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Constraining the Initial Mass Function of unresolved stellar populations

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Abstract

All studies of unresolved stellar populations rely on a proper characterization of the stellar initial mass function (IMF), i.e. the distribution of stellar masses at birth. Over the past few years, several avenues of research have suggested a systematic variation of the IMF in early-type galaxies, with a departure from the standard IMF in the most massive systems towards both an enhanced contribution from low-mass dwarves (derived from line strength constraints); and an excess of stellar M/L (from galaxy dynamics and gravitational lensing constraints). We present here some of the recent results, focusing on constraints based on spectral line strengths and the consequences derived from galactic chemical enrichment.

1 Introduction

The stellar Initial Mass Function (hereafter IMF) is the mass distribution of stars at birth. Given the dominant dependence of all properties of stellar evolution on mass (Vogt-Russell theorem), the IMF plays a key role in all derivations of physical properties from the observations of unresolved stellar populations. Therefore, the derivation of stellar mass, age, metallicity, chemical composition, returned gas fraction, supenovæ feedback or star formation rates in galaxies strongly depend on an assumption about the IMF.

This contribution is based on a talk focussed on the recent results of our group regarding the constraints on the IMF from the analysis of spectral features that are especially sensitive to the presence of cool, low-mass stars. We also discuss the consequences of the analysis on galactic chemical enrichment, leading to the conclusion that if massive galaxies have a significant excess of low-mass stars, the initial mass function must have undergone a transition during the strong, short-lived and intense episode of star formation that creates the bulk of the stellar mass in these galaxies. This talk does not consider the alternative methods to constrain the IMF based on dynamical modelling or strong gravitational lensing.

2 Looking for low-mass stars in an unresolved population

Aside from a few nearby targets, the vast majority of the stellar populations we can observe in galaxies are unresolved. Therefore, all properties are derived via comparisons with population synthesis models, where the basic ingredients of a stellar population are combined to create "basic" units, called simple stellar populations, that correspond to a set of stars with the same IMF, age and chemical composition. Early-type galaxies (hereafter ETGs) constitute the best candidates for the analysis of stellar populations given their more homogeneous distribution of stellar ages, and the comparatively lower contribution from non-stellar sources to the optical spectra (i.e. from dust and gas), with respect to disc galaxies.

The pioneering studies in this field started over half a century ago with Spinrad's work towards nearby galaxies [33, 34, 35]. The methodology focused on the analysis of specific spectral lines which are predominant in the atmospheres of cool dwarfs, and absent in cool giants –which are the main contributors to the luminosity of an evolved stellar population. These studies proposed a significant contribution from low-mass dwarves in the bulge of M 31 (up to 30% in V-band light), with an implied M/L as high as 44. These studies were followed by many other researchers with mixed results (see, e.g., [13, 5, 12]). In the new millennium, advances in detector technology and better characterization of the spectral line strengths with improved population synthesis models allowed for a revision of this problem, with tentative trends in IMF variations proposed from CaT studies [28, 6], followed by additional gravity-sensitive line strengths in the NIR [37, 29, 30].

Our group took advantage of the enormous spectroscopic dataset provided by the Sloan Digital Sky Survey (SDSS), enabling us to carefully select a large number of high quality spectra from ETGs compiled within the SPIDER survey ([20]), stacking over 24 thousand individual spectra into a reduced set of 18 "über-spectra", classifed as a function of velocity dispersion, which is the zeroth order driver of the properties of stellar populations in galaxies [2]. In a first study [15] we combined this high-quality data set with the latest population synthesis models MIUSCAT ([40], an extension of the MILES models towards redder wavelengths, reaching the CaT region). In Fig. 1 (left) we show one of the trends derived in [21], via a combination of line strengths and spectral fitting. Regardless of the methodology used, we robustly obtained a systematic variation in the IMF slope towards an excess of low-mass stars in galaxies with a higher velocity dispersion. The interpretation of line strengths is complicated by a large number of issues (see next section), which were considered in a more extended paper [21]. Although the translation of the observational data into a systematic variation of the IMF is prone to model biases, we confirmed the robustness of the claim against issues such as [α/Fe] enhancement, individual elemental abundances, or observation-related biases. Our results strongly constrain velocity dispersion (or any indirect proxy) as the main driver of IMF variations. However, we also rule out [α/Fe] as a driver of this trend

