The effects of star formation history in the SFR-$M_\ast$ relation of HII galaxies

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ABSTRACT

We discuss the implications of assuming different star formation histories (SFH) in the relation between star formation rate (SFR) and mass derived by the spectral energy distribution fitting (SED). Our analysis focuses on a sample of HII galaxies, dwarf starburst galaxies spectroscopically selected through their strong narrow emission lines in SDSS DR13 at $z < 0.4$, cross-matched with photometric catalogs from GALEX, SDSS, UKIDSS and WISE. We modeled and fitted the SEDs with the code CIGALE adopting different descriptions of SFH. By adding information from different independent studies we find that HII galaxies are best described by episodic SFH including an old (10 Gyr), an intermediate age (100–1000 Myr) and a recent population with ages $< 10$ Myr. HII galaxies agree with the SFR–$M_\ast$ relation from local star-forming galaxies, and only lie above such relation when the current SFR is adopted as opposed to the average over the entire SFH. The SFR–$M_\ast$ demonstrated not to be a good tool to provide additional information about the SFH of HII galaxies, as different SFH present a similar behavior with a spread of $< 0.1$ dex.

Key words: galaxies: star formation - galaxies: stellar content - galaxies: dwarf - galaxies: starburst

1 INTRODUCTION

A widely used method to characterize galaxy star forming properties consists of fitting a model spectral energy distribution (SED) to observed photometry. In this technique assumptions must be made to create synthetic SEDs such as initial mass function, simple stellar population models, extinction law, star formation history and metallicity (see Walcher et al. 2011; Conroy 2013, for reviews). Many authors attempted to verify the influence of different assumptions on this fitting process (e.g. Wuyts et al. 2007; Conroy et al. 2009; Muzzin et al. 2009; Marchesini et al. 2009; Maraston et al. 2010; Pforr et al. 2012; Mitchell et al. 2013).

As an ingredient to create the model SEDs, the star formation history (SFH) can be described in simple parametric forms expressed by the relation between the star formation rate (SFR) and time. Many works applying simple analytical forms to model galaxies SFH can be found in the literature (e.g. Papovich et al. 2001; Gladders et al. 2013; Simha et al. 2014; Buat et al. 2014; Boquien et al. 2014; Abramson et al. 2016; Ciesla et al. 2017; Sklias et al. 2017).

A common parameterized function is a single-component exponentially decreasing known as $\tau$-models. This class of parameterization suffers from the outhing effect for recent star formation in star-forming or/and high redshift galaxies, where the luminous young stars dominate the SED, often leading to an underestimation of old stars, thus stellar mass. Several works based on mock catalogs from semi-analytical or hydrodynamical galaxy formation models tried to improve the results in high-redshift galaxies proposing other SFH trends such as rising histories (e.g. Finlator et al. 2011) and delayed models (e.g. Lee et al. 2010). Moreover, depending on the galaxy types different behaviors for the SFH were proposed. For example, Michałowski et al. (2012) studied the double exponential SFH in submillimetre galaxies, and Banerji et al. (2013) used the exponential declining with additional burst to fit data from analogues of Lyman break galaxies.

Similarly to the previous mentioned works we search for the best analytical SFH to a given type of galaxy. Our focus is on HII galaxies, compact dwarf starburst galaxies, characterized by a spectrum with weak, blue continuum and strong, narrow emission lines. In the local Universe they are considered the simplest starburst systems due to properties such as low mass, low oxygen abundance, low dust content and their low-density environments. Their low mass and metallicity make these objects local analogues of galaxies in the primordial Universe. Therefore, the study of their star formation activity can provide us with clues about the underlying physical processes in galaxies in earlier times.

HII galaxies are known for their recent star formation but different authors found observational (e.g. Telles et al. 1997; Telles & Terlevich 1997; Westera et al. 2004; Lagos et al. 2011) and theoretical (from simulations, e.g. Pelupessy et al. 2004; Debsarma et al. 2005) evidence of the importance of a large amount of recent star formation in these objects, which may be missing in predictions of SFH based on simple $\tau$-models.
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2016) evidences to a multi‐episode SFH, i.e. they all have an older stellar populations. In this paper we elaborate on the work of Telles & Melnick (2018). The authors assume three episodes of star formation for their multi‐wavelength photometric data analysis. We use their selected galaxy sample to perform SED‐fitting tests assuming different descriptions of SFH. Due to limitations of the broad band SED fitting (e.g., Pforr et al. 2012; Buat et al. 2014; Ciesla et al. 2015; Boselli et al. 2016; Carnall et al. 2019), we do not expect to find detailed, realistic SFH but to find the parametric SFH that best represents our observables. Our choice of SFHs is restricted to a few, and is constrained by other reasonable assumptions derived from the physical conditions from spectroscopic properties, such as low metallicity, gas consumption rate, and ionization parameter. These imply that HII galaxies have the presence of a significant amount of ionizing O and B stars. (These imply that HII galaxies have the presence of a significant amount of ionizing O and B stars (\( M > 8M_\odot \)), but cannot have kept the present rate of star formation through a Hubble time. This allows a reasonable finite number of tests to be performed.

Based on the output from these tests we analyse, the SFR versus stellar mass \((M_\star)\), known as star‐forming main sequence (MS) or SFR\(−M_\star\) relation. Many recent papers have studied the MS up to \( z \sim 6 \) (e.g. Brinchmann et al. 2004; Noeske et al. 2007; Salim et al. 2007; Magdis et al. 2010; Elbaz et al. 2011; Whitaker et al. 2012; Chang et al. 2015; Tomczak et al. 2016). This correlation can be written as

\[
\log(\text{SFR}) = a \log(M_\star) + b,
\]

where \(a\) and \(b\) are free parameters. Speagle et al. (2014) compiled 25 papers from literature to discuss the evolution of both parameters as function of time. Other works suggest an extra dependence with mass, where low‐mass galaxies should have a steeper slope than massive ones (e.g. Whitaker et al. 2015; Morselli et al. 2017; Popesso et al. 2019).

