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MODEL STARS FOR THE MODELLING OF GALAXIES: α-ENHANCEMENT IN STELLAR POPULATIONS MODELS

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RESUMEN

Los modelos de poblaciones estelares (SP) constituyen una herramienta esencial para estudiar las observaciones de galaxias y cúmulos estelares. Uno de los principales ingredientes de un modelo SP es una biblioteca de espectros estelares. Tanto bibliotecas empíricas como teóricas pueden ser utilizadas para tal fin. En este artículo hago un breve resumen de los pros y los contras de utilizar las bibliotecas teóricas, i.e. modelos de estrellas, para producir los modelos de galaxias, y discuto como estas bibliotecas pueden ser utilizadas para modelar poblaciones estelares, en particular, para explorar el efecto del incremento de la abundancia de los elementos-α en las observables espectrales.

ABSTRACT

Stellar population (SP) models are an essential tool to understand the observations of galaxies and clusters. One of the main ingredients of a SP model is a library of stellar spectra, and both empirical and theoretical libraries can been used for this purpose. Here I will start by giving a short overview of the pros and cons of using theoretical libraries, i.e. model stars, to produce our galaxy models. Then I will address the question on how theoretical libraries can be used to model stellar populations, in particular to explore the effect of α-enhancement on spectral observables.

Key Words: galaxies: abundances — galaxies: stellar content — stars: abundances — stars: atmospheres

1. INTRODUCTION

To understand how galaxies form and evolve is one of the long-standing questions in astronomy. One of the ways to address that question is to study the stellar content of the galaxies through the use of stellar population (SP) synthesis techniques, i.e., the modelling of the spectral energy distribution (SED) emitted by evolving stellar populations (see Tinsley 1980). An evolutionary SP model has two main ingredients: a set of stellar evolutionary models (tracks or isochrones) that will predict how the stars are distributed in the HR diagram, and a library of stellar observables (e.g. colours, spectra, spectral indices, etc.) that coupled to the evolutionary models, will be used to predict the colours or spectra of a stellar population. By computing models for several choices of SP parameters (age t, metallicity Z, initial mass function *IMF*, etc.), it is possible to produce a grid of SP models that can be used to study a variety of systems, from early-type galaxies and spiral bulges to star forming galaxies at different redshifts.

A keystone to extract the star formation history *SFH* of unresolved stellar systems is through the analysis of their chemical abundance pattern. The chemical pattern is a tracer of the history of star formation because different elements are produced at different timescales during the evolution of a galaxy (e.g. Greggio & Renzini 1983, Matteucci & Greggio 1986). In fact, the α-elements over Fe abundances ([α/Fe]) is largely used to constraint the formation timescale of a galaxy, since the α-elements (O, Ne, Mg, Si, S, Ca, and Ti) are released early in the evolution of the galaxy by Type II supernovae (SNe II), while Fe is mainly produced by Type Ia supernovae (SNe Ia) on longer time-scales. Galaxies that had undergone rapid star formation present [α/Fe] values larger than the ratios found in the Milky Way disc, reason why SP models built with stars of the solar neighbourhood cannot reproduce the locus of more massive galaxies in Mg versus Fe indices plots (e.g. Worthey, faber, & Gonzalez 1992). Therefore, large efforts have being made by different groups in computing SP models with different [α/Fe]. I will focus on the role that the theoretical stellar spectra computations have in modelling populations with different [α/Fe].

2. THEORETICAL STELLAR LIBRARIES

The library of stellar spectra used in the SP models can be either empirical or theoretical, a choice which is subject to debate. There are plenty of models in the literature using both empirical (e.g.

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Vazdekis 1999; the visible range of Bruzual & Charlot 2003 and Le Borgne et al. 2004) or theoretical libraries (e.g. UV and IR range of Bruzual & Charlot 2003; Delgado et al. 2005; Maraston 2005; Zhang et al. 2005). An empirical library is based on observed stellar spectra covering as much as possible the parameters $T_{\rm eff}$, $\log g$, Z. It is not a simple task to assemble a library that simultaneously features high S/N, good flux calibration, large wavelength coverage, high-resolution and accurately derived stellar parameters, but great improvements have been made (e.g. Prugniel & Soubiran 2001; Valdes et al. 2004; Sánchez-Blázquez et al. 2006). The major drawback of an empirical library is that such high quality observations are limited to the closest stars, and therefore the coverage of the HR diagram and the stellar abundances are biased towards the solar neighbourhood.

