CHEMICAL ABUNDANCE CALIBRATIONS FOR THE NARROW-LINE-REGION OF ACTIVE GALAXIES

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ABSTRACT

We investigate two chemical abundance calibrations for the narrow-line-region (NLR) of active galaxies in terms of three easily observable optical emission-line ratios, namely, \([\text{OIII}]\lambda\lambda 4959,5007/\text{H}\beta\), \([\text{NII}]\lambda\lambda 6548,84/\text{H}\alpha\) and \([\text{OII}]\lambda 3727/(\text{OIII}]\lambda\lambda 4959,5007\). The calibrations are obtained from a grid of models on the assumption that the main process responsible for the production of these lines is photoionization by a “typical” active galactic nucleus continuum. The chemical elements vary their abundance together with oxygen, except nitrogen, which is assumed to be a product of secondary nucleosynthesis. The calibrations are calculated for the range \(8.4 \leq 12 + \log(O/H) \leq 9.4\), and tested using NLR data for a sample of Seyfert’s and LINER’s having HII regions in the vicinity of the nucleus. The gaseous abundances of these HII regions have been determined in previous works, and the NLR abundances are obtained on the assumption that they can be extrapolated from those of the HII regions. The calibrations work very well for the Seyfert’s, giving abundance values which agree with those obtained from the HII regions, and can thus be used for quick estimates of the chemical abundances of the NLR’s. For the LINER’s, the calibrations give lower values than those derived from the corresponding HII regions, suggesting that the assumptions of the models do not apply for them, and that there are different physical processes at work in the NLR of the LINER’s.

Subject headings: galaxies: active – galaxies: ISM – galaxies: nuclei – galaxies: Seyfert

1. Introduction

Since the works of Ferland & Netzer (1983) and Halpern & Steiner (1983), on the modelling of the the narrow-line-region (NLR) of active galactic nuclei (AGN), which were followed
by a large number of subsequent works (e.g. Stasińska 1984; Ferland & Osterbrock 1986; Binette, Robinson & Curvosier 1988), it has been shown that the relative fluxes of the stronger emission-lines can be successfully reproduced assuming that the main excitation mechanism of the NLR is photoionization. Alternative photoionization models include varying proportions of matter-bounded and ionization-bounded clouds in the NLR (Viegas-Aldrovandi 1988; Binette, Wilson & Storchi-Bergmann 1996), which are better suited to reproduce both the high and low excitation emission-line ratios. Viegas-Aldrovandi & Contini (1989) have also investigated the effect of shocks, concluding that clouds with shock velocities lower than 300 km s$^{-1}$ are radiation-dominated if the ionization parameter is larger than $U=10^{-4}$. Viegas-Aldrovandi & Gruenwald (1990) have also shown that, besides shocks, relativistic particles have to be taken into account to reproduce the spectra of LINER’s. More recent studies of the effect of shocks in the NLR or ENLR (extended narrow-line region – expression sometimes used to indicate that the NLR is obviously extended, usually to kpc scales) include the works of Viegas and Gouveia dal Pino (1992), Sutherland et al. (1993) and Dopita & Sutherland (1995).

The conical shape observed for the ENLR in a number of Seyfert galaxies seems to favor photoionization by a nuclear source as the ionizing mechanism (Wilson, 1995 and references therein). This is confirmed by long-slit spectroscopy along the extended gas for a few Seyferts, like NGC 3281 (Storchi-Bergmann, Wilson & Baldwin 1992), Mrk 573 (Tsvetanov & Walsh 1992) and NGC 5643 (Schmitt, Storchi-Bergmann & Baldwin 1994). The variation of the emission-line ratios with distance from the nucleus in these three galaxies can be reproduced by a sequence of models with varying ionization parameter, even when there is evidence of the presence of shocks with velocities $\sim 150$ km s$^{-1}$ in the gas (e.g. NGC 3281).