Different authors (e.g Peng et al. 2010; Sparre et al. 2015; Tacchella et al. 2016) suggest that the MS galaxies follow a single evolutionary track resulted from a combination of a myriad of physical processes such as infall of cold and hot gas, stellar mass loss, heating gas by stellar radiation, supernovae, active galactic nuclei. An alternative view has been presented by series of papers (Gladders et al. 2013; Abramson et al. 2015, 2016; Dressler et al. 2016; Oemler et al. 2017) where they argue that the MS is a natural outcome from most SFHs and has little astrophysical meaning. For our purpose we discuss the implications of different SFH in the SFR\(−M_\star\) relation for HII galaxies and compare it with the literature. Then we analyze if the MS can be used to infer any information about the SFH of HII galaxies.

The paper is divided in two complementary parts. The first part discusses the role of the SFH choice in the SED‐fitting analysis, with a particular focus on seeking the best analytical SFH for HII galaxies. The second part takes advantage of the results from different SFHs to check if the SFR\(−M_\star\) relation can be used to retrieve any knowledge about the SFH. The outline of the paper is as follows. §2 presents the data selection and its photometric properties. §3 describes the SED fitting procedure and §4 analyzes the results to search for the prefer SFH. §5 discusses how the SFH affects the derived SFR\(−M_\star\) relation for HII galaxies. Finally in §6 we summarize our conclusions.

2 DATA DESCRIPTION

HII galaxy sample was selected based on a cross‐match between Sloan Digital Sky Survey (SDSS) Data Release 13 (Albareti et al. 2017) and the emission‐LinePort table (Portsmouth stellar kinematics and emission line flux measurements, Thomas et al. 2013), according to the following criteria,

(i) subclass classification of STARBURST, i.e. equivalent width of H\(\alpha > 50\)\AA;
(ii) equivalent width of H\(\beta > 30\)\AA;
(iii) line ratios that fall within the upper left panel of the star‐forming regions in the BPT diagram (Baldwin, Phillips & Terlevich 1981; Kewley et al. 2006); 0 < \[\text{log}([\text{OIII}]/\text{H}\beta] < 1.2 \] and \(-2.5 < \text{log}([\text{NII}]/\text{H}\alpha] < -0.8\).
(iv) redshifts in the range 0.005 < \(z < 0.4\) to avoid local giant HII regions in nearby galaxies.

Conditions (ii) and (iii) were imposed to ensure a sample of extreme star‐forming galaxies with high excitation, low abundances, and low masses. Only objects with unique photometry in both far‐ultraviolet (0.1528 \(\mu\)m) and near‐ultraviolet (0.2271 \(\mu\)m) bands from Galaxy Evolution Explorer (GALEX, e.g Bianchi 2014) are chosen, resulting in a final sample of 2728 galaxies. Detailed data description can be found in Telles & Melnick (2018, hereafter TM18).

Besides the optical SDSS and ultraviolet regimes, our multi‐wavelength photometry comprise bands in the near‐infrared: Y (1.036 \(\mu\)m), J (1.250 \(\mu\)m), H (1.644 \(\mu\)m) and K (2.149 \(\mu\)m) from UKIRT Infrared Deep Sky Survey (UKIDSS, Lawrence et al. 2007) and the mid‐infrared: W1 (3.4 \(\mu\)m) and W2 (4.6 \(\mu\)m) from Wide‐Field Infrared Survey Explorer (WISE, Wright et al. 2010).

In order to minimize systematic effects we used Petrosian magnitudes except for GALEX which we use model magnitudes. The aperture matching effects are minimum due to the compactness of our objects that have a median Petrosian radius in the SDSS r band of 2.8 arcsec (see Fig. 2 in TM18).

3 SED MODELING AND FITTING

We perform the SED modeling and fitting analysis with CIGALE\(^1\) (Boquien et al. 2019). This is a package consisting of a series of modules that are combined to create a set of theoretical SEDs, then compared to the observed data (e.g. Noll et al. 2009; Roehly et al. 2014; Boquien et al. 2014; Ciesla et al. 2017). Each module corresponds to a physical component such as dust attenuation, SFH and single stellar population model. These components have their own parameters to be chosen. The comparison between theoretical and observed data results in a best‐fit model and a Bayesian‐like analysis, obtained by the probability distribution function of each parameter.

A key factor for our purpose and one of the main reasons for choosing CIGALE is its modular structure that facilitates the introduction of new SFH modules. Since our goal is to test SFHs, we set all other parameters with the same input values as described in Table 1. The behavior of the SFHs applied in our work is shown in Fig. 1. They have different numbers of star formation episodes and/or shapes as we discuss next. Throughout this paper, we will adopt the flat \(<\Lambda>CDM\) cosmology with \(H_0 = 71\) km/s/Mpc.

\(^1\) Code Investigating GALaxy Emission is available at https://cigale.lam.fr/
Table 1. List of CIGALE input parameters unchanged in all tests. For more details about the choice of these values, see TM18.

| Parameter                          | Value                          |
|------------------------------------|--------------------------------|
| **Module: Simple Stellar Population (SSP)** |                                |
| Model                              | Bruzual & Charlot (2003)       |
| Initial Mass Function (IMF)        | Chabrier (2003)                |
| Metallicity                        | 0.008                          |
| Separation between young and old pop [Myr] | 10                            |
| **Module: Nebular Emission**       |                                |
| Ionization parameter               | $\log U = -2.0$                |
| LyC photons escaping the galaxy     | 0.0                            |
| LyC photons absorbed by dust        | 0.0                            |
| Line width in km/s                  | 300.0                          |
| **Module: Dust Attenuation**       |                                |
| Name                               | Calzetti et al. (2000)         |
| E(B−V)$_{H_{\alpha}}$              | 0.0, 0.05, 0.1, 0.15, 0.2,     |
|                                   | 0.25, 0.3, 0.35, 0.4, 0.45     |
| E(B−V)$_{H_{\alpha}}$              | 0.44, 1                        |
| Amplitude of the UV bump           | 1.0                            |
| Slope delta of the power law       | -0.5                           |
| **Module: Dust Emission**          |                                |
| Dust template                       | Updated models of Drame & Li (2007) |
| Mass fraction of PAH                | 0.47, 1.12                     |
| Minimum radiation field            | 0.1                            |
| IR power law slope                  | 2.0                            |
| AGN template                        | NONE                           |
| Radio                              | NONE                           |

Figure 1. Illustration of the SFH used in our tests: double (red dash-dotted line), triple exponentially declining (green solid line), 3BF (black dashed line) and triple exponential with varying amplitude amongst the episodes of star formation (magenta dotted line).

