The Emission of Galaxies over the Whole Electromagnetic Spectrum

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The emission of galaxies is not limited to the usual optical range but extends to a wider spectral range with, most notably, emission in the X-ray, ultraviolet, infrared and radio ranges. Their detection and study brings a lot of information to the astrophysics because the physical phenomena at the origin of the various emissions are different. Each of them allows analysis of a different facet of the physics of galaxies: gas, stars, dust, Active Galactic Nuclei (AGN). However, gathering this multi-wavelength information is not an easy task as some of them do not reach ground-based telescopes and we have to design and launch space telescopes to catch and collect the relevant photons. This paper will present the tools that are available to the astrophysicist to decipher the message sent by local, distant or even the most remote galaxies observed in the universe.

1 Introduction

Understanding the Universe inevitably translates into understanding the main components of the Universe. On a cosmological scale, galaxies form the major component while storing inside their own components the history of the Universe. Like any other astrophysical object consisting of baryonic matter, galaxies emit light over the entire electromagnetic spectrum. Understanding this emission means that we can get a handle on the associated physical processes. It has become clear that addressing the question of the formation and the evolution of galaxies in a cosmological context implies that we understand their emission over the broadest electromagnetic spectrum, in opposition to mono-wavelength studies that provide us with a far more restricted view. For instance, far-infrared (FIR) data are mandatory if we wish to estimate the star formation rate density at $z < 4$ — the FIR traces dust–absorbed star formation — because the FIR contribution to the total star formation density can reach up to 90% below this redshift (Takeuchi et al., 2005; Burgarella et al., 2013). The first attempts at using a multi-wavelength information used correlations of measurements in two bands, e.g. far-ultraviolet (FUV) and FIR to constrain the dust characteristics or colors, e.g., FUV−B for the stellar ages and masses. But, even though we can still make use of this information, modern astrophysics prefers using multi-wavelengths data consistently as the emissions in the various spectral ranges can be physically connected, e.g. AGNs emit radiation in X-rays, in the optical, in mid-infrared and

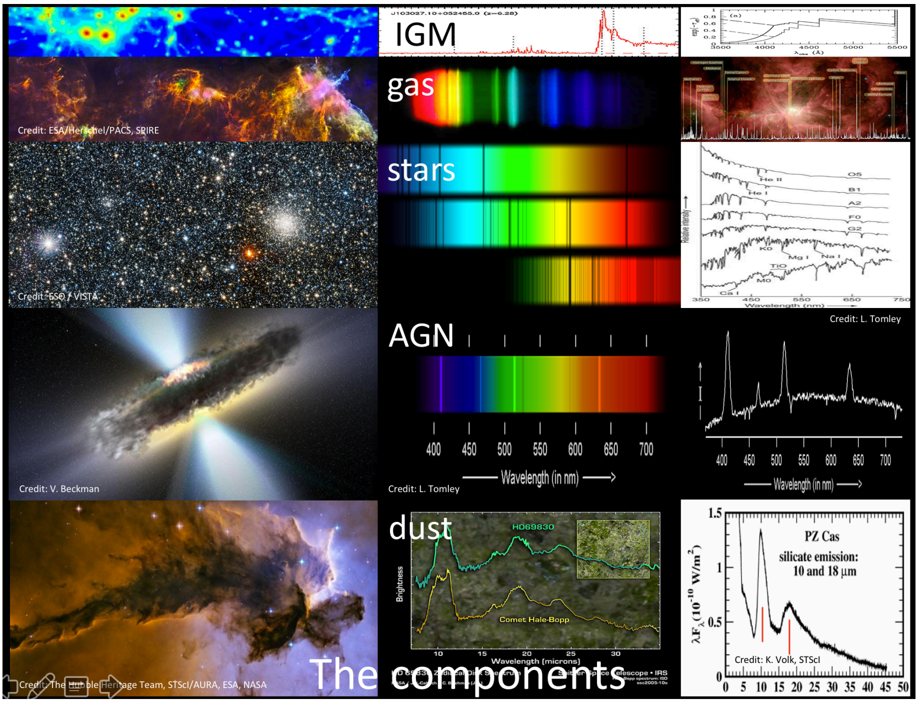

Fig. 1: Most physical processes at play in a galaxy contribute to the shape of the emitted SED

in radio. However, the drawback of this more informative approach is that we do have more information in terms of data. So, we need to handle them by using more powerful computers and codes that are able to deal with a wealth of data and a huge number of models. A statistical approach is mandatory.