Most works devoted to reproducing the emission-line ratios of the NLR or ENLR via photoionization models, adopt a solar composition for the gas. Collecting NLR emission-line ratios from a sample of 180 LINER’s and Seyfert 2’s, Storchi-Bergmann & Pastoriza (1990), have shown that the data is better reproduced if a range of nitrogen abundances, from solar to 4 times solar, is adopted.

In order to verify this result, Schmitt et al. (1994), Storchi-Bergmann, Wilson & Baldwin (1996a), Storchi-Bergmann et al. (1996b) have obtained long-slit spectroscopy of a sample of AGN with HII regions in the vicinity of the nucleus, such that the abundances could be determined from the HII regions spectra instead of using models for the NLR (on the assumption that the nuclear, or NLR abundance, is the same as that of the HII regions, due to their proximity to the nucleus). The derived nuclear oxygen abundances range from solar to two-three times solar, and the nitrogen shows a secondary behavior, such that its abundance can reach up to 4-5 times solar, in accordance with the previous results from the modelling of the NLR.

Nevertheless, the number of active galaxies for which such determinations are available is small, and there are also several active galaxies which lack HII regions close to the nuclei, such that the above method cannot be used. In this work, we use the HII region abundances
derived in previous works, to infer that of the NLR and constrain, via a grid of photoionization models, the average physical parameters of the NLR. We then investigate the relation between the emission-line-ratios and chemical abundances. Under a few assumptions, discussed below, we obtain two calibrations which allow the derivation of the chemical abundance of the NLR gas in terms of two easily observed optical emission-line ratios.

2. Calculations

The grid of models was constructed using the code CLOUDY (Ferland 1996), for three different ionizing continua: two power-laws $F_\nu \propto \nu^{-\alpha}$, for $\alpha = 1.0$ and 1.5 (turn-on and turn-off energies of 0.1eV and 100keV, respectively) and the option “Table AGN” in Cloudy, which uses a typical observed AGN continuum (a combination of power-laws; see Mathews and Ferland 1987). The gas densities were varied between $10^2 \leq N \leq 10^4$ cm$^{-3}$, as previous works (e.g. Schmitt et al. 1994; Storchi-Bergmann et al. 1992; Tsvetanov & Walsh 1992) indicate that most observed NLR gaseous densities are in this range. The ionization parameter was varied in the interval $-4.0 \leq log(U) \leq -2.0$, which allows the reproduction of the observed range in emission line ratios for typical NLR’s.

As pointed out in the introduction, the oxygen abundances obtained in previous works for the HII regions close to the nuclei of Seyfert galaxies range from about solar to a few times solar, and we have assumed that the NLR’s have similar abundance values. The oxygen abundance was thus varied in the range $8.4 \leq 12 + log(O/H) \leq 9.4$. The adopted solar abundance values are $12 + log(O/H) = 8.91$ and $12 + log(N/H) = 7.98$, from Aller(1987) and Grevesse(1984). All elements, except nitrogen, are assumed to have abundances equal to that of oxygen, relative to the solar value.

Nitrogen was assumed to behave as a secondary element. The main observational constraint on the origin of nitrogen is the behavior of the abundance ratio N/O as a function of the overall metallicity, as measured by the O/H ratio. In the “simple chemical evolution model” (Edmunds 1990), N/O will be a constant for a primary origin of nitrogen, whilst N/O will be proportional to O/H for a secondary origin. Vila-Costas & Edmunds (1993) have used HII region data for a number of spiral and irregular galaxies to reach the conclusion that the N/O and O/H ratios can be consistently explained by models in which nitrogen has mostly a secondary origin at high abundances, namely for $12 + log(O/H) > 8.5$. We have reached a similar conclusion analysing the data of a number of nuclear starbursts (Storchi-Bergmann, Calzetti & Kinney 1994), and of HII regions in the vicinity of active nuclei (Storchi-Bergmann et al. 1996a,b). As we intend to obtain a calibration for the NLR, which is located in the nuclear region of luminous and metal rich galaxies we will thus assume that nitrogen has a secondary behavior also in the NLR, with abundance given by the relation:
\[
\log(N/O) = 0.96 \times [12 + \log(O/H)] - 9.29
\]

which was obtained by Storchi-Bergmann et al. (1994) for nuclear starbursts.