3.1 Star formation histories

Following papers on spectral and imaging analysis of HII galaxies such as Telles et al. (1997), Westera et al. (2004) and Lagos et al. (2011) that found evidence of underlying older stellar populations, TM18 proposed a SFH composed of three main episodes of star formation, given by

$$SFR(t) = \begin{cases} C & \text{for } t < t_{\text{int}} - t_{\text{old}} \\ C & \text{for } t_{\text{int}} - t_{\text{old}} < t < t_{\text{int}} \\ C & \text{for } t_{\text{int}} - t_{\text{old}} < t < t_{\text{y}} \\ 0 & \text{otherwise,} \end{cases}$$

(2)

where $C$ is a constant value estimated by the code, $t_i$ and $\tau_i$ are the starting time and duration of each star formation event. The subscript ($i = \text{old, int, y}$) indicates an old, an intermediate age and a young (ionizing) stellar population. This expression leads to the amount of stars created depending only on $\tau_i$ interval. This is not a standard SFH module in CIGALE and it was created by M. Boquien for that paper.

Throughout this paper we will refer to this SFH as three burst function (hereafter 3BF). We will also maintain the labels, old, intermediate and young, to describe stellar populations with ages $\sim 10$ Gyr, $\sim 100$–$1000$ Myr and $\leq 10$ Myr, respectively.

Alternatively we can assume two main episodes of star formation with the first one being very extended. By imposing no intermediate age stellar population in the 3BF description, we have a two burst function, hereafter 2BF.

Another simple way of modeling a SFH with two episodes of star formation is assuming two decaying exponentials combined as (e.g. Boquien et al. 2019),

$$SFR(t) \propto \begin{cases} \exp(-t/t_1) & \text{for } t < t_0 - t_1 \\ \exp(-t/t_1) + k \exp(-t/t_1) & \text{for } t \geq t_0 - t_1, \end{cases}$$

(3)

where $t_1$ is the age of the second episode of star formation relative to $t_0$, $\tau_0$ and $\tau_1$ are the e-folding times of the old and recent stellar populations, and $k$ represents the relative amplitude of the second exponential defined by

$$k = \left( \frac{f_2}{1 - f_2} \right) \left( \frac{k}{1 - k} \right) \sum_{i=0}^{1} \exp(-t_i/t_1),$$

(4)

with $f_2$ being the mass fraction of the late stellar population. We will label this description as 2exp.

Finally, we considered two SFHs that expand upon the 3BF. First, we altered the description assuming three exponential declining functions instead of constant SFH described by,

$$SFR(t) \propto \begin{cases} \exp(-t/t_{\text{old}}) & \text{for } t < t_{\text{old}} \\ \exp(-t/t_{\text{int}}) & \text{for } t < t_{\text{int}} \\ \exp(-t/t_{\text{y}}) & \text{for } t < t_{\text{y}}, \end{cases}$$

(5)

where $t_{\text{old}}, t_{\text{int}}$ and $t_{\text{y}}$ are the ages of the oldest star in each stellar population, old, intermediate and young, respectively, with their associated interval of star formation, $\tau_{\text{old}}, \tau_{\text{int}}$ and $\tau_{\text{y}}$. By definition this function imposes that the maximum SFR in every star formation event to be the same. We will refer to this SFH as 3exp.

Secondly, we introduce a triple exponential with varying amplitude given by

$$SFR(t) \propto \begin{cases} \exp(-t/t_{\text{old}}) & \text{for } t < t_{\text{old}} \\ k_1 \exp(-t/t_{\text{int}}) & \text{for } t < t_{\text{int}} \\ k_2 \exp(-t/t_{\text{y}}) & \text{for } t < t_{\text{y}}, \end{cases}$$

(6)
where \( k_1 \) and \( k_2 \) are the amplitudes of intermediate and young age population defined by

\[
k_1 = \left( \frac{f_{\text{int}}}{1 - f_{\text{int}} - f_y} \right) \frac{\sum_{i=\text{int}}^{t_{\text{int}}=t_{\text{old}}-1} \exp(-t_i/t_{\text{old}})}{\sum_{i=\text{int}}^{t_{\text{int}}=t_{\text{old}}-1} \exp(-t_i/t_{\text{int}})},
\]

and

\[
k_2 = \left( \frac{f_y}{f_{\text{int}}} \right) \frac{\sum_{i=\text{int}}^{t_{\text{int}}=t_{\text{old}}-1} k_1 \exp(-t_i/t_{\text{int}})}{\sum_{i=\text{int}}^{t_{\text{int}}=t_{\text{old}}-1} \exp(-t_i/t_y)},
\]

with \( f_{\text{int}} \) and \( f_y \) being the mass fractions of the intermediate and young populations, respectively. As this SFH follows a 3exp behavior added by two new free parameters in the form of mass fraction, we will label it 3exp+mf.

4 THE STAR FORMATION HISTORY OF HII GALAXIES

We need to combine observational knowledge from other independent studies to assist in the search for the best analytical SFH. For example, detailed studies of nearby objects reveal that regardless of morphological type, all dwarf galaxies contain old (10–12 Gyr) stars (e.g., Grebel & Gallagher 2004; Glatt et al. 2008; Da Costa et al. 2010; Grebel 2012). Therefore, independently of the shape of the SFH, the star formation should start around 10–12 Gyr.

HII galaxies are known for their strong current star formation, dominated by a stellar population of <10 Myr that must be included in the description of these galaxies.

The constraints for the SFH are:

(i) starts at \( t_{\text{old}} \approx 10 \) Gyr;
(ii) has young, ionizing, massive stellar population at \( t_y < 10 \) Myr;
(iii) requires an intermediate age population at \( 100 < t_{\text{int}}/\text{Myr} < 1000 \).

TM18 showed that models assuming a 3BF SFH description with their set of input parameters provides a good fit to the photometric data. For this reason we apply this function with a similar range of input values, and use it as a base of comparison for other tests. This run is labeled as test0.

