

The (galaxy-wide) IMF in giant elliptical galaxies: From top to bottom

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ABSTRACT

Recent evidence based independently on spectral line strengths and dynamical modelling point towards a non-universal stellar Initial Mass Function (IMF), implying an excess of low-mass stars in the most massive elliptical galaxies. Here we show that a time-independent bottom-heavy IMF is compatible neither with the observed metal-rich populations found in giant ellipticals nor with the number of stellar remnants observed within these systems. We suggest a two-stage formation scenario involving a time-dependent IMF to reconcile these observational constraints. In this model, an early strong star-bursting stage with a top-heavy IMF is followed by a more prolonged stage with a bottom-heavy IMF. Such model is physically motivated by the fact that a sustained high star formation will bring the interstellar medium to a state of pressure, temperature and turbulence that can drastically alter the fragmentation of the gaseous component into small clumps, promoting the formation of low-mass stars. This toy model is in good agreement with the different observational constraints on massive elliptical galaxies, such as age, metallicity, α -enhancement, M/L, or the mass fraction of the stellar component in low-mass stars.

Key words: galaxies: evolution – galaxies: star formation – galaxies: stellar content – stars: luminosity function, mass function

1 INTRODUCTION

One of the most fundamental properties of a stellar population is the distribution with respect to mass at birth, i.e. the stellar initial mass function (IMF). It is a highly important distribution function in astrophysics, as stellar evolution is mostly determined by stellar mass. The IMF therefore regulates the chemical enrichment history of galaxies, as well as their mass-to-light ratios, and influences their dynamical evolution. Studies of resolved stellar populations in the Milky Way (MW) and the Magellanic clouds suggest that the IMF is invariant over a large range of physical conditions like gas density and metallicity (Kroupa 2002; Bastian et al. 2010; Kroupa et al. 2013). This evidence motivated the use of a fixed IMF for the description of the stellar populations of whole galaxies, irrespective of their star formation history. However, the underlying assumption that the IMF – derived from and tested on star cluster scales in the MW

and nearby galaxies – is the appropriate stellar distribution function for more complex stellar populations lies beyond present observational capabilities.

The advances of large-scale observational surveys comprising tens of thousands of galaxies, as well as more detailed stellar modelling, led to a number of results questioning the universality of the IMF (see, e.g. Hoversten & Glazebrook 2008; Meurer et al. 2009; Lee et al. 2009; Gunawardhana et al. 2011; Dabringhausen et al. 2009, 2012; Cappellari et al. 2012; Ferreras et al. 2013). Some of the results seem to be conflicting, especially in galaxies involving high star formation rates. For example, Gunawardhana et al. (2011) find that the IMF becomes top-heavy in strong star-bursts while Ferreras et al. (2013) derive very bottom-heavy IMFs for massive elliptical galaxies, which ought to have formed in star-bursts. Such variations in the IMF can have important implications in the derived star formation histories and stellar masses of galaxies (Ferré-Mateu et al. 2013; La Barbera et al. 2013).

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In a volume-limited study of 260 early-type galaxies (hereafter ETGs) via integral field spectroscopy and photometry, Cappellari et al. (2012) find that, regardless of the assumptions about the underlying dark matter halos, the SDSS r -band mass-to-light ratios agree neither with the assumption of a single slope Salpeter IMF (Salpeter 1955), nor with the Kroupa-IMF (Kroupa 2002). Cappellari et al. (2012) conclude that either a very bottom-heavy (dominated by low-mass stars), or a very top-heavy IMF (dominated by remnants) can explain the derived stellar M/L ratios. Falc3n-Barroso et al. (2003) find a similar trend in the bulges of late-type galaxies, and Cenarro et al. (2003) suggest a bottom-heavy IMF as a viable explanation to the low Calcium triplet abundances in massive early-type galaxies. van Dokkum & Conroy (2010, 2012) provided strong evidence towards a bottom-heavy IMF from the analysis of additional gravity-sensitive features, such as Na8190 and FeH in massive elliptical galaxies. However, chemical evolution models of the MW and M31 bulges seem to suggest that a top-heavy IMF is necessary (Baller0 et al. 2007).

This letter is structured as follows. In §2 the implications of a bottom-heavy IMF on the chemical evolution and the amount of remnants in massive elliptical galaxies is discussed, while in §3 the chemical evolution model used is presented, along with the results for three choices, using different IMFs. Finally, in §4 the results of this work are discussed.

