Multilayer photoionization models of the nuclear and circumnuclear regions of type 2 AGN

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Abstract. We present the results of a new photoionization model, designed for simulating the spectra of the NLR of galaxies hosting an Active Galactic Nucleus (AGN). The validity of the model is verified reproducing the line ratios measured in the spectra of a sample of 1344 nearby (z<0.1) AGN of class 2, Seyfert 2 galaxies, extracted from the SDSS, and comparing them with the results obtained using different models proposed by other authors in literature. The reliability of the proposed model is discussed.

Introduction
We shortly introduce in a schematic form the general properties of Active Galaxies before approaching the specific problem of this review.

1.1. Morphology
Active Galaxies are morphologically characterized by a bright, semistellar Nucleus (Figure 1), the Luminosity of which is typically: \( L_{\text{AGN}} \sim 10^{41} - 10^{47} \text{ erg s}^{-1} \sim 10^8 - 10^{14} \text{ L}_{\odot} \), a value which is several order of magnitude larger than the typical luminosity of the nuclei of normal spiral galaxies: \( L_{\text{NUC}} \sim 10^6 - 10^8 \text{ L}_{\odot} \) and often even larger than the luminosity of the whole underlying galaxy: \( L_{\text{HOST}} \sim 10^9 - 10^{11} \text{ L}_{\odot} \). AGN with absolute magnitude fainter than -23 (\( M_B > -23 \)) are called Seyfert galaxies and have usually redshift \( z < 0.1 \).

Figure 1. Images of the Seyfert Galaxies NGC 5548 (left) and NGC 3227 (right)
1.2. Spectroscopic features

1.2.1 Emission line spectrum. The spectra of AGN are characterized by emission lines arising from forbidden transitions from metastable levels of heavy elements at different ionization degree and by recombination lines of HI, HeI, HeII, FeII and of heavy highly ionized elements (Figure 2).

On the basis of the features of the emission line profiles there are at least two classes of AGN, namely Seyfert galaxies in the local Universe (z<0.1): Seyfert 1 and Seyfert 2 galaxies. Spectra of Seyfert 1 nuclei are characterized by a composite line profile of the permitted lines, characterized by a broad component (FWHM ~ $10^4$ km s$^{-1}$) with superimposed a narrow one (FWHM ≤ $10^3$ km s$^{-1}$) and by narrow (FWHM ≤ $10^3$ km s$^{-1}$) forbidden lines. On the contrary Seyfert 2 galaxies are characterized by forbidden and permitted lines with a narrow profile (FWHM ≤ $10^3$ km s$^{-1}$), Figure 3. At first approximation the emission line spectrum of Seyfert 2 galaxies is very similar to the narrow line spectrum of Seyfert 1 galaxies. The absence of broad forbidden lines indicates that the typical density of the regions where the broad lines arise is larger than the critical density of the metastable levels from which the forbidden lines are emitted. These facts together with the typically different velocity fields derived from the line profiles of permitted and forbidden lines in the spectra of Seyfert 1 nuclei suggest that there are quite likely two different, kinematically separated, emitting regions around the nuclei of Seyfert 1 galaxies: a Broad Line Region (BLR) and a Narrow Line Region (NLR). In addition the similar features of Seyfert 2 spectra and narrow component Seyfert 1 spectra indicate that the two classes of active galaxies are quite likely different aspects of the same phenomenon. The typical parameters of BLR and NLR are reported in Table 1.

![Figure 2. Typical composite spectrum of an AGN [1].](image_url)

| Table 1. Typical features of BLR and NLR in AGN. |
|-----------------------------------------------|
| Broad Line Region (BLR) | Narrow Line Region (NLR) |
| R~0.1pc | R~100pc |
| High velocity, FWHM ~ $10^4$ km s$^{-1}$ | Low velocity, FWHM ~ $10^3$ km s$^{-1}$ |
| High electron density: | Low electron density: |
| • No broad [O III] lines | • Broad C III]1909 line |
| $N_e$~$10^8$-$10^{10}$ cm$^{-3}$ | $N_e$~$10^{2.3}$ cm$^{-3}$ |
1.2.2 The continuum of AGN. The typical ultraviolet, optical and infrared continuum of AGN is reported in Figure 4. The continuum of Seyfert 1 galaxies is dominated in the optical by a featureless non thermal component. On the contrary the continuum of Seyfert 2 galaxies is dominated in the same range by the stellar component of the galaxy hosting the active nucleus. In a schematic and qualitative form we can summarize these features with the following statements:

