Challenges in Panchromatic Modelling with
Next Generation Facilities
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Going beyond galaxy ages with dense basis star formation history reconstruction

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Abstract. Panchromatic SED fitting allows us to better resolve degeneracies between quantities like the star formation rate and dust. This in turn allows us to more robustly extract information about the different stellar populations that comprise a galaxy's Star Formation History (SFH). Using the Dense Basis SED fitting method (Iyer & Gawiser 2017), we reconstruct the SFHs with uncertainties for a large sample of galaxies using an atlas of SEDs corresponding to a physically motivated basis of SFHs. Using Gaussian Process Regression, we encode the parameters describing these SFHs in a functionally independent form. This give us more robust estimates for quantities like Stellar Masses and Star Formation Rates, that directly depend on the SFH. These SFHs can additionally be used to answer questions like the time at which a galaxy's star formation peaked, and how many major episodes of star formation occurred in a galaxy's past, allowing us to go beyond the traditionally estimated 'Galaxy Age', which is often poorly constrained. They also allow us to probe the high-redshift low-stellar mass regime of the SFR-M* correlation by constructing trajectories in SFR-M_* space for each galaxy.

Keywords. galaxies: star formation history, galaxies: evolution, techniques: photometric

1. Introduction

Galaxy surveys like CANDELS (Grogin *et al.* (2011); Koekemoer *et al.* (2011)) provide us with high-quality multiwavelength spectral energy distributions (SEDs) for $\mathcal{O}(10^5)$ galaxies, with this number rising to $\mathcal{O}(10^8)$ with upcoming surveys. Galaxy catalogs compiled by analyzing these SEDs often report quantities like stellar masses (M_*), star formation rates (SFR), and galaxy ages (Santini *et al.* (2015)). However, these quantities are summary statistics that depend on the star formation history (SFH): a record of when and how a galaxy formed its stars. Approximations for the SFH in SED fitting can thus cause biases in estimating these quantities, which could then propagate into more involved analyses of galaxy evolution such as mass functions (Baldry *et al.* (2008)), estimates of the cosmic star formation rate density (SFRD) (Madau & Dickinson (2014)), and scaling relations like the $SFR - M_*$ correlation (Speagle *et al.* (2014)) and the mass-metallicity correlation (Tremonti *et al.* (2004)).

Estimating physical quantities from broadband photometric SEDs has long been done using SFHs that follow a simple parametric form like exponentially declining (Skelton *et al.* (2014)) or lognormal SFHs (Gladders *et al.* (2013)), or are binned in time (Dye (2008)). In Iyer & Gawiser (2017) we quantified the bias and scatter in estimating different physical quantities due to different SFH parametrizations, while devising a flexible approach towards describing galaxy SFHs that encodes the maximal amount of SFH information in a minimal number of parameters, called the Dense Basis method. Recent improvements to the method (Iyer *et al.* (2019)) make the problem of estimating SFHs