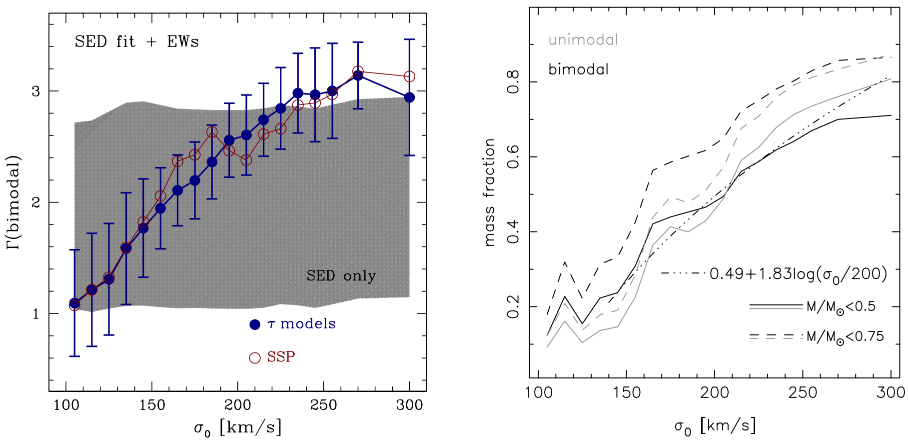

Figure 1: Constraints on the IMF slope from the analysis of gravity-sensitive line strengths. *Left:* trend between IMF slope (assuming a bimodal function) and central velocity dispersion. The grey area illustrates how weakly one can constrain the IMF if a "blind" spectral fit is applied. The points correspond to the analysis where spectral fit and individual gravity-sensitive line strengths are combined to create a joint likelihood. Open and solid dots represent two different parametrizations of the star formation history. *Right:* the constraint via spectral indices mainly affects the mass fraction, at birth, in low-mass stars. This figure shows that irrespective of the functional form used (bimodal vs unimodal), the data suggest higher mass fractions in low-mass stars towards increasing velocity dispersion (adapted from [21]).

(La Barbera et al., submitted), a consistent result with respect to constraints on the IMF based on galaxy dynamics ([4, 32]).

In addition, Fig. 1 (right panel) illustrates that the analysis based on spectral indices of evolved populations can only constrain the relative contribution between cool giants and cool dwarves. This figure shows that the main "observable" in this process is the mass fraction, at birth, in stars below some threshold ($M < 0.5\,\mathrm{M}_\odot$: solid lines, and $M < 0.75\,\mathrm{M}_\odot$: dashed lines). Note that even though two very distinct functional forms of the IMF are used in the figure (unimodal: single power law; bimodal: high-mass end power law tapered to a constant IMF at low masses), the measurements give equally good fits to both, as long as the fraction in low-mass stars is the same. Notice that these two functional forms of the IMF give rise to very different stellar M/L. Therefore, spectral line strength analysis complements (and does not repeat) the constraints based on galaxy dynamics (e.g. [3]) or strong lensing (e.g. [36]).

3 Caveats of the interpretation

The interpretation of the gravity-sensitive line strengths gets complicated because of a number of reasons, most notably:

- Constraining the low-mass end of the IMF relies on being capable of quantifying the

