The intriguing life of massive galaxies
Proceedings IAU Symposium No. 295, 2012
D. Thomas, A. Pasquali & I. Ferreras, eds.

doi:10.1017/S174392131300505X

Stellar Population Models

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Abstract. Modelling stellar populations in galaxies is a key approach to gain knowledge on the still elusive process of galaxy formation as a function of cosmic time. In this review, after a summary of the state-of-art, I discuss three aspects of the modelling, that are particularly relevant to massive galaxies, the focus of this symposium, at low and high-redshift. These are the treatment of the Thermally-Pulsating Asymptotic Giant Branch phase, evidences of an unusual Initial Mass Function, and the effect of modern stellar libraries on the model spectral energy distribution.

Keywords. galaxies: formation; galaxies: evolution; galaxies: high-redshift; galaxies: spiral; galaxies: initial mass function; stars: AGB and post-AGB; stars: atmospheres; stars: carbon.

1. Introduction

Forty years ahead of this Symposium, Beatrice Tinsley (1972) provided the theoretical background for describing the physical properties of populations of stars as functions of relevant parameters, and their evolution with time. The approach she put forward, by exploiting knowledge of stellar evolution, allows the calculation of models which can be evolved with time hence can be used to study the redshift evolution of galaxies. These same models are used to make predictions for galaxy formation (see C. Tonini, this volume).

The stellar populations of galaxies are used as probes of the process of galaxy formation and evolution (see Renzini 2006, and T. Naab and P. Johansson, this volume). Obviously the analysis of stellar populations is based on models, therefore depends on the adopted models and their characteristics. In this review I shall first provide an overview of current models, and highlight results around the most discussed topics, namely the contribution of Asymptotic Giant Branch stars (see also Bruzual, this volume); the latest generation of stellar spectral libraries; the initial mass function of massive galaxies from a population model perspective (see McDermid, Corsini and Renzini, this volume).

2. Overview of stellar population models

Since the pioneering work by Tinsley, much progress has been made on so-called "evolutionary population synthesis" (EPS) models (see Figure 1), thanks to relevant contributions, some of which we list below (see Greggio & Renzini 2011 and Conroy 2013 for reviews). Renzini (1981) introduces analytical relations (the *fuel consumption theorem*) for controlling the energetics of stellar populations. Bruzual (1983) and Bruzual & Charlot (1993, 2003; see G. Bruzual, this volume) propose a convenient approach to population synthesis which exploits isochrones, and made available widely used computer codes. Leitherer *et al.* (1999) focus on the treatment of young massive stars and the effect of their surrounding gas on spectra. Maraston (1998; 2005) extends the *fuel consumption theorem* approach to EPS models and includes a semi-empirical treatment of the

Thermally-Pulsing Asymptotic Giant Branch (TP-AGB) using real Carbon star spectra. Thomas, Maraston & Bender (2003a) calculate comprehensive grids of absorption-lines of EPS models for various element abundance ratios. Conroy, Gunn & White (2009) quantify global uncertainties on EPS models. Conroy & van Dokkum (2012) study the modelling of near-IR lines as a function of the IMF.

The state of the art for the models can be summarised with a few key bullet points.

All major stellar evolutionary phases are now included in the models, but a vivid debate remains on the energetics and spectra of the TP-AGB phase (see Section 3). The latter is relevant to galaxies at high-redshift, and spiral and star forming galaxies at low redshift. It is also important for galaxy formation models (Tonini *et al.* 2009; Monaco & Fontanot 2010; Henriques *et al.* 2011; see Tonini's contribution).

The spectral resolution of models is nowadays optimal in the optical wavelength range (up to 8000 Å) and the ultraviolet, thanks to the advent of several stellar libraries, both empirical (STELIB, Le Borgne *et al.* 2003; ELODIE, Prugniel *et al.* 2007; MILES, Sánchez-Blázquez *et al.* 2006) and theoretical (Rodriguez-Merino *et al.* 2005; Gustfaffson *et al.* 2008), with a resolution as high as 0.1 Å. Several EPS engines have incorporated one or more of these libraries in their modelling, starting with Bruzual & Charlot (2003, based on STELIB); Pegase-HR (based on ELODIE); Vazdekis *et al.* (2010, based on MILES); Maraston & Strömback (2011), which use them all.