A theoretical stellar library (also called synthetic stellar library) is based on model atmospheres and atomic and molecular line lists. A *model atmosphere* is the run of temperature, gas, electron and radiation pressure, convective velocity and flux, and more generally, of all relevant quantities as a function of some depth variable (geometrical, or optical depth at some special frequency, or column mass). The *synthetic spectrum*, or *flux distribution* is the emergent flux computed based on a model atmosphere, and is required for comparison with observations. Theoretical libraries have the advantadge of covering the parameter space in $T_{\rm eff}$, $\log g$, and abundances at will. Moreover, a synthetic star has very-well defined atmospheric parameters and infinite S/N, and covers a larger wavelength coverage with (possibly) higher resolution than a single observed spectrum. To compute a large synthetic library can be demanding in terms of computational time, but it is usually feasible. There is a caveat though: being based on our knowledge on stellar atmospheres and databases of atomic and molecular transitions, those libraries are limited by the approximations and (in)accuracies of their underlying models, and in fact we are not able to reproduce accurately all spectral types (see e.g. Gustafsson et al. 2007). There is a lot to be done yet in terms of including in a realistic way effects of 3D hydrodynamics, asphericity, N-LTE, winds, non-radiative heating, chromospheric contribution, etc. Moreover, the databases of atomic and molecular transitions provide relatively few lines with highly accurate oscillator strengths and broadening parameters, besides being often incomplete (see the progress report by Kurucz 2006). An additional point of confusion for the SP modeller (and user) is that theoretical libraries can be categorised into two groups:

- libraries computed with a good treatment of the line-blanketing, therefore being good for spectrophotometric predictions and low-resolution studies (e.g. Castelli & Kurucz 2003; Gustafsson et al. 2003; Brott & Hauschildt 2005);
- libraries which are computed with shorter, fine-tuned, empirically calibrated atomic and molecular line lists, being the ones more appropriate for high-resolution studies (e.g. Peterson, Dorman, & Rood 2001; Rodríguez-Merino et al. 2005; Coelho et al. 2005). But in general they are not suitable to predict colours due to missing line-blanketing.

The ability of some of the recent theoretical libraries in reproducing observations was recently assessed in Martins & Coelho (2007). Concerning the libraries for low-resolution studies, broad-band colours predictions by three libraries were compared to an empirical $UBVRIJHK$ calibration. Models can reproduce with reasonable accuracy the stellar colours for a fair interval in effective temperatures and gravities, but there are some problems with $U-B$ and $B-V$ colours and very cool stars in general ($V-K \gtrsim 3$). The results for the $B-V$ and $V-I$ colours are illustrated in Figure 1. As for the libraries aimed at high-resolution studies, Martins & Coelho (2007) analysed the performance of three libraries by comparing their predictions for spectral indices to measurements given by empirical libraries. Figure 2 shows the results for three indices against the empirical library MILES (Sánchez-Blázquez et al. 2006). In general the libraries present similar behaviours and systematic deviations. In particular, the lists of atomic and molecular lines need further improvement, specially in the blue region of the spectrum and for the stars with $T_{\rm eff} \lesssim 4500$ K.

3. INCLUDING α-ENHANCEMENT EFFECTS IN STELLAR POPULATION MODELS

As mentioned in the Introduction, the spectra of the stars carry the chemical signatures that are imprints of the SFH of the galaxy they belong to. Hence, and despite the current limitations of the theoretical libraries as mentioned in § 2, we cannot rely solely on the empirical libraries if we intend to reproduce the spectra of galaxies which have undergone a star formation different from that of the solar neighbourhood. In fact, there is more than one way of computing SP models with variable [α/Fe] values.

3.1. *The first SP models with non-solar patterns*

The first attempts to model SPs beyond the solar-scaled pattern date back to mid-90s. Barbuy