Another aspect which has also become evident in recent studies (e.g. Schmitt et al. 1994; Storchi-Bergmann et al. 1992; Mulchaey, Wilson & Tsvetanov 1996) is that the nuclear region of Seyfert 2 galaxies is obscured, denoting the presence of dust in the NLR. The presence of dust was considered using the command “grains” in CLOUDY, and depleting the heavy elements abundances as follows: for a solar abundance nebula, the abundance of the depleted gas, relative to the solar value is: He=1.0, C=0.39, N=0.81, O=0.62, Ne=1.0, Mg=0.26, Al=0.01, Si=0.045, S=0.59, Ar=0.44, Ca=0.00009, Fe=0.0089, Na=0.024 and Ni=0.01. These values correspond to the observed abundance of the interstellar medium (Cowie & Songaila 1986). For chemical compositions different than solar, the depletions were scaled accordingly.

### 3. Discussion

Under the above assumptions, the parameters which determine the emission-line ratios of the NLR are: the spectrum of the ionizing continuum, the ionization parameter, the chemical abundance and the gaseous density.

The most easily observed optical emission-lines from the NLR of Seyferts are \([\text{OII}]\)\(\lambda 3727\) (hereafter \([\text{OII}]\)), \(H\beta\), \([\text{OIII}]\)\(\lambda\lambda 4959,5007\) (hereafter \([\text{OIII}]\)), \(H\alpha\), \([\text{NII}]\)\(\lambda 6548,84\) (hereafter \([\text{NII}]\)) and \([\text{SII}]\)\(\lambda\lambda 6717,31\) (hereafter \([\text{SII}]\)). From these, a number of line ratios can be obtained, for example: \([\text{OII}]/[\text{OIII}]\), which is independent of the chemical abundance and is a good indicator of the ionization parameter; \([\text{OIII}]/H\beta\), which depends on all the parameters, but also frequently used as an indicator of the ionization parameter; \([\text{NII}]/H\alpha\), mostly sensitive to the gaseous abundance; \([\text{SII}]\)\(6717/6731\), which is sensitive to the density.

If we adopt the simplifying assumption that the density is indicated by the \([\text{SII}]\) ratio, and that the ionizing spectrum is also known, then we can choose two other emission line ratios as indicators of the ionization parameter and chemical abundance. From the theoretical point of view, the ratio \([\text{OII}]/[\text{OIII}]\) is the best choice for the derivation of the ionization parameter, as it does not depend on the chemical abundance of the gas. But, from the observational point of view, it has the disadvantage of being sensitive to the reddening. In order to avoid this problem, the ratio \([\text{OIII}]/H\beta\) can be used instead, but it will be also sensitive to the abundance, and should be used together with the ratio mostly sensitive to the abundance, which is \([\text{NII}]/H\alpha\). These last two ratios have the advantage of not being sensitive to reddening.

In order to derive a chemical abundance calibration for the NLR, we have explored two diagrams: \([\text{NII}]/H\alpha \times [\text{OIII}]/H\beta\) and \(\log([\text{OII}]/[\text{OIII}]) \times \log([\text{NII}]/H\alpha)\). In Fig. 1 we present a grid of models in the plane \([\text{NII}]/H\alpha \times [\text{OIII}]/H\beta\), for a range of oxygen abundances
8.4 ≤ 12 + log(O/H) ≤ 9.2. [Hereafter, we will refer to 12+log(O/H) as (O/H).] In these models, the gas density is 300 cm\(^{-3}\) (typical for the NLR) and the ionizing continuum is the segmented power-law of Mathews & Ferland (1987) (typical of AGN). In Fig. 2, the same grid of models is plotted in the plane \(\log([\text{OII}]/[\text{OIII}]) \times \log([\text{NII}]/H\alpha)\), for a range of oxygen abundances 8.4 ≤ 12 + log(O/H) ≤ 9.4.