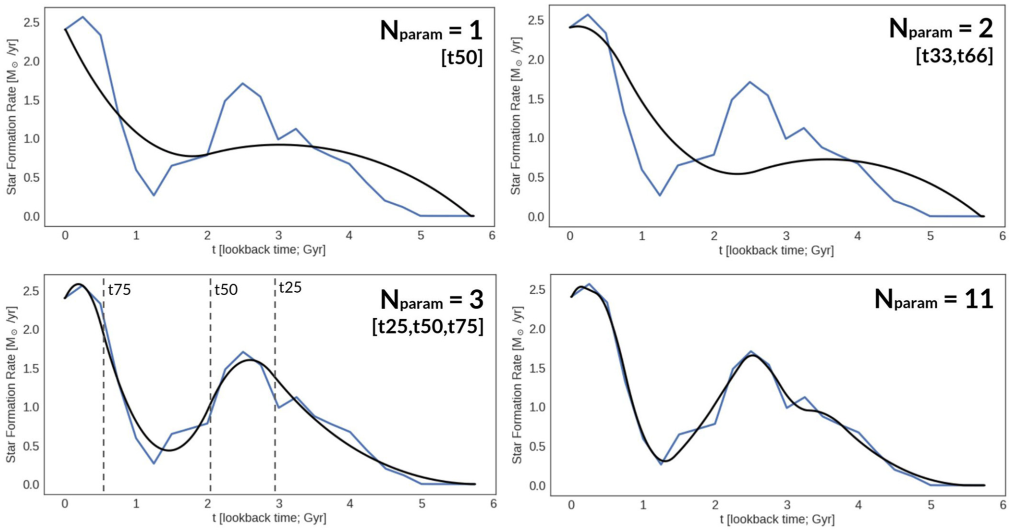

Figure 1. Constructing smooth, nonparametric star formation histories corresponding to an example galaxy in the Somerville, Popping & Trager (2015) semi-analytic model (blue line). Working here in SFH space, we estimate the SFH using varying numbers of parameters $\{t_x\}$, which denote the lookback times at which the galaxy forms various equally spaced quantiles of its stellar mass. The Dense Basis SFH constructed from these parameters is shown as a solid black line for various values of N_{param} given in the top-right corner of each plot. The accuracy of the GP-SFH approximation increases as we go to higher N_{param}, although we obtain a good approximation of the truth for as low as $N_{param} = 3$.

more well-conditioned, leading to novel methods of studying galaxy evolution that are now accessible with these smooth, nonparametric SFHs derived from the observations.

2. The Dense Basis method

The Dense Basis method provides a flexible, nonparametric description for galaxy SFHs that can be incorporated into any SED fitting code. In this framework, a star formation history is described using a tuple:

$$SFH \equiv (M_*, SFR, \{t_x\}) \tag{2.1}$$

where the set $\{t_x\}$ describes the lookback times at which a galaxy formed N uniformly spaced quantiles of its stellar mass, where N is a free parameter that can be informed by the data being fit. Figure 1 shows an example SFH from the Santa-Cruz semi-analytic model (Somerville, Popping & Trager (2015)), with the N = 3 panel showing the lookback times at which the galaxy formed 25%, 50% and 75% of its stellar mass at the time of observation, respectively. These parameters represent integral constraints that help specify the shape of the SFH. To construct smooth SFHs that satisfy these constraints, we use Gaussian Processes (Rasmussen & Williams (2006)), a machine learning technique for nonparametric regression that generalizes the gaussian probability distribution to the space of functions. In Figure 1 we calculate the $(M_*, SFR, \{t_x\})$ tuples for the example SFH with $N_{param} = 1, 2, 3,$ and 11, and then use the GP-SFH routine to generate smooth, nonparametric SFHs corresponding to these N-tuples. While we chose an SFH that is not well described by any standard parametric form for this example, the results are generally applicable to any SFH, with the construction of the smooth SFH well approximating the true SFH shape with as little as 3 parameters for $\{t_x\}$. Extending this from working purely in SFH space to SED fitting is described in detail in Iyer *et al.* (2019). Examples of SFH reconstruction through SED fitting are shown in Figure 2. In this framework,

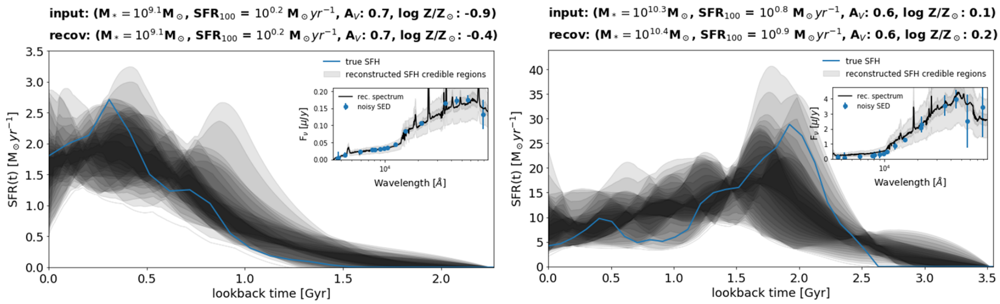

Figure 2. Reconstructing the SFHs of galaxies from broadband photometric SED fitting using the Dense Basis method. The panels show two randomly chosen examples of galaxies at $z \sim 1$ from the semi-analytic model Somerville, Popping & Trager (2015), with the true (blue) SFH and the reconstructed SFH posterior (black shaded regions - darker regions indicate higher probability). The inset panels show the simulated noisy SED and reconstructed spectrum from SED fitting for the two galaxies. Text above below the figures give the true and estimated values for stellar mass, SFR, dust attenuation and stellar metallicity.

the 'age' of a galaxy would be t_0, which formally has S/N $\rightarrow 0$ and is thus very poorly constrained by observations.

