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Models of stellar population at high redshift, as constrained by PN yields and luminosity function

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Abstract. The stellar phase of Thermally-Pulsating Asymptotic giant branch is the last major evolutionary stage of intermediate-mass stars which afterwards evolve into planetary nebulae. The TP-AGB phase is affected by mass-loss and instabilities which notoriously make its theoretical modelling uncertain. This review focuses on the effects such modelling has on stellar population models for galaxies, with particular focus on the high-z Universe where galaxies are young and contain a large number of short-living TP-AGB stars. I shall present the models, discuss how different prescriptions for the treatment of the TP-AGB affect the theoretical integrated spectral energy distribution and how these compare to galaxy data, and discuss implications for the PN nebulae luminosity function stemming from the various assumptions. Finally I shall discuss the inclusion of hot evolved stars on stellar population models and how they compare to data for old galaxies at our present time.

Keywords. stars: AGB and post-AGB, stars: carbon, galaxies: high-redshift, galaxies: evolution

1. Introduction

Stellar population models (e.g. Maraston 1998, hereafter M98; Bruzual & Charlot 2003, hereafter BC03; Maraston 2005, hereafter M05) are the tool to derive the physical properties of real galaxies from data, or predict them in conjunction with galaxy formation models. Stellar population models are based on stellar evolution and models for stellar atmospheres and as such are affected by the same uncertainties that are inherent to these basic theories. These uncertainties are related to the three main unknowns, mass-loss, convection (in the core or the envelope), and line-list and opacities especially for cold stars. These processes which mostly affect post-Main sequence phases of stellar evolution, lack a robust prediction from first principles. As such, their effect needs to be assessed using empirical data. For integrated stellar populations a constructive approach is to use nearby stellar systems whose parameters age and metallicity are known independently of the stellar population model predictions (Renzini & Fusi Pecci 1989; M98, M05). These checks and comparisons are particularly needed for short evolved stellar phases. The Thermally-Pulsating Asymptotic Giant Branch (TP-AGB) is notoriously the most complicated to model, due to the concomitance of strong mass-loss, double shell burning and dynamical pulsation, and low temperatures, which hamper the detailed prediction of energetic and effective temperature evolution (besides the chemical yields, for a discussion of which I refer to P. Ventura, *this volume*). On the other hand, the TP-AGB is a very luminous phase in intermediate-age stellar populations ($t \sim 1$ Gyr, M98; M05). It has even been shown to affect the understanding of the spectral energy distributions of high-redshift galaxies observed by the Spitzer Space Telescope (Maraston *et al.* 2006).

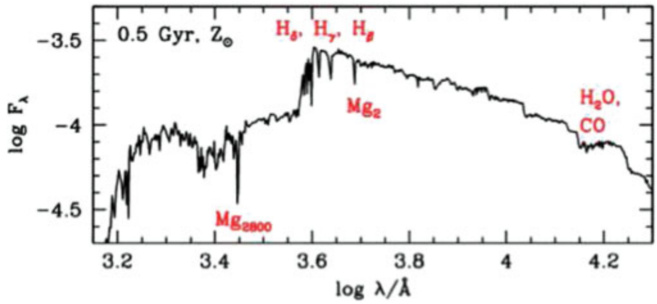

Figure 1. Theoretical SED of a 0.5 Gyr old simple stellar population (SSP) model with solar metallicity, adapted from M05. The spectral features in the near-IR in these models are due to the contribution of cold Carbon stars evolving through the TP-AGB phase.