It can be concluded from Figures 1 and 2 that a pair of ratios [O III]/H\(\beta\), [NII]/H\(\alpha\) or \(\log([\text{OII}]/[\text{OIII}])\), \(\log([\text{NII}]/H\alpha)\) can determine an abundance value. Notice the clean sequencing of models in terms of the abundance values in the figures, specially in the latter diagram (Fig. 2). This diagram is particularly recommended for high abundances \((O/H) > 9.2\) because of some degeneracy of the models in the first diagram (Fig. 1).

We have then fitted two-dimensional second-order polynomials to each of the diagrams in order to derive a calibration for the oxygen abundance in terms of the above emission-line ratios. For the first diagram (Fig. 1) we obtain, for \(x = [\text{NII}]/H\alpha\) and \(y = [\text{OIII}]/H\beta\), interpolating in the interval 8.4 ≤ (O/H) ≤ 9.2:

\[
(O/H) = 8.34 + 0.212x - 0.012x^2 - 0.002y + 0.007xy - 0.002x^2y + 6.52 \times 10^{-4}y^2 + 2.27 \times 10^{-4}xy^2 + 8.87 \times 10^{-5}x^2y^2
\]

(2)

For the second diagram, the best fit obtained for \(u = \log([\text{OII}]/[\text{OIII}])\) and \(v = \log([\text{NII}]/H\alpha)\) in the interval 8.4 ≤ (O/H) ≤ 9.4 is:

\[
(O/H) = 8.643 - 0.275u + 0.164u^2 + 0.655v - 0.154uv - 0.021u^2v + 0.288v^2 + 0.162uv^2 + 0.0353u^2v^2
\]

(3)

For both expressions, the fitted values are within 0.05 dex of the model values, with \(\chi^2\) of 1.04 \times 10^{-3} and 6.9 \times 10^{-4}, respectively.

The dependence of the calibrations on the density can be quantified as far as the density stays approximately within the range 100 ≤ N ≤ 10000 cm\(^{-3}\). For larger densities, [NII]/H\(\alpha\) is not a good abundance indicator anymore, because it is suppressed as its critical density is 8.6 \times 10^4 cm\(^{-3}\), and the calibrations are not valid. As the density is increased, both [OIII]/H\(\beta\) and [NII]/H\(\alpha\) ratios increase sistematically, and the dependence of the two calibrations on the density is approximately linear in the logarithm of the density. This dependence can be incorporated into our calibrations, as:

\[
(O/H)_{\text{final}} = (O/H) - 0.1\log(N/300)
\]

(4)

where \(N\) is the gaseous density in cm\(^{-3}\), and the equation is valid for 100 ≤ \(N\) ≤ 10000 cm\(^{-3}\).
Calibrations using power-law ionizing continua $F_\nu \propto \nu^{-\alpha}$, for $\alpha = -1$ and -1.5, were also obtained. As compared with the above calibrations, for which we used the typical AGN continuum of Mathews and Ferland (1987), it can be concluded that they give systematically larger values for the calculated abundances. The second calibration (in terms of $\log([\text{NII}]/H\alpha$ and $\log([\text{OII}]/[\text{OIII}])$) is less dependent on the ionizing continuum, giving abundance values from 0.1 to 0.3 dex larger with the power-law than with the AGN continuum. For the first calibration, the difference is increased, reaching values larger than 0.5 dex. We point out that, although the shape of the ionizing continuum in AGN is not very well established, UV and X-ray observations of at least the brightest AGN show that it is closer to a composition of power-laws than to a unique power-law (e.g. Sanders et al. 1989; Alloin et al. 1995), favoring the “AGN continuum” used above over the single power-laws.

