80	5.00	2.80	2.60	0.60	0.50	Sy1.9	8
Mrk 226SW	5.23	0.08	1.50	4.50	3.35	2.07	0.29	0.25	Sy2	9
NGC 3081 <sup>(a)</sup>	2.16	0.23	4.53	12.62	2.73	2.33	0.60	0.62	Sy2	10
NGC 3281 <sup>(a)</sup>	2.33	0.22	2.77	7.59	2.64	2.54	0.53	0.60	Sy2	10
NGC 3982 <sup>(a)</sup>	3.92	0.03	5.64	18.68	2.76	2.57	0.76	0.82	Sy2	10
NGC 4388 <sup>(a)</sup>	2.68	0.15	3.67	10.63	2.71	1.44	0.68	0.60	Sy2	10
NGC 5135 <sup>(a)</sup>	2.01	0.10	1.40	4.47	2.64	2.35	0.37	0.35	Sy2	10
NGC 5643 <sup>(a)</sup>	5.11	0.42	4.56	15.4	2.64	3.07	0.97	0.90	Sy2	10
NGC 5728 <sup>(a)</sup>	3.41	0.44	3.70	10.98	2.65	3.71	0.41	0.41	Sy2	10
NGC 6300 <sup>(a)</sup>	15.48	1.39	8.32	23.32	2.59	6.62	1.42	1.26	Sy2	10
NGC 6890 <sup>(a)</sup>	2.77	0.72	7.48	20.05	2.75	4.26	0.65	0.52	Sy2	10
IC 5063 <sup>(a)</sup>	5.06	0.28	3.37	10.31	2.77	2.67	0.69	0.60	Sy2	10
IC 5135 <sup>(a)</sup>	4.05	0.25	2.07	6.88	2.65	3.30	0.49	0.46	Sy2	10
Mrk 744	2.38	0.33	3.18	8.84	2.47	3.62	2.83	2.83	Sy2	11
Mrk 1066	3.34	0.08	1.22	3.84	2.76	2.42	0.51	0.55	Sy2	11
NGC 5506	2.84	0.14	2.46	7.69	2.84	2.53	0.92	0.99	Sy1.9	12
NGC 2110	4.38	0.26	1.61	4.76	2.66	3.76	1.52	1.38	Sy2	12
NGC 3281 <sup>(a),(b)</sup>	4.30	0.42	2.44	7.34	2.60	2.60	0.78	0.73	Sy2	13
Akn 347 <sup>(a)</sup>	2.98	0.42	4.95	15.01	2.65	3.23	0.75	0.75	Sy2	14
UM 16 <sup>(a)</sup>	2.90	0.22	4.62	14.00	2.72	1.70	0.45	0.45	Sy2	14
Mrk 533 <sup>(a)</sup>	1.59	0.13	4.03	12.23	2.72	2.72	0.39	0.45	Sy2	14
IZw 92 <sup>(a)</sup>	2.60	0.34	3.54	10.14	2.78	1.00	0.40	0.43	Sy2	14
Mrk 612 <sup>(a)</sup>	1.88	0.17	2.99	9.37	2.67	3.60	0.74	0.55	Sy2	14
Mrk 622 <sup>(a)</sup>	10.06	0.03	1.90	5.44	2.47	2.33	0.19	0.14	Sy2	14

References— (1) Kraemer et al. (1994), (2) Contini et al. (2012), (3) Koski (1978), (4) Cohen (1983), (5) Alloin et al. (1992) (6) Schmitt et al. (1994) (7) Radovich & Rafanelli (1996), (8) Osterbrock (1981), (9) Osterbrock & Dahari (1983), (10) Phillips et al. (1983), (11) Goodrich & Osterbrock (1983), (12) Shuder (1980), (13) Durret & Bergeron (1988), and (14) Shuder & Osterbrock (1981). <sup>(a)</sup> Data corrected for reddening in this work. <sup>(b)</sup> Value of  $I[\text{O III}]\lambda 4959$  estimated from the theoretical relation  $I[\text{O III}]\lambda 4959=I[\text{O III}]\lambda 5007/3.0$ .

from the collisional de-excitation (Rubin 1989) or the direct recombination of the forbidden lines used in the standard abundance determinations.

We found the electron temperature  $t_3$  to be in the range of 6 000 to 50 000 K, with an average value of  $\sim 20$  000 K. This value is somewhat higher than the one found by

Zhang et al. (2013) for Sy2s, who used data from SDSS DR7 and found an average value of 14 000 K.