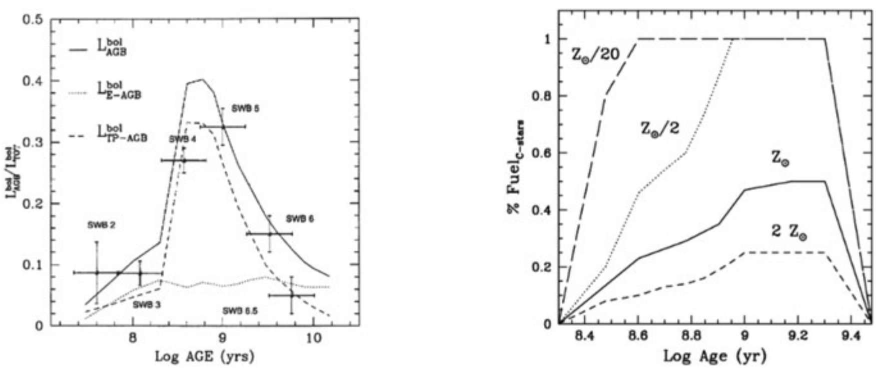

Figure 2. *Left-hand panel.* From M98: Calibration of the bolometric contribution of the TP-AGB phase for SP models (lines) with star clusters data (symbols with errors). *Right-hand panel* From M05: Dependence of metallicity on the TP-AGB fuel consumption.

The TP-AGB is the phase just before the envelope ejection and the planetary nebula phase, which is the main player of this Focus Meeting. In this review I will try and connect our knowledge of the energetic and colours of this phase as constrained by massive galaxies in order to gain clues on the subsequent planetary nebulae phase. At the end of the contribution I shall jump to old stellar populations and discuss the contribution by old and hot stars, which may be preceeding or concomitant to a planetary nebulae phase, to the near-IR H_α emission of old stellar populations. The paper is organised as follows. After a brief overview of stellar population (SP) models, I shall present results of models to data comparison for high-redshift galaxies and discuss the current debate in the literature. I shall conclude with describing models for emission in old galaxies as a signature of Post-AGB stars.

2. Stellar Population models in a nutshell

Stellar population (SP) models describe the integrated properties, e.g. the spectral energy distribution, the total stellar mass M^*, the mass in stellar remnants (see M98), the mass-to-light M/L ratio, of a population of stars with defined properties in terms of age and chemical composition, and their time evolution. These models target unresolved stellar populations such as galaxies and extra-galactic star clusters. The first definition

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of this type of models dates back to the pioneeristic work by Beatrice Tinsley (e.g. Tinsley 1972). State-of-art renditions of these models benefit from the enormous progress made in stellar evolution and model atmosphere calculations over the past thirty years. A few conundra remain, however, which directly impact on our capability of predicting on a full theoretical basis the energetic and spectra of short evolved phases affected by mass-loss. The most striking examples of these are: the Thermally-Pulsating Asymptotic Giant Branch (TP-AGB) which is a cold ($T_{eff} < 5000$ K) stellar phase with a major contribution at stellar masses around $M \sim 3 - 2\ M_{\odot}$, which translates into stellar population ages of $0.5 - 2$ Gyr; hot post-AGB phases emerging in old ($t >$ few Gyr) stellar populations, which include Planetary Nebulae, Hot Horizontal Branch (HHB), AGB-manque′ (Greggio & Renzini 1990). For the modelling of both phases, a useful approach is based on the so-called *fuel consumption theorem* (FCT, see M98 and references therein). This relates the energetics of post Main Sequence (post-MS) stellar phases to the *fuel* available to that phase. The fuel is the energetic involved in the particular stellar stage, and is related to the amount of Hydrogen and/or Helium (in $M_{\odot}$) available to burn.

3. Models with TP-AGB and high-redshift galaxies

Using the FCT M98 calculated the first SP models including a semi-empirical TP-AGB phase. The fuel calculated from theoretical tracks was calibrated using the observed bolometric contribution of the TP-AGB phase in Magellanic Clouds clusters (from Frogel, Mould & Blanco 1990). This procedure allows the account for mass-loss effects which are automatically included in the observed data. M05 extended those calculations in order to include the effect of the TP-AGB phase in the total spectral energy distribution. This required the use of spectra appropriate to stellar types evolving through the TP-AGB, typically Carbon and Oxygen-rich stars. These spectra are complicated to model due to the very low temperatures involved. M05 used empirical spectra (Lancón & Mouhcine 2002). In order to calculate SP models for different metallicities, M05 included a metallicity dependance in the fuel consumption following the theoretical expectations by Renzini & Voli (1981) (Fig. 2, *right-hand panel*), which sees an increasing production of C-stars with decreasing metallicity. This trend is qualitatively confirmed by observations of planetary nebulae in metal-poor galaxies by Stanghellini *et al.* (2007).