Thanks to the same stellar spectral libraries, models of absorption lines with variable abundance-ratios are now flux-calibrated (Thomas, Maraston, Johansson 2011; see Johansson's contribution), which, by being freed of the standard star calibration required to match the Lick index system, allows the use of these models to study galaxies at high-redshift.

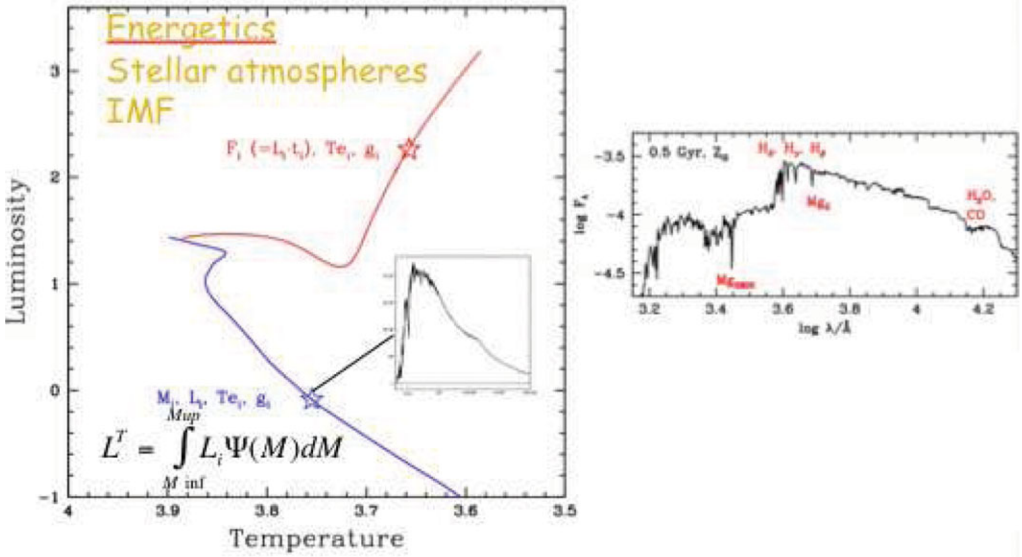

Figure 1. Sketch of evolutionary population synthesis modelling. *Left-hand panel* A theoretical HR diagram reproduced up to the tip of the RGB, with highlighted MS and post-MS stellar phase (blue and red, respectively). In order to obtain the integrated spectral energy distribution (*right-hand panel*) an integral either by mass or using the *fuel consumption theorem* is performed, on the luminosity-weighted stellar spectra (small inset). Models have three main ingredients, the energetics, the stellar spectra and the IMF.

3. The (infamous) TP-AGB

A lively debate arose around the treatment of this evolutionary phase in EPS models since Maraston (1998) pointed out that, if a sizeable TP-AGB contribution is present around $t \sim 1$ Gyr as suggested by studies in Magellanic Clouds star clusters available at the time (Frogel, Mould & Blanco 1990), this would have a strong impact on EPS models, especially in the rest-frame near-IR. Maraston (1998) develops a method to model the contribution of the TP-AGB phase using available data and the fuel consumption theorem. Maraston (2005) extends these models to the description of the full spectral energy distribution, by using real spectra of Carbon and Oxygen-rich TP-AGB stars (Lancón & Mouhcine 2002). When compared to other EPS models (Bruzual & Charlot 2003, Pegase, Starburst99) the Maraston models are substantially redder longward $\sim$ 6000 Å rest-frame and exhibit marked spectral features by Carbon stars.

As we shall discuss below, the comparison with observations is providing a sort of conflicting evidence. But before commenting on the observational evidence, let us explain why this evolutionary phase has gained so much attention and why the modelling is so complicated.

The answer to the first question is that this is a very luminous stellar phase that provides substantial contribution to the bolometric of the model. The answer to the second question is that the theoretical stellar evolution is complicated because these are dynamically unstable stellar configurations in double-shell burning (Iben & Renzini 1983).