Table 2 summarizes the parametrization of our test runs with CIGALE. Our aim is to test the following effects:

- number of episodes of star formation, e.g. test1 and test2 assume one extended event of star formation followed by a recent one, instead of 3 events (test0);
- shape of each episode, e.g. test3 assumes an exponential decay behavior rather than a constant one;
- test4 allows different intensities in the SFR for each stellar population.

We tested several other ranges of input parameters, but the results were consistent with the ones presented in this paper.

The goodness of the fit is assessed by the \( \chi^2_{\text{red}} \). Figure 2 presents an statistical overview of the results from all test. Both panels in this figure show that tests assuming three main episodes of star formation have a similar performance with median \( \chi^2_{\text{red}} \sim 1 \) and \( \approx 80\% \) of the galaxies with a good fit, whereas SFHs with two episodes of star formation have worse performance. We restrict our analysis in the next subsections to galaxies with \( \chi^2_{\text{red}} < 3 \) for all tests.

The worst results are derived by 2exp SFH, which fits only \( \sim 30\% \) of galaxies with \( \chi^2_{\text{red}} < 3 \). This is significantly worse than the output based on 2BF function that finds twice the number of galaxies with \( \chi^2_{\text{red}} < 3 \). However, the differences between both tests are mainly in the shapes of the SFHs. Similarly, 3BF provides better results than 3exp, but with a lesser difference in the efficiency.

An alternative statistical approach to discuss the goodness of the fit is the Bayesian Information Criterion (BIC, e.g. Liddle 2007) that penalizes heavily the model with more parameters. The BIC checks the improvement (or lack of it) in the fitting analysis by adding or subtracting parameters in our SFH. It can be estimated using the following expression

\[
\text{BIC} = \chi^2 + k \ln N,
\]

where \( \chi^2 \) is the non-reduced \( \chi^2 \) of the fit, \( k \) is the number of free parameters, and \( N \) is the number of data points. Figure 3 presents a histogram of BIC for the different tests (1 to 4) in comparison to test0. For \( |\Delta \text{BIC}|<2 \), the distinct SFHs present a similar efficiency to fit the data (delimited by purple dashed line). For a more conservative limit (delimited by dark blue dotted line), we set \( |\Delta \text{BIC}|<10 \). The higher the \( \Delta \text{BIC} \) value the bigger the difference in the efficiency between the compared models, with the corresponding sign informing which of the models is more efficient. A positive sign means that testi has a better performance than test0, while a negative sign has the opposite meaning. For example test2 has worse efficiency than test0 because \( \Delta \text{BIC} \) has a broad distribution towards the negative side of the plot.
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Table 2. Input parameters for the SFH modules in each test with their respective total number of SED models.

| Tests | SFH | Input parameters | Number of SED models |
|-------|-----|------------------|----------------------|
| test0 | 3BF | $t_{\text{old}}=10$ Gyr ; $t_{\text{old}}=[100,300,500]$ Myr  \hspace{1cm} $t_{\text{fus}}=[100,500,1000]$ Myr ; $t_{\text{fus}}=[10,50,100,200,300]$ Myr  \hspace{1cm} $t_y=[5,10]$ Myr ; $t_y=5$ Myr | 133200 |
| test1 | 2BF | $t_{\text{old}}=10$ Gyr ; $t_{\text{old}}=[100,300,500,1000,2000,3000,4000,5000,6000,7000,8000,9000,9500]$ Myr  \hspace{1cm} $t_{\text{fus}}=0$ ; $t_{\text{fus}}=0$ Myr  \hspace{1cm} $t_y=[5,10]$ Myr ; $t_y=5$ Myr | 38480 |
| test2 | 2exp | $t_0=10$ Gyr ; $t_0=100$ Gyr ; $t_1=5$ Myr  \hspace{1cm} $t_2=5$ Myr | 115440 |
| test3 | 3exp | $t_{\text{old}}=10$ Gyr ; $t_{\text{old}}=[100,300,500]$ Myr  \hspace{1cm} $t_{\text{fus}}=[100,500,1000]$ Myr ; $t_{\text{fus}}=[10,50,100,200,300]$ Myr  \hspace{1cm} $t_y=[5,10]$ Myr ; $t_y=5$ Myr | 133200 |
| test4 | 3exp+mf | $t_{\text{old}}=10$ Gyr ; $t_{\text{old}}=[100,300,500]$ Myr  \hspace{1cm} $t_{\text{fus}}=[100,500,1000]$ Myr ; $t_{\text{fus}}=[10,50,100,200,300]$ Myr  \hspace{1cm} $t_y=[5,10]$ Myr ; $t_y=5$ Myr  \hspace{1cm} $f_{\text{d}}=[0.1,0.5,0.9]$  \hspace{1cm} $f_{\text{d}}=[0.01,0.05,0.1,0.2,0.3,0.4,0.5]$  \hspace{1cm} $f_{\text{d}}=[0.01,0.05,0.1,0.2,0.3,0.4]$ | 5594400 |

parameters to create the models, and $N$ is the number of bands fitted that varies from 7 to 13. The only difference between the tests is the assumed SFH with its number of parameters that range from 2 to 6. We use the relative difference between the BIC from test0 and the other tests represented as

$$\Delta \text{BIC} = \text{BIC}_{\text{test0}} - \text{BIC}_{\text{testi}},$$

with $\text{testi} = \{\text{test1, test2, test3 or test4}\}$. This methodology implies that models with $|\Delta \text{BIC}|<2$ have similar fitting performance, i.e. the different SFH prescriptions and number of parameters do not greatly affect the fit. The influence is considered moderate if $2<|\Delta \text{BIC}|<10$, while $|\Delta \text{BIC}|>10$ means a strong influence from SFH expression. The sign of $\Delta \text{BIC}$ informs us which of the compared models is more efficient. A negative sign means that test0 has a better performance than testi, while a positive one means testi provides a better fit.

Figure 3 shows histograms of $\Delta \text{BIC}$ from tests 1 to 4 in respect to test0. There are important features to notice in this figure: where the peak of distribution is located, how broad it is, and how spread out the degeneracy is. For example, test1 has a slightly advantage in respect to test0, due to fitting only 2 parameters, but it is not strong enough for us to eliminate the intermediate age stellar population from the SFH modeling.