Fig. 1 shows the comparison between oxygen abundances in NLRs determined through the two methods presented above. Inspection of Fig. 1 reveals that the  $T_e$ -method provides oxygen abundances lower than the ones obtained via the relations of SB98 by up to  $\sim 2$  dex, with an average

**Table 2.** Object name, electron density, electron temperature, and oxygen abundance obtained via the  $T_e$ -method and via the calibrations of Storchi-Bergmann et al. (1998) (Equations 1 and 2) for the objects in our sample. Oxygen abundance value estimations outside the validity interval of the calibrations were not considered.

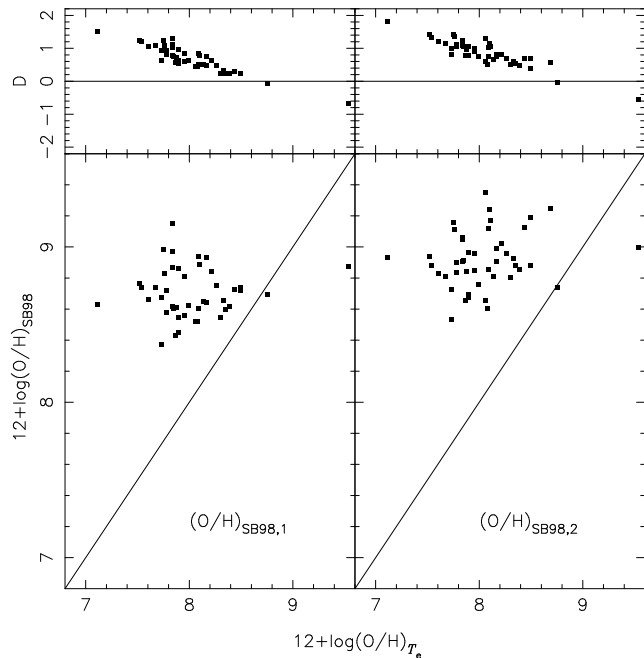
Object	$N_e$ (cm $^{-3}$ )	$T_e$ (10 $^4$ K)	12+log(O/H)		
			$T_e$ -method	SB98,1	SB98,2
NGC 7674	1148.0	1.14	8.49	8.72	9.19
IZw 92	822.0	1.95	7.90	8.44	8.67
NGC 3393	2022.0	1.09	8.69	—	9.24
Mrk 176	535.0	1.61	8.21	8.84	9.02
3c33	252.0	1.72	8.14	8.64	8.80
Mrk 3	948.0	1.49	8.26	8.75	8.96
NGC 1068	26993.0	1.44	8.40	—	—
Mrk 573	781.0	1.34	8.33	8.65	8.92
Mrk 78	370.0	1.22	8.49	8.74	8.88
Mrk 34	546.0	1.27	8.39	8.61	8.85
Mrk 1	767.0	1.50	8.17	8.63	8.90
3c433	50.0	2.38	7.84	8.96	9.04
Mrk 270	1027.0	1.97	7.99	8.62	8.75
3c452	50.0	1.76	7.95	8.80	8.95
Mrk 198	111.0	1.59	7.88	8.61	8.84
Mrk 268	260.0	2.68	7.52	8.76	8.93
Mrk 273	50.0	2.60	7.73	8.67	8.72
NGC 3227	647.0	2.49	7.75	8.98	9.15
Mrk 6	647.0	1.81	7.95	8.55	8.84
ESO 138 G1	685.0	2.22	7.73	8.40	8.53
NGC 5643	141.0	2.36	7.90	8.86	8.96
NGC 1667	281.0	3.12	7.84	9.15	9.06
Mrk 423	239.0	3.14	7.67	8.73	8.80
Mrk 609	239.0	4.41	7.11	8.62	8.92
Mrk 226SW	296.0	1.45	8.08	8.52	8.60
NGC 3081	693.0	1.84	7.85	8.60	8.91
NGC 3281	974.0	1.86	7.84	8.61	8.90
NGC 3982	819.0	0.68	9.54	8.87	8.99
NGC 4388	343	1.31	8.30	8.54	8.80
NGC 5135	492.0	1.61	7.78	8.57	8.83
NGC 5643	451.0	1.79	8.17	8.93	8.99
NGC 5728	606.0	2.26	7.84	8.86	9.05
NGC 6300	360.0	2.96	8.11	—	9.17
NGC 6890	176.0	2.11	8.06	—	9.35
IC 5063	311.0	1.79	8.06	8.51	8.65
IC 5135	471.0	2.12	7.78	8.72	8.90
Mrk 744	606.0	2.16	7.76	8.83	9.10
Mrk 1066	839.0	1.56	7.90	8.54	8.69
NGC 5506	809.0	1.46	8.09	8.60	8.85
NGC 2110	395.0	2.78	7.54	8.73	8.87
NGC 3281	471.0	2.87	7.61	8.66	8.83
Akn 347	606.0	1.82	8.09	8.93	9.11
UM 16	606.0	1.37	8.35	8.59	8.87
Mrk 533	1046.0	1.18	8.44	8.72	9.12
IZw 92	805.0	2.02	7.87	8.42	8.65
Mrk 612	75.0	1.46	8.10	8.89	9.24
Mrk 622	64.0	0.97	8.76	8.69	8.73