There are some facts on which presumably everyone would agree. Firstly, the TP-AGB cannot be fully modelled via first principles because of strong (and poorly known) mass loss affecting stellar evolution during this phase. The theoretical energetic must then be calibrated with data (Maraston 1998, 2005; Marigo & Girardi 2007). Secondly, TP-AGB stars are very cool ($T_{\rm eff} < 3500$ K) and the modelling of their spectral energy distribution, which is an ingredient of integrated models, is complicated, and result in just a few model realisations. Again here, a solution is to use stellar spectra from observations (Maraston 2005; Conroy, Gunn & White 2009).

What is a matter of choice among different authors is how the calibration is accomplished, and which data are used.

Maraston (1998; 2005) put forward the approach of using globular clusters (GCs) in the Magellanic Clouds, assuming their integrated colours are comparable to those of Simple Stellar Population (SSP) models, which are instantaneous bursts with homogeneous chemical composition†. This method is also adopted in Conroy & Gunn (2010). Two are the important assumptions here: i) the adopted ages of the GCs; ii) the observed integrated spectrophotometry.

Marigo & Girardi (2007), Marigo *et al.* (2008) and Bruzual (see Bruzual's talk) use instead resolved AGB stars in the Magellanic Clouds and compare their luminosity function with models with extended star formation histories. Here the crucial assumptions are: i) the star formation history of the Clouds and their metallicity distributions; ii) the photometric data, as before.

Let us now see how the results of the different procedures compare. Figure 2 shows the results of different EPS model calibrations. The left-hand panel shows the calibration of the bolometric contribution of the AGB phase with Magellanic Clouds clusters by Maraston (1998). According to this calibration, the phase onsets at about ~ 0.3 Gyr, peaks at ~ 1 Gyr and then decreases in importance at older ages. This result, and the related EPS models, are obviously completely dependent on the ages assumed for the

† The validity of approximating GCs to SSPs has been questioned in recent years

GCs, which in turn depend on the adopted stellar models and method used to derive them (e.g. Main Sequence turnoff fitting, Colour Magnitude Diagram fitting, integrated colour model matching). The results of Maraston (1998) were based on the age calibration by Frogel *et al.* (1990), in turn based on stellar models without inclusion of overshooting. These so-called *classic* tracks were also input to the Maraston's models, hence the procedure was self-consistent, though it may be now obsolete.

Marigo *et al.* (2008) (central panel) perform their calibration using resolved stellar populations. However, the resulting models (their model $V-K$ is the magenta line in the central panel of Figure 2) behave quite similarly to Maraston's models (dashed blue lines in the same figure). A slight shift in age (~ 0.3 Gyr) is evident between the Marigo *et al.* and the Maraston models, which is due to the different adopted age scale. Marigo *et al.* use ages derived with tracks including overshooting, which implies longer timescales on the Main Sequence, hence older ages.

Conroy & Gunn (2010) perform a similar model calibration as Maraston and Marigo, but adopt an age-scale that pushes Magellanic Clouds GCs to even older ages (right-hand panel in Figure 2). Furthermore, they adopt GCs colour data binned in age with a rather coarse age binning. This has the effect of diluting the AGB phase-transition. In the Conroy & Gunn re-calibration of the TP-AGB phase, the Maraston's models appear to be much off the data, but one should notice that the data have been pushed towards the right of the age scale. These and other differences, such as the adopted photometry, explain most part of the offset between the models (see Noell *et al.* 2013, *submitted*).

One may conclude that, in light of more recent GCs age determinations and photometry, the Maraston (2005) models have too a strong contribution from the TP-AGB phase. Zibetti *et al.* (2013) reach the same conclusions as Conroy & Gunn (2010), using post-starburst galaxies, following Lancón *et al.* (1999)'s suggestions that these are the optimal calibrators of the AGB phase.