These models are constructed with what were believed to be the best prescriptions for energetics, stellar spectra and theoretical knowledge about the metallicity dependance. They are obviously not perfect. For example, while the metallicity scaling of the fuel is likely to be correct, metallicity effects on the stellar spectra are not accounted for, as the same sample of Milky Way stars is used, although the fraction of C/O stars included in the integrated SP SED does vary with Z. Also, another important factor to note is that, as Figure 2 (*left-hand panel*) shows, the ages relevant to the TP-AGB phase development are locked to those of Magellanic Cloud clusters, which in turn depend on the stellar models used to derive them. We shall return to this point below.

The resulting SP spectra were markedly different from other SP models from the literature (Figure 18 of M05 and Figure 3 below) at the ages relevant to the TP-AGB in the models: the inclusion of luminous red TP-AGB stars increased the flux emitted longward $\sim$ 6000 Å and reveal deep absorption bands due to the cold C,O stars.

In spite of all the caveats one may envisage, several papers (van der Wel *et al.* 2005, Maraston *et al.* 2006, Cimatti *et al.* 2008, see Figure 3) find the M05 models to match the SEDs of galaxies at high-z ($z \sim 2 - 3$) better than models with a lower contribution

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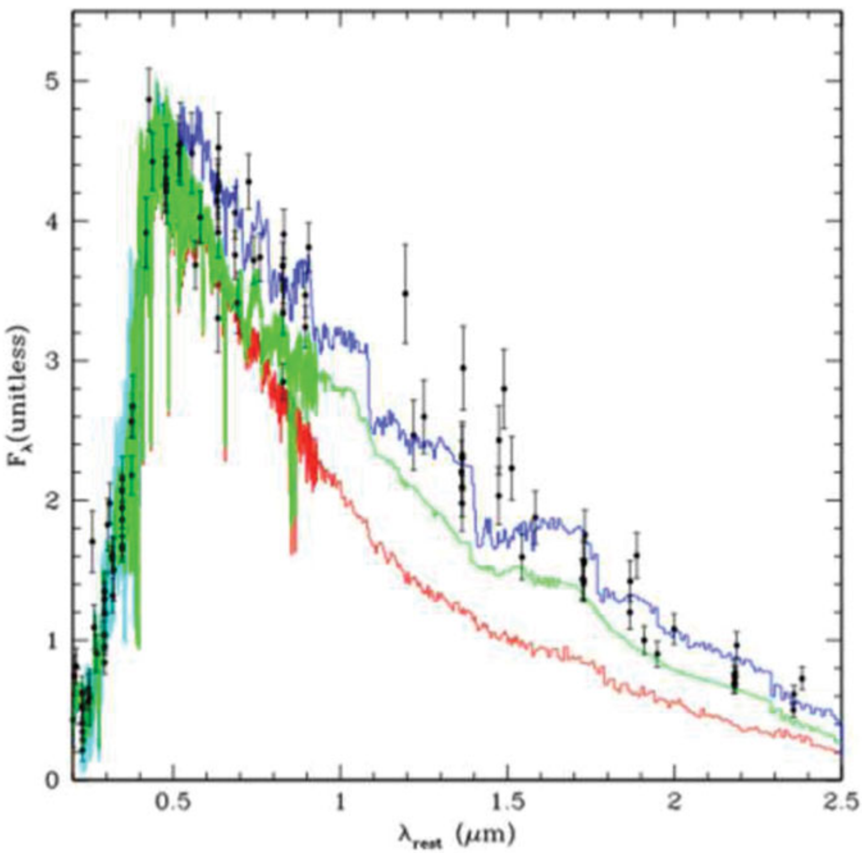

Figure 3. Comparison between data of $z \sim 2$ galaxies (symbols with errorbars) with SP models, by M05 (blue lines), BC03 (red lines) and an unpublished version of BC models with an intermediate TP-AGB contribution (green). The data clearly point to high near-IR rest-frame fluxes, which are naturally explained by the cold TP-AGB stars of the M05 models. From Cimatti *et al.* (2008).

from the TP-AGB phase (compare blue lines, M05 models, with red and green lines in Figure 3).