4. Comparison with Observations

In order to verify the validity of the above calibrations, we have collected from the literature the emission line ratios of the NLR of a few Seyfert’s and LINER’s, for which there are determinations of the oxygen and nitrogen abundances for HII regions close to the NLR. In this way, the NLR abundances could be extrapolated from those of the HII regions.

The collected data are shown in Table 1, along with the the Hubble type and absolute magnitude for each galaxy. The emission-line fluxes are listed relative to $H\beta$ and have been corrected for reddening, and their source is listed in the last column of the table. Also listed are the electronic densities calculated from the $\text{[SII]}\lambda\lambda 6716/6731$ line ratios as in Osterbrock (1989; Fig. 5.3). In applying the correction to the $(O/H)$ due to the density dependence (equation 4), we will assume that the gas density is approximately the same as the electronic density ($N \approx N_e$).

Typical radial abundance gradients for normal galaxies range between 0.05 and 0.1 dex kpc$^{-1}$ – see, for example, Vila-Costas & Edmunds (1992) and Kennicutt et al. (1993). Schmitt et al. (1994), Storchi-Bergmann et al. (1996a,b) have shown that, for the Seyfert 2 NGC 5643 and the LINER’s NGC 1097, NGC 1672 and NGC 1598, the observed gradients are similar to those typical of normal galaxies with the same morphological type. Here we thus adopt the latter hypothesis in the extrapolation of the NLR abundances, for the cases in which a gradient is not available.

In Table 2 we present the resulting $(O/H)$ values of the NLR’s obtained with each of the proposed calibrations – equations 2, 3 and 4 above, together with the derived values from the extrapolation using the abundances of the HII regions. We also show, in the last two columns of the table, the adopted gradient in $(O/H)$ and the references from which the HII regions’ abundances and gradients were obtained. Errors in the calibrations have been calculated from the errors in the emission-line ratios, while errors in the extrapolated values have been estimated from the errors in the HII regions abundances and gradients.

The O/H values obtained from the two calibrations have been plotted against the ones
extrapolated from the HII regions in Figure 3. It can be seen that, within the errors, there is a reasonable agreement between the extrapolated and calculated values for the Seyfert 2’s, with maximum differences of $\sim 0.2$ dex between the calculated and extrapolated values, indicating that the calibration works very well for the Seyfert 2’s.

The $(O/H)$ values obtained using the calibrations can also be compared with previous determinations via detailed modelling of the NLR, which we have for NGC 5643 (Schmitt et al. 1994) and another Seyfert 2 galaxy, NGC 3281 (Storchi-Bergmann et al. 1992). In both cases, the models indicated solar abundance for the gas $(O/H=8.91)$, while the calibrations give $(O/H)=9.00$ (equations 2 and 4) and $(O/H)=8.94$ (equations 3 and 4) for NGC 5643 and $(O/H)=8.81$ and 9.03, respectively, for NGC 3281, which confirm the validity of the calibrations.

On the other hand, for all the 4 LINER’s the calibrations give values which are systematically lower than those of the Seyfert’s. But we note that Storchi-Bergmann et al. (1996a,b) have concluded that the LINER nucleus of NGC 1672 presents emission line ratios which can be reproduced with photoionization by hot stars, and the absorption spectra from both this nucleus and that of NGC 1598 present signatures of young stars. From the discussion above, the calibrations would not be valid for these two cases, identified by open triangles in Fig. 3. But they should be valid for the other two LINER nuclei. As there is no systematic difference between the extrapolated nuclear abundances for the NLR’s of Seyfert’s and LINER’s, the different behavior of the LINER’s in the diagrams suggests a difference between the physical conditions and/or ionizing source in these objects as compared with the Seyfert’s. One possibility is that the energy distribution responsible for the photoionization of the gas in LINER’s is an absorbed continuum. Matter-bounded clouds from the BLR (Ferland et al. 1996) or from the NLR (Binette et al. 1996) would be responsible for the absorption. Nevertheless, our results are based on observations of only two objects. More LINER’s should be subject of this kind of study before a firm conclusion can be reached.