value of  $\sim 0.8$  dex, which confirms the existence of the so-called “temperature problem” in AGNs. This discrepancy is much larger than the one found for H II regions. For example, Kennicutt et al. (2003), using spectroscopy data of H II regions in spiral galaxies, found that O/H abundances computed from relations based on photoionization models of Kewley & Dopita (2002) are higher by 0.2 to 0.5 dex than the ones from the  $T_e$ -method.

The abundance discrepancy in AGNs could be caused by the presence of a secondary heating (ionizing) source

in addition to the radiation from the gas accretion onto the AGN. This secondary source is probably related to the shock. Indeed, Zhang et al. (2013) showed that the strong [O III] $\lambda$ 4363 flux in AGNs (and consequently high electron temperature) suggests the presence of some supplementary energy source(s), which could be due to the presence of shock waves (see also Contini et al. 2012; Prieto et al. 2005). Moreover, the presence of fluctuations of electron temperature (Peimbert 1967) in the gas phase of AGNs could also contribute for the discrepancies found in Fig. 1.



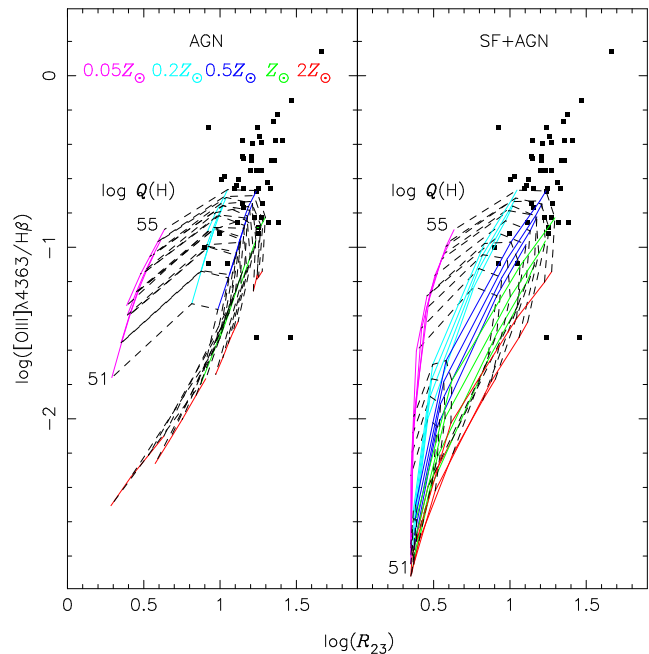


**Figure 1.** The bottom panel shows the comparison between the oxygen abundance obtained through the  $T_e$  method and through the two calibrations of SB98 as indicated in each plot. The upper panel shows the differences between those O/H estimations.

In order to examine if Sy2 galaxies have a secondary heating source, we performed a simple test. In Fig. 2, the intensity of  $[\text{O III}]\lambda 4363/\text{H}\beta$  versus the  $R_{23}$  parameter defined as  $R_{23} = [I([\text{O II}]\lambda 3727) + I([\text{O III}]\lambda 4959 + \lambda 5007)]/I(\text{H}\beta)$  for the objects in our sample and the ones predicted by a grid of photoionization models are shown.

We consider two models to reproduce the observational data: (i) the AGN model to describe the NLR spectra, and (ii) the SF+AGN model to describe composite (star-forming regions + AGN) spectra. We use the version 08.00 of the Cloudy code (Ferland et al. 1996) to construct NLR models similar to the ones used by Dors et al. (2012), but considering the Table-AGN model (Mathews & Ferland 1987) as the ionizing source. We considered a large range of values for the physical parameters: the number of ionizing photons,  $51 \leq \log Q(\text{H}) \leq 55$ ; electron densities,  $1.0 \leq \log(N_e) \leq 4.0$ ; and metallicities,  $0.05 \leq (Z/Z_\odot) \leq 2$ . The spectrum of the SF+AGN model is the sum of the predictions of the SF model and the AGN model. The SF model is constructed using the Cloudy code (Ferland et al. 1996) assuming the ionizing source to be a stellar cluster with an age of 2.5 Myr and  $\log Q(\text{H}) = 52.85$  whose spectrum is computed with the *STARBURST99* code (Leitherer et al. 1999). The metallicity of the gas phase was considered to be solar with an electron density  $N_e = 100 \text{ cm}^{-3}$ . These parameters are similar to the ones derived in circumnuclear star-formation regions observed in two galaxies (NGC 1097 and NGC 6951) containing a Seyfert 2 nucleus by Dors et al. (2008).

