Challenges in Panchromatic Modelling with Next Generation Facilities
Proceedings IAU Symposium No. 341, 2018
M. Boquien, E. Lusso, C. Gruppioni & P. Tissera, eds.

doi:10.1017/S1743921319002370

Variations of the stellar Initial Mass Function in semi-analytic models: Implications for the mass assembly of galaxies in the GAEA model

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Abstract. A wealth of observations recently challenged the notion of a universal stellar initial mass function (IMF) by showing evidences in favour of a variability of this statistical indicator as a function of galaxy properties. I present predictions from the semi-analytic model GAEA (GAlaxy Evolution and Assembly), which features (a) a detailed treatment of chemical enrichment, (b) an improved stellar feedback scheme, and (c) implements theoretical prescriptions for IMF variations. Our variable IMF realizations predict intrinsic stellar masses and mass-to-light ratios larger than those estimated from synthetic photometry assuming a universal IMF. This provides a self-consistent interpretation for the observed mismatch between photometrically inferred stellar masses of local early-type galaxies and those derived by dynamical and spectroscopic studies. At higher redshifts, the assumption of a variable IMF has a deep impact on our ability to reconstruct the evolution of the galaxy stellar mass function and the star formation history of galaxies.

Keywords. galaxies: evolution - galaxies: fundamental parameters - galaxies: stellar content

1. Introduction

The IMF quantifies the number of stars formed per stellar mass bin in a given episode of star formation. As such, it represents a key parameter to characterise galaxy evolution from photometric surveys. The IMF has long been assumed to have a universal shape, mainly because of near-invariant results obtained for the closest star forming regions in our Galaxy (see e.g. Kroupa 2001). However, recent observational developments put this notion in question. These evidences came mainly trough two separated channels. A systematic excess of the mass-to-light ratios derived using integral field stellar kinematics with respect to photometric values based on a universal IMF has been reported by many authors (see e.g. Cappellari *et al.*, 2012). Moreover, high-resolution spectroscopy of spectral features sensitive to IMF variations (due of their dependence on stellar surface gravity and/or effective temperature) suggests an excess of low- relative to intermediate-mass stars, compared to the universal IMF, in massive early-type galaxies (ETGs, see e.g. Conroy *et al.*, 2013 and La Barbera *et al.* 2013). In both cases, the reported excess increases with increasing galaxy stellar mass ($M_\star$) and/or velocity dispersion. It is worth stressing that the spectroscopic probe clearly favours a *bottom-heavy* scenario (i.e. an excess of low-mass stars with respect to the universal IMF), but it samples only to the low-mass end of the IMF ($<1\ M_\odot$). On the other hand, the dynamical probe is sensible to the whole shape of the IMF, but cannot distinguish between a *top-heavy* (i.e. an excess of high-mass stars with respect to the universal IMF) or a *bottom-heavy* scenario. The observational picture is further complicated by the radial IMF gradients reported for local

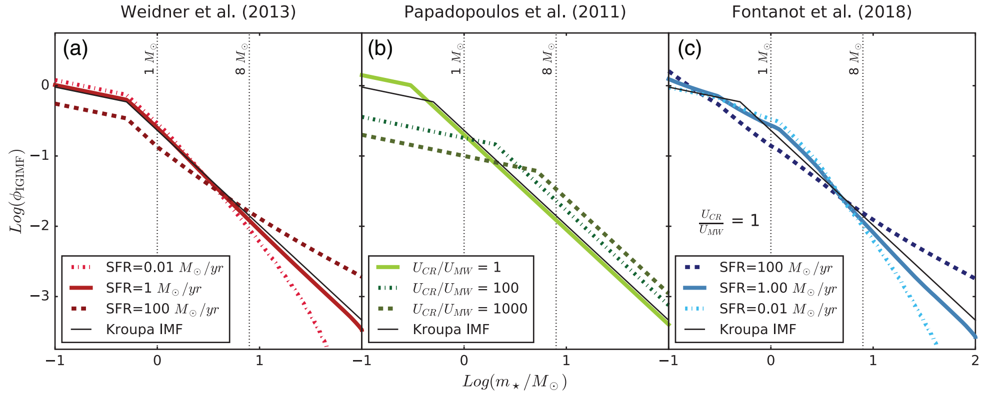

Figure 1. Variable IMF implementations discussed in this talk (in all panels the thin solid line represents the universal IMF in the solar neighbourhood as in Kroupa 2001). *Panel (a):* evolution of the IMF shape as a function of SFR, according to the IGIMF theory Weidner *et al.* 2013. *Panel (b):* evolution of the IMF shape as a function of cosmic ray energy densities, using the numerical results from Papadopoulos *et al.* (2011). *Panel (c):* composite IMF evolution as a function of SFR and cosmic ray energy densities (only the $U_{\rm CR} = U_{\rm MW}$ case is shown) as proposed in Fontanot *et al.* (2018b). In all panels, each IMF is normalized to 1 $M_\odot$ in the stellar mass interval 0.1-100 $M_\odot$.