The exception is test2, in which the $\Delta \text{BIC}$ distribution is broader, extending to values lower than -20, with a peak not as well defined as the other tests. The negative sign means that test0 provides a better fit solution, agreeing with the $\chi^2_{\text{red}}$ analysis (Figure 2).

Combining $\chi^2_{\text{red}}$ and BIC analysis it would be straightforward to conclude that HII galaxies need at least three main stellar populations to be well modeled. Also, test0, test3 and test4 seem provide a similar good fit. However, we should take these results with caution. First, we need to deepen our analysis by discussing the SFH procedure limitations.

4.1 Mock catalogue analysis

In order to verify the reliability of the derived physical properties, we use a mock catalogue to test our results (see Giovannoli et al. 2011; Boquien et al. 2012, for a more detailed description, and similar analysis with mock catalogues in CIGALE). This artificial catalogue is created based on the best fit for each object. The best fit of each physical parameter is set as a “true” measurement. Then to simulate new observations, it is added noise into the fluxes of this new catalogue. Finally, these synthetic observations are analyzed following the same procedure as the original data. The inferred physical properties are compared to their “true” values. This process is done automatically in CIGALE by setting mock_flag=True in the configuration file.

The degeneracy between age, metallicity and extinction can be a source of uncertainties in the SED fitting procedure. However, the metallicity is set as a fixed value for all galaxies, estimated by spectroscopic data. All tests have ~ 85% of the sample best-fitted by E(B-V) ≤ 0.1, therefore the mock analysis in this range of values should be representative of the whole sample. The peak of the estimated E(B-V) distribution has a good consistency with the expected values of 0 and 0.05 in all four panels in Figure 4. The worse case is for inputs of 0.1, which the peak of outputs is offset to 0.07, but these values are so close to each other that in practice there is no difference. The results from 3exp+mf SFH were not included because they are similar to 3exp SFH. The small derived E(B-V)s, ≤ 0.1, agrees with our expectations, as HII galaxies are known to have low dust content. The good reliability of E(B-V) for all tests indicates that most uncertainties must come from the parameters in the SFH.

Before individual discussions on the SFH parameters from each test, we need to make important remarks about known limitations of broadband SED-fitting technique and our choices of input parameters. For SFHs described by exponential functions, we tested $\tau_y$ ranging from 5 Myr to 15 Gyr, but no improvement was seen.
In these extra tests, the best-fit $\tau_\text{old}$ was $\sim 5$ Myr for 90% of our galaxy sample. As the results were mostly unchanged, we opted to use simplest combination of input parameters with $t_{\text{old}} = [5, 10]$ Myr, and $\tau_\text{young} = 5$ Myr.

Figure 5 presents the results of the parameters from 3BF SFH using mock catalogues. In these figures, and the ones that follow, the vertical lines correspond to the input ("true") values and the histograms are the output from the mock run. The better agreement of the histogram peaks with the vertical lines, the better is the retrieval of the input values, and the more robust are the results. For the old stellar population with age fixed at 10 Gyr, Figure 5a shows that a star formation duration of 300 Myr is better reproduced than 100 Myr or 500 Myr. Figure 5b demonstrates that stellar populations of 100 Myr and 500 Myr have robust measurements, whereas populations of 1 Gyr have underestimated ages. In Figure 5c, we see that the duration of formation of these intermediate age stars is fairly well reproduced, but with a overlap distribution between 10 Myr and 50 Myr, and 100 Myr and 200 Myr. Finally, Figure 5d exhibits a good agreement between estimate and true ages of stars with 10 Myr.

Figure 6 shows the reproduction of the input values from 3exp SFH. In Figure 6a, the duration of the oldest episode of star formation has better results for 300 Myr, similar to 3BF SFH. Figure 6b shows good estimates of ages for stars with 500 Myr and 1 Gyr. In Figure 6c, we find no good agreement for the intervals of intermediate age star formation, with most intervals being overestimated, except for 300 Myr where is underestimate. Figure 6d reveals that stars with 10 Myr have slightly worse reproduction of their ages for 3exp in comparison to 3BF SFH, shown by a broader range outputs.

Figure 7 presents the parameter results from 2BF SFH. By excluding the intermediate age stellar population, we have only 2 parameters to fit and analyze in 2BF, the duration of the formation of old stars $\tau_\text{old}$ and the age of young population $t_{\text{young}}$. In Figure 7a, we select $t_{\text{old}}$ inputs from 100 Myr to 1 Gyr, as these values are the best-fit of 82% of galaxies, therefore representative of the entire sample. This panel illustrates how well the peak of derive quantities (histograms) reconciles with each true value (dashed lines). Figure 7b demonstrates that both input ages are well reproduced by SED-fitting procedure.

Figure 8 shows the output parameters from 2exp SFH. In this case, the duration of the formation of old star has a large range of inputs. However we choose to analyze only 9.5 Gyr and 100 Myr, as 88% of the sample is best-fitted by either of these values. Figure 8a exhibits how poor is the estimate of such parameter, with most of the return values around 4.3 Gyr, instead of 100 Myr or 9.5 Gyr. In Figure 8b, we verify that stars of 10 Myr have fairly well derived ages. Figure 8c presents the mass fractions of the late stellar population $f_\text{y}$, we find a bad agreement between true and derived values. Most of objects have $f_\text{y} \sim 0.5$, even if they should be 0.1 or 0.9. We concluded that we cannot trust the mass fraction of young stars derived by 2exp SFH.

In Figure 9, we analyze the output parameters from 3exp+mf SFH.
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SFH. Figure 9a shows a poor reproduction of the duration of the oldest episode of star formation, with a thin distribution around 300 Myr for inputs of 100 Myr and 500 Myr. Figure 9b demonstrates that stellar populations of 500 Myr have reliable measurements of ages, while the ones with 1 Gyr have underestimated values. Stellar populations of 100 Myr have similar probabilities of precise estimates and overestimated ages at 500 Myr. In Figure 9c, we find that duration of star formation are overestimated for smaller inputs, 10 Myr, 50 Myr and 100 Myr, and underestimated for 200 Myr and 300 Myr. In Figure 9d, the ages of the ionizing stellar population are poorly constrained, with an offset on the peak of this age distribution from its input of 10 Myr, and a secondary peak at 8.7 Myr for inputs of 5 Myr. The 3exp+mf SFH have two more fitted parameters not shown here, mass fraction of young and intermediate age stars.
is not a surprise that both of them have poor outputs. This SFH description associated to our set of broadband data does not provide a trustworthy fit solution.