2 The variety of observed SEDs

Most physical processes have an effect on the observed SED (Fig. 1). However, both the wavelength range and the strength of the impact can vary. For instance the emission of an Active Galactic Nucleus (AGN) in a Seyfert 2 galaxy can strongly modify the SED in the mid-infrared but hardly in the far-infrared (Hatziminaoglou et al., 2010). Modelling the observed SED of a given galaxy or a sample of galaxy implies a gain of knowledge on the nature of the galaxy. But, if we wish to correctly model the observed SEDs, the code we plan to use must be able to encode the effect of the above physical processes into the SED. Furthermore, our knowledge keeps evolving and we might need to easily update or even replace part of the code. This is why modularity is crucial and astrophysicists usually do not like black boxes.

3 What information can be extracted from the Spectral Energy Distribution?

Theoretically, the observed SED contains information related to the nature of the galaxy. However, practically, it is not always easy to get back to the physical parameters behind the galaxy SED.

We can easily understand that the quality of the observed SED is at the origin of one of these limits: if data collected over some range of wavelengths have a low signal-to-noise ratio, it will be difficult to extract information securely. For instance, estimating the total star formation rate (SFR) of galaxies requires good quality data in the wavelength range corresponding to dust emission at tens to hundreds of Kelvins, that is in the rest-frame mid- to far-infrared. However, one of the issues is that the amount of data and therefore the amount of information is often quite limited. It is common that the dust emission is not well sampled or even that we only have an upper limit from which we must constrain the total dust emission. Collecting deep far-infrared data can be a strong challenge for intrinsically faint nearby objects or for bright but distant objects. Without reliable infrared data, crucial parameters such as the dust mass or the dust temperature cannot be safely inferred. Even the amount of dust attenuation can be a problem: we can use, e.g., the slope of the ultraviolet spectrum or the stellar mass to obtain an estimate of the dust attenuation (A_V or A_{FUV}).

Besides, even when good data are available, we might face degeneracies when using broad-band measurements. For instance, the reddening of the ultraviolet-optical spectrum can be due to dust and/or to the age of the stellar populations. With the help of far-infrared data, we can raise this degeneracy by using redundant information on the dust attenuation which means that we can, to some extant, hope to decouple the effects of dust attenuation from that of the age on the ultraviolet-optical spectrum.

So, it is wise when performing any SED modelling to estimate the uncertainties on the physical parameters. However, beyond these uncertainties, it is even wiser to control the number of degeneracies by carrying out tests on a mock catalogue built to be not-too-far from the observed data and for which we have a full knowledge (as best as we can from a model) of the parameters we are trying to estimate (Giovannoli et al., 2011). These tests allow us to compare the input and output values of the physical parameters and quantitatively evaluate our capacity to estimate them and, sometimes, even estimate in which range we can trust our results (Fig. 2).

4 Two generic types of SED modelling codes

4.1 Radiative Transfer codes

In the presence of dust grains in the environment around stars, the emission of the stellar radiation is scattered, absorbed and re-emitted by dust. That is what we refer to when we mention the dust attenuation. The spectrum emerging from this circumstellar processing provides the astronomer with the only available information about the embedded stellar populations.

Radiative Transfer codes model the transport of radiation in these dusty circumstellar environments by making assumptions about important parameters such as the chemical composition, the star formation history, and the dust/star geometry of galaxies. These codes solve the radiation transport equation coupled self-consistently with the equation of motion for the outflow of gas and dust grains. They include the properties for the most common types of astronomical dust and supports various analytical forms for the density distribution in galaxies.

Among the main phases in building the modelled SEDs, the specification of geometry is an important one. This means that the user must specify the distributions of stars and dust, both at different scales in the model. This is a fundamental phase be-

