How to measure star formation rates in galaxies?

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Our knowledge of cosmic mass assembly deeply relies on measurements of star formation rates as a function of redshift. This parameter must be estimated in a consistent manner, with a good knowledge of systematics, before studying its correlation with other quantities such as stellar or gas masses. Constraining the rate at which galaxies form stars across the Universe is of utmost importance if we want to understand galaxy formation and evolution.

1 Introduction

One of the most complex processes in galaxies is star formation, and understanding it and its evolution with time remains a challenge for modern astronomy. The evolution of dark matter is now modelled with high accuracy and is shaping the large scale structures in the universe. The physics of baryons, including star formation, is much more difficult to understand and to implement in models of galaxy formation and evolution. The first natural step is to find constraints from observations by measuring a reliable star formation rate (SFR) at various scales and redshifts, and studying the main drivers of its variations.

The SFR and stellar masses ($M_{\rm star}$) are the main parameters estimated from large samples of galaxies. A large number of works found a tight relation between the SFR and $M_{\rm star}$ both at low and high redshift, often called the *Main Sequence* (MS) of galaxies (e.g. Noeske et al., 2007; Rodighiero et al., 2011, and reference therein). The slope and the scatter of this relation, as well as its evolution with redshift, put constraints on the star formation history of the galaxies as a function of their mass: the galaxies located on this MS may experience a rather smooth star formation evolution during several Gyr and the starburst mode seems to play a minor role in the production of stars (Rodighiero et al., 2011).

Major progress has been made in the measure of the SFR inside the disk of nearby galaxies, with a strong relation found between the SFR and the molecular gas content (e.g., Bigiel et al., 2008), and measurement of the star formation efficiency in galaxies is now possible up to large redshifts (e.g., Tacconi et al., 2013). Besides these studies aimed at understanding the process of star formation, the global amount of star formation in the universe is measured by building statistical samples, with observables related to the recent star formation (Madau & Dickinson, 2014, for a review).

2 General characteristics of star formation calibrations

Various calibrators are used, covering the full electromagnetic spectrum, from the X-ray through the ultraviolet (UV), the optical, the infrared (IR), all the way to the radio. Both continuum emission and emission lines have been calibrated in terms of SFR. The derivation of the SFR relies on conversion factors depending on the indicator used. In this section I will present the general way to derive the SFR from direct stellar emission, and then discuss the uncertainties of the calibrations due to variations of the star formation histories. Very complete reviews about different star formation indicators were published recently (Kennicutt & Evans, 2012; Boissier, 2013).

2.1 Basic equation and standard calibrations

The fundamental equation to link the intrinsic luminosity emitted by stars at wavelength λ and time t is

$$\mathrm{L}(\lambda,\mathrm{t}) = \int_0^{\mathrm{t}} \int_{\mathrm{M_{low}}}^{\mathrm{M_{up}}} \mathrm{F}_\lambda(\mathrm{m},\theta)\mathrm{SFR}(\mathrm{t}-\theta)\psi(\mathrm{m})\ \mathrm{dm}\ \mathrm{d}\theta \tag{1}$$

where $\mathrm{F}_\lambda(\mathrm{m},\theta)$ are the evolutionary stellar tracks, $\psi(m)$ the initial mass function, and $SFR(t)$ the star formation rate function. From this fundamental equation there are two ways to derive SFRs. One can use stellar population synthesis models with various $SFR(t)$ to fit a large set of data at different wavelengths; the current SFR is an output parameter of the fit (with the stellar mass and other parameters depending on the specific code used). Another, very popular, way to proceed is to derive simple recipes. One assumes a SFR constant over a timescale T and the SFR becomes simply proportional to the luminosity integrated over T. The timescale T is chosen in order that the luminosity at wavelength λ reaches a steady state:

$$\mathrm{SFR} = \Big(\int_0^{\mathrm{t}} \int_{\mathrm{M_{low}}}^{\mathrm{M_{up}}} \mathrm{F}_\lambda(\mathrm{m},\theta)\mathrm{SFR}(\mathrm{t}-\theta)\psi(\mathrm{m})\ \mathrm{dm}\ \mathrm{d}\theta\Big)^{-1} \times \mathrm{L}(\lambda) \tag{2}$$

