Challenges in Panchromatic Modelling with Next Generation Facilities
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Modeling the panchromatic emission of galaxies with CIGALE

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Abstract. Panchromatic modeling is one of the most powerful tools at our disposal to measure reliably the physical properties of galaxies across cosmic times. We present here an entirely new implementation in `python` of one such tool: `CIGALE`. Developed along three main design principles: simplicity, modularity, and efficiency, it has proven to be a versatile code that in addition to estimating the physical properties of galaxies (or regions within galaxies), can generate arbitrary sets of theoretical models or be used as a library to build other tools. Among its defining features, it is a truly panchromatic code ranging from the far-ultraviolet to the radio that takes into account numerous physical components (including active nuclei or synchrotron emission), that can fit non-photometric data, handle upper limits, determine photometric redshifts, and even build mock catalogs.

Keywords. galaxies: evolution, ultraviolet: galaxies, infrared: galaxies, methods: numerical, methods: statistical

1. Introduction

To undestand the formation and evolution of galaxies, it is critical that we are in a position to measure their physical properties reliably across cosmic times. Doing so is challenging. First, assembling the necessary observations is a considerable effort. Then, converting these observations into physical quantities such as the stellar mass, the attenuation, the star formation rate (SFR), etc. is not straightforward. Uncertainties and variations in the stellar populations (metallicity, rotation, binary evolution, etc.), the star formation history, the properties of the dust and its relative distribution to the stars, etc. all can affect tremendously the emerging radiation from galaxies.

While simple recipes can provide estimates of some physical properties from a single band (e.g., near-infrared to measure the stellar mass, or the far-infrared for the SFR), such recipes are inherently limited and rely on strong assumptions. To address some of the limitations, more advances recipes have been created combining two or more bands (e.g., near-infred and optical color for the stellar mass, far-infrared and far-ultraviolet or Hα for the SFR). Even though such recipes have the advantage of simplicity, they remain limited in their range of applicability. A more general solution that has been emerging over the past two decades is the modeling of the spectral energy distribution (SED) of galaxies. By combining observations over a broad range of wavelengths, it is not only possible to waive a certain number of assumptions made to conceive these simple recipes, but it also allows to break degeneracies plaguing these estimators (e.g., the combination of far-ultraviolet to far-infrared data permits to disentangle the age of stellar population from attenuation by dust). Such an approach taken by the `CIGALE` code (Burgarella *et al.* 2005; Noll *et al.* 2009), which has proven to be highly fruitful (e.g., Buat *et al.* 2011, 2012, 2014, 2018; Boquien *et al.* 2013, 2014, 2016; Ciesla *et al.* 2015, 2016, 2017; Salim *et al.* 2016, 2018). We present here an entirely new implementation in `python` of `CIGALE` (Boquien *et al.* 2018).

2. CIGALE: Code Investigating GALaxy Emission

In a nutshell `CIGALE` is a panchromatic (ultraviolet to radio) energy balance (the emission absorbed by dust in the ultraviolet-to-near-infrared) Bayesian (the physical properties are derived from the marginalized likelihood distributions) SED modeling code written in `python`. It is the successor of a code of the same name written in `FORTRAN` (Burgarella *et al.* 2005; Noll *et al.* 2009).

2.1. *Design principles*

It has been developed following three main design principle based on the experience from the `FORTRAN` version: simplicity, modularity, and efficiency.

2.1.1. Simplicity

The aim is for `CIGALE` 1) to be easy to run from the point of view of a user, 2) to be transparent as to what it does to avoid a "black box effect", and 3) to be easily adaptable to new use cases with simple modifications of the code.

To achieve these aims `CIGALE` has a dynamically generated configuration file that is abundantly documented and provides most of the information necessary to run the code. In addition `CIGALE` is written in a modern version of `python`, a language that is now very broadly used in astronomy, ensuring that a large part of the community can adapt the code if need be. To facilitate such modifications, the code follows a very modular structure (see Sect. 2.1.2). Finally to make the code accessible and to facilitate external contributions, `CIGALE` is developed in a fully open manner on a public git repository.

2.1.2. Modularity

The spectral models are built through a succession of modules, each of them dedicated to a specific component: SFH, stellar populations, nebular emission, dust absorption, dust emission, non-thermal radio emission, absorption from the intergalactic medium, redshifting. In a similar way the estimation of the physical properties is also a module in itself. Each module can be transparently substituted for another module of the same category (e.g., two different dust emission models). That is to say that modules are largely self-contained and independent from one another.

2.1.3. Efficiency

The code relies heavily on major `python` libraries such as Numpy, Scipy, or Astropy to carry out the heavy lifting of the computation. Where these algorithms proved to be bottlenecks, optimized routines have been implemented. Special care has been made to avoid computing identical quantities several times with a cache system. Finally, to exploit the architecture of modern computers, `CIGALE` has a high-level parallelism making use of multiple cores both to compute the models and estimate the physical properties (Fig. 1 left).

