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GALAXY SED FITTING

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ABSTRACT

Modelling and fitting the spectral energy distribution (SED) of galaxies or regions of galaxies is one of the most useful methods available to the astronomer nowadays. By modelling the SEDs and comparing the models to the observations, we can collect important information on the physical processes at play in the formation and evolution of galaxies. The models allow to follow the evolution of the galaxies from their formation on. The versatility of code is crucial because of the diversity of galaxies. The analysis is only relevant and useful if the models can correctly reproduce this diversity now and across (as best as possible) all redshifts. On the other hand, the code needs to run fast to compare several million or tens of millions of models and to select the best (on a probabilistic basis) one that best resembles the observations. With this important point in mind, it seems logical that we should efficiently make use of the computer power available to the average astronomer. For instance, it seems difficult, today, to model and fit SEDs without a parallelized code. We present the new Python version of CIGALE SED fitting code and its characteristics. CIGALE comes in two main flavours: *CIGALE Classic* to fit SEDs and *CIGALE Model* to create spectra and SEDs of galaxies at all redshifts. The latest can potentially be used in conjunction with galaxy evolution models of galaxy formation and evolution such as semi-analytic ones.

Key words: Galaxies: models – Galaxies: multi-wavelength

1. INTRODUCTION

Galaxies are complex physical systems containing stars, gas, dust, active galactic nuclei (AGN) and dark matter. Their Spectral Energy Distribution (SEDs) over the widest available spectral range contain a wealth of information. They are the most direct probes to study the galaxy formation and evolution, both through direct observations and modelling. However, understanding a given galaxy or even a galaxy population means that we need to probe different spectral ranges as each of them is dominated by a specific emission source. For instance, stars emit in the ultraviolet (UV), optical and near-infrared (NIR) wavelength range. The mid-infrared (MIR) provides us with an information on Active Galactic Nuclei (AGN). The majority of absorbed starlight is reprocessed and emitted by dust grains in the far-infrared. Finally, emission lines are due to UV photons that ionize and excite the gas to create H II regions and its nebular emissions to produce a continuum and lines over the entire electromagnetic spectrum.

A better understanding of the emission and the physics of galaxies implies a modelling of galaxy emission and an identification of the several physical processes that make up the total emission. But a small set of models can hardly account for the broad diversity of galaxies. A representative and large enough set of models is needed to allow for a meaningful, quantitative and qualitative comparison of the observed and modeled SEDs in the SED fitting (see, e.g., Walcher et al., 2008).

Old FORTRAN CIGALE	New PYTHON CIGALE
Energy Balance	✔
Upper limits	✔ (Sawicki 2012)
Different dust attenuation for old and young stellar pops	✔
UV Dust attenuation laws (bump, slope)	✔
Star Formation History	Constant, exponential, delayed, analytical, from file
AGN component	✔ (Fritz 2006, Dale 2014)
Parallelization of runs	✔ (Python 3)
Creation of modelled SEDs from SFH	✔
Wavelength range	Far-UV to Far-IR and radio will be added this summer
Lines	✔ (from Far-UV to Far-IR)
Mock catalogue	✔
IR emission	Templates and models (Draine & Li 2007, Dale 2014, coupled greybody/powerlaw)

Figure 1. Comparing the old and new CIGALE: a new way of exploring galaxy emissions.

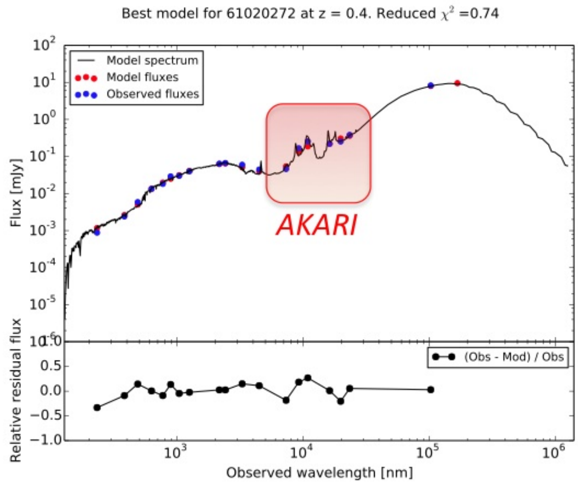

Figure 2. An example of fitting an observed SED with CIGALE. The top panel provides the best fit SED along with the data and the modelled flux densities. The bottom panel, on the same wavelength range, presents the residual (Obs. - Mod) / Obs for the best model. This gives a global idea of the quality of the fit.

Of course, the process of modelling and fitting the SEDs of galaxies from the far-UV to the FIR and the submillimeter/radio is needed if we are to meet our goal. Uncertainties due to all the steps from the modeling to the fitting must be reflected in the final interpretative phase to provide statistically significative results.