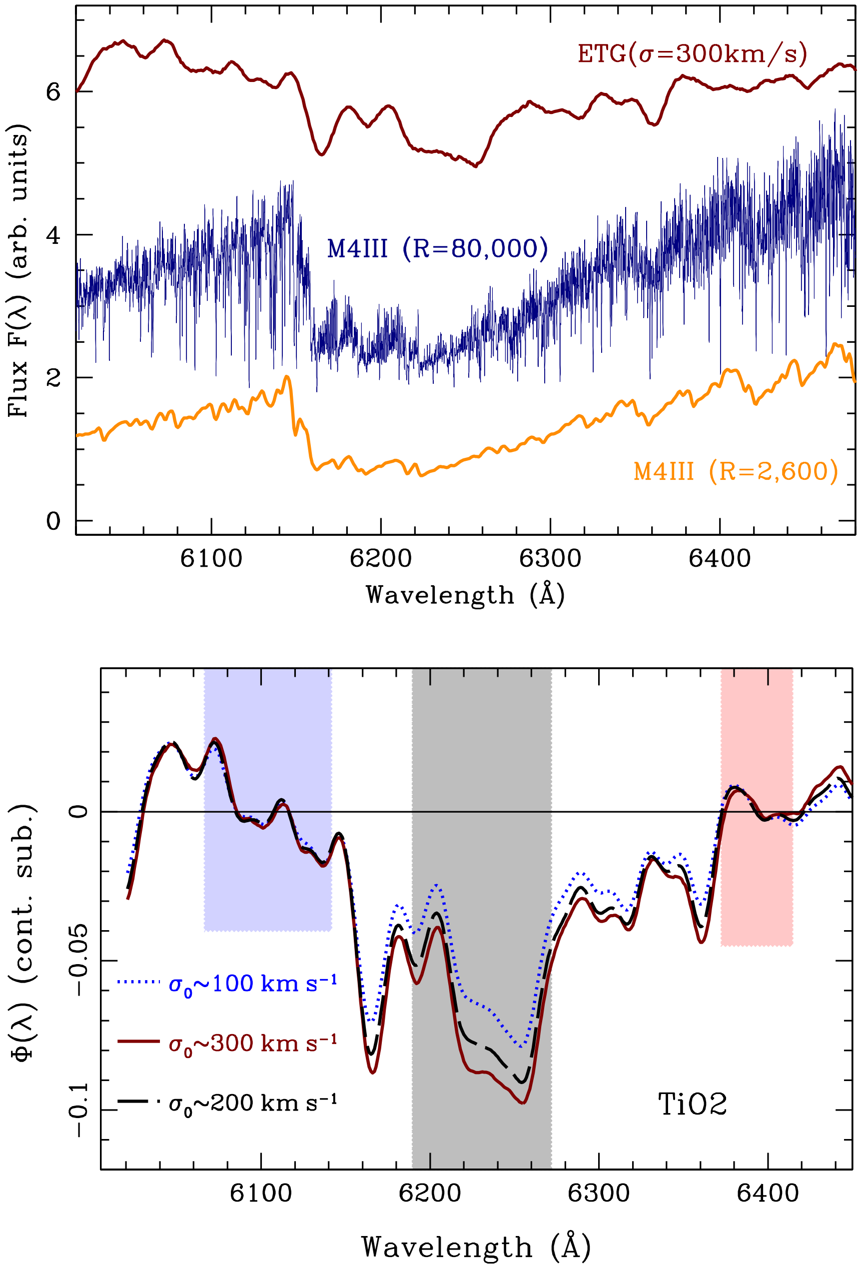

Figure 2: *Top:* The difficulty in extracting stellar population information from low-resolution spectra is apparent in this comparison between the unresolved population of a massive ETG at the resolution of SDSS (top); an M4 giant star at very high resolution (middle, from UVESPOP, [1]); and a similar star at a resolution comparable with SDSS (bottom, from MILES, [27]). The spectral window focuses on the gravity-sensitive TiO2 line strength. *Bottom:* Variation of TiO2 with respect to the velocity dispersion of ETGs from stacked SDSS spectra at high SNR. The shaded regions mark (from left to right) the blue, central and red bandpass from the definition of the index. The SEDs have been smoothed to a common velocity dispersion of 300 km s^{-1} at the spectral resolution of SDSS, and continuum subtracted with a second-order polynomial. Adapted from [15].

contribution (in luminosity) of low-mass dwarf stars in the integrated spectrum of a galaxy. The older, more-homogeneous populations found in massive ETGs make this one a more tractable problem. However, even in this case, the variations in the line strengths expected for a reasonable range of low-mass IMF slopes stays at a few parts in 100.