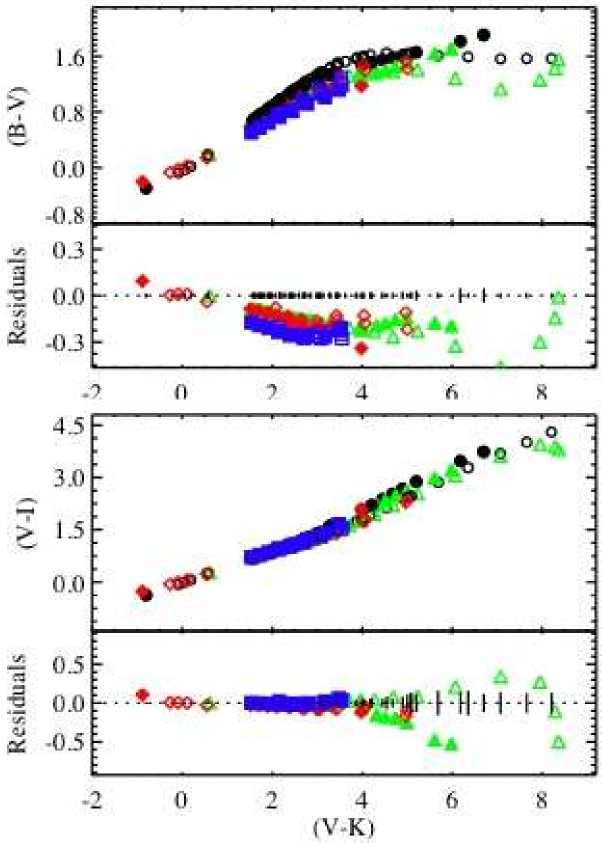

Fig. 1. Comparison between the colours predicted by synthetic flux distributions and the colour-temperature relation by Worthey & Lee (2006), for stars representative of a 10 Gyr population. Red-diamonds correspond to ATLAS9 (Castelli & Kurucz 2003), green-triangles to PHOENIX (Brott & Hauschildt 2005) and the blue squares to MARCS models (Gustafsson et al. 2003). Filled and open symbols represent dwarf and giant stars respectively. Filled black-circles are the values expected from the empirical relation. The bottom of each colour plot shows the residuals (difference between models predictions and empirical calibration; the thin black vertical lines are the error bars of the empirical calibration). Adapted from Martins & Coelho (2007).

(1994) used synthetic stellar spectra to predict the Mg_2 index for ages and abundances typical of those of bulge globular clusters. Weiss, Peletier, & Matteucci (1995), using observed spectra of bulge stars and for the first time including α-enhanced evolutionary tracks for a high metallicity population, computed models for Mg_2 and <Fe> indices. Alternatively to the use of spectra, Borges et al. (1995) adopted empirical fitting functions[2] with explicit de-

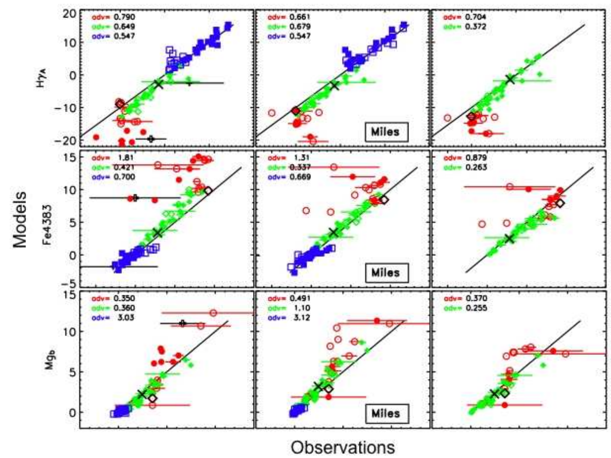

Fig. 2. Comparison between the predictions of three synthetic libraries in the y-axis (Martins et al. 2005 in the left-hand column; Munari et al. 2005 in the middle colum; Coelho et al. 2005 in the right-hand column) and indices measured in the MILES empirical library in the x-axis, for three spectral indices indicated in the figure. Blue squares are stars with $T_{\rm eff} < 7000$K, green diamonds for $4500\text{K} < T_{\rm eff} \leq 7000$K and red circles for $T_{\rm eff} \leq 4500$K (filled and open symbols are dwarf and giant stars respectively). The solid line is the one-to-one relation. The thick black symbols represent a Sun-like dwarf (diamond) and an Arcturus-like giant (cross). Adapted from Martins & Coelho (2007).

pendence on [Mg/Fe] or [Na/Fe] to model SP indices with variable Fe, Mg and Na abundances. Other authors further explored the conclusions and methods of the pioneer efforts, e.g., Idiart et al. (1996); Vazdekis et al. (1997); Tantalo, Chiosi, & Bressan (1998). Those first models were limited to a few indices or to a restricted range of SP parameters.

3.2. *Fitting functions & Sensitivity tables*

The study by Tripicco & Bell (1995) opened a way to produce non-solar-scaled models for *all* the Lick/IDS indices. Based on synthetic spectra calculations, they quantified how each of the Lick/IDS indices changes with variations of individual chemical elements. These *sensitivity tables* (also called *response functions*), were computed for three combinations of $T_{\rm eff}$ and $\log g$, which correspond to a main-sequence dwarf, a turn-off star and a red-giant star of a 5 Gyr-old stellar population.