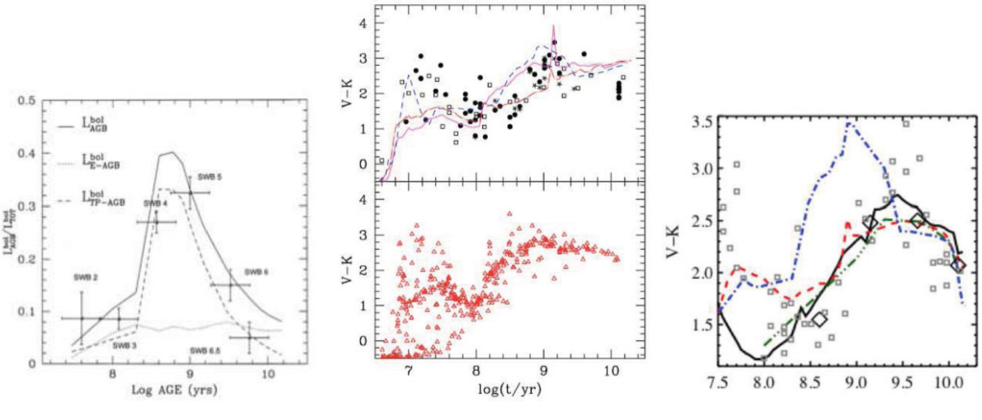

Figure 2. Calibration(s) of the TP-AGB phase for EPS models. *Left-hand panel.* Calibration of the bolometric contribution (split into E-AGB and TP-AGB, short and long-dashed) with Magellanic Clouds clusters (points with errorbars). The observed contribution is an average over clusters with similar ages, performed in order to minimise stochastic fluctuations due to the shortness of the AGB phase ($1-4$ Myr). From Maraston (1998). *Central panel.* Calibration of the integrated $V-K$ model colour with Magellanic Clouds clusters (points with errorbars). Models are constrained using resolved stars rather than GCs, but the net result is similar to the one from Maraston. From Marigo *et al.* (2008). *Right-hand panel* As in central panel, but note the shift towards older ages of most data (the x-axis shows ages as $\log t/yr$). From Conroy & Gunn (2010). All calibrations are obviously strongly dependent on the assumed ages for the star clusters.

The situation remains unsettled, however. Bruzual (this volume, see arXiv:1212.5381) comparing the Bruzual & Charlot (2003) models with resolved AGB stars in the Magellanic Clouds conclude, consistently with Marigo *et al.* (2008) that the BC03 models under-predict their LF, in other words these models do not contain enough TP-AGB.

Post-starburst (post-SB) galaxies in the local universe probably have only a small fraction of their stellar mass at the relevant ages, and this mass contribution could scatter between galaxies. Indeed, the integrated near-IR colours of the post-SB galaxies used in Conroy & Gunn (2010) and in Zibetti *et al.* (2013) seem to be quite different. This intrinsic variation, plus uncertainties in their star formation histories do not make post-SB galaxies such ideal calibrators. For example, Zibetti *et al.* succeed at modelling post-SB galaxies with BC03 models but using single-burst rather than composite models (see Figure 3), which appears contrived.

A more stringent test is represented by massive galaxies at high-redshifts ($z \sim 2-3$), where a larger fraction of stellar mass could be in the relevant age range. Comparisons using these galaxies suggested models more similar to Maraston (2005) with a substantial TP-AGB contribution. This has been widely discussed in the literature, therefore we focus here on a type of comparison which is relatively new. This uses near-IR data of spiral galaxies in the local universe, in which star formation is ongoing and must have produced at least a fraction of TP-AGB stars. MacArthur *et al.* (2010) can only fit optical and near-IR colours of these galaxies using M05 models, as the colours of other models are too blue.

Riffel *et al.* (2013, *in preparation*) perform spectral fitting in the near-IR of a massive local spiral using different models (see Figure 4 and 5).

The M05 models give a very good fit to the near-IR spectrum (Figure 4, left-hand plot), consistent with a broad age distribution, from $\sim 10^8$ to $\sim 10^{10}$ (Figure 4, right-hand plot, middle panel), which is sensible given the age spread of stars expected to be present in a spiral. When the same fit is performed with M05 models not including any TP-AGB (Figure 5, left-hand plots for the sole solar metallicity), the fits degrade substantially. Moreover, the derived age distribution is now stretched towards old ages, a solution which is obviously an artefact. When fitting with BC03 models and a range in