2 ISSUES FROM A TIME-INDEPENDENT BOTTOM-HEAVY IMF

2.1 Chemical enrichment

One important problem not sufficiently discussed in the literature is that a bottom-heavy IMF, especially as steep as proposed by Ferreras et al. (2013), leads to a severe underproduction of metals in massive galaxies. These systems are known to have solar or even super-solar metallicities (e.g. Trager et al. 2000; Annibali et al. 2007), but an IMF with a power-law index¹ of $\mu = 2.4$ for stars above $1 M_{\odot}$ only results into 10^8 stars more massive than $8 M_{\odot}$ for a galaxy of $10^{11} M_{\odot}$ while a Kroupa (2001) IMF gives 10^9 such stars – a factor of 10 times more. This reduction of the number of massive stars carries severe consequences for the chemical enrichment of the galaxy. For instance, the amount of O^{16} released by massive stars for the $\mu = 2.4$ case, and extrapolating the Nomoto et al. (2006) yields up to stellar masses of $100 M_{\odot}$, results in a 7 times lower than solar oxygen abundance. This is a simple, back-of-the-envelope estimate that can be significantly affected by a process of continuous gas infall and enrichment. In Sec. 3 we discuss in more detail the issue of galactic chemical enrichment by exploring a set of toy models, confirming the inability of a time-independent,

¹ In this letter we use the bimodal IMF proposed by Vazdekis et al. (1996), which consists of a power law, with index μ , for high masses, tapering off to low masses around $0.4 M_{\odot}$. With this function, a $\mu = 1.3$ case is indistinguishable from a Kroupa (2001) or Chabrier (2003) IMF (see, e.g., Fig. 3 of La Barbera et al. 2013).

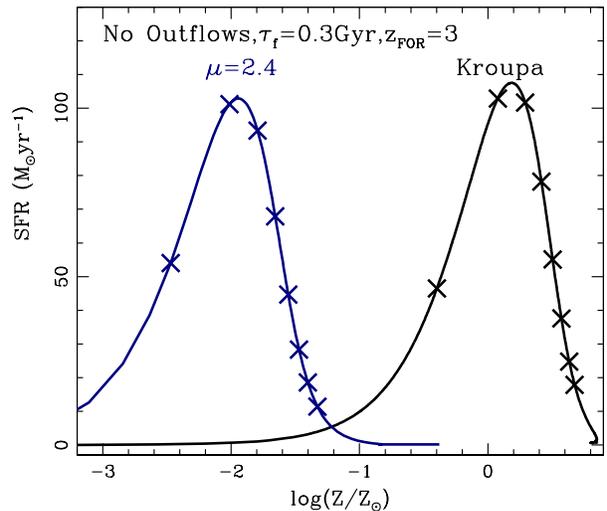


Figure 1. Metal enrichment history and star-formation history for three models assuming a fixed bimodal IMF, and a total stellar mass of $10^{11} M_{\odot}$. In addition to a standard Kroupa (2001) IMF, we include the result for a bimodal IMF (see text for details) that corresponds to early-type galaxies with central velocity dispersion of $\sigma_0 = 200 \text{ km s}^{-1}$ ($\mu = 2.4$), according to the relationship obtained in La Barbera et al. (2013) using a hybrid method combining spectral fitting and targeted line strength analysis. The chemical evolution model has no outflows, with a gas infall time-scale of 0.3 Gyr, and a formation redshift of $z_{\text{FOR}}=3$. The crosses in both models, from left to right, mark ages from 0.25 to 2 Gyr in steps of 0.25 Gyr.

bottom-heavy IMF to explain the metal-rich populations of massive ETGs.

2.2 Stellar remnants

An independent test of the shape of the IMF of massive early-type galaxies comes from the stellar remnants of the population. The assumption of a time-independent, bottom-heavy IMF naturally leads to a low number of low-mass X-ray binaries (LMXB). As these systems consist of a neutron star and a low-mass companion, their number is directly influenced by the lower number of remnants expected from such an IMF.

Studies of LMXBs in elliptical galaxies show that these exotic binaries are not underrepresented in elliptical galaxies. Kim et al. (2009) study three nearby ellipticals with masses of about $10^{11} M_{\odot}$ and find that between 7 and 14% of their globular clusters have LMXB associated with them, and that each galaxy has about 80 to 160 LMXBs in its field population. These numbers compare well with studies of the MW. Grimm et al. (2002) list 15 known LMXBs in 12 MW globular clusters, translating into 8% of 157 known globular clusters of the 2010 edition of the Harris (1996) catalogue of globular clusters. Furthermore, there are about 100 LMXBs known in the field population of the MW. These numbers imply that massive early-type galaxies cannot have a fixed bottom-heavy IMF, as this would lead to much fewer LMXB's than observed (see § 4).

