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Stellar population synthesis of galaxies with chemical evolution model

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Abstract. The derivation of accurate stellar populations of galaxies is a non-trivial task because of the well-known age-metallicity degeneracy. We aim to break this degeneracy by invoking a chemical evolution model (CEM) for isolated disk galaxy, where its metallicity enrichment history (MEH) is modelled to be tightly linked to its star formation history (SFH). Our CEM has been successfully tested on several local group dwarf galaxies whose SFHs and MEHs have been both independently measured from deep colour-magnitude diagrams of individual stars. By introducing the CEM into the stellar population fitting algorithm as a prior, we expect that the SFH of galaxies could be better constrained.

Keywords. galaxies: stellar content, galaxies: evolution, galaxies: abundances

1. Introduction

Star formation history (SFH), i.e. the amount of stars formed in galaxies as function of time, is one of the elements of galaxy evolution. Stars are formed from cool phase gas and then evolved stars return metals into the interstellar medium (ISM). The ISM cools and new generation of stars form. Among this circle, the SFH is the key factor that links the gas cooling and metallicity enrichment history (MEH) of galaxies.

However, recovering the SFH of galaxies is difficult (Conroy, 2013). For very nearby galaxies, the deep colour-magnitude diagram (CMD) reaching the turn-off stars is known as the only direct and most reliable method that can recover both of their detailed SFHs and MEHs. For galaxies at larger distances, stellar population synthesis methods have been developed and used to fit their observed integrated spectral energy distributions (SEDs). In an idealized case, the SED of a galaxy can be viewed as a composition of single stellar populations (SSPs) with different ages and metallicities. However, because of the similarities of the old SSPs ($t > 1$ Gyr) and the age-metallicity degeneracy among SSPs, recovering the detailed weights of each SSPs, especially for those with $t > 1$ Gyr, is very difficult. In reality, the observables are further complicated by many other details, e.g. stellar kinematics, ionised gas emissions, central AGNs, dust attenuation and emission etc. Therefore, typically, only the first order description of the SFH, e.g. the average age or the fraction of young stellar populations, rather than its detailed shape, could be reliably derived from the observed SEDs of galaxies.

2. Recovering detailed SFH

In popular SED fitting algorithms (e.g. STARLIGHT, Cid Fernandes *et al.* 2005), the ages and metallicties of SSPs are considered as independent parameters. To recover the detailed SFH and MEH of a galaxy, a library of SSPs with different ages and metallicities

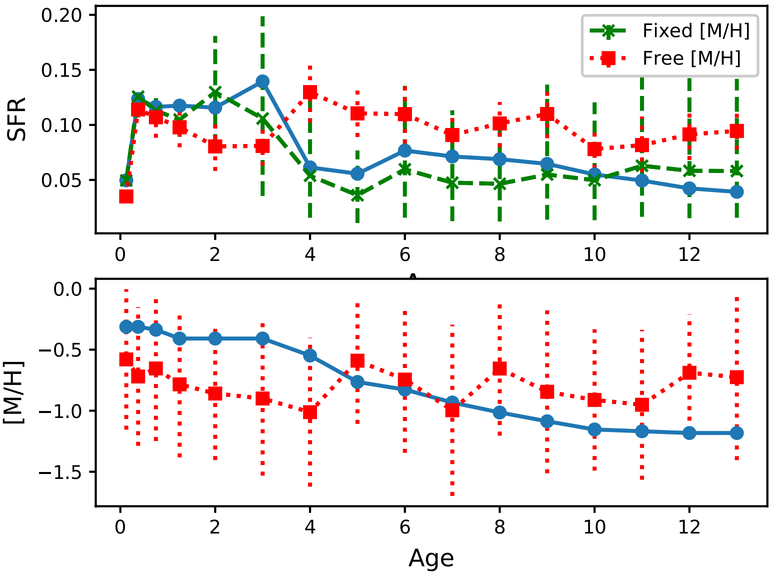

Figure 1. The SFH (top panel) and MEH (bottom panel) of a mock galaxy. The solid circles represent the input SFH and MEH, whereas the red squares show the SFH and MEH recovered from the mock spectrum with no prior information. The green crosses in the top panel show the recovered SFH when its MEH is assumed to be the blue circles in the bottom panel.

is first built, then the best combinations of these SSPs are searched in the library space. However, because of the age-metallicity degeneracy, the recovering of the SSP weights from SED is an ill-posed problem in mathematics.