We can see in Fig. 2 that the ratio  $[\text{O III}]\lambda 4363/\text{H}\beta$  is underpredicted by the AGN and SF+AGN models when compared the observations. This line ratio depends strongly on the electron temperature, therefore the electron temperatures in AGNs predicted by our models are lower than the ones estimated using the  $T_e$ -method. Thus, this discrepancy

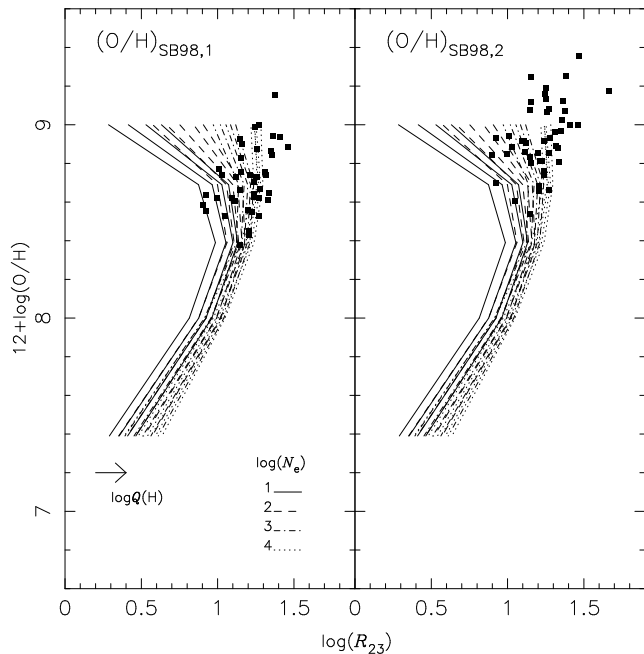


**Figure 2.** The  $[\text{O III}]\lambda 4363/\text{H}\beta$  line ratio as a function of the  $R_{23} = [I([\text{O II}]\lambda 3727) + I([\text{O III}]\lambda 4959 + \lambda 5007)]/I(\text{H}\beta)$  parameter. The left panel shows the predictions of the AGN model. The predictions of SF+AGN model are plotted in right panel. The points are the objects of our sample (see Table 1). The typical error (error bars not shown) of the emission-line ratios is about 10 per cent. The solid lines connect the predictions of the models with the same metallicity  $Z$ , while dashed lines connect models with the same ionizing photon number ( $Q(\text{H})$ ).

could be attributed to the presence of gas shock waves propagating at supersonic velocities through the NLRs, which does to enhance the intensity of  $[\text{O III}]\lambda 4363$  producing larger electron temperature values and, consequently, low (unrealistic) O/H values when using the  $T_e$ -method (see Nagao et al. 2001 and references therein).

Due to the result above, in our paper the  $T_e$ -method is no longer used to compute the metallicity of AGNs.

SB98 pointed out that an averaged value of  $Z$  obtained from both relations (Eq. 1 and 2) should be used. Instead of doing that we use our models to choose which of the relations by SB98 yields more reliable abundances. For that, we use the standard O/H –  $R_{23}$  empirical diagram. The  $R_{23}$  parameter was suggested by Pagel et al. (1979) as indicator of the oxygen abundance when the  $T_e$ -method cannot be applied. Although  $R_{23}$  has a strong dependence on metallicity, it also depends on the ionization degree of the nebulae, which should be taken into account (Pilyugin 2001, 2000). We compare the predictions of our AGN models with the observed O/H –  $R_{23}$  diagram for the objects in our sample, where the oxygen abundances are estimated using both relations of SB98 (see Fig. 3). Since the AGN and SF+AGN models predict similar values of  $R_{23}$  in the zone of Fig. 2 where our data are located, only the former models are shown in Fig. 3. In this figure we can see that a better agreement is obtained when the abundances are determined through the first relation of SB98. Hereafter this relation will be used.