Recently, Conroy & Gunn (2010) questioned the validity of the Maraston's calibration. Using a mix of newer or newly combined data for Magellanic Clouds GCs and a new age scale for the observed clusters, they conclude that the M05 models are too red, in other words contain too much TP-AGB, at early ages. The BC03 models with their low TP-AGB are found to fit their re-calibration better (see Figure 3, *right-hand panel*). Kriek *et al.* (2010) report a similar result for high-z galaxies.

In the context of this Focus Meeting it should be noted that such a late TP-AGB onset would imply a late appearance of planetary nebulae, which does not seem to be the case (see R. Ciardullo, *this volume*). Noëll *et al.* (2013) re-analyse the re-calibration of Conroy & Gunn (2010) and using a compilation of the most recent and as homogeneous as possible, ages for Magellanic Clouds GCs, could not reproduce the late onset of the TP-AGB argued by Conroy & Gunn. They confirm instead the early calibration by M98, that the TP-AGB phase rises quite abruptly around 1 Gyr of age of a stellar population (Figure 3, *right-hand panel*).

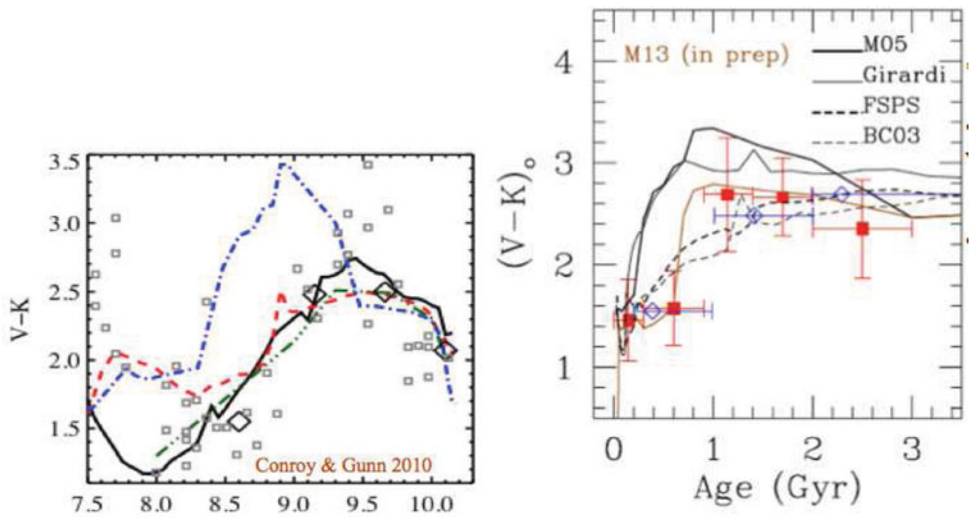

Figure 4. *Left-hand panel.* Re-calibration of the TP-AGB for SP models by Conroy & Gunn (2010), using the $V-K$ colour of stellar population models as indicator. Plotted towards their revised age scale, the M05 models (blue line) appear mis-calibrated. The BC03 models are shown as red lines. Large diamonds are averages of Magellanic Clouds GCs data. *Right-hand panel.* Re-calibration of the Conroy & Gunn's re-calibration by Noëll *et al.* (2013). The early results of M98, namely the onset of the TP-AGB as a sharp transition around 1 Gyr of age, are confirmed.