We also show in Figure 4, the results of the two calibrations plotted against each other. Although the correlation is not perfect, (as the calibrations are fits to the sequences of models), the Spearman correlation coefficient between the two calibrations is $r_s = 0.80$, indicating a good correlation. It can also be noticed that there is a systematic shift between the two calibrations, such that the second gives $(O/H)$ values on average 0.11 dex larger than the first calibration. As judged from the comparison with the observations, the $(O/H)$ value to be adopted when both calibrations can be used is the average from the two.

As pointed out in the previous section, we have also calculated calibrations for power-law ionizing continua instead of the “AGN continuum” used to obtain the calibrations of equations 2 and 3. Nevertheless, the comparison of the calculated $(O/H)$ with the observed ones (from the HII regions) give a much poorer agreement. The calibration in terms of $\log([NII]/H\alpha)$ and $\log([OII]/[OIII])$ (second calibration) gives a somewhat better result than the one in terms of $[NII]/H\alpha$ and $[OIII]/H\beta$ (first calibration): although the calculated $(O/H)$ are sistematically
overestimated when compared with the observed ones, the difference stays within the range 0.1 to 0.3 dex. But the first calibration gives (O/H) values larger than the observed by 0.5 dex in some cases. These results suggest that the “AGN continuum” is a better representation of the ionizing continuum than the single power-laws for the sample galaxies.

It is important to point out that there may be at least one source of confusion in observed emission line ratios from the NLR: the proximity of HII regions, such that the observed emission-line ratios could be due to a mixture of gas photoionized by an AGN continuum and by blue stars. In principle, such cases could be sorted out using diagnostic diagrams (Baldwin, Phillips & Terlevich, 1981; Veilleux & Osterbrock 1987). The calibration is valid only for those cases in which the emission-line ratios are clearly located in the region of the diagrams corresponding to the Seyferts. In the “mixed” cases, the line ratios are intermediate between those of Seyfert’s and those of HII regions, and the calibration is not valid.

5. Summary and Final Remarks

We have collected chemical abundance data of HII regions in the vicinity of the nuclei for a sample of 11 active galaxies and have used them to extrapolate the chemical abundances of the corresponding NLR’s. These abundances were used to test calibrations which allow the determination of the chemical abundance of the NLR of Seyfert galaxies in terms of two easily observed optical emission-line ratios. Two calibrations were obtained, the first involving a linear combination of the ratios [NII]/Hα and [OIII]/Hβ and the second, a linear combination of the decimal logarithms of [NII]/Hα and [OII]/[OIII]. Although the first calibration involves ratios less sensitive to the reddening, we have concluded that the second calibration is less sensitive to the ionizing continuum spectrum. Thus, whenever possible, both calibrations should be used (equations 2, 3 and 4) and the (O/H) abundance calculated as the average between the two values. The calibrations work well for all the Seyfert’s, suggesting that the hypotheses in the modelling of the NLR are valid for most Seyfert’s.

The calibration seems not to work for the LINER’s, suggesting that different ionization mechanisms occur in these objects. Nevertheless, more LINER’s should be studied before a firm conclusion can be reached, as there are only 4 LINER’s in the sample, and for 2 of them there seems to be contamination of the NLR by surrounding HII regions, and the calibrations do not work in these cases.