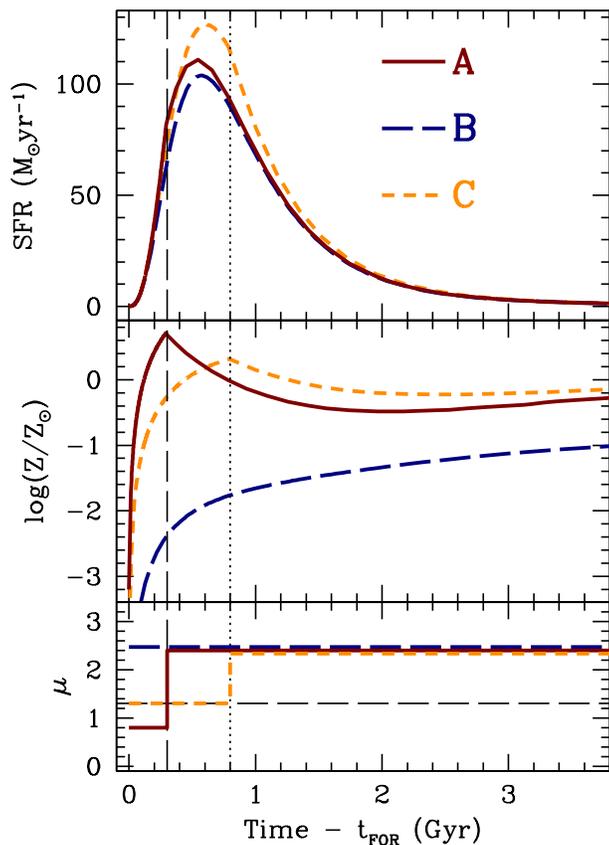


Figure 2. Comparison of three models of chemical enrichment, as described in Tab. 1. All three are chosen to reproduce the age distribution of a massive early-type galaxy (i.e. early formation and narrow distribution of ages to create the old, α -enhanced populations observed in these galaxies). The top panel shows the star formation rate, assuming a total stellar mass of $10^{11} M_{\odot}$. The middle panel tracks the gas-phase metallicity. The bottom panel illustrates the evolution of the slope of the IMF (a bimodal IMF is assumed in all cases, see text for details).

3 TWO-STAGE FORMATION SCENARIO

To address these problems, we make use of a simple modelisation of chemical enrichment as set out in Ferreras & Silk (2000a,b). In essence, the buildup of the stellar component of a galaxy is described by four parameters: a gas infall timescale (τ_f), a star formation efficiency (C_{eff}), that follows a Schmidt law, a formation redshift (z_{FOR}) at which the whole process starts, and a fraction of gas ejected in outflows (B_{out}). We refer the reader to those references for details. For our purposes, we choose the values required to explain the old, metal-rich populations found in massive early-type galaxies: a short infall timescale ($\tau_f = 0.3$ Gyr), an early start ($z_{\text{FOR}} = 3$), a high efficiency ($C_{\text{eff}} = 20$), and negligible outflows ($B_{\text{out}} = 0$). Fig. 1 shows the relationship between the star formation rate and the gas-phase metallicity – giving a direct estimate of the stellar metallicity distribution – assuming a time-independent IMF. Notice that at the high values of μ needed by the line strength analysis of the SDSS massive early-type galaxy data ($\mu \gtrsim 2$,

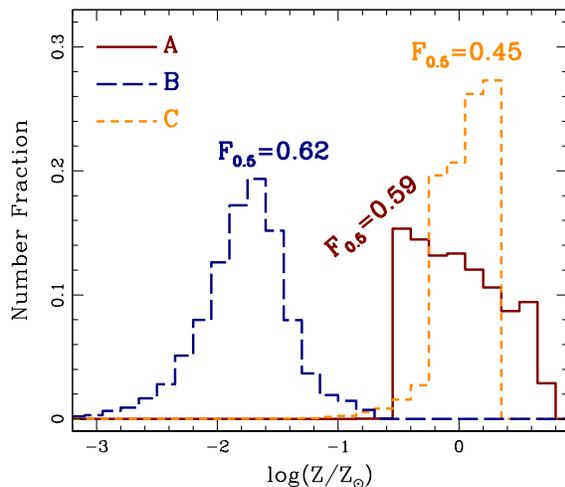


Figure 3. Stellar metallicity distribution corresponding to the three models shown in Fig. 2. The number for each example corresponds to the mass fraction in stars below $0.5 M_{\odot}$.

Ferreras et al. 2013; La Barbera et al. 2013), it is not possible to obtain enough metals to reach the solar/super-solar metallicities found in these galaxies, confirming the simple estimate made in the previous section. Therefore, any model assuming a time-independent IMF is not capable of explaining *both* the metal-rich content and the excess fraction in low-mass stars.