The value of the conversion factor $C = SFR/L(\lambda)$ is calculated with a spectral synthesis code. The SFR calculated using a conversion factor can be different from the average of the star formation activity during T if the actual SFR is strongly varying during this period. The assumption of a constant SFR is likely to be valid on short timescales only and the SFR should be derived from the emission of stars with short lifetimes, preferentially in the ultraviolet for recombination lines of ionizing photons. The timescale to reach a steady state increases with wavelength from $\sim$ 100 Myr in the UV to more than 1 Gyr in optical-near IR. The timescale found for ionizing photons (i.e. recombination lines) is of the order of few Myr (Kennicutt & Evans, 2012; Boissier, 2013). There is some evidence (see next subsection) for a SFR constant over few hundred Myrs, at least in the nearby universe: standard calibrations can be calculated, very popular ones being those of Kennicutt (1998). Note that the calibration depends also strongly on the initial mass function (e.g. Pflamm-Altenburg et al., 2009).

Another widespread method to derive these physical parameters is to exploit the full panchromatic information available for a given sample by fitting the spectral energy distributions (SEDs). The first step is to model the stellar emission using an evolutionary population synthesis method, assuming a star formation history, and with some recipes for dust attenuation and then to compare the theoretical SEDs to data. This method is particularly convenient when a large range of redshift is studied and when the wavelength coverage is wide. The method will be detailed in an other chapter of this volume.

2.2 *Impact of a varying star formation rate*

The assumption of a constant star formation rate is quite strong. It is very important to check that this condition is fulfilled before using standard calibrations. In the nearby universe the tight correlation found between the Hα and UV luminosity of large star forming galaxies is a strong argument in favor of a rather constant star formation rate over the typical timescale for the UV light to reach a steady state (i.e. $\sim$ 300 Myr) as illustrated in Fig.2 of Hao et al. (2011). Conversely, nearby dwarf galaxies are likely to experiment rapid changes of their star formation rates (e.g., Weisz et al., 2012), implying variations in their Hα to UV flux ratio. Boquien et al. (2014) explore the impact of both long term and short term variability of the star formation history on the measurements of the SFR using classical estimators. Using simulations to model plausible star formations histories, they find that, except for the Lyman continuum (and therefore recombination lines like the H_α one), classical estimators assuming a constant SFR over 100 Myr overestimate the true SFR as shown in Fig. 1. This effect is attributed to the long term variations of the SFR and to the contamination from stars living longer than the calibration timescale of 100 Myr. The authors suggest adopting SFR estimators calibrated over 1 Gyr rather than the commonly used 100 Myr to take into account this contamination. The Lyman continuum is by far the the best tracer of the 'instantaneous' rate of star formation.

3 Entering the real world: dust absorption and re-emission of stellar light

3.1 *IR and composite star formation tracers*

The rest-frame UV emission is frequently privileged to measure SFRs. The observations of the *GALEX* satellite up to $z = 1$ and the numerous optical surveys give very sensitive UV rest-frame measurements from the nearby universe to high redshifts and for large samples of galaxies (e.g., Salim et al., 2007; Cucciati et al., 2012). However, UV emission suffers from a major issue, which is dust attenuation. In the nearby universe and within galaxies like the Milky Way, about half of the stellar light is absorbed and re-emitted by dust at wavelengths larger than $\sim 5\mu$m, and that fraction can increase to more than 90% in starbursting objects. Therefore measuring the IR emission of galaxies has been identified as mandatory for measuring the total SFR, and adding both UV and IR emissions is now recognized as a very robust method to measure the SFR. Some calibrations combine different wavelengths and account for all the star formation directly observed in UV-optical or reprocessed in thermal IR (e.g. Kennicutt & Evans, 2012, and references therein).