- Type 1: continuum = power-law: $F_{\nu} \propto \nu^\alpha$ ($\alpha \sim -1, -1.5$) + host galaxy
- Type 2: continuum = host galaxy
1.3. *The standard unified model*

The mostly accepted model for explaining the observed properties of Seyfert galaxies is sketched in Fig. 5. Seyfert 1 and Seyfert 2 have essentially the same nuclear structure: a dusty torus surrounding a Super Massive Black Hole, SMBH, \(M_{\text{SMBH}} \sim 10^7 - 10^9 \ M_{\odot}\), is accreting mass (Accretion Rate: 0.2 - 2.0 \(M_{\odot} \ y^{-1}\)) which is in part transformed in radiating energy at a rate of \(10^{45} - 10^{46} \ \text{erg s}^{-1}\). This radiation illuminates the BLR located within the torus and the most extended NLR outside of it. In this way the different spectroscopic features of Seyfert 1 and Seyfert 2 nuclei depend only by an orientation effect of the line of sight, that is unable to see the BLR when its direction is skew to the axis of the torus, whereas can reach directly the BLR and the central emitting engine when oriented close to the axis of torus itself. The radiation emitted by the SMBH is forced by the dusty torus to shine within a conus which illuminates the NLR and the surrounding gaseous regions of the hosting galaxy.

The study of these regions, photoionized by the radiation emitted from the nucleus, is crucial for understanding the physics of the nuclear engine and the origin of the activity. A model describing correctly their features and tested over a large homogeneous sample of spectroscopically classified Seyfert 2 galaxies is therefore necessary.

This is the aim of our work, which is essentially devoted to identify a statistically significant sample of spectroscopically selected objects of the Seyfert 2 class and to investigate the physical features of the gas of their NLR up to a distance of 3 kpc \((z=0.1, H= 75 \ \text{km s}^{-1} \ \text{Mpc}^{-1})\) from the nucleus.

2. *Selection of the objects*

**1344 Seyfert 2** galaxies have been extracted from the SDSS-DR6 (6860 square degree) in order to simulate and to reproduce their spectra using a photoionization code. The first selection criterium was to impose the presence of the following emission lines in the spectra of all galaxies: H\(\beta\), \([\text{OIII}]\lambda 5007\), H\(\alpha\), \([\text{NII}]\lambda 6584\), \([\text{SII}]\lambda\lambda 6717-6731\).

In order to define a complete sample of emission line galaxies no constraint was imposed to the redshift and at the end we extracted a set of 216166 galaxies. The \(z\) versus Petrosian r-magnitude, corrected for Galactic extinction is shown in Figure 6. A cut at magnitude 17.7 reduced to 201425 the number of galaxies. The condition that \([\text{NII}]\lambda 6584\) and H\(\alpha\) are separated was a good filter for selecting spectra with a narrow H\(\alpha\) line profile.

![Figure 6. Redshift z as a function of the magnitude r of the extracted objects.](image)

2.1. *Classification criteria*

2.2. The classification of the emission line galaxies has been performed using the Baldwin, Phillips, Terlevich (BPT) diagrams [2], based on the four optical line ratios \([\text{OIII}]/H\beta\), \([\text{NII}]/H\alpha\), \([\text{SII}]/H\alpha\), \([\text{SII}]/H\beta\), etc.
[O\textsubscript{I}]/H\alpha and the borderline between starburst and AGN evaluated by Kewley et al. [3]. This line divides the plane of the diagram in two regions: the upper-right region is occupied by AGN, the lower-left region by HII- and Sturburst-like objects.

