AGNfitter 2.0: Fitting spectral energy distributions of active galaxies from radio to X-ray

Laura N. Martínez-Ramírez[1*], Gabriela Calistro Rivera[2,†], Juan C. B. Pineda[1] and Luis A. Núñez[1,3]

[1]Escuela de Física - Universidad Industrial de Santander, 680002 Bucaramanga-Colombia.
[2]European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching-Germany.
[3]Departamento de Física - Universidad de Los Andes, Mérida 5101, Venezuela.

E-mail: [*]`laura.martinez13@correo.uis.edu.co`, [†]`gabriela.calistrorivera@eso.org`

Abstract. We present a new version of AGNfitter, a Bayesian algorithm that uses Monte Carlo Markov chains to fit the spectral energy distribution (SED) of active galaxies from radio to X-rays. AGNfitter fits SEDs built from photometric data with theoretical and semi-empirical models of the AGN and host galaxy emission, including the accretion disk, the hot dust torus, the radio and X-ray emission of the AGN, the stellar populations, and cold dust and radio emision from the star-forming regions. Improvements to the previous version of the code include: new theoretical emission models and the easy inclusion of priors based on empirical correlations between fluxes in certain regions of the spectrum. This code determines in a robust way the probability density functions of the most relevant physical properties of active galaxies, allowing a diagnostic of the physical processes taking place. The most relevant physical and technical aspects of the improvements to the code are described below. In addition, we present results of a test performed over a sample of 9 active galaxies in $z < 0.16$ with unique photometric coverage from radio to X-rays, comparing the output of AGNfitter 2.0 against the physical properties reported by the literature.

Keywords. Galaxies, Active galactic nucleus, Spectral energy distributions.

1. Introduction

Active galactic nuclei (AGNs) are the astrophysical objects responsible for the most energetic emission processes in the Universe and are believed to play a fundamental role in the evolution of their host galaxies. Observations and simulations of active galaxies have revealed that: 1) there is a correlation between the luminosity of the bulge and the mass of the central super-massive black hole [1] [2] and 2) low-luminosity AGNs are more frequently found in elliptical galaxies, while high-luminosity AGNs are found in spirals [3]. These observations suggest a process of co-evolution of the host galaxy and its active nucleus, and understanding its implications requires the most complete possible characterization of the physical properties of these systems.

This diagnostic can be obtained from modelling the spectral energy distribution (SED), which is made up of the radiation emitted by the physical processes in the different regions of active galaxies. By fitting the observed photometric SEDs with a combination of emission models of the physical components it is possible to extract information about the nature of the AGN. This technique is called SEDfitting and currently there are many Bayesian algorithms designed for this purpose, including AGNfitter.

Although the AGN model in the original version of AGNfitter demonstrated to be a good overall description of the photometric emission in galaxies and AGN (eg. [4], [5], [6]), there was room for several valuable improvements and additions. Firstly, the hot dust emission in the AGN was modelled using a homogeneous and geometrically thick torus emission model which has shown to be inconsistent with high resolution observations [7] [8]. Secondly, the accretion disk and cold dust emission models had no fitting parameters other than the amplitude, and therefore it didn't provide information about the physical properties of the black hole and star formation regions. Most crucially, the model didn't consider regions of the spectrum such as X-rays and radio which tell us about the physical processes occurring in the relativistic jets and hot gas corona in the innermost region of the accretion disk. In this context we present the second version of AGNfitter, with new theoretical emission models for the torus, cold dust and the accretion disk, and the inclusion of models for the radio and X-ray emission in the fitting process.

2. Implementations

The aim of these implementations is to perform more informative and reliable SED fitting, using more detailed models and a higher number of physically-motivated parameters. Nevertheless, due to the limited amount of photometric data, this may lead to an overfitting of the SEDs. To avoid this, the following implementations 1) increase the number of parameters in a restricted way, 2) make use of empirical correlations between fluxes instead of complex theoretical models to avoid redundant physical parameters and 3) include new priors based on observations to constrain the exploration of the parameter space.

2.1. New theoretical emission models

2.1.1. Nuclear hot dust torus: We added two new axisymmetric models to which we will refer to as NK0 and SKIRTOR. These both models assume the existence of separate dust clouds, resulting in lines of sight with probabilistic opacities that depend on the cloud distribution. The clumpy model by Nenkova et al. [9] (NK0) starts from a torus with a cloud distribution that follows a gaussian profile in the polar angle and a power law profile in the radial cordinate. The model of Stalevski et al. [10] (SKIRTOR) on the other hand, assumes a torus composed of dense clouds embedded in a homogeneous distribution of low-density dust. The geometry of the torus is that of a flared disc, where the clouds follow a power law distribution with an exponential cut-off as a function of the radius and polar angle. Original NK0 and SKIRTOR models had 7 and 6 parameters, respectively, including geometrical and optical ones. This result in large sets of SEDs which is prohibitive in terms of the computation time and may lead to overfitting of the data as it was explained. For that reason, in both cases the number of SED templates was reduced to 9, after averaging all models with respect to the other parameters except the inclination angle, which turned out to be the most important one.