To show this problem more intuitively, we make a mock galaxy spectrum and test how good a full spectrum fitting algorithm can recover its SFH and MEH. We take the SFH and MEH of the LMC bar region, which are derived from the deep CMD fitting (Ruiz-Lara *et al.* 2015) and are shown as the solid circles in Fig. 1. We use SSPs from MILES library (Falcón-Barroso *et al.*, 2011) to generate the mock spectrum in the wavelength range $3600 - 7500\mathring{A}$ with a resolution of $R = 2000$ and S/N=50 per pixel. For simplicity, we neither consider the kinematics of stellar populations nor consider the dust attenuation.

For this idealized case, can we recover the input SFH and MEH accurately using a full spectrum fitting? We take the same MILES SSP library and use a MCMC algorithm to probe the full age and metallicity space for the best solution. The resulting SFH and MEH, converted from the likelihood distributions of SSP weights, are shown as the red squares in each panel of Fig. 1. Except the weights of young stellar populations ($t < 1$ Gyr), the weights of the old stellar populations and the shape of the MEH are both not well constrained.

Is an accurate MEH knowledge helpful to recover the accurate SFH? To test this idea, we set the metallicities of the different age SSPs to follow the input MEH (the blue circles in the bottom panel of Fig. 1). We then make the full spectrum fitting again. Now, we only need to probe the weights of the SSPs in age space. The resulted SFH is shown as the green crosses in the top panel of Fig. 1. As can be seen, when MEH is known as a prior, the SFH is recovered with much better accuracy.

Fig. 1 shows that the prior information on the MEH, which breaks the age-metallicity degeneracy, is crucial for recovering the accurate SFH of galaxies. Actually, the importance of the prior information on SFH or MEH have already been explored by many

SED fitting codes. For an example, the code STECKMAP (Ocvirk *et al.* 2006) allows a penalization of the best fitting with an assumed MEH. However, a realistic MEH needs a physical justification. Indeed, that is the chemical evolution model we will discuss next.

3. Chemical evolution model

We consider galaxy as a pool of stars and gas. At any given time, there are both inflow and outflow of gas into the pool. The inflow gas is primordial, i.e. with zero metallicity. Stars formed from gas, and died stars return enriched gas into the pool. Some of the enriched gas makes up of the outflows.

We write the time dependent star formation rate (SFR), gas inflow and outflow rate as $\Psi(t)$, $f_{in}(t)$ and $f_{out}(t)$ respectively. Stars are born from gas pool following an initial mass function (IMF). We assume that the massive stars ($M > 1M_{\odot}$) die immediately and return gas into the pool, while the low mass stars ($M < 1M_{\odot}$) have infinite lifetime. We take the classical Salpter IMF, which has a gas return fraction $R \sim 0.3$. Thus, the evolution of gas in pool is

$$\frac{dM_{gas}(t)}{dt} = -(1-R)\Psi(t) + f_{in}(t) - f_{out}(t). \tag{3.1}$$

On the other hand, the surface star formation rate density of a galaxy is known to be tightly correlated with its surface gas density Σ_{gas}, i.e. the well-known Kennicutt-Schmidt relation, $\Psi_{\Sigma} \propto \Sigma_{gas}^{1.4}$ (Kennicutt, 1998). For gas outflow, we assume it is driven by supernova explosion so that it is proportional to SFR and inversely correlated with the potential well of the galaxy,

$$f_{out}(t) = \eta \left[0.5 + \left(\frac{v_{vir}}{70 \text{ km s}^{-1}}\right)^{-3}\right] \cdot \Psi(t) \tag{3.2}$$

where v_{vir} is the circular velocity of the galaxy halo, and η is the wind efficiency.

The evolution of metallicity $Z(t)$ is a balance between the star formation and metal outflow, which is written as

$$\frac{d(ZM_{gas})}{dt} = -Z(1-R)\Psi(t) + y(1-R)\Psi(t) - Zf_{out}, \tag{3.3}$$

where y is the yield and we take $y = 0.1$.