The diagnostic line ratios, like $\log[N\textsubscript{II}]6548-83/\text{H}\alpha$-$\log[O\textsubscript{III}]5007/\text{H}\beta$ etc., have been derived measuring the intensity of the emission lines after subtraction of the stellar component from the spectra of the selected galaxies. This procedure allows to avoid the influence of the underlying absorption component in the determination of the intensity of the recombination lines. The effects of such subtraction are shown in Figure 7, obtained analyzing the data published by Kewley et al. [3]. As an example it is shown that the point representing the line ratios of an object moves from top to bottom and from right to left after subtraction of the galactic stellar component.

Figure 7. BPT diagnostic diagram. Red and blue points represent objects before and after subtraction of the stellar continuum from their spectra.

It is clear that the absence of any subtraction of the stellar continuum tends to move in the BPT diagrams the line ratios measured in starburst objects in the AGN region. A pre-classification of the whole sample before any correction from the influence of the underlying galaxy permits to isolate most of the starburst objects, leaving the identification of the remaining galaxies to a more accurate classification after the subtraction of the stellar component. The Figure 8 and Figure 9 show the results of this pre-classification obtained using the line intensities measured automatically by the SDSS.

Figure 8. – 9. BPT diagnostic diagrams applied to the line ratios measured automatically in the spectra of 201425 preselected galaxies.
The objects classified as **suspected AGN** are now 31724. They are: **Seyfert galaxies**, some Starburst galaxies, many LINERS (a subclass of low ionization AGN, that we want to avoid).

In order to reduce the number of LINERS we make the following considerations:

1) If we take the \( L([\text{OIII}] \lambda 5007) \) luminosities of LINERS and Seyfert galaxies, measured in the \( \sim 85000 \) emission line galaxies classified by Kewley et al. [3], using the diagnostic diagrams after subtraction of the stellar component, we find a distribution which shows that galaxies with \( L \ [\text{OIII}] > 0.5 \cdot 10^{40} \text{ erg s}^{-1} \) mainly belong to the Seyfert class, as suggested by Figure 10.

2) Since the \([\text{OIII}] \) line flux is independent from the subtraction or not of the underlying stellar component, it is a good parameter for reducing the presence of LINERS among AGN.

![Figure 10. Number of Liners and Seyfert as a function of their [OIII] \( \lambda 5007 \) luminosity measured in the Kewley sample [3].](image)

The extraction of the objects with \( L \ [\text{OIII}] > 0.5 \cdot 10^{40} \text{ erg s}^{-1} \) lowers the number of objects of our sample to 14372 galaxies, which are good Seyfert 2 (S2) candidates. We impose now the condition that \( z \leq 0.1 \) in order to limit our sample to nearby objects, for which the morphology can be studied in detail [4] and we further put as constraint that the error in the determination of \( F([\text{NII}] \lambda 6584) \) be smaller than 5%. We have now 2458 objects remaining and completeness is guaranteed up to \( m \sim 16.0 \). All these spectra have been now corrected by stellar component using the spectral synthesis code STARLIGHT [5] and the line fluxes have been measured manually. The line ratios have been then plotted in the BPT diagrams, Figure 11, and we have identified 1344 Seyfert 2.

![Figure 11. BPT diagnostic diagram showing the identification of the 1344 Seyfert 2 galaxies of our sample.](image)
3. Analysis of the Sample

3.1. Internal extinction
Internal extinction of each galaxy has been evaluated using the measured Balmer decrement $\frac{H\alpha}{H\beta}$ and assuming that its theoretical value is $2.95$ [6]. The so derived values of $A_v$ have the distribution shown in Figure 12, peaked around $\sim 1.3$ and are linearly correlated with the stellar absorption values evaluated with STARLIGHT, Figure 12. All emission line fluxes have been then corrected by extinction.

![Figure 12. Distribution of the visual extinction $A_v$ evaluated from the measured Balmer decrement (left) and comparison with the same parameter derived by STARLIGHT (right).](image)

3.2. Electron Temperature and Density. Ionization mechanism
The electronic densities and temperatures have been measured using different line ratios in order to look for different regions with different physical properties.