- These gravity-sensitive line strengths are mostly located in the red part of the spectrum, where sky contamination from airglow, and – most importantly – from telluric absorption, makes the analysis prone to systematics. Our SDSS sample of ETGs allowed us to select those redshift ranges where these effects were minimised. But such an approach is not possible with the stellar libraries used in the population synthesis models.

- The naturally low spectral resolution caused by the velocity dispersion of the stars in massive galaxies causes a severe blending of stellar absorption lines that introduces a degeneracy in the interpretation of the line strengths with respect to other population parameters such as age, metallicity or [α/Fe] (see Fig. 2). Combination of several spectral indices sensitive in different ways to these parameters is essential to break this degeneracy. In addition, the NIR spectral window at $\lambda > 1\mu$m offers new line strengths that will allow us to derive more accurate constraints on the relative contribution from low-mass stars in unresolved populations.

- Individual abundance variations (i.e.changes in the chemical composition of *single* elements with respect to the standard trends of the α- and Fe-group elements) will affect the interpretation of the lines. The targeted absorption lines will be directly affected by the enhancement/depletion of specific elements. In addition, given the blending of stellar absorption lines in a galaxy spectrum, such variations will also affect line strengths for which that specific element is not targeted. Therefore the trends of the line strengths are very difficult to disentangle into simple population-based parameters. A lot of work remains to be done on the modelling side to properly characterize stellar atmospheres in order to correct for these issues.

4 Constraints from galactic chemical enrichment

Systematic variations of the IMF will leave an imprint on galactic chemical enrichment. Although the low-mass end is a relatively “inert” component as far as chemical enrichment is concerned –given the much longer timescales to return gas and metals back into the ISM, low-mass stars lock large fractions of mass with the chemical composition of the gas at their formation time, therefore leaving a signature on the average stellar metallicities. A first analysis of the consequences of the variations found through line strengths was explored in [41], where it was found that such a scenario would produce too many low-mass stars during the first intense, but metal-poor phases of star formation. A time-dependent variation of the IMF was considered instead, so that the first phase would proceed with a top-heavy IMF –reconciling such a scenario in observations of on-going strong star forming systems ([17])–