It would be important to test the calibrations in more objects, with a larger abundance range, but presently there are no other active galaxies for which there are determinations of the chemical abundance of their HII regions in the literature. A first step to look more closely into the abundances of HII regions in a larger number of Seyferts has been made by Evans et al. (1996), who have recently published an atlas with the optical positions of HII regions in 17 Seyferts. The following step would be to make spectroscopic observations of the individual HII regions.
In summary, we point out that determining the chemical abundance of the NLR in Seyfert’s is not an easy task. In previous works we have explored two methods: modelling of individual NLR and abundance determination of HII regions in the vicinity of the NLR. In this work we propose an alternative method: simple calibrations to be used when just a quick estimate of the chemical abundance is necessary.

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| Galaxy    | Type $^a$ | $M_B$$^{a,b}$ | [OII] | [OIII] | Hα  | [NII] | $N_e$(cm$^{-3}$) | Ref.$^c$ |
|----------|----------|---------------|-------|-------|-----|------|---------------|--------|
| **Seyfert’s** |          |               |       |       |     |      |               |        |
| IC 1816  | Sab      | -20.3         | 2.0±0.2 | 17.9±0.5 | 2.9±0.2 | 6.9±0.3 | 650 | 1        |
| NGC 1068 | (R)SA(rs)b | -21.3         | 1.2±0.2 | 16.5±0.4 | 2.6±0.2 | 6.1±0.3 | 8000 | 2        |
| NGC 1386 | Sa       | -19.0         | 2.2±0.2 | 15.9±0.4 | 3.0±0.2 | 5.0±0.3 | 650 | 1        |
| NGC 1566 | SAB(rs)bc | -21.2         | 2.0±0.3 | 15.0±0.4 | 3.1±0.4 | 4.1±0.4 | 650 | 3        |
| NGC 3081 | S0/a     | -20.1         | 1.5±0.2 | 15.1±0.4 | 3.0±0.2 | 3.7±0.2 | 200 | 1        |
| NGC 5643 | SAB(rs)c  | -20.3         | 5.20±0.5 | 16.4±0.4 | 3.0±0.2 | 4.2±0.2 | 200 | 4        |
| NGC 6814 | SAB(rs)bc | -19.5         | 3.3±0.2 | 15.8±0.4 | 2.8±0.2 | 6.0±0.3 | 650 | 5        |
| **LINER’s** |          |               |       |       |     |      |               |        |
| NGC 1097 | SB(rs)bc  | -21.0         | 4.0±0.4 | 5.1±0.3 | 2.9±0.2 | 7.2±0.4 | 400 | 6        |
| NGC 1326 | RSBa     | -19.7         | 13.2±0.6 | 2.6±0.2 | 2.9±0.2 | 5.8±0.3 | 650 | 1        |
| NGC 1598 | Sbc      | -20.2         | 0.7±0.1 | 2.3±0.2 | 3.0±0.2 | 4.7±0.2 | 100 | 1        |
| NGC 1672 | SB(s)b   | -19.9         | 1.3±0.1 | 2.1±0.2 | 2.9±0.2 | 4.1±0.2 | 250 | 6        |

Table 1: Emission-line fluxes relative to H$\beta$ (reddening-free)

$^a$From Storchi-Bergmann et al. 1996a, and 1996b, except for NGC 1068, NGC 1566, NGC 5643 and NGC 6814, for which we have used the NED-IPAC Extragalactic Database