ETGs using integral field unit spectroscopy (see e.g. Sarzi *et al.* 2018). These findings suggest that the low-mass stars excess increases in the innermost regions of these galaxies. However, these trends stand in apparent contradiction with the well-known metallicity gradients in ETGs: the increasing α-enhancement towards the centre seems to require a larger contribution from Type-II SNe, thus a larger fraction of high-mass stars.

2. Variable IMF implementations in GAEA

In my contribution, I present recent results obtained in the framework of the semi-analytic model GAEA (GAlaxy Evolution and Assembly; Hirschmann, De Lucia & Fontanot, 2016). This state-of-the-art model features key improvements in the treatment of (a) chemical enrichment (i.e. it follows the differential evolution of AGB stars, Type-Ia and Type II SNe) and (b) stellar feedback (i.e. it implements an ejective feedback prescription that combines results of high-resolution hydrodynamical simulations with energy conservation arguments). This model is able to provide a self-consistent picture of galaxy evolution, reproducing the evolution of the galaxy stellar mass function (GSMF) and cosmic star formation rate (SFR) up to $z \sim 8-10$ (Fontanot, Hirschmann & De Lucia, 2017b).

In a series of recent papers, we include in GAEA prescriptions that link the variability of the IMF to physical properties of model galaxies. In particular, in Fontanot *et al.* (2017a) we test the integral galaxy-wide IMF theory (IGIMF - Weidner *et al.* 2013 - Fig. 1, *panel (a)*): this analytic model predicts an evolution of the high-mass-end slope of the IMF as a function of the global SFR of galaxies. In Fontanot *et al.* (2018a), we build on the results of numerical simulations from Papadopoulos *et al.* (2011) to relate the position of the knee of the IMF with the cosmic ray density field ($U_{\rm CR}$, normalized to the Milky Way reference value $U_{\rm MW}$) associated with model galaxies (Fig. 1, *panel (b)*). In a variable IMF scenario, it is only possible to calibrate the models against photometric data; in detail we consider $z=0$ luminosity functions (LF) in the $g-$, $r-$, $i-$, and $K-$band, and the redshift evolution of the K- and $V-$band LFs. In order to compute self-consistent synthetic photometry for our variable IMF realizations, we construct Single Stellar Populations libraries (for different ages and metallicities) corresponding to each assumed IMF shape, using an updated version of Bruzual & Charlot (2003) models. Synthetic photometry

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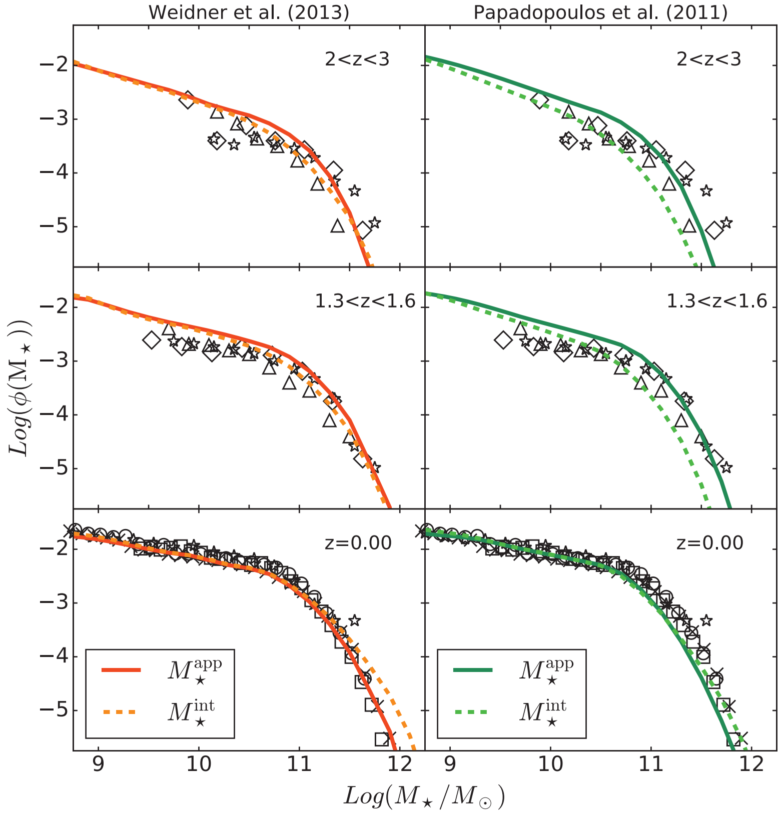