The SED of galaxies are dominated by dust emission at least to z $\sim$ 4 (Burgarella et al., 2013). If we are to model and fit galaxies over the wider wavelength/frequency range, we absolutely need to account for the dust emission in a consistent way.

Two main approaches are used:

1. The most complex one explicitly solves the equation of radiative transfer in a dusty medium with various degrees of sophistication and/or geometrical realism. A good (of course, depending on the quality of the data and of the models) estimate of these properties implies a large set of parameters related to, e.g., the absorption and scattering for different dust compositions and distributions. Even though this method requires a large computational power, both the algorithms and the computers used have considerably improved. The dust radiative transfer codes are now more realistic and powerful. However, even in an optimistic and rich environment, this approach remains complex and implies a large computational effort because of the treatment of dust effects. Most studies can only analyze a small number of galaxies (e.g., Schechtman-Rook et al., 2012) on NGC 891 where the various components of the galaxy (i.e., the stellar disc, dust disc and central bulge) can be distinguished. Note, however, that faster radiative transfer of dust reprocessing in semi-analytic models with artificial neural networks can be now achieved (see: Silva et al., 2012). But, very large galaxies samples collected by recent multi-wavelength surveys (e.g. Matsuhara et al., 2012) are still out of reach.
2. The most efficient method is illustrated by two of the most widely used codes presented by DaCunha et al. (2008) (MagPhys) and Noll et al. (2009) (CIGALE). They introduce a new class of empirical but physically motivated model to study the UV-to-FIR SEDs of galaxies in a consistent way, where the energy taken off the UV and optical by the dust grains is re-emitted in the FIR. The spectral evolution of the stellar populations is modeled using a Single Stellar Population population synthesis models and a star formation history (SFH) to form Complex Stellar Populations (CSP). In MagPhys and the old CIGALE, to obtain CSPs, the SSPs of different ages are weighted and added according to the star formation scenario chosen. “Box models” with constant star formation over a limited pe-

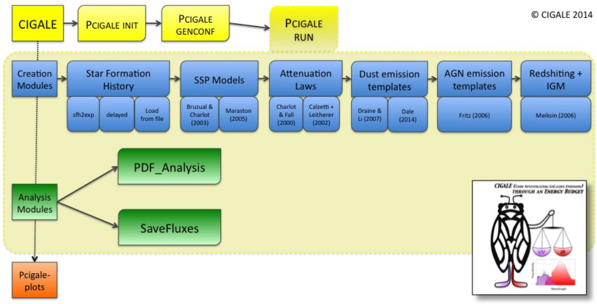

Figure 3. How does CIGALE work?. The yellow boxes build the input file used to run CIGALE. This file (pcigale.ini) contains the main parameters of the models. The blue boxes lists the main available modules for each category (star formation history, SSP, attenuation law, dust emission and ANG emission). The green boxes represent the two CIGALE modes: *CIGALE Classic* and *CIGALE Model*. Finally, it is possible to plot several results like the probability distribution functions for each parameter and object, the best model and its component (red box).

riod and "τ models" with exponentially decreasing star formation rate (SFR), are available in CIGALE while for MagPhys two components: an underlying continuous model, characterized by an exponentially declining SFR, and random bursts superimposed on this continuous model. To account for the time-dependent dust attenuation of starlight, a two-component model like in Charlot & Fall (2000) is assumed in MagPhys and in CIGALE. Moreover, in CIGALE, the shape of dust attenuation laws and the amount of dust attenuation control the luminosity absorbed and re-emitted by dust in stellar birth clouds and in the ambient ISM in galaxies respectively. This is how this luminosity is distributed to compute the IR SEDs. The distributions are assumed to follow models or templates in CIGALE and are the sum of three black body components in MagPhys. In CIGALE, an AGN component and a radio emission can also be added.

2. THE BAYESIAN METHOD

The "Bayesian fitting" method (Bayesian method, hereafter) consists in computing a large set of multi-wavelength SEDs that are fit to the observed data. For the modelling phase, models and/or template are used to build the modelled SEDs. Usually, the Bayesian method is preferred when fitting multi-wavelength data because the problem of solving for the galaxy physical parameters is not linear, when phenomena like the dust attenuation, the emission lines, and the dust emission is

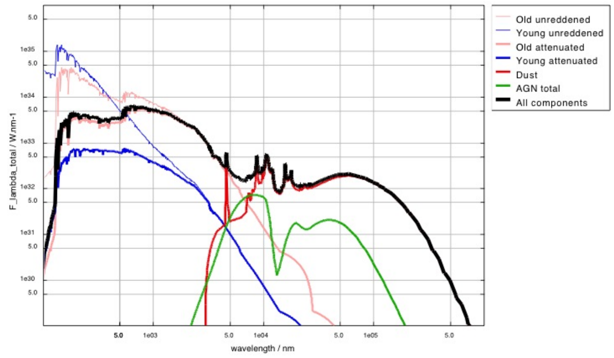

Figure 4. The components used to fit the observed SED can be plotted separately as shown in this figure..