$^b$H$_0$ = 75 km s$^{-1}$ Mpc$^{-1}$

$^c$References: (1) Storchi-Bergmann et al. 1996b; (2) Koski 1978; (3) Alloin et al. 1985; (4) Schmitt et al. 1994; (5) Our unpublished data; (6) Storchi-Bergmann et al. 1996a
| Galaxy        | O/H<sup>a</sup> | O/H<sup>b</sup> | O/H<sup>c</sup> | Δ(O/H)<sup>d</sup> | Ref.<sup>e</sup> |
|--------------|-----------------|-----------------|-----------------|--------------------|-----------------|
| **Seyfert’s**|                 |                 |                 |                    |                 |
| IC 1816      | 9.35±0.09       | 9.34±0.04       | 9.3±0.1         | -0.06              | 1               |
| NGC 1068     | 9.14±0.08       | 9.35±0.06       | 9.1±0.1         | -                   | 2,3             |
| NGC 1386     | 9.02±0.06       | 9.15±0.04       | 8.9±0.1         | -0.06              | 1.5             |
| NGC 1566     | 8.87±0.07       | 9.07±0.07       | 9.1±0.2         | -0.08              | 1               |
| NGC 3081     | 8.90±0.05       | 9.17±0.05       | 9.1±0.2         | -0.02              | 1.5             |
| NGC 5643     | 9.00±0.05       | 8.95±0.04       | 9.0±0.1         | -0.05              | 6               |
| NGC 6814     | 9.15±0.07       | 9.14±0.05       | 9.3±0.2         | -0.07              | 2,5             |
| **LINER’s**  |                 |                 |                 |                    |                 |
| NGC 1097     | 8.84±0.04       | 8.97±0.04       | 9.3±0.1         | -0.05              | 7               |
| NGC 1326     | 8.70±0.03       | 8.70±0.03       | 9.0±0.1         | -0.06              | 1               |
| NGC 1598     | 8.71±0.02       | 9.03±0.04       | 9.2±0.1         | -0.06              | 1               |
| NGC 1672     | 8.64±0.02       | 8.83±0.03       | 9.2±0.2         | -0.06              | 7               |

Table 2: Oxygen abundances of the NLR

<sup>a</sup>12+log(O/H) from the first calibration (eqs. 2 and 4)
<sup>b</sup>12+log(O/H) from the second calibration (eqs. 3 and 4)
<sup>c</sup>Extrapolating from the HII regions
<sup>d</sup>Adopted gradient in dex kpc<sup>−1</sup>
<sup>e</sup>(1) Storchi-Bergmann et al. 1996b; (2) Evans & Dopita 1987; (3) Oey & Kennicutt 1993; (4) Hawley & Phillips 1980; (5) Vila-Costas & Edmunds 1992; (6) Schmitt et al. 1994; (7) Storchi-Bergmann et al. 1996a
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Fig. 1.— Sequence of photoionization models in which the gaseous density is 300 cm$^{-3}$, the dust-to-gas ratio is solar, and the ionization parameter is varied in the range $-4 \leq \log(U) \leq -2.0$. Each sequence corresponds to a different chemical abundance, from $12 + \log(O/H) = 8.4$ (bottom) to 9.2 (top).

Fig. 2.— Same as Fig. 1 for the plane $\log([\text{OII}]/[\text{OIII}]) \times \log([\text{NII}]/\text{H}\alpha)$, in the range $8.4 \leq 12 + \log(O/H) \leq 9.4$.

Fig. 3.— The oxygen abundance values $[12+\log(O/H)]$ for the NLR obtained from the two proposed calibrations, plotted against the values obtained from the HII regions. Filled symbols represent the Seyfert 2 galaxies, and open symbols the LINER’s. The triangles represent the LINER’s for which there are signatures of recent star formation in the nucleus. Bottom: first calibration, involving the line ratios $[\text{NII}]/\text{H}\alpha$ and $[\text{OIII}]/\text{H}\beta$ (Fig. 1); top: second calibration, involving $\log([\text{NII}]/\text{H}\alpha)$ and $\log([\text{OII}]/[\text{OIII}])$ (Fig. 2). Both calibrations have been corrected by a small dependence on the gas density (see text). The loci of equal values for the two quantities are drawn as a line for comparison.

Fig. 4.— The oxygen abundance values $[12+\log(O/H)]$ obtained with the second calibration (Fig. 2), plotted against the values obtained with the first calibration (Fig. 1). For comparison, the loci of equal values for the two quantities are drawn as a continuous line, and those corresponding to a systematic shift of the second calibration to $[12+\log(O/H)]$ values 0.11$\text{dex}$ larger, as a dashed line. Symbols as in Fig. 3.