The used line ratios are:

- Ne $\rightarrow$ [SII] 6717/6731, [ArIV] 4710/4740
- Te $\rightarrow$ [OIII] (4959+5007)/4363, [SII] (6717+6731)/4074, [OII] 3727/7325

The Full Width Half Maximum (FWHM) of the different emission lines has been measured in each one of the 1344 spectra. The electronic temperatures derived using the [OIII], [OII] and [SII] emission line ratios are all comparable and all are lower than 20000 K:

- $Te$ ([OIII]) $\sim 14900 \pm 3900$ K, $Te$ ([OII]) $\sim 11400 \pm 2800$ K, $Te$ ([SII]) $\sim 12800 \pm 6000$ K

An equilibrium temperature $< 20000$ K is consistent with photoionization as main ionization mechanism of the gas. This is confirmed by the BPT diagnostic diagrams where we have plotted the line ratios of Supernova Remnants, namely regions ionized by shocks and the line ratios of photoionized regions, Figure 13. It is evident that our AGN belong to the second class of objects.

![Figure 13. BPT diagnostic diagrams showing regions ionized by shock (SNR) and by radiation [7].](image)
The electronic density distribution measured using the [SII] 6717/6731 line ratio is shown in Figure 14. The peak value is at log \( N_e ([\text{SII}]) \sim 2.5 \) cm\(^{-3}\). Density measured in objects where [ArIV] is also detected shows the presence of two different density regions peaked at: log \( N_e ([\text{SII}]) \sim 2.5 \) cm\(^{-3}\) and log \( N_e ([\text{ArIV}]) \sim 3.7 \) cm\(^{-3}\).

**Figure 14.** Density distribution in our sample. \( N_e ([\text{SII}]) \) in the upper histogram, \( N_e ([\text{SII}]) \) and \( N_e ([\text{ArIV}]) \) in the lower histogram.

A plot of the electron densities log \( N_e ([\text{SII}]) \) and log \( N_e ([\text{ArIV}]) \) as a function of the extinction for the objects in which both lines are present, Figure 15, shows that the electron density remains almost constant by increasing \( A_v \). This suggests that \( A_v \) is a good measure of the geometrical thickness of the gas we are investigating in the NLR. The peak value of the electron density at log \( N_e ([\text{SII}]) \sim 2.5 \) cm\(^{-3}\) is found again plotting log \( N_e ([\text{SII}]) \) as a function of \( A_v \), derived from the Balmer decrement Figure 16. Here we find again that 1.3 is the most frequent value of \( A_v \), an indication on the most frequent size of the NLR. The electron temperature does not show any correlation with \( A_v \), Figure 17.

**Figure 15.** Log \( N_e ([\text{SII}]) \) and log \( N_e ([\text{ArIV}]) \) as a function of the extinction \( A_v \).

**Figure 16.** Log \( N_e ([\text{SII}]) \) as a function of \( A_v \).
It is remarkable to note that the FWHM of the [OIII] $\lambda$5007 nebular line is larger for objects with $Av > 3.0$ than for objects with $1.4 < Av < 1.6$, Figure 18, namely for objects with a smaller geometrical depth. Assuming that the velocity dispersion is due to gravitational effects, namely to the orbiting velocity of the gas around the nucleus, this suggests the possibility that thin NLRs are more far away from the nucleus than thick NLRs are.

3.3. Luminosity of the emission lines
The measured luminosities of some selected forbidden and recombination lines are plotted in Figure 19 - 20, as a function of Av. They show a straightforward linear correlation between line luminosity and extinction, namely geometrical thickness, which suggests in the case of recombination lines the absence of self absorption or opacity in the lines itself.

4. Photoionization models
4.1. A little bit of history
The simulation of the NLR spectra has been developed in the recent past by few authors and for very small samples of objects. As an example we report schematically the models proposed by two authors in Table 2. Figure 21 represents the geometrical structure of the Matter bound + Ionization bound
slabs, proposed by Binnette et al. [7] and Whittle et al. [8]. Radiation reaches a high density Ionization Bound (IB) cloud after having interacted with a thin Matter Bound (MB) cloud.