The development of IR facilities allows the building of statistical samples of galaxies detected in IR, although the lower sensitivity of IR detectors combined with poor spatial resolution makes comparison with UV-optical surveys still difficult. The

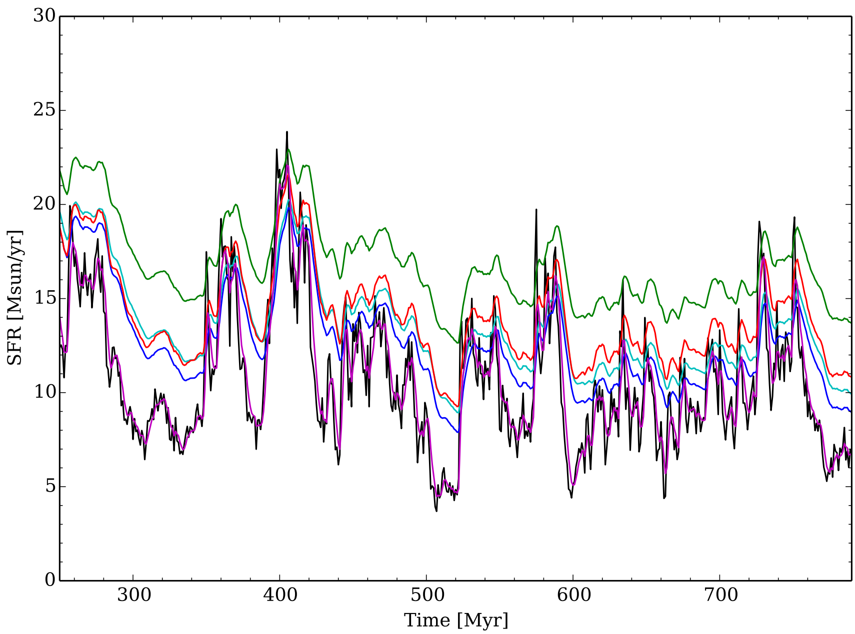

Fig. 1: SFR measurements for simulated galaxies from fig. 3 of Boquien et al. (2014). True SFR from simulations is shown in black. The SFRs measured with standard calibrators are plotted with coloured lines: magenta for the Lyman continuum, blue for the FUV (150 nm), cyan for the NUV (230 nm), green for the U band and red for the total infrared (IR) emission from dust, based on the assumption that the galaxy is entirely obscured. Note that the true SFR and SFR from Lyman continuum are nearly blended.

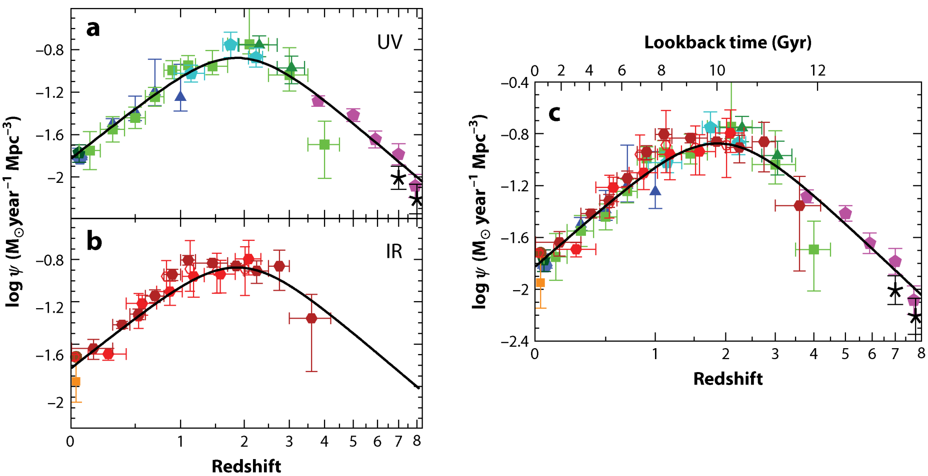

Fig. 2: SFR density measurements from UV (a), IR (b) , UV+IR (c) measurements, from Madau & Dickinson (2014). The IR measurements only sample redshifts lower than 3, beyond this limit only UV measurements are available, which are potentially affected by dust attenuation

Spitzer and *Herschel* deep observations combined with ground-based optical surveys give us a complete view of the star formation up to $z \sim 2$. The very high redshifts ($z \gg 2$) remain almost unexplored in IR even with *Herschel* (Madau & Dickinson, 2014, see Fig. 2) and stacking methods are intensively used to find the average IR emission of optically faint objects not detected individually (e.g., Heinis et al., 2013).