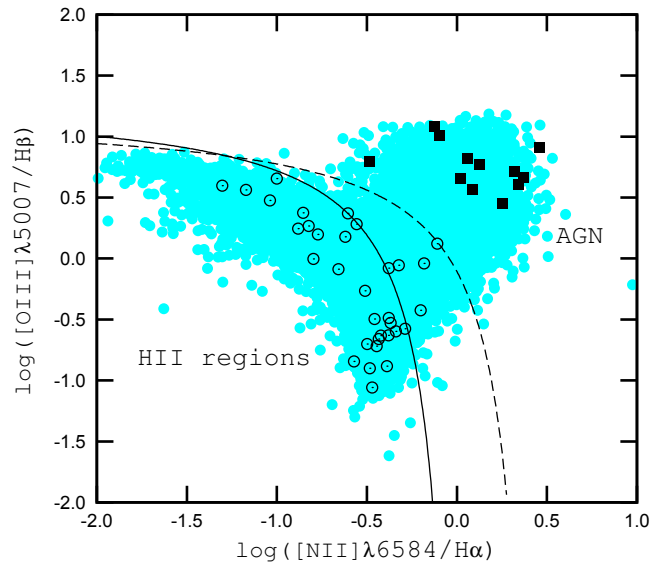
**Figure 3.**  $12+\log(\text{O}/\text{H})$  vs.  $\log(R_{23})$ . The points represent oxygen abundances in our objects estimated through the two relations (see Sect. 2.2) proposed by SB98 as indicated in each plot. Lines show our photoionization model results for different values of electron densities, as indicated, and the logarithm of the ionizing photon numbers ( $\log Q(\text{H})=51-54$ , with a step of 1 dex). The arrow indicates the direction in which the logarithm of the ionizing photon numbers increases in each model set.

### 3 ABUNDANCE AT THE CENTRE OF A GALAXY VS. CENTRAL INTERSECT ABUNDANCE

#### 3.1 The data

It is a widely accepted practice to specify the abundance at the center of a galaxy by the central intersect abundance obtained from the radial abundance gradient (e.g., Vila-Costas & Edmunds 1992; Zaritsky et al. 1994; van Zee et al. 1998; Pilyugin et al. 2004, 2007; Gusev et al. 2012, among others). The radial abundance gradients in the disks of nearby late-type galaxies were recently determined by Pilyugin et al. (2014, 2015). The extrapolation of the radial abundance gradient to the zero galactocentric distance gives the central intersect abundance  $(\text{O}/\text{H})_0$  in galaxies. On the other hand, Ho et al. (1997) obtained emission-line spectra of the central regions of many nearby galaxies. This provides a possibility to estimate the oxygen abundances at the centers of those galaxies. The comparison between central oxygen abundance estimated from the spectrum of the center of the galaxy with that obtained from the radial abundance gradient can tell us something about the chemical evolution of the central parts of galaxies.

We compare the central O/H abundances estimated from the spectra of Ho et al. (1997) and the central intersect abundances obtained by Pilyugin et al. (2014, 2015). We selected from the sample of Ho et al. (1997) only the galaxies with central spectra classified by Ho et al. (1997) as H II-like regions or Seyferts and which are also in the Pilyugin et al. (2014, 2015) list. Our selected sample contains 45 objects



**Figure 4.** BPT  $[\text{O III}]\lambda 5007/\text{H}\beta$  vs.  $[\text{N II}]\lambda 6584/\text{H}\alpha$  diagnostic diagram. Filled squares and open circles stand for the AGNs and star-forming central regions selected from the work of Ho et al. (1997). Solid and dashed curves mark the boundary between AGNs and H II regions defined by Kauffmann et al. (2003) and Kewley et al. (2001), respectively. The filled circles show a large sample of emission-line SDSS galaxies studied by Thuan et al. (2010).

(12 AGNs and 33 star-forming regions) whose emission-line intensities and derived oxygen abundances (see below) are listed in Table 3. Fig. 4 shows the positions of the 45 sample objects in a BPT diagnostic diagram (Baldwin et al. 1981), together with a large sample of emission-line SDSS galaxies studied by Thuan et al. (2010), which are plotted with cyan (grey) symbols. In this figure we also plotted the boundary lines obtained by Kauffmann et al. (2003) and Kewley et al. (2001) that separate the H II-like objects and AGNs in the diagram.

Pilyugin et al. (2014, 2015) derived oxygen abundances from the published emission-line intensities of disk H II regions through the  $C$  method (see Pilyugin et al. 2012). This is an empirical method based on the comparison between strong emission-line intensities in the spectrum of a target H II region and those in a set of reference H II regions with known abundances. The strong emission-lines considered in this method are  $[\text{O II}]\lambda 3727$ ,  $\text{H}\beta$ ,  $[\text{O III}]\lambda 5007$ ,  $[\text{N II}]\lambda 6584$  and  $[\text{S II}]\lambda 6716$ ,  $\lambda 6731$ . The optical data of Ho et al. (1997) consist of long-slit spectroscopy of the nuclear region ( $r \lesssim 200$  pc) of a large sample of nearby galaxies covering the 4200-5200Å and 6200-6900Å spectral ranges with spectral resolutions of about 4 and 2.5 Å pixel<sup>-1</sup>, respectively. We use again the first relation of SB98 to estimate the central abundances of the NLRs of the active galaxies  $[(\text{O}/\text{H})_{\text{SB98,1}}]$ . In the case of galaxies with central H II-like regions we use the  $C_{\text{NS}}$  method (Pilyugin et al. 2012, 2013) to estimate the oxygen abundances  $[(\text{O}/\text{H})_{\text{CNS}}]$ . The  $C_{\text{NS}}$  method is a variant of the  $C$  method applicable when the  $[\text{O II}]\lambda 3727$  emission-lines are not available.