included in the fitting process. We stress that by pre-computing a set of models followed by the selection of the best one, i.e., the one for which the χ^2 is lower, implies by itself a Bayesian approach. By choosing which models to compute, one introduces a prior, which, while possibly flat in terms of a given parameter, assumes that the data can be represented by that model and that parameter space. By using χ^2 as a maximum likelihood estimator one finds the most probable model(s), or in Bayesian terms, the probability of the data given that model. In the method presented here, the lowest-χ^2 models are used to build a probability distribution function (PDF) and estimate the physical parameters.

The computation of the library of models is probably the essential step because it translates our prior knowledge about the galaxy sample (what do we care and what can we neglect without impacting the results too strongly?).

3. THE NEW CIGALE

The new version of CIGALE, available at http://cigale.lam.fr has been developed in Python 3 and it supersedes the old Fortran CIGALE (which is noneless still available via the same URL). In addition to the traditional SED fitting use (we call it *CIGALE Classic*) that offers one of the best (in terms of available models, speed, versatility) codes to fit multi-wavelength data, CIGALE can now be used to predict the emission (spectra, SEDs) of galaxies based on assumed input parameters. We call it *CIGALE Model*. This means that CIGALE can be plugged onto, e.g., semi analytical models (SAMs) to predict the emission of galaxies. Beside the modularity and the parallelization of CIGALE, this is probably one of the most important changes in the new version. We also improved *CIGALE Classic* by enlarging and updating the library of models and templates and more specifically by providing CIGALE users with post-Herschel models.

Porting CIGALE from Fortran to Python has been an important change. This change is mainly justified by 1) a larger modularity and readability of the code allowing to easily modify/update CIGALE and to add new modules whenever needed and 2) an automatic parallelization of the code allowing an acceleration of each run, depending on the number of processors available. Figure 1 lists the main differences between CIGALE Fortran, CIGALE Python and Figure 2 shows an illustrative fit using the important AKARI data in the North Ecliptic Pole deep field.

Figure 3 shows the main modules available in CIGALE (both *CIGALE Classic* and *CIGALE Model* as of today (Sept. 2014). Figure 4 plots the components (available for an output table) used to fit a given galaxy in the NEP deep field.

4. CONCLUSION

Fitting SEDs of galaxies or of large enough portions of local galaxies is a very powerful way to estimate the physical parameters of the studied objects. However, given the large amount of data and the diversity of galaxies, we need to use a code that is simultaneously fast and versatile, allowing the modelling the emission of stars, dust, AGNs. This is especially true in the AKARI fields and, more specifically, the AKARI NEP where a wealth of data is available in the mid-infrared range. These data are crucial to decipher the respective roles of star formation and AGN. The addition of Herschel data in the far-infrared is also an important added value since it brings a constraint on the dust emission.

We have presented the new SED fitting + modelling code CIGALE and showed that it is designed to face the challenge brought by modern large surveys with both a large number of galaxies and a high spectral density of data from the far-ultraviolet to the far-infrared. CIGALE is an open-source and Python package developed to study the evolution of galaxies by creating modelled SEDs from given star formation histories (any type) and comparing these models to observed ones from the far-ultraviolet to the radio.

The new version of CIGALE is written in Python (version 3.4 or higher) and its modularity makes it easy to evolve and update. Several stellar populations models are available to model the stellar emission. For the dust emission, several libraries of templates can be used and the far-infrared (FIR) is evaluated through an energy balance with the energy lost in FUV because of dust. To carry that out, synthetic attenuation curves based on a modified Calzetti law (a 217.5nm and a variation of the slope can be introduced) are used. A full treatment of the ionizing photons allows to evaluate the flux of the emission lines. Finally, an AGN component can also be taken into account. From the modeled spectra, we compute the flux densities at the input redshifts in the given filters and compared to the observed data using a Bayesian approach. To speed up CIGALE, we developed it to run in parallel on several processors in modern computers.

The new CIGALE is simultaneously more powerful (i.e. more science capabilities), faster (i.e. optimized and parallelized) to fit observed SEDs but also to plug on the output of galaxy formation models to model their spectra from the FUV to the radio. The new CIGALE will be described in Burgarella et al. (2015, *CIGALE Classic*) and Boquien et al. (2015, *CIGALE Model*) and Ciesla et al. (2015, AGN emission).

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