We proceed to check how well we can derive total stellar masses. Each panel in Figure 10 compares the estimated parameters with the true counterparts in 3BF, 2BF, 3exp and 3exp+mf SFHs, respectively. These panels present a similar scatter of ~0.3 dex around the linear relation. Such spread agrees with the typical 1σ error associated to the estimated masses in this four SFHs. In Figure 10d, we find that masses obtained by 2exp SFH are mostly underestimated from their inputs. Therefore, in general stellar masses have robust measurements for different SFHs, the exception is 2exp SFH.

All of these mock results indicate that the derived parameters are more robust for 3BF, 2BF and 3exp SFH than for 2exp and 3exp+mf SFHs. Thus, we decided to exclude 2exp and 3exp+mf SFHs from further analysis.

The 2BF SFH does not create intermediate age stars because it seems to favor intervals of star formation of < 1 Gyr, starting at 10 Gyr. Therefore, it does not reproduce the constraint (iii) set at the beginning of section 4. But due to the good fit results we will keep its result for general discussions.

Nevertheless, we find that the best description for HII galaxies are 3BF and 3exp SFHs, as they provide good fitting results and respect all constraints imposed by other independent measurements.

4.2 Stellar mass results

By definition the total stellar mass is given by

$$M_{\text{total}} = \int_{0}^{t_0} \text{SFH}(t) \, dt = t_0 < \text{SFR} >,$$

where $t_0$ is the time when the star formation begins. Consequentially different assumptions in the SFH result in the creation of different amounts of stars. Figure 11 shows a comparison of the $M_{\text{total}}$ from test1 and test3 in respect to test0.

The left panel compares the results based on 2BF SFH. By excluding the intermediate age population, and allowing the star formation episode of the old population to extended up to 9.5 Gyr, the masses are shifted to higher values than 3BF SFH. Total masses from 2BF can be up to 0.5 dex more massive than 3BF. The difference in the stellar masses are directly related to how long the old population keeps creating stars. Most galaxies have a variation in $\log(M_{\text{total}})$ of $\leq 0.3$ dex because the extension of star formation is < 1Gyr. Indeed, only 15% of objects were fitted by very extended episodes of star formation, i.e. > 1 Gyr, corresponding to differences in $\log(M_{\text{total}})$ of 0.5 dex.

The right panel reveals the similarity on the $M_{\text{total}}$ generated by 3BF and 3exp SFHs, described in Eqs. (2) and (5). The scatter in the relation between the derived mass from both tests is $< 0.3$ dex that is less than the intrinsic median error of the masses, typically ~0.3 dex. We concluded that a change in the shape of the SFH function does not strongly affect $M_{\text{total}}$.

4.3 Stellar population results

CIGALE only outputs stellar masses for stars older and younger than a given input age separation. This separation can be set independent of the SFH assumed. Therefore, we do not have a direct measure of the mass of intermediate population in a SFH with three star formation episodes.

In order to estimate each stellar population mass we made two runs with the same SFH parameters but with different age separations: 10 Myr and 3 Gyr. The first run separates the young population mass, while the second one segregates the old stellar masses. We obtain the intermediate age stellar masses by subtracting the young and old stellar population masses from the total.

As 2BF SFH assumes two stellar populations, we only need one run with an age separation of 10 Myr. We find that young stars represent less than 10% of the total amount of stellar mass, and by consequence the old stars dominate the total stellar mass.

Figure 12 presents the ratio between the mass of each population in respect to the $M_{\text{total}}$ from 3BF and 3exp SFHs. The left panel shows the results for 3BF SFH, in which young stars represent a small fraction of total mass, less than 10%, while the contribution of intermediate age and old stars are more complex. Clearly, there are galaxies dominated by old stars, with 80% or more of their mass. Nevertheless, there are about 20% of galaxies with their total mass constituted by 50% or more of intermediate stars.

The right panel in Figure 12 presents the mass fraction results from test3 where we alter the SFH description from 3BF to 3exp but kept the same input parameters. For the young stellar population the mass fraction remains small, <10%. Although the total masses are not strongly affected by a change of shape, as seen in Figure 11, the contributions of each stellar population to these masses are modified. We find that the number of galaxies dominated by...
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Figure 10. Estimated total stellar mass versus true mass from mock catalogues. Each panel presents the results from a given test. Upper panels from left to right: 3BF, 2BF and 3exp SFHs; lower panels: 2exp and 3exp+mf SFHs. The solid red lines represent the 1:1 relation to assist the plot interpretation.

Figure 11. Total stellar masses derived from: test1 and test3 compared to the ones from test0. Test0 assumes a 3BF SFH with the following inputs: $t_y < 10$ Myr, $\tau_y = 5$ Myr, $100 < t_{int}$/Myr $< 1000$, $10 < \tau_{int}$/Myr $< 300$, $t_{old} = 10$ Gyr and $0.1 < \tau_{old}$/Gyr $< 0.5$. The red dashed line is the 1:1 relation in both panels. Typical errors of stellar mass are $\sim 0.3$ dex in these three tests.

Intermediate age stars (>50% of $M_{int}/M_{total}$) decrease from 20% (found in 3BF) to 6% of the whole sample.

Complementary to the left panel in Figure 12, Figure 13 demonstrates that galaxies with higher mass fraction of intermediate age stars, and consequently lower fraction of old population are seen only at lower redshifts, $< 0.1$. This result is for 3BF SFH, but a similar behavior is found for 3exp SFH with a smaller number of objects, as previously mentioned.

All of these results reveal that the intermediate age stars can be a very important and significant component of HII galaxies, particularly at $z<0.1$. 

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5 MAIN SEQUENCE OF HII GALAXIES

Star-forming galaxies define a narrow relation between their total masses and star formation rates generally known as Main Sequence (MS). In this section, we analyze the implications of the SFH in the MS for HII galaxies.