Figure 19. Luminosity versus Av for a selected number of forbidden lines.
4.2. Two-cloud models

We propose in our approach a new model in which two different clouds photoionized by the central source are considered, Figure 22. For each object we look for the better agreement between the

**Figure 20.** Luminosity versus Av for three recombination lines of different ionization potential.

**Table 2.**

| Model                                                                 | Author                      |
|----------------------------------------------------------------------|-----------------------------|
| Matter bound + Ionization bound slabs                               | Binette et al. (1996)       |
| Single gaseous cloud photoionization models                          | Mkn78                       |
| Single gaseous & dusty cloud photoionization models                   | Mkn78                       |
| Matter bound + Ionization bound models                               | Mkn78                       |
| Single cloud shock models                                            | Whittle et al. (2005)       |

**Figure 21.** Matter bound + Ionization bound slabs as proposed by Binette (2006).

**Figure 22.** Two-cloud model proposed in this paper.

4.2. Two-cloud models

We propose in our approach a new model in which two different clouds photoionized by the central source are considered, Figure 22. For each object we look for the better agreement between the
combination of a grid of input parameters and the output of the photoionization code CLOUDY, version 06.02.09c [9] applied to two clouds.

For each model we constrain the spectral index $\alpha$ of the central source and the chemical composition $Z$ of the clouds to be the same. The line fluxes that we try to reproduce are quoted in Table 3.

**Table 3. Lines to reproduce: Ion - $\lambda$ (Å).**

| [O II] 3727 DOUBLET | [Ne III] 3869 | [S II] 4070 DOUBLET | H$\gamma$ 4340 | [O III] 4363 | He II 4686 |
|---------------------|---------------|---------------------|--------------|-------------|-----------|
| [AR IV] 4711         | [AR IV] 4740  | H$\beta$ 4861       | [O III] 4959 | [O III] 5007 | [N I] 5199 |
| [Fe VII] 5720        | He I 5876     | [Fe VII ] 6087      | [O I] 6300   | [N II] 6548  | He $\alpha$ 6563 |
| [N II] 6583          | [S II] 6716   | [S II] 6731         | [Ar III] 7136 | [O II] 7325 | DOUBLET   |

In order to define a grid of models, we have combined for each single cloud the following set of values of the 5 input parameters of the photoionization code CLOUDY, which should reproduce the observed line fluxes of the emission lines listed in Table 3:

- $Z = 0.5; 0.75; 1.0; 1.5; 2.0; 3.0; 4.0$
- $\alpha = -1.0; -1.3; -1.6; -1.9$
- log(U) = -1.6; -2; -2.4; -2.8; -3.2; -3.6
- log $n_e$ [cm$^{-3}$] = 1.0, 1.5, 2.0, 2.5, 3.0, 4.0
- log $n_e$ (H$^+$) = 19.0 → 22.4 step 0.4

The number of models to be considered is **10584**. The combination of the previous input parameters, assuming the presence of two different clouds, gives a number of ~ $10^7$ models, which correspond to five possible values of the ratio of the solid angles under which the central source subtends the clouds.

This number of models is reduced to ~ $5 \cdot 10^6$ if we consider the line ratios which are in the AGN region of the BPT diagrams.

For comparison purposes we have calculated 15000 simulations of spectra using the Binette MB+IB model and the input parameters reported in Table 4. Only 5500 of them fit reasonably the diagnostic diagrams

**Table 4. Grid of input parameters used for the simulations with the MB+IB model.**

| Cloud | Z  | $\alpha$ | log(U) | log(n$_e$ cm$^{-3}$) | log(n$_e$ (H$^+$)) |
|-------|----|----------|--------|----------------------|-------------------|
| MB    | 0.5; 0.75; 1.0; 1.5; 2.0; 3.0; 4.0 | -1.0; -1.3; -1.6; -1.9 | -1.2; -1.4; -1.8; -2.0; -2.2; -2.4 | 1.7 | 19.0 → 22.4 step 0.2 |
| IB    | “...” | Transmitted ionizing spectrum | Calculated by CLOUDY | 3.4 | To reach $T_e < 4000K$ |
4.3. Comparison of the single and double cloud models with the MB+IB models