**Table 3.** De-reddened nuclear emission-line fluxes (normalised to the flux of  $H\beta=1.00$ ) taken from Ho et al. (1997) and oxygen abundances derived by us. The oxygen abundances  $12+\log(O/H)$  for the NLRs of AGNs and central star-forming regions are estimated through the SB98 calibration (Eq. 1) and through the  $C_{NS}$  method, respectively. The values of  $12+\log(O/H)_0$  are the central intersect abundances in the galaxies obtained from the radial abundance gradients.

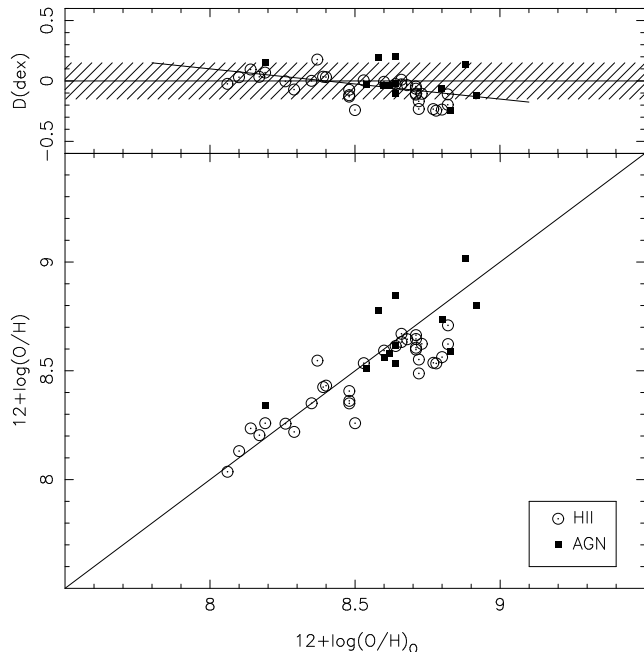
Object	[O III] $\lambda$ 5007	[N II] $\lambda$ 6584	[S II] $\lambda$ 6717+ $\lambda$ 6731	$12+\log(O/H)$	$12+\log(O/H)_0$
NLRs of AGNs					
NGC 1058	3.64	3.50	1.95	8.58	8.62
NGC 1068	12.10	2.17	0.68	8.54	8.64
NGC 2336	2.84	5.12	2.99	8.74	8.80
NGC 3031	4.07	6.38	3.89	8.78	8.58
NGC 3227	5.92	3.82	1.95	8.62	8.64
NGC 3486	4.50	3.01	2.64	8.56	8.60
NGC 4258	10.20	2.29	2.61	8.51	8.54
NGC 4395	6.23	0.93	2.04	8.34	8.19
NGC 4501	5.15	6.02	2.66	8.80	8.92
NGC 4725	6.68	3.27	1.82	8.59	8.83
NGC 5033	4.59	6.76	2.99	8.85	8.64
NGC 5194	8.09	8.26	2.28	9.01	8.88
Nuclear star-forming regions					
NGC 598	1.57	0.48	0.61	8.35	8.48
NGC 783	0.19	1.03	0.55	8.65	8.68
NGC 925	0.81	0.63	0.96	8.41	8.48
NGC 1156	4.51	0.28	0.46	8.24	8.16
NGC 2403	1.91	0.79	1.03	8.36	8.48
NGC 2537	1.84	0.43	0.48	8.35	8.35
NGC 2903	0.08	0.97	0.52	8.71	8.82
NGC 2997	0.31	1.00	0.77	8.56	8.80
NGC 3184	0.12	0.94	0.55	8.67	8.66
NGC 3198	0.23	1.19	0.84	8.59	8.60
NGC 3310	0.91	1.88	0.71	8.55	8.37
NGC 3319	0.99	0.46	1.71	8.26	8.50
NGC 3344	0.83	1.20	1.15	8.49	8.72
NGC 3351	0.25	1.31	0.66	8.62	8.82
NGC 3359	0.54	0.88	1.55	8.43	8.40
NGC 3631	0.29	1.23	0.68	8.60	8.71
NGC 3738	2.99	0.26	0.81	8.13	8.10
NGC 3893	0.21	1.05	0.61	8.62	8.73
NGC 4088	0.19	0.91	0.48	8.65	8.71
NGC 4214	3.66	0.19	0.33	8.20	8.20
NGC 4254	0.87	1.37	0.59	8.54	8.77
NGC 4303	1.32	2.23	1.12	8.53	8.78
NGC 4449	2.36	0.40	0.65	8.26	8.26
NGC 4490	2.34	0.71	1.89	8.22	8.29
NGC 4535	0.13	1.17	0.61	8.66	8.71
NGC 4559	0.32	1.20	1.10	8.53	8.53
NGC 4631	1.51	0.69	0.63	8.42	8.39
NGC 4654	0.14	0.77	0.60	8.63	8.66
NGC 4656	3.96	0.14	0.50	8.04	8.06
NGC 5248	0.26	1.48	0.64	8.61	8.64
NGC 5457	0.23	1.08	0.70	8.61	8.71
NGC 5474	1.75	0.37	0.72	8.26	8.19
NGC 6946	0.37	1.81	0.81	8.55	8.72