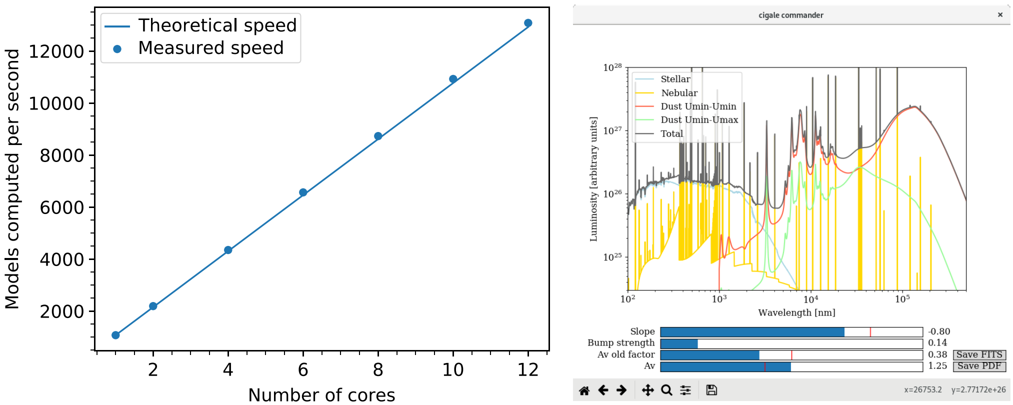

Figure 1. Left: Number of models computed per second as a function of the number of cores used. While the velocity depends somewhat on the actual parameter space explored, in this case computing a single model on a single core takes ∼1 ms. Right: Example of a pedagogical tool built on `CIGALE` to explore the effect of the dust attenuation curve.

2.2. *A versatile code*

Following the aforementioned principles `CIGALE` proves to be a very versatile code. It can not only be used to estimate the physical properties of galaxies, its main goal, but it can also to be used to compute sets of theoretical models or even as a library to build other softwares. For instance a small pedagogical tool has been built to interactively explore the impact of various physical properties on the SED of galaxies (Fig. 1, right).

In addition to this, `CIGALE` is also a very feature-rich code. We describe hereafter some of its defining features in a non-exhaustive way.

2.2.1. Panchromatic code

Handling data ranging from the far-ultraviolet to the radio domain, `CIGALE` is a genuine panchromatic code. Such a broad wavelength coverage is essential to break degeneracies and measure the physical properties of galaxies as reliably as possible.

2.2.2. Bayesian code

The physical properties and the related uncertainties are estimated as the likelihood-weighted means and standard deviation of the model values on a grid, which can reach several hundred million models to sample the parameter space. This allows to take into account the fact that different models with different physical properties can be likely to reproduce the observations.

2.2.3. Fitting non-photometric data

Beyond the standard approach of fitting fluxes in passbands, `CIGALE` can also fit any spectral line flux, or intensive or extensive physical property computed by the code: ultraviolet slope β, D_n4000 index, equivalent width, total infrared luminosity, etc.

2.2.4. Upper limits

Astronomical observations are not always as deep as we would like. To take this reality into account, `CIGALE` takes into account the presence of upper limits following the approach of Sawicki (2012).

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2.2.5. Numerous modules

Numerous modules are provided with `CIGALE`, covering a wide range of components, including active nuclei, nebular emission, and the synchrotron emission of galaxies. For some components, such as the dust, several modules are provided.

2.2.6. Photometric redshift

In case the redshift is unknown, `CIGALE` can be used in a photometric redshift mode, either to determine the redshift in isolation or to factor into the estimation of the physical properties the fact that the redshift is unknown a priori. One major advantage over photometric redshift codes that are limited to stellar emission is that the emission by dust can bring further contraints.

2.2.7. Mock catalogs

Mock catalogs are a useful tool to explore the self-consistency of the modeling and assess the reliability of the estimation of the physical properties. To this aim `CIGALE` can automatically compute mock-catalogs for any sample, allowing the comparison of known and estimated physical properties.

3. Conclusion

The `CIGALE` tool is pursuing further developments to fulfill the ever evolving needs in the field of SED modeling, including for instance full spectro-photometric fits, or X-ray and photo-dissociation region models. It is freely available for download at https://cigale.lam.fr.

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Discussion

Miyaji Takamitsu: Please explain the development of the X-ray implementation in a little more detail.

Médéric Boquien: This is an on-going effort led at the moment by Guang Yang. The main challenge is to relate the X-ray emission to the physical properties of the galaxy as X-ray binary evolution can be complex and depend on factors such as the star formation history. At the moment we rely on the results of Mezcua *et al.* (2018b). The first results appear promising but it requires further validation.

Dan Taranu: What is the fundamental problem with spectro-photometric modeling?

Médéric Boquien: In my view we face two main challenges. First, if we naively combine photometric with spectroscopic observations, the latter are so numerous relative to the former that they completely drive the likelihood. This strongly reduces the relative weight of panchromatic photometric data. The consequence is that bands bringing a lot of information (e.g., far-ultraviolet and far-infrared observations probe the emission massive stars and dust that by far unconstrained with optical spectra) end up having little bearing on the fit. The other issue, and it is what makes the first one problematic, is that fits are necessarily affected by systematic errors both on the models themselves (dust models or single stellar populations are not only sensitive to the choice of ingredients such as stellar atmosphere, rotation, or binary evolution, but also to the quality of the stellar spectra or models to build them) and on the observations (e.g., imperfect flat field or wavelength-dependent flux calibration). Even small errors will considerably lower the likelihood of models due to the sheer number of spectral data points relative to the photometric data points.

Adam Carnall: How do you include Bayesian priors in the grid-based approach?

Médéric Boquien: The priors on can be set by playing on the spacing between the input physical properties. For instance an evenly spaced set of parameters will be equivalent to a flat prior, whereas if a specific range of parameters has a shorter spacing, this will make this region denser relative to the rest, thus yielding a non-flat prior. The priors can either be given through an explict list of values or defined through any function provided in Numpy, such as `logspace` for instance.

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