The method offers several advantages:

• The $\{t_x\}$ parameters are physically motivated, and directly trace galaxy growth.

• The parameters used to describe the SFHs are all continuous, have comparable S/N, and can be readily incorporated into any SED fitting code or bayesian analysis.

• Well motivated priors for each parameter can be designed using SFHs from both analytic models and cosmological simulations of galaxy formation and evolution.

3. Studying galaxy evolution with nonparametric SFHs

The smooth, nonparametric SFHs obtained through the Dense Basis method enable us to study galaxy evolution using approaches that were previously inaccessible through SED fitting. A flexible number of parameters allows us to specify the SFH to arbitrary precision, and in practice can be informed by the data that is being fit. Panchromatic SEDs bring in additional information that allows us to constrain more flexible dust models by balancing energy between dust absorption and re-emission in the far-IR (Smith & Hayward (2015)) and accounting for AGN contributions (Rivera *et al.* (2016)) using the full X-ray to radio SED. In turn, this allows us to better constrain galaxy SFHs and study the different modes by which galaxies in different demographics: quiescent, starburst, green valley, late bloomer, etc. form their stellar mass. While better constraining SFHs without parametric assumptions yields more robust estimates of stellar masses and star formation rates, the method can also be used to study:

• **The number of major episodes of star formation in a galaxy's past** (Iyer & Gawiser (2017), Iyer *et al.* (2019)). Galaxies with multiple strong episodes of star formation are particularly interesting because they bear imprints from processes that inefficiently quench the star formation such as AGN feedback or ram-pressure stripping, or are experiencing a rejuvenation event, where inflows or mergers trigger star formation.

• **The origin and evolution of scaling relations** like the SFR-M_* correlation (Iyer *et al.* (2018)). The SFHs of galaxies allow us to propagate galaxies backwards in time along their SFR-M_* trajectories to study the correlation at high redshifts and low masses, regions that are hard to probe with direct observations due to galaxies growing fainter. They allow us to test whether galaxies move along the evolving correlation as they grow, as opposed to the correlation resulting from the central limit theorem (Kelson+14).

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• Studies have also considered using SFHs to estimate the cosmic SFRD (Leja *et al.* (2018)), and can be used to estimate the timescales on which galaxies become quiescent, building on the work by Carnall *et al.* (2017).

• In **comparison with distributions of SFHs from cosmological simulations of galaxy formation**, observational SFHs can provide useful constraints and help inform the next generation of simulations by testing mechanisms and implementations of preventive and ejective feedback chemical enrichment, and star formation.

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Discussion

Denis Burgarella: Can you talk more about results from the comparison between the different SED fitting codes?

Kartheik Iyer: The code comparison exercise from Pacifici *et al.* (2019) uses estimates of stellar masses, star formation rates, and dust attenuation from 14 different SED fitting codes that make different model assumptions for dust, SPS models, and star formation histories to quantify the inter-code variability between different SED fitting methods, which contains information about the modeling uncertainties in addition to the formally estimated uncertainties on these parameters. By looking at the distribution in Stellar Mass, we find the inter-code variability to be ~ 0.16 dex, and for SFRs to be ~ 0.29 dex.

Adam Carnall: Will the code implementing the Gaussian Process Star Formation Histories be made public? I am interested in incorporating it in my SED fitting code.

Kartheik Iyer: The Dense Basis code is available as a Github repository at http://github.com/kartheikiyer/dense_basis, and the documentation can be found at http://dense-basis.readthedocs.io. While our SED fitting code is highly optimized, capable of fitting $\sim 10,000$ galaxies per second per code, the Dense Basis SFH parametrization is general enough to be incorporated into any sophisticated SED fitting code.