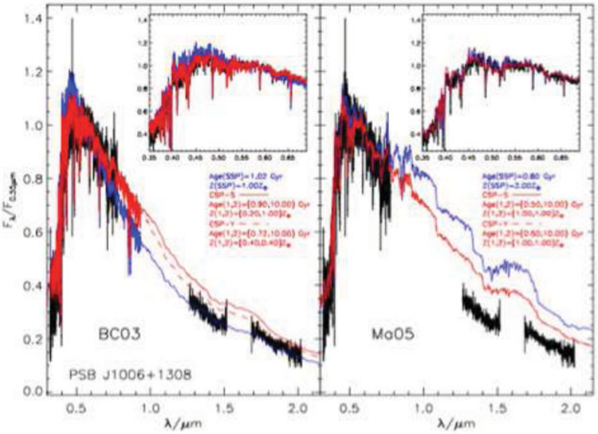

Figure 3. Spectral fitting of post-SB galaxies by Zibetti *et al.* (2013), using BC03 and M05 models (left-hand and right-hand panels, respectively), with single-burst (red) and composite (blue) models. The best fit to the whole optical plus near-IR fluxes is achieved with BC03 SSP models, though the optical fit is not very satisfactory (insets in both panels) and is better with M05 models. From Zibetti *et al.* (2013), see discussion therein.

metallicity (Figure 5, right-hand plots), the fitting improves thanks to the high metallicity components (though it is not as good as with the TP-AGB stars, see Fig. 4). However, the derived ages are still only the old ones.

In conclusion, the question whether the TP-AGB should be as strong as in the M05 or as weak as in the BC03 models has not yet been given a satisfactory answer, with local GCs and post-SB galaxies favouring BC03, and high-redshift and spiral galaxies favouring M05. Work is in progress by all of us now and the question will possibly get a consistent answer in the near future.

4. Modern spectral libraries and high-resolution models

As mentioned in the Introduction, most stellar population synthesis models have now been upgraded to a high spectral resolution, thanks to the advent of a multiplicity of stellar libraries, both empirical and theoretical. The former in particular contain now a sufficient number of stars in the various evolutionary phases which leads to sensible models, though they are still mostly defined in the optical range. Let us just recall the pros and cons of the two approaches. Empirical libraries contain spectra of real stars, but have a pattern of abundance ratios which reflect the chemical history of the Milky Way as a function of total metallicity. Thomas, Maraston & Bender (2003a) correct for such *bias* analytically, for obtaining models which can be applied to distant galaxies, where the chemical pattern is unknown and has to be determined with these models. Another limitation is that TP-AGB Carbon stars are usually not included, nor are Bulge old and $[\alpha/Fe]$-enhanced stars.