The Star Formation Rate (SFR) is defined as the mass of stars formed over a given time interval, such interval is not always explicitly informed in the literature, which can misguide the interpretation of such quantity. Different indicators are commonly used to infer the SFR such as H$\alpha$ luminosity, total infrared luminosity or ultraviolet luminosity among others. Each observable probes different timescales that can vary from tens to hundred Myr, most of them being sensitive to scales smaller than 200 Myr (Kennicutt & Evans 2012). The conversion of these observational indicators to SFR estimates are related to a number of assumptions such as spectral synthesis models, IMF, and SFH.

Popesso et al. (2019) used a local SDSS spectroscopic galaxy sample to investigate the biases introduced by different SFR indicators and methods to locate the MS, and found that the slope of the relation can be strongly affected by the indicator used. Elbaz et al. (2018) showed that starbursts at 1.5 < z < 2.0 have their SFR underestimated by SED-fitting when compared to the SFR obtained from UV plus IR light, with the dust attenuation being the main reason for such difference. Here, we only consider SFRs derived from SED modeling and fitting. By deriving the SFR and $M_{\text{total}}$ from the same methodology, we avoid inconsistencies between these quantities due to different methods, adopting different assumptions. Such inconsistencies may lead to misinterpretation on the evolutionary paths of different galaxy types.

We take advantage of CIGALE allowing estimates of SFR based on different intervals, to discuss the connection between the averaged time-scales and the SFHs in the SFR–$M_*^4$ diagram for HII galaxies.

Figure 14 shows the SFR–$M_{\text{total}}$ relation for 3BF, 2BF and 3exp SFHs averaged on different time-scales: 10 Myr, 100 Myr, and total SFH. For SFR$_{10\text{Myr}}$, we are only estimating the strength of the recent burst, which according to Table 2 has to start between 5 and 10 Myr and to last 5 Myr. Furthermore, one has to bear in mind that a correlation between total SFR and $M_{\text{total}}$ is always expected, since $M_{\text{total}}$ is the time integral of star formation history (SFR(t)).

In Figures 14a, we find that the SFR varies with the assumed averaged time-scale, for 3BF SFH. As expected, SFRs based on the last 10 Myr are higher than the others, due to typical young, ionizing stars in HII galaxies. Such SFRs correlates to total masses with a spread of less than 0.5 dex. SFRs averaged over 100 Myr present a drop in the amplitude and a larger scatter in comparison to SFR$_{10\text{Myr}}$ as a consequence of no (or fewer) stars being formed between 10 Myr and 100 Myr. The total SFRs provide lower values and a tight relation with $M_{\text{total}}$, which is explained by the imposition of all galaxies to begin star formation at the same time, i.e. 10 Gyr.

Figure 14b presents how the different definitions of SFR behave in respect to the total mass, assuming 2BF SFH. As seen in Figure 14a, the SFRs derived within 10 Myr are higher than the other defined SFRs. However, the spread found here, > 2 dex, is much

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Figure 12. Mass fraction for each stellar population (old: red, intermediate: green, young: blue) based on the SED fitting results from 3BF and 3exp SFHs. Both cases assume the same range of input parameters, see test0 and test3 in Table 2.

Figure 13. Mass fraction of intermediate age population from 3BF SFH versus redshift. The colorbar represents the mass fraction of old stars. The black dashed line signalizes redshift of 0.1, when intermediate age stars stop contributing with more than 50% of total mass.
larger than the one found in 3BF. SFRs averaged over the last 100 Myr are lower, in some cases even lower than the total SFR. This is a consequence of this particular SFH, where by definition there is no star formation between 10 and 100 Myr. The relation found between total SFR and mass is very thin.

Figure 14c illustrates the same three definitions of SFR, but based on 3exp SFH. Similar to the results from 3BF SFH seen in Figure 14a, time-scales of 10 Myr produce higher SFRs with smaller spread, while the ones of 100 Myr yield lower SFRs with larger spread. Total SFRs provide the lowest values of the three definitions, and a very tight relation with mass. In order to give credibility to our SFR discussion, Figure 15 compares outputs and inputs of different definitions of SFR, assuming 3BF SFH. These results were obtained following the procedure introduced in Subs. 4.1 based on mock catalogues. We chose to discuss results from 3BF SFH, but similar behaviors are found for 3exp SFH, and even better ones for 2BF.

In Figure 15a, we see a good correspondence between true and derived SFRs averaged over 10 Myr. Meanwhile, Figure 15b shows a larger spread around the 1:1 relation for 100 Myr, with most values overestimated in respect to the inputs. Figure 15c demonstrates a fairly good correlation between true and obtained total SFRs, where the spread is less than the uncertainties of the SFR, i.e. 0.3 dex.

5.1 Total and current SFR for HII galaxies

In order to understand the effects of SFH in the SFR–$M_\text{total}$ diagram we need to compare results from different SFH descriptions. Panel A in Figure 16 compiles SFR$_\text{total}$ based on the results from: 3BF (test0); 2BF (test1); and 3exp (test3).

From the previous section we know that an observational constraint for HII galaxies is the age of the oldest star. By imposing age=10 Gyr for different SFHs we find that their SFR–$M_\text{total}$ results are in close agreement, almost falling upon each other. The main difference is the total mass range which follows the relation presented in Figure 11.

The amount of mass created will depend on the shape of the SFH and the duration of the episode(s), i.e. the integration time as shown in Eq.(11). If we assume a similar star formation time, i.e. the SFR is averaged over the same interval, the galaxies will change their position following a similar path with a small variation associated to the different SFHs at a given mass. This interpretation agrees with Oemler et al. (2017) who argued that if the bulk of galaxies are roughly coeval, then only the shape of SFHs would set the scatter in the relation, at fixed mass.

In the cases where the star formation time is established as 10 Gyr, the MS becomes in close agreement with the results found by other works such as Brinchmann et al. (2004) and Chang et al. (2015) but with different slopes. This proximity with the MS from other datasets based on “normal” star forming galaxies was unexpected, because HII galaxies are starburst systems, characterized by high SFR for their masses. Studies based on starburst-type galaxies suggest that these objects typically lie above the MS (e.g. Elbaz et al. 2011; Rodighiero et al. 2011; Sargent et al. 2012). Although Elbaz et al. (2018) discussed the possibility of a number of starburst galaxies being hidden in the MS due to the compactness of their starburst regions.