To circumvent this problem, we follow the approach of Vazdekis et al. (1996, 1997), namely invoking a time dependent IMF. We assume that the formation of a massive galaxy starts with a very efficient star formation, quickly achieving high star formation rates, triggering a top-heavy IMF as expected of starbursting systems (Weidner et al. 2011). However, after a period of time, one would expect that the physical conditions of the gas are such that the IMF turns to a bottom-heavy shape. In our toy model, we assume a $\mu = 0.8$ initial slope, followed by a $\mu = 2.4$ distribution after 0.3 Gyr. Figs. 2 and 3 shows that this simple model (red solid lines) is capable of explaining the age and metallicity distribution of a massive ETG, along with a high fraction in low-mass stars. For reference, we also include the bottom-heavy, time-independent case (blue long-dashed lines), and a time-dependent case, where the original distribution follows a Kroupa/Chabrier function (orange short-dashed lines), with the transition to a bottom-heavy IMF occurring at a later time (to allow for the buildup of metallicity to solar levels). Note that all three cases give a very similar star formation history (Fig. 2, top panel), producing the expected old, α -enhanced populations found in massive ETGs (see, e.g. Trager et al. 2000; Thomas et al. 2005; de La Rosa et al. 2011). Tab. 1 gives additional information about these models. The $[\alpha/\text{Fe}]$ values, which are indicators for the length of the star-formation period (Trager et al. 2000), are derived following the relationship between α -enhancement and $T_{M/2}$, defined as the time lapse to form one half of the final stellar mass of the galaxy (see Eq. 2 in de La Rosa et al. 2011). We note that these estimates of $[\alpha/\text{Fe}]$ give a rough approximation, since they are based on a Kroupa IMF, the age distributions are deter-

Model	μ_1	μ_2	Δt_{IMF} Gyr	$\langle \text{Age} \rangle$ Gyr	$\langle \log Z/Z_{\odot} \rangle$	$[\alpha/\text{Fe}]^1$	$F(<0.5M_{\odot})$	M/L SDSS r	# Remnants per star
A	0.8	2.4	0.3	10.29	+0.01	+0.26	0.59	4.93	1/139
B	2.4	2.4	—	10.26	-1.78	+0.26	0.62	2.21	1/2419
C	1.3	2.4	0.8	10.27	+0.03	+0.26	0.45	4.33	1/367

¹ We follow the proxy between the time to form half of the stellar mass and $[\alpha/\text{Fe}]$ from de La Rosa et al. (2011).

Table 1. Properties of the three toy chemical enrichment models shown in Figs. 2 and 3. All models begin at $z_{\text{FOR}} = 3$, with an infall timescale $\tau_f = 0.3$ Gyr, high star formation efficiency ($C_{\text{eff}} = 20$) and no outflows ($B_{\text{out}} = 0$). The parameter Δt_{IMF} is the time lapse when the system has an IMF slope μ_1 , changing abruptly to μ_2 afterwards. The average values of age and metallicity are weighted by the star formation rate.

mined via spectral fitting, and the relationship present a scatter of ~ 0.1 dex. It should also be noted here that the first population only constitutes about 10% of the present-day light of the galaxy (see fig. 21 in Vazdekis et al. 1996) and therefore its weight to the overall galaxy spectral energy distribution is expected to be negligible.

4 DISCUSSION & CONCLUSIONS

The different pieces of observational evidence about the IMF in massive ETGs seem to be conflicting at a first glance. The combination of line-strengths and mass-to-light ratios imply a bottom-heavy IMF (La Barbera et al. 2013; Cappellari et al. 2012). However, the solar or super-solar metallicity of these systems does require at least a Kroupa-like IMF, a result supported as well by the observed number of low-mass X-ray binaries. Although a time-independent, bottom-heavy IMF is clearly in tension with the metal-rich populations, it is necessary to account for the high fraction in low-mass stars observed through the presence of the gravity-sensitive line strengths (Cenarro et al. 2003; van Dokkum & Conroy 2010; Ferreras et al. 2013). In La Barbera et al. (2013), it is estimated that over 50% of the stellar mass created in a massive ETG should be in the form of $\lesssim 0.5 M_{\odot}$ stars. A possible solution, presented in this letter, involves a two-stage galaxy-formation model² with a variation of the IMF. The case of a non-universal IMF has already been considered since the first studies of star formation in galaxies (e.g. Schmidt 1963), and a number of later works have invoked changes in the IMF to explain the properties of elliptical galaxies (see, e.g., Worthey et al. 1992; Elbaz et al. 1995; Vazdekis et al. 1996). This simple two-stage approach serves to illustrate how a time-dependent IMF can explain the different observational data. A more realistic model should assume a smoother transition. However, we note that Omukai et al. (2005) find a very sharp change in the fragmentation behaviour of molecular clouds when considering metallicities above and below $[Z/H] = -5$ which would indicate a rapid change of the power-law index.