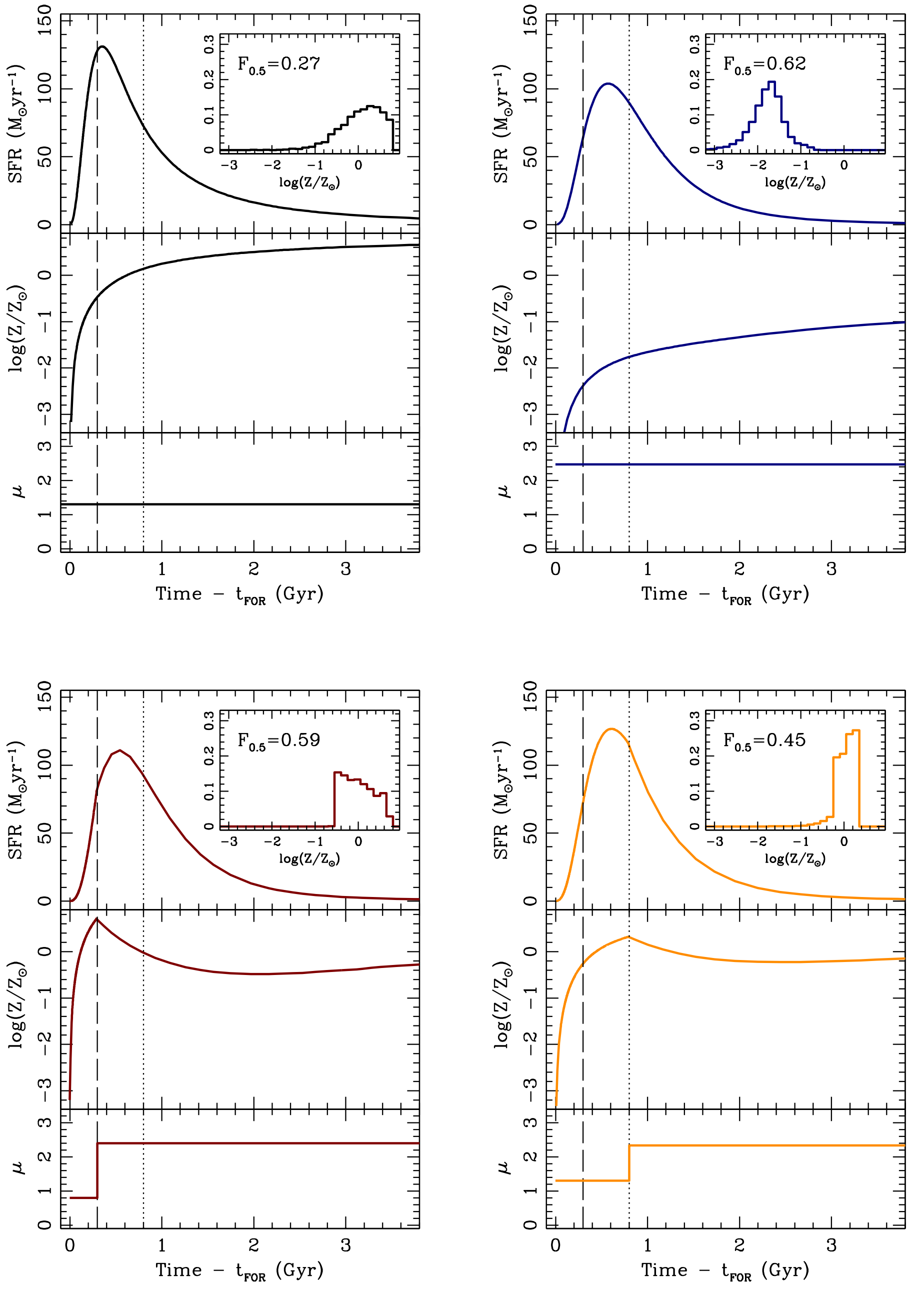

Figure 3: Evolution of the star formation history and chemical enrichment of a population formed during an intense burst at early times –mimicking the formation of a massive early-type galaxy. From top to bottom, the star formation rate, metallicity and IMF slope are shown as a function of time. The inset gives the metallicity distribution in each case, including the average fraction formed in stars with $M < 0.5\,\mathrm{M}_{\odot}$, represented by $F_{0.5}$. Clockwise from top-left, a Kroupa-universal; time-independent bottom-heavy IMF; and two options for a time-dependent IMF are shown. Note that gravity-sensitive line strengths suggest values of $F_{0.5} \gtrsim 0.6$ in massive ETGs. Adapted from [41].

followed by a bottom-heavy IMF that would lock a large fraction of the available gas in low-mass stars, but at the observed metallicities (see also [38, 39]).

In Fig. 3, we illustrate the need for a time-dependent IMF. Each panel shows the evolution of the star formation rate (top) and metallicity (middle) as a function of time. The IMF chosen in each case is shown in the bottom of each panel, parameterized by the IMF slope (μ), assuming a bimodal function (the case $\mu = 1.3$ is close a Kroupa/Chabrier IMF, whereas bottom-heavier IMFs are obtained for $\mu > 1.3$). The insets give the distribution of stellar metallicities. The top-left figure represents a standard, Kroupa/Chabrier-like ([19, 8]), time-invariant IMF. Such a model yields average ages and metallicities compatible with the observations of massive ETGs. However, the fraction in low-mass stars, given in the inset by $F_{0.5}$ –defined as the mass fraction *at birth* in stars with $M < 0.5\,\mathrm{M}_\odot$– is too low with respect to the constraints from gravity-sensitive features (see Fig. 1). The top-right figure assumes a bottom-heavy IMF, which gives compatible values of $F_{0.5}$, but locks too much mass in low-metallicity stars. The two figures in the bottom give alternative options to explain all observational constraints, requiring a change in the IMF. They show a degeneracy between the time scales of IMF variations and the amount of change in the IMF, but they consistently show that some time variation is necessary.