3.2 Dust attenuation corrections

When dust emission is measured, accurate star formation rates can be derived by combining IR and UV data as described above , but these data are often not available, in particular for deep optical surveys. As a consequence, it is particularly important to study the dependence of dust attenuation on parameters such as the observed luminosity, the stellar mass, or the slope of the UV continuum, since it could be used to correct large samples for the effect of dust attenuation, at least in a statistical way. The global amount of dust attenuation is robustly estimated by comparing dust and stellar emission, through the $L_{\rm IR}/L_{\rm UV}$ ratio (e.g. Buat et al., 2005). When IR data are not available, the shape of the UV continuum (< 3000) has been proposed as a proxy to measure the amount of attenuation. D. Calzetti, G. Meurer and collaborators have shown that the UV continuum of local starburst galaxies can be fit by a power law ($f_\lambda({\rm erg\ cm^{-2}s^{-1}nm^{-1}}) \propto \lambda^\beta$) for $\lambda > 120$ nm. β correlates with the amount of dust attenuation measured by $L_{\rm IR}/L_{\rm UV}$ (Calzetti (2001) for a review). This local starburst relation is widely used to estimate dust attenuation in high-redshift galaxies although the universal validity of the relation is questioned even for local galaxies (e.g. Takeuchi et al., 2012).

Dust attenuation is also found to be correlated with the stellar mass as already reported from the local universe up to high redshifts and the relation does not seem to evolve with redshift (Heinis et al., 2014; Bernhard et al., 2014) . Recently Buat et al. (2015) found that the different amount of attenuation in galaxies selected either in UV or in IR can be explained when considering the stellar mass of the objects and the attenuation-stellar mass relation.

4 The reliability of SFR measurements: confrontation with simulated catalogues

Comparison of the observed and simulated spectral energy distributions of galaxies informs us as to which fitting method provides correct galaxy parameters. Properties of mock galaxies are known *a priori*, by definition, and using their simulated emission helps us understand the effectiveness of the assumptions made to derive the SFR, even though there is no guarantee that the simulated galaxies have star formation histories similar to the real ones in the Universe. Simulated catalogues are either outputs of hydrodynamical or semi-analytical codes or generated from real catalogues and simple assumptions to reproduce the observed SEDs (e.g. Wuyts et al., 2009; Pforr et al., 2012; Boquien et al., 2014; Ciesla et al., 2015). These studies showed that it is very difficult to reconstruct the whole star formation history, and the true stellar age of stellar populations is underestimated because of the overshining of the young populations in star-forming galaxies, with obvious effects on stellar mass determinations (e.g. Pforr et al., 2012). The difficulty of reproducing realistic star formation histories with simple modelling is illustrated in Fig. 3 from the work of Ciesla et al. (2015). If dust attenuation is well constrained with IR data the recent star formation rates are well reproduced (Buat et al., 2015).

5 Conclusions

Multiwavelength data are mandatory to recover both visible and hidden star formation. Classical recipes are based on strong assumptions about the recent star formation history (over at least ~ 100 Myr), Outputs of SED fitting codes also depend on the assumed star formation history. Very short term variations of the star formation rate (< 10 Myr) are only seen with the measurement of the ionizing flux, the UV light keeps track of variations on timescales shorter than a few tens of Myr. However even the UV emission is likely to be affected by the contribution of old stars. The users must always check that the underlying assumptions are consistent with the expected properties of the galaxies they study.