Figure 2. Evolution of the GSMF. In each panel, solid lines correspond to the GSMF as a function of the apparent photometrically-equivalent stellar mass $M_\star^{app}$, while dot-dashed lines show the GSMF as a function of the intrinsic galaxy stellar mass $M_\star^{int}$. Dark points show a collection of observational measurements as in Fontanot *et al.* (2009).

represents the only observable we can directly compare with observational constraints. Indeed, most of the estimates for physical properties of galaxies available in the literature are derived under the hypothesis of a universal IMF, and it could be problematic to compare them with the *intrinsic* properties of model galaxies, as predicted by our variable IMF runs. To better explain this issue, in the following we focus on galaxy stellar masses. We define a photometrically-equivalent *apparent* stellar mass ($M_\star^{app}$) by applying to our synthetic photometry mass-to-light versus colour scalings typically used in photometric surveys (see e.g. Zibetti, Charlot & Rix 2009). In this way, we derive the $M_\star$ an observer would associate to our synthetic photometry assuming a universal IMF.

3. Results

Both our variable IMF realizations provide consistent results in terms of galaxy properties and their evolution. In particular, they are able to naturally solve the long-standing problem of α-enhancement in massive ETG (see e.g. Fig.B1 in Fontanot *et al.* 2018a). We compare the intrinsic stellar masses $M_\star^{int}$ as predicted by the models with $M_\star^{app}$ and we find that our realisations are able to reproduce the excess of dynamical mass (that closely correspond to $M_\star^{int}$) with respect to the photometrically derived stellar mass (see e.g. Fig.B3 in Fontanot *et al.* 2018a). In the framework of photometric surveys, the most interesting results involve the study of galaxy evolution, as traced by statistical estimators such as the GSMF. In this case, the effect of assuming a variable IMF might be dramatic, as shown in Fig. 2. Solid lines represent the GSMF evolution derived using

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$M_\star^{\rm app}$: in most cases it agrees quite well with the observational estimates (also obtained from photometric surveys assuming a universal IMF). On the other hand, dashed lines correspond to the intrinsic evolution of the GSMF in the same GAEA runs: it is clear from this comparison that the variable IMF hypothesis can change our understanding of galaxy evolution, as seen using photometric surveys. In particular, the real GSMF might differ significantly from estimates based on photometry, assuming a universal IMF.

It is worth stressing that all variable IMF approaches we consider so far do not predict a change in the low-mass end of the IMF. Therefore, they wouldn't be able to reproduce the spectral features observed in ETG spectra. Nonetheless, these models are able to reproduce the metal enrichment of ETGs better than universal IMF runs. In Fontanot *et al.* (2018b) we present a new derivation for the variable IMF, that combines the IGIMF theory with the numerical results of Papadopoulos *et al.* (2011). We assume the IMF shape depends on both the SFR and $U_{\rm CR}$. As a representative example, in Fig. 1, *panel (c)*, we show the evolution of the IMF shape as function of SFR, for a MW-like $U_{\rm CR}$. This scenario provides a possible explanation for the observed IMF and metal gradients in ETGs. Indeed, at increasing SFR the predicted IMF shape becomes *the same time* shallower at the high-mass end (which implies a larger number of massive stars) and steeper at the low-mass end (thus predicting an excess of low-mass stars).

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Discussion

Kentaro Nagamine: Could you explain a little more on how you link SFR to the evolution of IMF? I.e. does a higher SFR imply a more top heavy IMF?

Fabio Fontanot: In the IGIMF model, an higher SFR directly correspond to a top-heavy IMF. In the Papadopoulos *et al.* model I am using the SFR density as proxy for CR energy density. This implies that a higher SFR at fixed disc radius indeed provide a more top-heavy IMF. Several combination (of SFR and scale-radii) are possible in the GAEA framework, but in general higher SFRs tend to correspond to higher SFR densities (see e.g. Fig. 3 in Fontanot *et al.* 2018b).

Gergö Popping: Do I understand correctly that the [α/Fe] trend comes from a top heavy IMF during bursts and the bottom heavy IMF from more passive star-formation?

Fabio Fontanot: The [α/Fe] trends are mainly driven by the top-heavy IMF expected in the strong SFR events connected with the formation of more massive galaxies. The current model do not implement a bottom-heavy IMF yet, but we are working in this direction.

Themiya Nanayakkara: How can you link the models of IMF dependence in GAEA to reproduce high mass slope variations observed by Hoverste & Glazebrook (2008), Gunawardhana *et al.* (2011) at $z = 0$ and Nanayakkara *et al.* (2017) at $z = 2$?

Fabio Fontanot: The observations of Gunawardhana *et al.* (2011) at $z = 2$ have been explicitly taken into account in the definition of the IGIMF model, so that they are reproduced by definition. We didn't check the other samples, but that would be an interesting test for our model.