In our model, during the first stage, a small fraction ($\sim 10\%$ of the population by mass) form in a very short burst, lasting $\lesssim 0.3$ Gyr, with a top-heavy IMF (Fig. 2, red lines). This first stage is very efficient at building up a

metal-rich ISM, and also results in a high injection of energy from type II supernovae. This process is followed by a second stage where the bulk of the stellar mass is formed in about 1 Gyr, with a bottom-heavy IMF. Although no theory of star formation has been capable so far of explaining the most fundamental properties of the IMF from the physics of the ISM, we can motivate this model, as after a sustained period with a high star formation rate, one would expect that a highly turbulent ISM, with a very high velocity dispersion would be conducive to enhanced fragmentation (Hopkins 2013). Such a scenario is also consistent with the results of Ricciardelli et al. (2012), where a comparison between broadband photometry of SDSS galaxies and a wide Monte Carlo library of synthetic models found very few compatible solutions, often involving a superposition of two old populations with a top-heavy and a bottom-heavy IMF, i.e. similar to our case A. Fig. 3 shows that such a model (red solid line) creates a distribution of metallicities compatible with the observations, and without the low-metallicity tail in the distribution, typical of closed box models with a time-independent IMF. The average metallicities quoted in Tab. 1 for models A and C are compatible with those obtained in the line strength analysis of the most massive ETGs in La Barbera et al. (2013). All three models roughly agree on the mass fraction of the population in stars with mass below $0.5 M_{\odot}$, quoted in Fig. 3 as $F_{0.5}$. A comprehensive analysis of line strengths and spectral fitting (La Barbera et al. 2013) shows that an elliptical galaxy with $\sigma_0 = 200 \text{ km s}^{-1}$ – which is the fiducial case considered here – requires a fraction $\gtrsim 50\%$. Note that models A and C give very similar observational constraints, reflecting an inherent degeneracy between the IMF slope difference of the two phases ($\mu_1 - \mu_2$), and the transition timescale (Δt_{IMF}). Notwithstanding this degeneracy, the purpose of this letter is to prove that the case $\mu_1 = \mu_2$ (i.e. model B) is readily ruled out by the observations. In addition, the low fraction of stellar mass created during the top-heavy stage implies that the M/L of our model (which uses a bimodal IMF) is fully compatible with dynamical mass estimates (see Fig. 21 of La Barbera et al. 2013). It is worth emphasising here that a model with *only* a high star formation efficiency is not capable of explaining all the observational constraints in massive ETGs. A variation of the IMF is a further requirement, as shown in this letter.

Finally, the last column in Tab. 1 shows the expected number of remnants (per star in the galaxy), a quantity directly related to the population of LMXBs. We note that a Kroupa (2001) IMF produces one remnant per 145 stars, a result that is similar to our Model A, whereas a time-independent, bottom-heavy IMF (model B) gives a much

² To avoid confusion, we emphasise that these two stages relate to the early formation of the core of a massive galaxy, and have nothing to do with the two phases of formation of, e.g. Oser et al. (2010), where reference is made to the formation of the core and the outer region of a massive galaxy through cosmic history.

lower number of remnants, in conflict with the observations of LMXBs in massive ETGs.

Note that a theory based on empirical relations exists which allows variations of the galaxy-wide IMF with the star-formation rate of a galaxy – the integrated galactic IMF (IGIMF, Kroupa & Weidner 2003; Weidner & Kroupa 2005; Kroupa et al. 2013). In this letter we extend the original concept of the IGIMF – which uses the star formation rate as a *proxy* of the physical conditions that lead to a change in the IMF – to include the cumulative effect that a previous stage sustaining a high SFR can have on the IMF.

This letter presents strong evidence against the hypothesis of a time-independent, bottom-heavy IMF in massive galaxies. We propose instead a scenario where the observational data can be explained by a two-stage formation process, involving a variation of the IMF during the star formation history of a massive galaxy. Although we currently lack a complete theory of star formation, such a scenario can be motivated by the fact that a sustained high SFR will undoubtedly alter the physical conditions of the interstellar medium, leading to significant differences in the fragmentation process of gas clumps into cores and then stars. The letter is not meant to fully solve the problem but, rather, to give a plausible interpretation that detailed theoretical models of star formation should address.

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