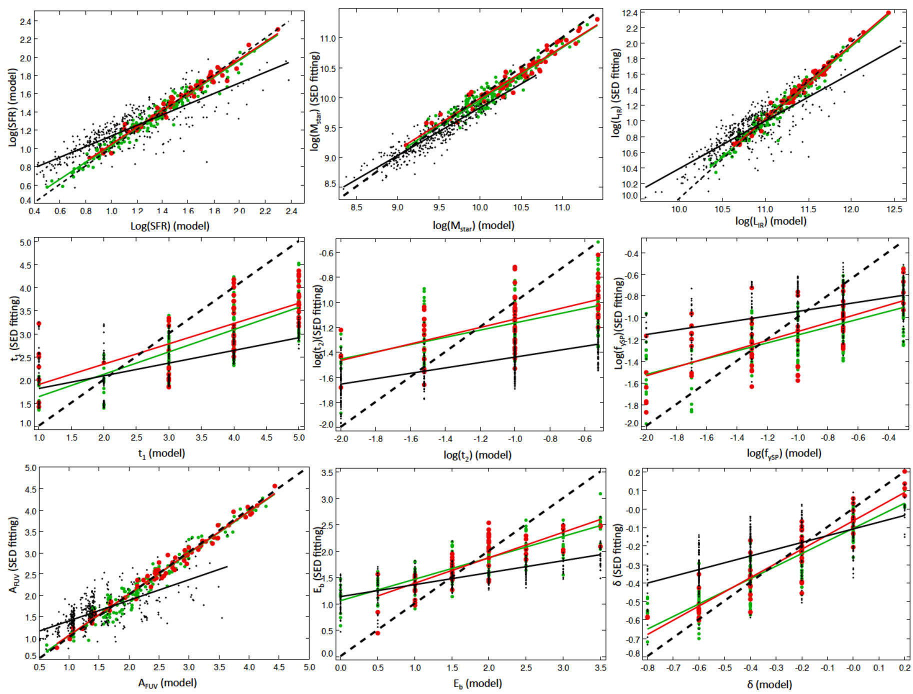

Fig. 2: From Buat et al. (2012). Building mock catalogues as shown in this mosaic from the SED modelling code *CIGALE* (`http://cigale.lam.fr`), allows us to evaluate the quality of the parameter estimation process.

Comparison of parameters estimated by SED fitting for the catalogue of artificial galaxies. The initial values of the parameters are on the x-axis and the values estimated after SED fitting on the y-axis. The galaxies without IR data are plotted as black dots, the galaxies with only a MIPS detection with green filled circles and those also detected with PACS with large red filled circles, the regression lines for each subsample are also plotted as solid lines and the 1:1 relation as a dashed line. From the left top to the bottom right the parameters considered are the SFR, M_{star}, L_{IR}, and various other parameters estimated by *CIGALE* among which the strength of the 217.5nm bump (E_b) and the slope of the dust attenuation in ultraviolet (δ).

fore actually running the radiative transfer calculations to derive the radiation fields in galaxies which will permit evaluation of the temperature distribution of grains of different sizes and the composition as a function of position in the galaxy. Finally, by integrating over all positions in a given galaxy, we obtain the modelled SED (e.g. Popescu et al., 2011; Baes et al., 2011; Silva et al., 2009; Efstathiou et al., 2013).

4.2 *Physically oriented codes with energy balance: the CIGALE example.*

Several phenomenological codes use the energy balance to model SEDs and fit observed ones (*MagPhys*: da Cunha et al., 2008; *CIGALE*: Noll et al., 2009; Boquien et al., 2017 in prep.). In the rest of this section, we will more specifically present *CIGALE* (`http://cigale.lam.fr`).

These physically motivated codes use a different philosophy. They model the various phenomena that contribute to the total galaxy SED and combine them to produce a global modelled SED. The first phase consists of assuming a star formation history. Depending on which code is used several options are available.

In the *CIGALE* code, a wide range of analytical star formation histories can be used (constant, exponentially increasing or declining, delayed, periodic, etc.) but it is also possible to use a table describing the time evolution of the star formation history that might be, for example, the output of semi-analytical models.

In the next phase, we define which Simple Stellar Population (SSP) model is chosen for this run. *CIGALE* provides a choice between Maraston (2005) and Bruzual (2003) in the public version. Once the SSP is selected, it is combined with the star formation history to obtain the dust-free emission of the complex stellar population, i.e., a galaxy. In the presence of dust, we have to account for the dust attenuation. In *CIGALE*, we offer the possibility of having a parametric dust attenuation law where the basis is the Calzetti law. However, since we know that this law is not valid for all galaxies, we can modify the slope and/or add a bump at 217.5 nm (see Eq. 1) as described in Buat et al. (2012):

$$\frac{A(\lambda)}{E_{B-V}} = \left[k(\lambda) \times \left(\frac{\lambda}{5500}\right)^{\delta}\right] + \left[\frac{E_{bump}\lambda^2\gamma^2}{(\lambda^2 - \lambda_0)^2 + \lambda^2\gamma^2}\right], \tag{1}$$

where $k(\lambda)$ is the composite dust attenuation law from Leitherer et al. (2002) below 150 nm and by Calzetti et al. (2000) above 150 nm. Since young and old stars do not suffer from the same amount of dust attenuation, it is possible to constrain the ratio $E_{old}(B-V)/E_{young}(B-V)$ in *CIGALE.*

As in any energy balance model, *CIGALE* assumes that all the energy processed by dust is re-emitted in the infrared. The shape of the emission is provided by one of several options. In the public version, Draine (2007), Dale et al. (2014) and Casey (2012) are available at the moment.

The nebular emission (continuum and lines) is also computed from the ultraviolet to the near-infrared (if requested). Given the number of Lyman continuum photons, *CIGALE* computes the Hβ line luminosity and then the other lines using the metallicity and radiation field intensity-dependent templates that provide the ratio between individual lines and Hβ (Inoue, 2011). The nebular continuum is scaled directly from the number of ionizing photons.