Capozzi *et al.* (2015) using the largest sample of high-z galaxies with spectroscopic redshifts confirm the early results, namely that a strong TP-AGB as in the M05 models fit the data better.

4. H_α emission in old galaxies

After the completion of the TP-AGB, stars venture into the PN phase, or generically into the post-AGB phase. In this section we explore whether models based on the fuel consumption incorporating a description of post-AGB phases are able to explain the low-ionization H_α line in emission observed in quiescent early type galaxies (e.g. Cid-Fernandes *et al.* 2011; Yan & Blanton 2012). The observed emission cannot be attributed to a low-power AGN or ongoing star formation, rather these authors explored the possibility that hot stars from the resident old populations (e.g. post-AGB) could be ionizing the gas.

We have revisited the case and calculated models based on the fuel consumption varying the two pretty much unconstrained parameters affecting the P-AGB modelling, namely the fuel and the effective temperature. Figure 5, *left-hand panel* displays the resulting SEDs of SP models, with different colours referring to different amount of fuel (in $M_\odot$) burned at the same temperature of 25,000 K. The magenta-coloured model is calculated for a higher temperature (40,000 K). As expected, all models display a UV upturn, whose onset wavelength and intensity depends on these parameters. How to choose among these? Our option is to use a model that match the typical UV upturn observed in elliptical galaxies (Maraston & Thomas 2000), which is shown as the magenta and cyan lines in Figure 5. These models release an H_α emission around 2 Å ($\log H_\alpha \sim 0.3$), which is exactly what is observed in SDSS quiescent galaxies (R. Yan, *private communication*). The content of this section will be published in a future paper.

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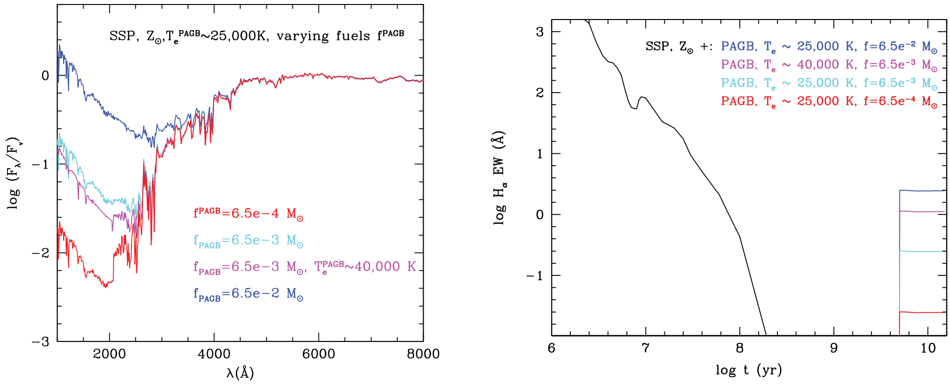

Figure 5. *Left-hand panel.* Model SEDs with different fuel and temperature for the P-AGB phase. *Right-hand panel* Predicted H_α emission from the models shown in the left-hand panel. Models are identical at young ages (solid black lines).

5. Conclusions

A proper description of late evolutionary stages in stellar population models requires the calibration of free parameters with data. Both stellar clusters and massive galaxies are useful in this respect. The modelling of the TP-AGB phase, which preceeds the Planetary Nebulae phase, strongly affects galaxy evolution and, unlike PN, leaves a clear signature on galaxy spectra.Models based on the fuel consumption theorem can successfully reproduce the spectra of $z \sim 2$ as well as $z \sim 0$ galaxies. The TP-AGB phase should last $\sim$ 1 Myr, consume 0.2-0.3 Msun of fuel, onset at 0.3 Gyr and peak at 1 Gyr. Later onset ages ($t \sim 3$ Gyr) as recently suggested (Conroy & Gunn 2010) seem in contradiction with data.

In old galaxies, a direct signature of P-AGB evolution is mild H_α emission. Again using the fuel consumption theorem, we calculated models that are able to match the observed strength of H_α in SDSS galaxies and the observed UV upturn at the same time.

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