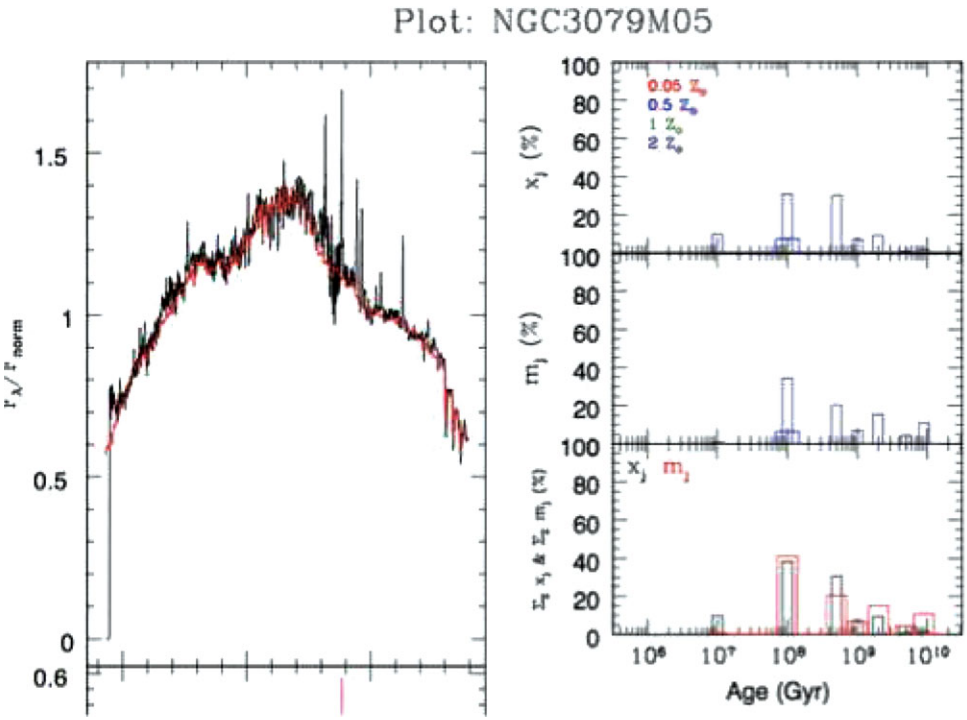

Figure 4. Spectral fitting of the near-IR spectrum of a massive spiral. *Left-hand panel.* Model fitting using M05 models. The spectrum is very well fitted. *Right-hand panel.* Derived age distribution (middle panel), which spans ages from 10^8 yr to 10 Gyr.

Theoretical libraries span an arbitrarily large parameter space in temperature. gravity and metallicity, but suffer from incomplete line list (Korn *et al.* 2005). Maraston & Strömback (2011) calculate stellar population models for a variety of empirical libraries and theoretical libraries, and we refer to this work for comprehensive discussion and comparisons. Here we briefly stress the fact that the theoretical SEDs of population models depend on the adopted library (Figure 6, *left-hand panel*) and in principle the choice of the library, along with the assumed stellar evolution, may affect the resulting galaxy evolution which is deduced from spectral fitting of data. The case is shown in Figure 6 (*right-hand panel*, from Wilkinson *et al.*, *in preparation*), who derive spectral fitting ages of galaxies from the SDSS-III/BOSS survey, using Maraston's models based on different spectral libraries. Older ages are obtained using models based on the MILES library with respect to models based on the STELIB library, which was the backbone of galaxy evolution results obtained with the SDSS-I and II data through the BC03 models. That MILES-based models imply the derivation of older ages was found in Maraston & Strömback (2011) when fitting the Milky Way GC M67.

Again we like to stress how galaxy evolution results depend on the adopted population modes. Works as Wilkinson *et al.* will be important for understanding the effect of population model ingredients on the physical properties of galaxies derived from high-resolution spectral fitting.

5. The evergreen case for a non universal IMF: effect of population models

The Initial Mass Function (IMF) is a mere parameter of population models, and can be included using arbitrary assumptions. On the other hand, the actual IMF is a crucial parameter of our understanding of gas and gravitation physics, telling us how a gas cloud breaks into individual stars and the efficiency of stellar feedback. The IMF assumed in the models is also the important quantity to determine stellar masses and deduce the amount of dark matter (see Cappellari, McDermid and Spiniello *this volume*). The physics around this parameter is complicated, hence we usually rely on empirical determinations of the IMF (or, better said the present mass function) in local fields and star clusters. However, several works have attempted to a *direct* determination of the IMF in distant galaxies. In particular, the past couple of years have witnessed a *revival* of a case for a non-universal IMF, in particular for a bottom-heavy IMF in massive elliptical galaxies. These results

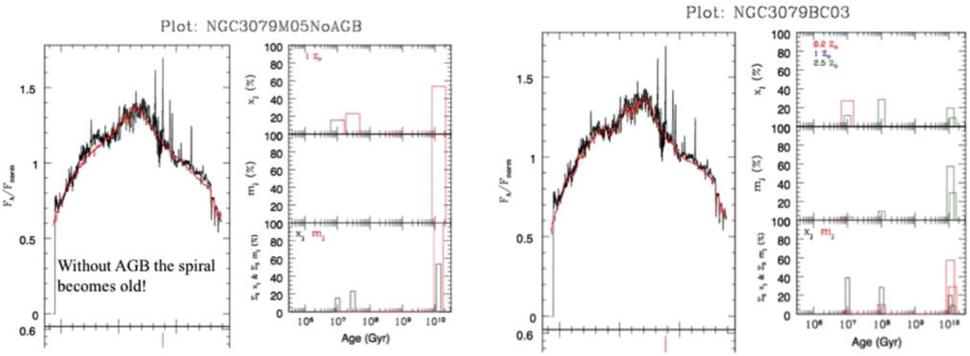

Figure 5. As in Figure 4, but using models with no TP-AGB (M05notp, *left-hand panel*) or with a reduced contribution, but several metallicities (BC03, *right-hand panel*). The spectral fitting degrades and the age distribution shows only old ages, which is clearly a model artefact.

are of two kinds. They can be based on comparing luminous M^*/L to dynamical M/L, or on identifying spectral features sensitive to the IMF and performing spectral fitting (Ferreras *et al.*, this volume). In both cases the results depend on the population models, but more strongly and directly in the second approach. Hence, we briefly summarise recent findings based on spectral fitting and leave to Renzini (this volume) to comment extensively on both cases.