As the SFH of HII galaxies expands along 10 Gyr with a complex mixture of populations, the total SFR becomes similar to “normal” star forming galaxies. McGaugh et al. (2017) point out that the current SFR may fluctuate, but if the SFR$_\text{current}$ > mean SFR extends for long, it increases SFR$_\text{total}$ but also builds up stellar mass. In other words, a very high SFR, if sustained, makes enough stars to drive back the galaxy to a MS of slope close to unity. Of course, there can be temporary excursions with SFR$_\text{current}$>SFR$_\text{total}$.

The behavior of the MS is still debatable in the literature. If we assume a single power law the values of the slope vary widely with the SFR indicator and/or with the selected sample (for a detailed discussion see Speagle et al. 2014). However, several authors suggest that the SFR–$M_\text{total}$ relation is not a single power law but it exhibits a curvature or a broken power law with a flatter slope at the high-mass relative to the low-mass regime (Lee et al. 2015; Schreiber et al. 2015; Whitaker et al. 2015; Tomczak et al. 2016; Popesso et al. 2019). Indeed, Renzini & Peng (2015) discussed that the pre-selection of a sample could partially be the cause of the bending at high masses.

In our analysis restricted to HII galaxies at $z < 0.4$, we find a single power-law with slopes close to unity for all SFR in Panel A from Figure 16. Indeed, we expected slopes of unity because the MS compares mean SFR (total SFR) with an integral of the SFH (total SFR).
Figure 15. Estimated SFR versus true SFR for 3BF SFH, based on mock catalogues. Each panel presents results from a different different averaged time-scale: 10 Myr (left), 100 Myr (middle) and the total SFH (right). The red solid line represent the 1:1 relation.

Figure 16. Panel A: Total SFR versus stellar mass from results based on different SFH assumptions: 3BF (blue crosses), 2BF (green circles) and 3exp SFHs (red triangles). Panel B: Current SFR versus total mass for each SFH. The typical errors for the log($M_{\text{total}}$) and log(SFR) are both ~0.3 dex, for all assumed SFH. The best-fit of each SFH is represented by a solid line of its respective color, as in legend. The black dashed line is based on Brinchmann et al. (2004) data.

mass), both estimated by SED fitting. Therefore, we conclude that the slope of this relation does not provide any information about the SFH.

One should always be careful to apply the same assumptions to estimate the mass and the SFR. Any calibration of SFR has implicitly choices of IMF, stellar synthesis models, SFH (or at least an age for simple stellar populations). If the assumptions used to obtain the SFR differ from the ones used to estimate the stellar mass, the slope of the MS could be affected and be different than one.

In order to be sensitive to the high current SFR, we should consider the SFR average over the last 10 Myr. In Panel B from Figure 16 we represent the SFR$_{10\text{Myr}}$ for different SFHs. Although the SFR$_{\text{total}}$ follows a similar path for different SFHs assuming the same age, the current SFR exhibits the expected starburst behavior with HII galaxies being placed above the MS for most histories applied.

The differences found between panel A and B in Figure 16 is a consequence of SFR$_{10\text{Myr}}$ being greater than the mean SFR over the whole SFR (10 Gyr).

In order to infer the efficiency in forming of stars in recent times, we estimate the specific SFR, sSFR=SFR/$M_{\text{total}}$ only in the last 10 Myr. Following TM18, we calibrate the current SFR in respect to the observed $L(H\beta)$ for 2BF, 3exp and 3BF, resulting in

$$\log(\text{sSFR}) = -39.97 \pm 0.29 + \log L(H\beta) \ (rms = 0.25),$$

$$\log(\text{sSFR}) = -40.10 \pm 0.21 + \log L(H\beta) \ (rms = 0.20),$$

$$\log(\text{sSFR}) = -40.02 \pm 0.21 + \log L(H\beta) \ (rms = 0.22),$$

respectively. Figure 17 shows the SFR$_{10\text{Myr}}$ versus $L(H\beta)$ for different SFHs, and their best-fit. Also we include the commonly used Kennicutt (1998) calibration for comparison. The differences in the...
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reaching that of 30 Dor. Thus, HII galaxies are the simplest starbursts in galactic scale with the highest star formation efficiencies.

6 CONCLUSIONS

We performed a SED analysis assuming SFHs with different shapes and input parameters to search for the best analytical description of HII galaxies. Our sample contains local objects (z<0.4) selected by SDSS spectroscopy, and photometric data from GALEX, SDSS, UKIDSS, and WISE surveys. Combining our $\chi^2_{red}$, BIC and mock analysis from the SED fitting we find that

- double exponential function yields the worst fit of all tests, thus is excluded;
- SFHs containing three star formation episodes provide good fits to the observational data;
- three episodic SFH with a varying amplitude does not give trustworthy outputs, then is eliminated;
- a constant extended SFR started at 10 Gyr, followed by a quiescent period with a recent burst does not provide bad fitting results, but lacks intermediate age stars.

Therefore, we confirm the findings of TM18 that HII galaxies are better described by SFHs following exponentially declining or constant functions containing at least three star formation episodes: an old (10 Gyr); an intermediate (100–1000 Myr); and a young stellar population where the most recent episode must have ages < 10 Myr.

We analyzed the so-called main sequence of star formation (MS), the relation between SFR and total stellar mass ($M_{total}$) for HII galaxies using the values derived from SED fitting. The main conclusions are

- for a fixed age of 10 Gyr different SFHs produce only minor variations in the MS. HII galaxies will move along a similar path depending on the shape(s) or duration of the star formation episode(s);
- the slope of the SFR$_{total}$ – $M_{total}$ relation does not provide any information about the SFH, with a close to unity value for all cases discussed here;
- HII galaxies only lie above the local MS when the SFR is averaged over the last 10 Myr.

The star forming main sequence can not be used as a tool to provide additional information about the SFH of HII galaxies. The excursions from the MS depend on the detailed description of the SFH, not only the average over Hubble time, and total mass and SFR must be jointly estimated consistently to avoid mis-interpretations on galaxy evolution.

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