Finally, emission from an AGN can be added using e.g. the Fritz et al. (2006) models. For a detailed description of fitting SEDs using an AGN model we refer to Ciesla et al. (2015).

Finally, the last and mandatory module in CIGALE redshifts the modelled SEDs and adds the absorption from the inter-galactic medium (Meiksin, 2006).

Note than models can be built without any observed data. After fitting, plotting the best model that matches the observed SED (Figs. 4.2 and 4.2) allows us to check the quality of the fit. However, beyond this best model described in the first output file, *CIGALE* provides an output file with the parameters and the associated uncertainties for each galaxy and each analysed parameter.

Two important features of *CIGALE* are:

1. SED fitting analysis can be long for a very large number of models and/or very large sample of objects. To make runs possible in a reasonable amount of time, *CIGALE* is parallelized and can run on multi-core computers.

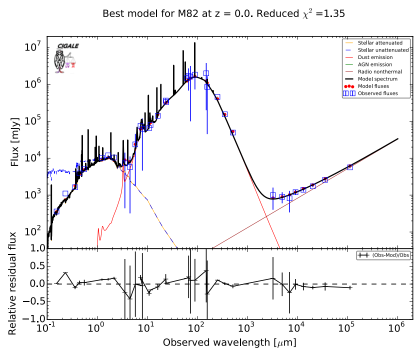

Fig. 3: *CIGALE* best fit for Messier 82. The blue line is the unattenuated stellar spectrum. The orange line represents the attenuated spectrum. The red line is the dust emission. Note that radio emission is also included for this fit.

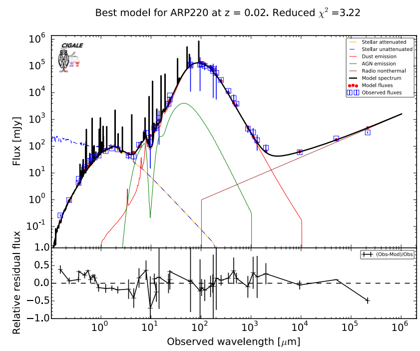

Fig. 4: *CIGALE* best fit for Arp 220 that also includes (green) an AGN emission. In both panels, the lower sub-plot presents the residual relative flux computed as $(f_{observed} - f_{model})/f_{observation}$ in the same wavelength range.

2. *CIGALE* is very modular (Fig. 5) and it is easy to add new models, templates, star formation history, dust attenuation law, etc. simply by adding a new module (with the right interface) in the appropriate directory.

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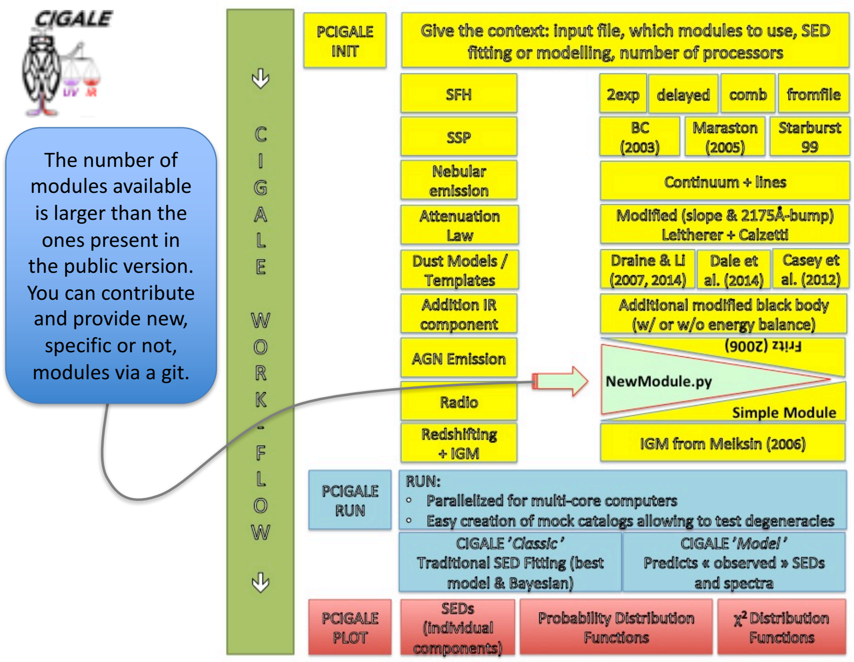

Fig. 5: The modularity of *CIGALE* is illustrated in this flow chart. Any new module can be added to modify, or introduce new functionality into, *CIGALE*.

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