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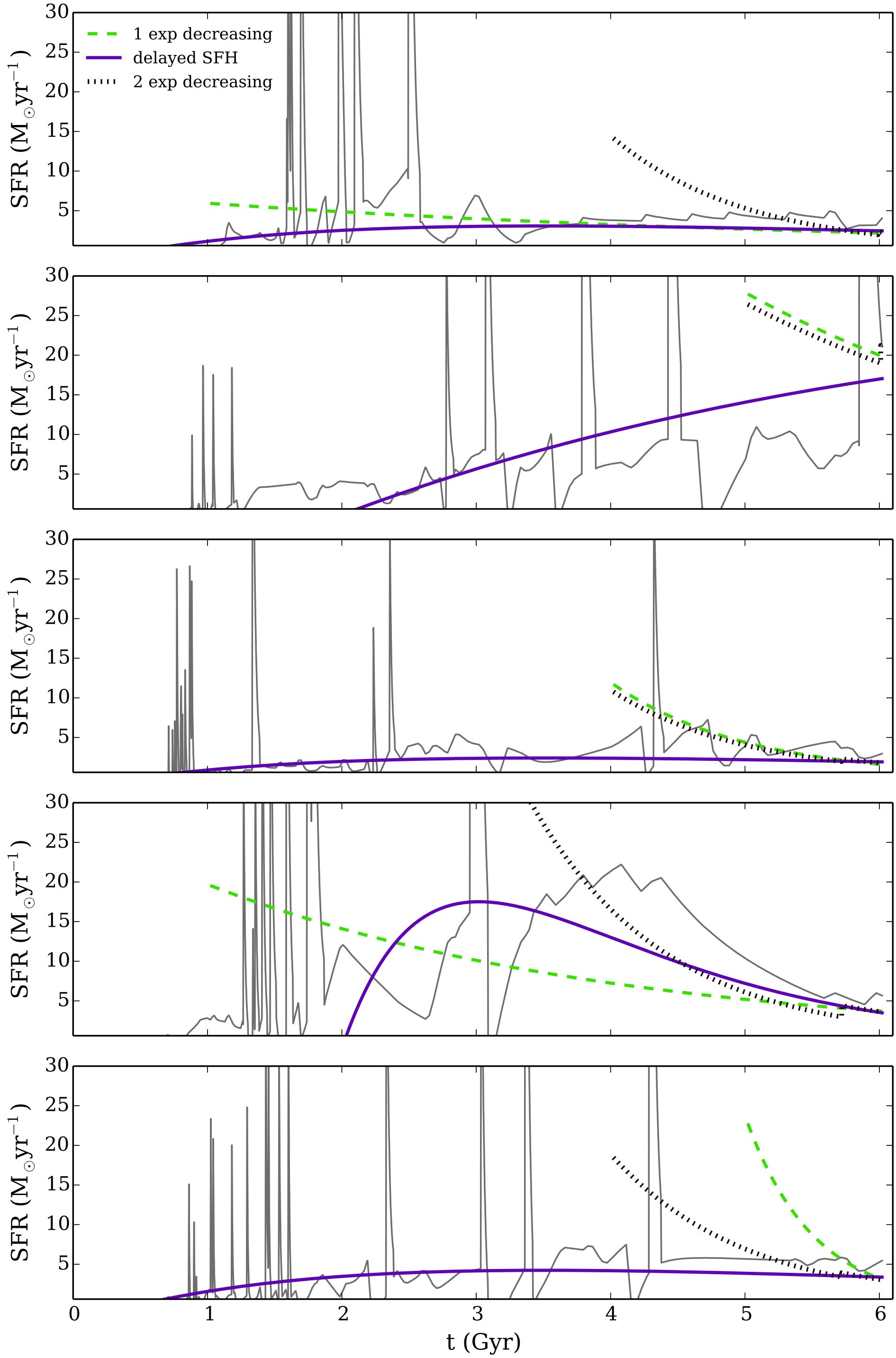

Fig. 3: Star formation histories from semi-analytical modelling (black line) and the corresponding best fits obtained with the code CIGALE and 3 different models of star formation (Ciesla et al., 2015, their Fig.7)

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