2.1.2. Cold dust: We added a new model proposed by Schreiber et al. [11] which assumes that the emission spectrum of cold dust is given by the contribution of two components: large ($> 0.01\,\mu m$) and small ($< 0.01\,\mu m$) silicate or carbonate grains, and complex molecules such as polycyclic aromatic hydrocarbons (PAHs). The first ones emit as a black body in the MIR and FIR and the PAHs, with characteristic vibrational and rotational modes, lines between $3.3 - 12.3\,\mu m$. The most relevant parameters of this model are the temperature of the dust (T_{dust}) and the mass fraction of the PAH component (f_{PAH}). This model is composed by a combination of the SED of the dust emission and the SED of the PAHs, each of them defined for one of 150 possible temperatures. Furthermore, 64 values of the f_{PAH} parameter are considered, resulting in a total of 9600 SEDs.

2.1.3. Accretion disk: For the accretion disk component we added the emission model by Slone & Netzer [12], which consists of the α-disk model of an optically thick and geometrically thin accretion disk. It also includes the effect of winds, which change the accretion rate ($\dot{M}$) locally, relativistic temperature corrections and a treatment of the comptonization in its atmosphere. The most relevant parameters of this model are: the mass of the super masive black hole (SMBH) (M_{BH}), the accretion rate ($\dot{M}$) and the standardized spin of the SMBH (a). We take the approximation of a windless disk and a spineless black hole to reduce the model to 108 SEDs given by 9 values of M_{BH} and 12 of $\dot{M}$.

2.1.4. Radio emission: We model the radio emission with two components, one for the AGN and one asociated with the star formation in the host galaxy. For the AGN, we based our model on the results presented by Tisanic et al. [13], considering the radiation of multiple AGN structures such as cores, jets and lobes. The coexistence of these structures and their related physical processes give rise to an emission spectrum that cannot be explained by a simple power law, as it is usually done. For this reason, it is assumed that there is a combination of populations of sources with synchrotron aged and self-absorption spectral shapes. This is modeled in a simplified way by means of a broken power law with mean values of the exponents: $\alpha_1 = -0.1 \pm 0.1$ and $\alpha_2 = -0.55 \pm 0.09$ calculated for a sample of compact galaxies from the VLA-COSMOS 3 GHz Large Project.

For the radio emission from the host galaxy we use the empirically calibrated IR-radio correlation [14] [15]. This correlation estimates the radio emission of the galaxy from the infrared emission of the star-forming regions. To this end, an empirical relationship is used between the integrated luminosity in the IR and the emission at 1.4 GHz ($L_{1.4GHz}$ in erg s^{-1} Hz^{-1}) :

$$q_{IR} = log\left(\frac{L_{IR}}{(3.75 \times 10^{12} \text{ Hz })L_{1.4GHz}}\right), \tag{1}$$

where L_{IR} is the total luminosity between 8 and 1000 μm (in erg s^{-1}). We adopted the value of $q_{IR} = 2.64 \pm 0.26$ from the literature [16] and assumed that $L_{1.4GHz}$ is given by the superposition of two power laws that model the synchrotron emission of the galaxy and the thermal braking radiation of the star-forming regions.

2.2. X-ray emission:
To model the X-ray emission from the AGN we use an empirical correlation between the UV and X-ray fluxes. This correlation allows to connect the corona emission in X-rays with the intrinsic emission of the accretion disk in UV. It aims to provide additional information to break the degeneracy between the emission from the accretion disk and the galaxy in the UV. This model assumes that the X-ray AGN emission spectrum is given by a power law with an exponential cut-off [7]. The remainning constant of proportionality is calibrated from the flux at 2 keV. For this purpose, the empirical correlation $\alpha_{ox} - \mathrm{L}_{2500\text{Å}}$ that connects the AGN's luminosity in 2500 Å ($L_{2500\text{Å}}$) and the slope of the SED between 2500 Å and 2 keV (α_{ox}) [17] [18] is used:

$$\alpha_{ox} = -0.137 \log(L_{2500\text{Å}}) + 2.638. \tag{2}$$

where α_{ox}, is given by:

$$\alpha_{ox} = -0.3838 \log(L_{2500\text{Å}}/L_{2\mathrm{keV}}). \tag{3}$$

3. AGNfitter's operation

AGNfitter 2.0 allows the user to model the photometric SEDs from the submillimeter to the UV, or from the radio to the X-rays when these data are available. For this purpose, it fits the observed fluxes with those calculated from a combinations of models governed by 15 parameters, which describe the emission of five components: the accretion disk, the torus, the radio emission, the stellar population of the galaxy, and cold dust emission from the star-forming regions. In addition, these calculated fluxes are filtered with the transfer functions of the telescopes used and redshifted afterwards. By comparing the resulting model SED to the data, the probability of each parameter combination is estimated by sampling the parameter space using a Monte Carlo Markov Chain algorithm, taking priors into account. Finally, the probability density functions (PDFs) of each of the parameters and some secondary products such as the star formation rate and integrated luminosities are constructed.

4. SED fitting results

This new version of the code was tested with a subsample of 9 active galaxies from the AGN SED ATLAS [19], characterized by a low redshift, high-quality data, and availability of radio and X-ray data. To validate the robustness of AGNfitter, we compared the physical properties found by the code when performing the SED fitting with those reported by the NASA/IPAC extragalactic database (NED). The results for the entire sample of AGN showed an accurate description of the data by the models, quantified by the negligible residuals (figure 1). Additionally, a good agreement was found between the physical properties inferred by the old and new models, suggesting that the fits are physically consistent using both of them.

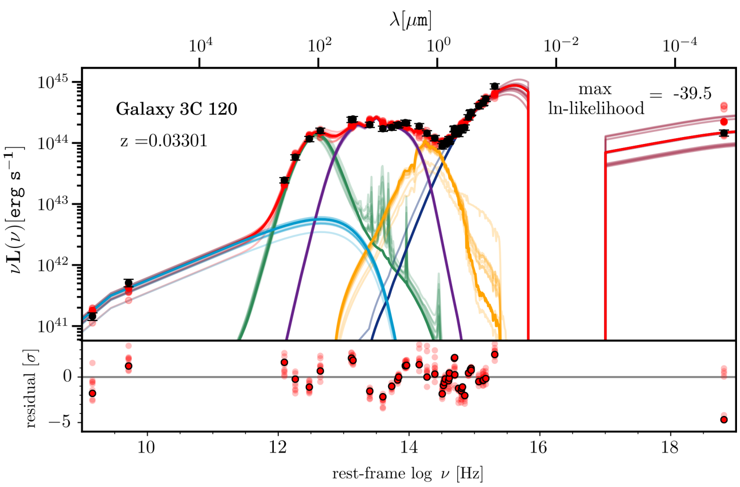

Figure 1. Observed SED and ten different realizations of the SED fitting of the galaxy 3C 120 using AGNfitter. Black points correspond to the measured fluxes, while the red points in the lower plot are the residuals of the fit. The green, yellow, purple, blue and light blue lines represent the emission of cold dust, the stars of the galaxy, the nuclear dust torus, the accretion disk, and the AGN in radio, respectively.

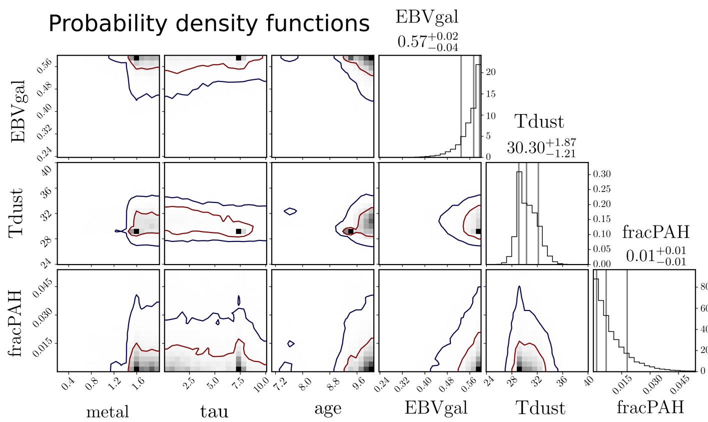

Figure 2. 2-dimensional and 1-dimensional PDFs of some of the physical fitting parameters. The black zones indicate the regions of highest probability and the red and blue contours delimit the regions at 0.5 and 1 σ, respectively.

5. Conclusions

AGNfitter 2.0 is a robust algorithm to perform both mathematically and physically consistent fittings of AGN and galaxy SEDs. The reported updates carried out allow to obtain a more complete diagnostic of the physical state of the AGN and its host galaxy, to impose more physical restrictions on the parameters and to perform a better exploration of the parameter space. In addition, this version offers the user freedom to define the type of model to be included for each component during the fit and more options in the settings, which can be adapted to the type of study to be realized with the SED fitting.

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