### 3.2 Abundance at the centre vs. central intersect abundance

In the bottom panel of Figure 5 we show the comparison between the central intersect abundances in the selected galaxies  $(O/H)_0$  obtained from the radial abundance gradients and central abundances  $(O/H)_{SB98,1}$  and  $(O/H)_{C_{NS}}$  determined from the spectral measurements of the central regions of Ho et al. (1997). This figure shows that the  $(O/H)_{SB98,1}$

abundances in the NLRs are close to or slightly lower than the central intersect abundances in the host galaxies. The central abundances in galaxies with central H II-like regions show a similar behaviour. Thus the metallicity in the NLRs obtained through the relation of SB98 is close to the central metallicity of the host galaxy estimated from the radial abundance gradient. The mean difference (D) between the direct and intersect central oxygen abundances (see up-





**Figure 5.** Comparison between central intersect oxygen abundances derived from the radial abundance gradients  $(O/H)_0$  and the central abundances determined from the spectra of the central regions from Ho et al. (1997) through the SB98 calibration for the AGNs (filled squares) and through the  $C_{NLS}$  method for the H II-like regions (open circles). The diagonal line in the bottom panel is the one-to-one relation. The upper panel shows the differences between the spectral and central intersect abundances. The hatched area indicates a band of 0.15 dex adopted for the oxygen abundance uncertainty (see Section 2.1). Solid line shows the linear regression [ $D = (-0.25 \pm 0.06) \times 12 + \log(O/H)_0 + 2.10 (\pm 0.59)$ ] considering all data.

per panel of Figure 5) for H II-like objects is  $-0.11 \pm 0.09$  at high metallicities ( $12 + \log(O/H) > 8.5$ ) and  $0.00 \pm 0.08$  at low metallicities ( $12 + \log(O/H) < 8.5$ ). The mean difference for AGNs is  $-0.01 \pm 0.13$  at high metallicities. The differences for the high metallicity AGNs seem to follow a linear regression with a slope of  $-0.32 (\pm 0.33) \text{ dex}^{-1}$ . The differences for H II-like objects follow a regression with a slope of  $-0.45 (\pm 0.23) \text{ dex}^{-1}$  at high metallicities, and with a slope of  $-0.23 (\pm 0.15) \text{ dex}^{-1}$  at low metallicities. We also performed a linear regression considering all points in Fig. 5 due to the small sample we are using. It yields a slope of  $-0.25 (\pm 0.06) \text{ dex}^{-1}$ .

The differences are within the uncertainty in the abundance estimations (i.e., compatible with zero). However, the existence of a trend in the differences suggests that the direct central abundance in some high metallicity galaxies can be lower than the central intersect abundance. It should be noted that Sánchez et al. (2014) have also found observational evidence of lower central oxygen abundances than that predicted by the central abundance extrapolation of the gradients in a number of spiral galaxies. A possible explanation of the trend of the differences with metallicity could be the accretion of metal-poor gas onto the centers of galaxies. In the case of the low-metallicity galaxies, where the metallicity of the accretion material is similar (or not so different) to that of the gas in the central region, the infalling gas should not significantly change the local metal-

licity. In contrast, in the case of high-metallicity galaxies this low-metallicity infalling gas would dilute the heavy element content of the gas in the central region. Therefore this effect would be more relevant in high-metallicity galaxies than in low-metallicity ones.