About ten years ago, Saglia *et al.* (2002) (Figure 7, *lower panel*) report the puzzling result that the near-IR calcium triplet (CaT) index observed in massive galaxies cannot be reproduced by population models, unless assuming a substantial steepening of the power-slope exponent of the IMF (~ 3.5, when the Salpeter's one is 2.35), toward the massive end of the galaxy population. Though Thomas, Maraston, Bender (2003b) discuss possible alternatives such as a depressed Calcium abundance, we are still lacking a robust explanation for the mismatch. Maraston *et al.* (2003) show that in order to match the magnesium vs iron indices of massive galaxies without invoking a substantial $[\alpha/Fe]$-enhancement (which is the accepted solution based on comparison with star clusters, same paper), requires again an exponent as steep as 4 (in the same Salpeter's notation). Recently, van Dokkum & Conroy (2010) resume the near-IR indices introduced in the '70s and other near-IR features, including the CaT, to argue for a dwarf-dominated IMF in massive local ellipticals (Figure 7, *upper panel*). Spectral features in the near-IR are sensitive to gravity, hence are sensitive to the stellar dwarf-to-giant ratio, which depends on the assumed IMF. On the other hand, these same features are also sensitive to other population parameters, such as the element abundance ratios, the total metallicity and also the age composition of the stellar populations. These intricate model dependencies are discussed at length in Conroy & van Dokkum (2012), and more work in this direction will be beneficial to isolate the actual usable features and assess whether there is a steepening of the IMF with increasing galaxy mass.

In fact, the Wing-Ford band which was supposed to be highly sensitive to the dwarf end of the IMF, does not appear to depend much on the galaxy velocity dispersion (Figure 8, upper plot, central panel) within the same galaxies (black points) from which Cappellari *et al.* detect a dwarf-dominated IMF from dynamical considerations.

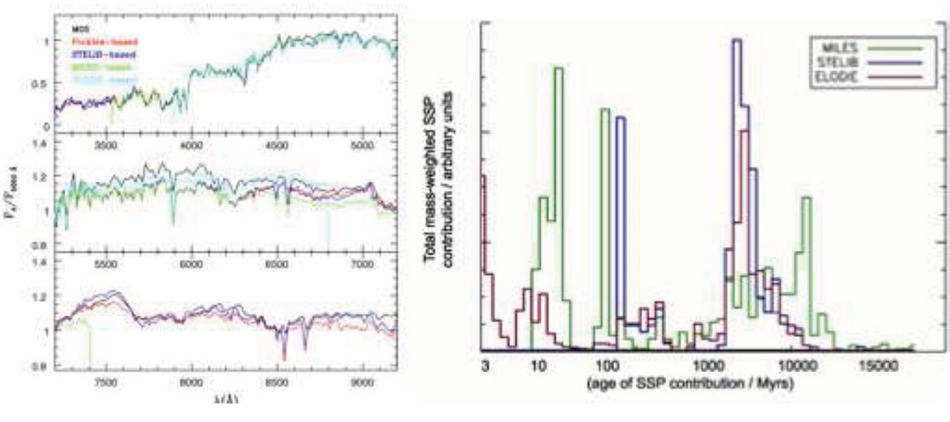

Figure 6. *Left-hand panel* Spectrum of a 12 Gyr old stellar population model obtained using different spectral libraries as input. From Maraston & Strömback 2011. *Right-hand panel* Galaxy ages derived using Maraston models based on different spectral libraries, from Wilkinson *et al.* (2013, *in preparation*).

As a final remark, one would like to note that the IMF result depends on stellar population models with high metallicity, where the ingredient stellar models and model atmospheres are most uncertain due to the paucity of local calibrators.