This model was applied recently to a more generic parameterisations of the IMF. The bimodal IMF used by our group (after the definition in [38]) uses a single parameter that affects both the high-mass end and the low-mass end of the IMF. In [16], we applied our chemical enrichment models to the parameterisation of the IMF used by [11], where the high-mass end of the IMF is kept fixed at the Salpeter value down to some pivot mass, and the low-mass end is controlled by an independent power law index. A time-independent IMF is consistently ruled out, even for more general cases where all the low-mass end parameters (i.e. the pivot mass, low-mass slope and low-mass cutoff) are left free.

From the theoretical point of view, the bottom-heavy IMF scenario can be justified by an enhanced process of gas fragmentation under the physical conditions in a strong star forming system. Various authors have explored this issue (see, e.g. [25, 18, 9]), where bottom-heavy mass-functions are expected in a supersonic, highly turbulent interstellar medium. One could envisage that the time-dependence arises from the increasing energy deposition from stellar feedback. If one assumes that in massive galaxies $\sim 10^{11}\,\mathrm{M}_\odot$ in stars are created within $1-2\,\mathrm{Gyr}$ in an intense burst (see e.g. [14]), then such qualitative changes in the physical conditions of the interstellar medium should be expected.

5 The next steps

We emphasize that this paper is biased towards the spectral analysis of stellar populations in massive ETGs. Therefore the steps ahead presented here concern this specific aspect. The solution to this very complicated problem should include similar advances on the dynamical and strong gravitational lensing models and on the numerical simulations of star forming regions under the physical conditions expected during the formation of massive galaxies.

Stellar population models: Unfortunately, all population synthesis models rely on limited sets of empirical stellar libraries. This problem is more acute when dealing with low-temperature giant and dwarf stars. For instance, the MILES stellar library ([27]), that comprises a total of 985 stars, only includes 12 M-type dwarves and 22 M-type giants. In addition, strong telluric absorption in the spectral regions of interest to the analysis of gravity-sensitive features complicates the interpretation of the model predictions. Theoretical modelling of stellar atmospheres is a tremendously difficult task (e.g.[10]), and still stays at a semi-quantitative level, especially concerning the low-temperature stars for which the IMF discriminating power is significant. It will be essential to improve on the stellar library side, extending the analysis to the NIR spectral range, where gravity-sensitive features should be more reliable. In addition, it is important to quantify and understand the effect of a systematic change in the IMF over a large spectral range, where accurate broadband photometry could contribute additional "constraining power" (see, e.g. [26]). Medium band filters will also provide additional tools as they effectively represent low-resolution spectra but with excellent flux calibration, and –with upcoming surveys such as J-PAS (see, e.g. [7])– will comprise a very large number of sources.

Radial variations: The vast majority of the studies have concentrated on integrated measurements, which –given the surface brightness profiles of massive ETGs– are biased towards the very central regions. Spatially resolved measurements of the IMF in massive ETGs are starting to appear ([23]), giving promising hints at the connection between IMF variations and *local* properties such as velocity dispersion, [α/Fe] enhancement or metallicity.

High-redshift galaxies: Massive ETGs have characteristically old, metal-rich populations, suggesting an early, intense and short-lived star formation history. Therefore, we should expect similar properties in the stellar populations of massive galaxies at moderate redshift. A tentative result targeting the TiO bands of massive galaxies at $z \sim 1$ with the WFC3 NIR grisms of HST confirms the trends found at low redshift ([24]). Good quality, high-SNR NIR spectra are required to test this issue in a robust way. In addition, emission line spectra of massive galaxies at $z \sim 2$ will shed light on the high-mass end of the IMF.

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