Observational evidence of the presence of gas flows from the outer parts (with low-metal content material) to the centre of the galactic disc (high metal content) has been found for isolated barred galaxies (Martin & Roy 1994; Zaritsky et al. 1994) and interacting ones (Rosa et al. 2014; Ellison et al. 2011, 2010; Kewley et al. 2010). Likewise, there are several kinematical studies based on optical and infrared integral field spectroscopy that support the scenario where gas is infalling toward the central region of AGNs (e.g. Schnorr-Müller et al. 2014, 2011; Riffel et al. 2013b, 2008; Storchi-Bergmann et al. 2007; Fathi et al. 2006). Moreover, Rupke et al. (2010) performed numerical simulations of galaxy mergers and found that the central underabundances observed in this kind of systems could be accounted for by a radial infall of low-metallicity material coming from the outskirts of both galaxies involved.

### 3.3 Is there an extraordinary chemical enrichment of the NLRs?

It was found by Pilyugin et al. (2006, 2007) that there is an upper limit to the oxygen abundances in galaxies, i.e., there is a maximum attainable oxygen abundance. These authors found that this maximum value of oxygen abundance in galaxies is about twice the solar abundance (adopting the solar oxygen abundance to be  $12 + \log(O/H)_\odot = 8.69$ ; Allende Prieto et al. 2001).

The abundances in the NLRs of AGNs taken from the list of Ho et al. (1997) are in the range  $8.5 < 12 + \log(O/H) < 9.0$  or  $0.6 < Z/Z_\odot < 2$ , which does not exceed the maximum attainable abundance for galaxies. This suggests that there is no an extraordinary chemical enrichment of the NLRs. Similar AGN abundances were obtained by Matsuoka et al. (2009) from the analysis of the  $C\text{IV}\lambda 1549/\text{He}\text{II}\lambda 1640 - C\text{III}\lambda 1909/C\text{IV}\lambda 1549$  diagram calibrated in terms of gas abundance through photoionization models using the CLOUDY code (Ferland et al. 1996). Dors et al. (2014) also obtained similar abundances using a new index ( $C_{43} = \log[(C\text{IV}\lambda 1549 + C\text{III}\lambda 1909)/\text{He}\text{II}\lambda 1640]$ ) defined by them as a metallicity indicator for AGNs.

However, it should be noted that we found metallicities larger than twice solar up to  $Z/Z_\odot \sim 6.5$  [ $12 + \log(O/H)_{\text{SB98,1}} \sim 9.5$  (see Fig. 1)] for five AGNs from Table 1. Similarly extra high metallicities for some NLRs were obtained by SB98. Further study of the galaxies with possible extra high metallicity AGNs should be carried out (in particular, radial abundance distributions and central intersect abundances should be obtained in those galaxies) in order to be able to draw solid conclusions about the upper limit to the oxygen abundances in NLRs.

## 4 SUMMARY AND CONCLUSIONS

We compiled from the literature a sample of spectra of narrow-line regions of active galactic nuclei with avail-

able optical emission lines: [O II] $\lambda$ 3727, [O III] $\lambda$ 4363, H $\beta$ , [O III] $\lambda$ 5007, H $\alpha$ , [N II] $\lambda$ 6584, [S II] $\lambda$ 6717, and [S II] $\lambda$ 6731. We estimated the oxygen abundances in those NLRs through the classic  $T_e$  method and through the strong-line method (the calibration of Storchi-Bergmann et al. 1998). We found that the abundances determined through the  $T_e$  method are lower by up to  $\sim 2$  dex than the abundances estimated through the calibration of SB98, i.e., we confirmed the existence of the so-called “temperature problem” in AGNs.

We also considered a second sample of galaxies for which the emission-line spectra of the central regions were measured by Ho et al. (1997) and the central intersect abundances were found by Pilyugin et al. (2014, 2015). The direct central abundances of the AGNs and Star-forming regions in those galaxies were estimated through the calibration of Storchi-Bergmann et al. (1998) and through the  $C_{NS}$  method (Pilyugin et al. 2012, 2013), respectively. We found that the abundances of the NLRs and HII-like objects estimated from the direct spectral measurements are close to or slightly lower than the central intersect abundances obtained from the radial abundance gradients. This may suggest that the infall of the low-metallicity gas onto the centers of the galaxies can take place in some galaxies where the central abundance estimated from the direct spectral measurements is lower than the central intersect abundance.

The abundances in the NLRs of the AGNs in our samples do not suggest that there is an extraordinary chemical enrichment of the narrow-line regions. There are only a few AGNs with oxygen abundances higher than the maximum attainable abundance for galaxies ( $\sim 2$  times the solar value; Pilyugin et al. 2006, 2007). Additional investigations of the galaxies with possible extra high metallicity AGNs are necessary to draw reliable conclusions on the upper limits of the oxygen abundances in NLRs.

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