With above equations (3.1 to 3.3), once with structure parameters (to convert gas mass to surface density), for any given $\Psi(t)$ of a galaxy, we can predict both its $Z(t)$ and gas inflow/outflow histories.

4. Test on LCID galaxies

We test above CEM with LCID galaxies (Gallart, 2007), whose detailed SFHs and MEHs have been obtained using deep CMDs from HST. As an example, we take the SFHs of three different type LCID galaxies, Tucana (dSph), LGS-3 (dTran), IC 1613 (dIrr), and predict their $Z(t)$ from the above CEM. We calculate their average surface densities inside the half-light radii and use their stellar masses to estimate the circular velocities. The wind efficacy is set as $\eta = 0.4$ in all the cases. The results are shown in Fig. 2. For all three galaxies, our CEM reproduces their MEHs from SFHs reasonably well.

5. Conclusion

Encouraged by Fig. 2, we conclude that our CEM can be used to break the age-metallicity degeneracy in stellar population synthesis studies. Specifically, we may start from the SED fitting with both SFH and MEH free. With a preliminary SFH, a new MEH could be predicted from our CEM, which then could be used as a prior in the

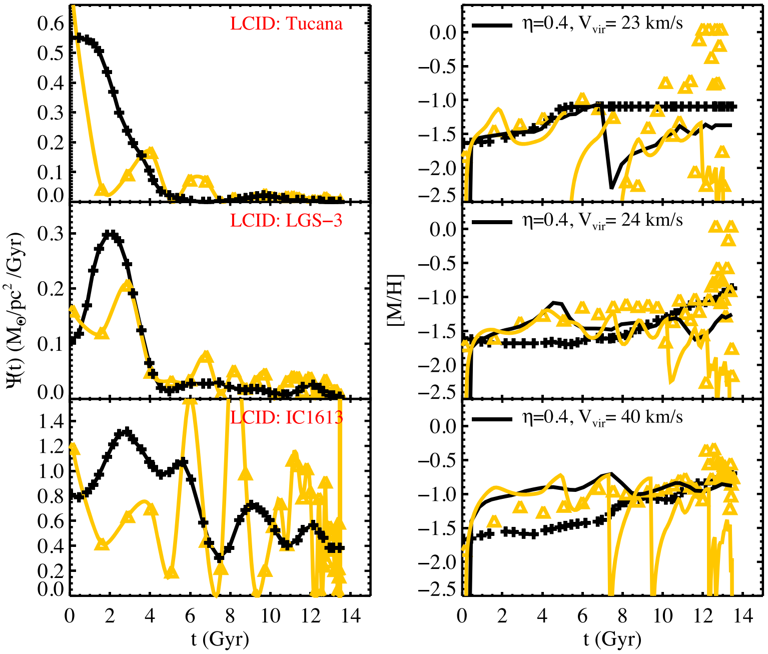

Figure 2. The SFH (left panels) and MEH (right panels) of 3 LCID galaxies. The black crosses show the best estimations of SFHs and MEHs from LCID project, whereas the yellow triangles show one of their Monte-Carlo realization (indicating the uncertainty, *Dan Weisz, private communication.*). The solid lines in the left panels are the continuous SFHs used as the input of CEM, while the model predicted MEHs are shown as the solid curves with corresponding colours in right panels.

second round SED fitting (as we done in Fig. 1). With several iterations, a self-consistent SFH and MEH could be finally obtained. We expect that this algorithm would reduce the uncertainties of the final SFH estimation, and is proper for isolated disk galaxies.

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Discussion

Themiya Nanayakkara: Can your CEM be used to predict $[O/Fe]$ enhanced stellar populations as shown by Stedel et al. (2016) in $z\sim 2$ galaxies?

Shiyin Shen: No, currently, our model only considers global metallicity, and do not distinguish α and Fe metals. But this is a good idea, we will consider it in the future.

Themiya Nanayakkara: What about the role of mergers in the CEM?

Shiyin Shen: For the major merger events, the halo mass will change significantly. Our model can not deal with this situation yet.