By combining empirical and theoretical information, Trager et al. (2000) proposed a method to use the sensitivity tables by Tripicco & Bell (1995) to apply corrections to the empirical fitting functions

[2]The *fitting functions* describe how stellar spectral indices vary as a function of the stellar parameters $T_{\rm eff}$, $\log g$, [Fe/H] or [Z/H] and sometimes, abundance [X/Fe] of another element relative to iron.

by Worthey et al. (1994), in order to produce SP model indices with arbitrary compositions[3]. The method was extended by Thomas, Maraston, & Bender (2003) who published a large set of SP models for all Lick/IDS indices and variable values of [α/Fe], [α/Ca] and [α/N]. Until the present time, this technique is the most widely used to model SPs indices with variable abundances patterns, and both model indices and ingredients (sensitivity tables and fitting functions) are constantly updated (e.g. Houdashelt et al. 2002; Tantalo & Chiosi 2004; Korn, Maraston, & Thomas 2005; Lee & Worthey 2005; Annibali et al. 2007; Martín-Hernández et al. 2007; Schiavon 2007).

Important advancements in our knowledge of the chemical composition of galaxies have been achieved through the use of those models (e.g. Kuntschner et al. 2001; Proctor & Sansom 2002; Proctor, Forbes, & Beasley 2004; Thomas et al. 2005; Kelson et al. 2006; Smith et al. 2006; de la Rosa et al. 2007). Nevertheless this approach is subject to some limitations:

- the responses of three synthetic stars are used to correct all stars in an SP model and the impact of this approximation in the accuracy of the model predictions is uncertain;
- only Lick/IDS indices can be modelled, and full-spectrum high-resolution models remain constrained to the solar neighbourhood chemical pattern;
- the effect of the abundance variations on the isochrones is often not included in a consistent way.

3.3. *Fully theoretical approach*

Recent progress in the modelling of high-resolution stellar spectra opened the door to a new kind of models, in which the effects of abundance variations can be studied at any wavelength. This is enabled by the publication of several libraries of theoretical, high-resolution stellar spectra for both solar-scaled and α-enhanced chemical mixtures (Brott & Hauschildt 2005; Coelho et al. 2005; Munari et al. 2005).

The first fully theoretical high-resolution SP models for an α-enhanced mixture were presented in Coelho et al. (2007), who used an improved version of the stellar library in Coelho et al. (2005) to compute SP models for solar-scaled and α-enhanced compositions for three values of iron abundance [Fe/H] and ages from 3 to 14 Gyrs. These models employ newly computed stellar tracks (Weiss, Ferguson, & Salaris 2007) with the same abundances as the stellar library. For the α-enhanced mixture it is adopted a flat-enhancement of 0.4 dex for the abundance ratios of all the classical α elements (O, Mg, Si, S, Ca and Ti). The impact of the spectral and evolutionary effects is illustrated on the Figures 3 and 4 for broad-band colours and spectral indices, respectively. The modelling of colours requires that both effects are taken into account, as they often have comparable effects. As for the spectral indices, the spectral effect is overall the dominant one, but the evolutionary effect can be non-negligible (e.g. Balmer indices and near-IR indices).

Another theoretical study at high-resolution is being developed by Lee et al. (2007, in prep.), based on the stellar evolutionary tracks by Dotter et al. (2007) and with the flexibility to explore the effect of abundance variations in an element-by-element basis.

The fully-theoretical method has the advantage of providing a larger coverage in wavelength at higher resolution than the methods in § 3.2, and of providing more accurate predictions given that the effect of the α-enhancement on the stellar evolutionary tracks and spectral library is included in a consistent way. The caveat of this approach is that given the limitations of the synthetic libraries mentioned in § 2, these models are more affected by zero-point problems than semi-empirical methods. Hence they are not a straightforward replacement for the models based on empirical libraries, being more suitable to differential analysis[4].

3.4. *Spectral corrections*

There is ongoing work that aims at combining the versatility of the method in § 3.3 in terms of exploring wider wavelength ranges at higher resolution, and the accuracy of SP models based on empirical libraries. Similarly to using response functions to correct indices given by fitting functions, theoretical stellar libraries can be used to differentially correct SP models based on empirical libraries. To my knowledge, there are two groups working on this approach. Prugniel et al. (2007) recently used the theoretical library by Coelho et al. (2005) to differentially correct the stars of the empirical library ELODIE (Prugniel & Soubiran 2001). Two 'semi-empirical' libraries were produced with [Mg/Fe] =

[3]Alternatively, theoretical fitting functions with explicit dependence on α/Fe (Barbuy et al. 2003) can be employed to compute α-enhanced models (Mendes de Oliveira et al. 2005), but the theoretical fitting functions were limited to a few Lick/IDS indices.