6. Conclusive remarks.

This review summarises current achievements in stellar population modelling, with particular reference to massive galaxies, the protagonists of this symposium.

Massive galaxies have strong Spitzer fluxes at high-z that can be interpreted when models include a sizeable contribution by AGB stars. The same result is found for near-IR spectra of local massive spirals. Other classes of galaxies suggest a low contribution from these advanced stellar phases, which is a challenge to the models and perhaps also to our understanding of their star formation histories. Over the last couple of years, several pieces of evidence have been collected in favour of a dwarf-dominated IMF in local massive early-types. At the same time, galaxy formation models need to assume a top-heavy IMF for modelling EROS and sub-millimetre galaxies, which may be the progenitors of the local massive galaxies which should instead host a dwarf-rich IMF. A firm definition of all these exciting suggestions will require even more sophisticated stellar population models than the already high standard at disposal nowadays. In conjunction,

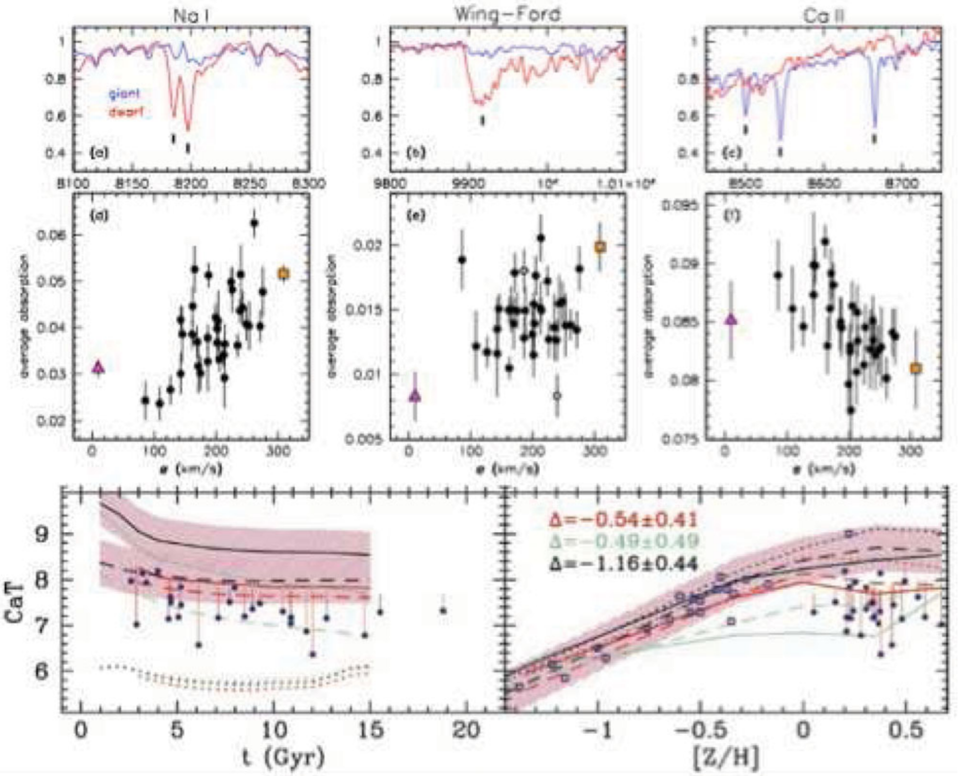

Figure 7. Evidence of a bottom-heavy IMF in massive early-type galaxies. *Lower panel.* The puzzlingly low CaT index of massive ellipticals can only be matched invoking a dwarf dominated IMF, or a Calcium underabundance (Thomas, Maraston, Bender 2003b). From Saglia *et al.* (2002). *Upper panel.* Other near-IR features and again the CaT, from van Dokkum & Conroy 2012. We note that the value of the Wing-Ford band (central panel) does not seem to depend much on the galaxy velocity dispersion within the Sauron galaxies (black-points).

observational data in the near-IR, where both AGB giant stars and dwarf Main Sequence stars leave their fingerprints, are fundamental and quite difficult to obtain, but technology is rapidly catching up. This symposium has clearly been a landmark to our knowledge on massive galaxies, which has stimulated our fantasy and pointed the most interesting directions for future research.

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