The reduced $\chi^2$-Test applied to the set of spectra (1344) obtained isolating for each object the model, which best fits its spectrum, shows that the **two-cloud** models better fit the observed data than the **one-cloud** and **mb+ib** models, Figure 23. A confidence of the fits of the order of 90% is verified for a reduced $\chi^2$ value $\chi^2 \leq 1.5$. The number of objects, which are characterized by a $\chi^2 \leq 1.5$ is 868/1344 $\rightarrow$ two-cloud 498/1344 $\rightarrow$ one-cloud 503/1344 $\rightarrow$ mb+ib

![Figure 23. $\chi^2$-Test for the three families of models.](image)

The goodness of the results is shown qualitatively by the BPT diagrams, Figure 24, where we have plotted observed and simulated line ratios.

![Figure 24. Observed (red dots) and simulated (blue dots) line ratios, obtained using the two-cloud models.](image)

5. Conclusions

The work we have presented in this review is still in progress. We can then give only some preliminary results.

First of all the identification through a spectroscopic survey of 1344 Seyfert 2 galaxies has allowed to identify an homogeneous sample of objects well suited for statistical studies (completeness up to $m \sim 16.0$) on the morphology ($z < 0.1$) of the galaxies hosting the AGN and for the investigation of the physical properties of the NLR, the primary purpose of this work. The line profiles, the dependence of their width (FWHM) from $A_v$, the finding that $A_v$ is quite likely a good indicator of the geometrical size of the NLR along the line of sight, the linear correlation between $A_v$, luminosity of the forbidden
lines and luminosity of the recombination lines are all crucial sources of information for revealing the geometrical and dynamical structure of the NLR and then for investigating on its origin.

Table 5. Results of the simulations, a and b indicate the two clouds.

|                  | One cloud models | Binette’s models | Double cloud models |
|------------------|------------------|------------------|---------------------|
|                  | mean   | σ       | mean | σ       | mean | σ       |
| Z                | 2.6    | 0.9     | 2.3  | 0.7     | 2.4  | 0.8     |
| α                | -1.7   | 0.2     | -1.6 | 0.3     | -1.6 | 0.3     |
| log(U_a)         | -3.0   | 0.2     | -1.5 | 0.3     | -2.7 | 0.5     |
| log(Ne_a)        | 2.3    | 0.9     | 1.7  | **      | 2.9  | 0.8     |
| log(Ne_a)        | 20.9   | 0.6     | 20.7 | 0.6     | 21.0 | 0.6     |
| log(U_b)         | -3.4   | 0.3     | -3.3 | 0.3     |       |         |
| log(Ne_b)        | 3.4    | **      | 1.8  | 0.6     |       |         |
| log(Ne_b)        |       | α       | 20.0 | 0.7     |       |         |

Not less important are the attempts to reproduce the observed spectra of the NLR of our sample of galaxies using different combinations of clouds and photoionization codes. The results of such simulations, when reliable, allow to restrict the range of values of the physical parameters, which govern the features of the NLR. Within the same class of objects we can for example identify subclasses, characterized by different physical parameters. This fine tuning of the physical parameters is then a tool for isolating phenomena which otherwise would hang over.

An example is shown in Table 5 where the combinations of the average values which best fit the observations are given for each model considered in this work. The mean values of the parameters and their dispersion give the possibility to isolate objects which deviate from the mean model and these will be object of our further investigation.

However looking at the mean values of our two-cloud model it is evident that the metallicity of the clouds is very high $Z \sim 2.4$, the two clouds have different electron density $\log \text{Ne}(a) \sim 2.9$, $\log \text{Ne}(b) \sim 1.8$, but more or less the same column density, namely different geometrical depth as already argued in section 3.2.

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