[4]For interesting work on deriving the stellar population parameters in a differential way, avoiding zero-point problems that affect both models and data see, e.g. Nelan et al. (2005); Kelson et al. (2006).

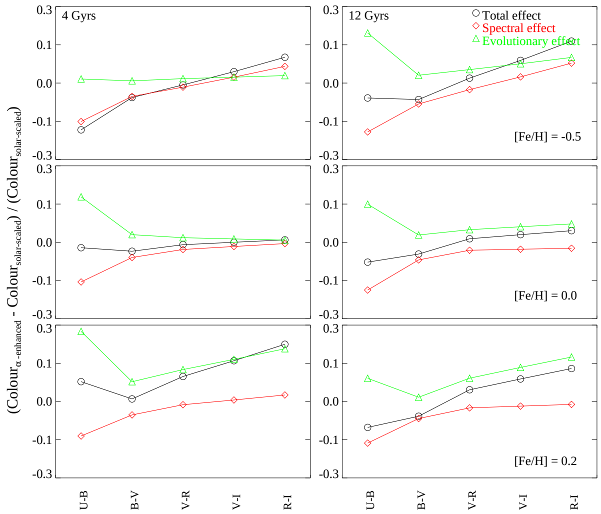

Fig. 3. Differences between the α-enhanced predictions and the solar-scaled ones, in units of the solar-scaled value, for broad-band colours shown on x-axis. Each row corresponds to a different [Fe/H] value, indicated in the figure. Left- and righ-hand columns show the predictions for 4 Gyr and 12 Gyr SSPs respectively. The green-triangles and red-diamonds lines correspond to the evolutionary effect and spectral effects respectively. The black-circles line are the predictions when both effects are considered together. From Coelho et al. (2007).

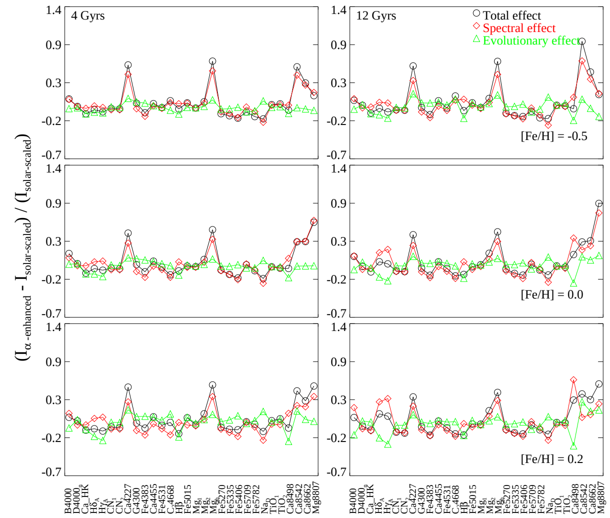

Fig. 4. Differences between the α-enhanced predictions and the solar-scaled ones, in units of the solar-scaled value, for several spectral indices shown on x-axis. Each row corresponds to a different [Fe/H] indicated in the figure. Left- and right-hand columns show the predictions for 4 Gyr and 12 Gyr SSPs, respectively. The green-triangles and red-diamonds lines correspond to the evolutionary effect and spectral effects respectively. The black-circles line are the predictions when both effects are considered together. From Coelho et al. (2007).

0.0 and +0.4, and intermediate values were linearly interpolated as a function of the mass ratio of Mg to Fe. This semi-empirical library can then be used to build SP models with variable [Mg/Fe]. Alternatively, the correction to the α-enhanced pattern can be applied *a posteriori*: SP models computed with theoretical stars are used to differentially modify SP models based on the empirical library. An application of this method was presented in Cervantes et al. (2007), using newly computed theoretical stars to correct SP models based on the MILES library (Vazdekis et al., in prep.).

4. CONCLUDING REMARKS

Considerable efforts have being applied in the modelling of SP models with variable chemical patterns. Following the pioneer efforts mentioned in § 3.1, the models that combined fitting functions and sensitivity tables (§ 3.2) were a breakthrough, and they had an important impact on our knowledge of the abundances in galaxies derived by spectral indices. Recently, fully-theoretical models (§ 3.3) started to fill a gap which existed among the full spectral high-resolution SP models, providing ways of modelling a much larger number of observables and including spectral and evolutionary effects in a consistent way. And there are other methods being developed nowadays, like the empirical corrections mentioned in § 3.4. Each of the methods has its strong and weak points and we can expect future improvements in all of them. I think that there is not a 'best' approach. The user of stellar population models should choose the model family that best suits his/her application, always keeping in mind the weakness and strengths of each approach. But we can be certain of one thing: one way or another, we do need model stars in our galaxy models.

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