Testing the accuracy of synthetic stellar libraries

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\textbf{ABSTRACT}

One of the main ingredients of stellar population synthesis models is a library of stellar spectra. Both empirical and theoretical libraries are used for this purpose, and the question about which one is preferable is still debated in the literature. Empirical and theoretical libraries are being improved significantly over the years, and many libraries have become available lately. However, it is not clear in the literature what are the advantages of using each of these new libraries, and how far behind models are compared to observations. Here we compare in detail some of the major theoretical libraries available in the literature with observations, aiming at detecting weaknesses and strengths from the stellar population modelling point of view. Our test is twofold: we compared model predictions and observations for broad-band colours and for high-resolution spectral features. Concerning the broad-band colours, we measured the stellar colour given by three recent sets of model atmospheres and flux distributions, and compared them with a recent $UBVRIJHK$ calibration which is mostly based on empirical data. We found that the models can reproduce with reasonable accuracy the stellar colours for a fair interval in effective temperatures and gravities. The exceptions are (1) the $U-B$ colour, where the models are typically redder than the observations, and (2) the very cool stars in general ($V-K \gtrsim 3$). Castelli & Kurucz is the set of models that best reproduce the bluest colours ($U-B$, $B-V$) while Gustafsson et al. and Brott & Hauschildt more accurately predict the visual colours. The three sets of models perform in a similar way for the infrared colours. Concerning the high-resolution spectral features, we measured 35 spectral indices defined in the literature on three high-resolution synthetic libraries, and compared them with the observed measurements given by three empirical libraries. The measured indices cover the wavelength range from \~3500 to \~8700 Å. We found that the direct comparison between models and observations is not a simple task, given the uncertainties in parameter determinations of empirical libraries. Taking that aside, we found that in general the three libraries present similar behaviours and systematic deviations. For stars with $T_{\text{eff}} \lesssim 7000$ K, the library by Coelho et al. is the one with best average performance. We detect that lists of atomic and molecular line opacities still need improvement, specially in the blue region of the spectrum, and for the cool stars ($T_{\text{eff}} \lesssim 4500$ K).

\textbf{Key words:} stars: atmospheres – stars: evolution – stars: general.

1 INTRODUCTION

Evolutionary population synthesis models describe the spectral evolution of stellar systems, and are fundamental tools in the analysis of both nearby and distant galaxies (e.g. Cerviño & Mas-Hesse 1994; Fioc & Rocca-Volmerange 1997; Leitherer et al. 1999; Vazdekis 1999; Buzzoni 2002; Bruzual & Charlot 2003; Jimenez et al. 2004; Le Borgne et al. 2004; Delgado et al. 2005; Maraston 2005; Schiavon 2006). They are needed to derive the star formation history and chemical enrichment in a variety of systems, from early-type galaxies and spiral bulges to star-forming galaxies at different redshifts.

Libraries of stellar spectra are one of the main ingredients of stellar population models, and both empirical and theoretical libraries have improved dramatically in recent years, allowing the construction of more detailed models. Observations are also becoming increasingly better and demanding more from the modelling point of view.

Recently, many new empirical libraries suitable to stellar population synthesis have been made available with improved spectral resolution and parameter coverage: e.g. STELIB (Le Borgne et al. 2003), UVES POP (Jehin et al. 2005), Indo-US (Valdes et al. 2004),
ELODIE (Prugniel & Soubiran 2001), MILES (Sánchez-Blázquez et al. 2006) and NGSL (Gregg et al. 2004).

The choice of using either an empirical or a synthetic library in stellar population models is a subject of debate. Many aspects are important when considering a library for stellar population synthesis, and parameter coverage is one of the main issues. A good parameter coverage is not trivial for empirical libraries, which are limited to whatever is possible to obtain given observational constraints (resolution, wavelength coverage, exposure time etc.). They have to cover not only a good wavelength range (which limits the spectral resolution), but also cover from cool to hot stars, dwarfs and giants and different chemical abundances.

Amongst the synthetic libraries, perhaps the most widely used is the flux distribution predicted by the Kurucz (1993) model atmospheres. The Basel Stellar Library (BaSeL) (Lejeune, Cuisinier & Buser 1997, 1998; Westera et al. 2002) extended these flux distributions including spectra of M stars computed with model atmospheres by Bessell et al. (1989, 1991), Fluks et al. (1994) and Allard & Hauschildt (1995). However, the spectral resolution of the BaSeL library is limited to ~20 Å, which is by far lower than the modern observed spectra of both individual stars and integrated stellar populations. Resolution ceased to be a limitation recently, with many high-resolution theoretical libraries appearing in the literature (Chavez, Malagnini & Morossi 1997; Barbuy et al. 2003; Bertone et al. 2003; Gustafsson et al. 2003, hereafter MARCS; Lanz & Hubeny 2003; Murphy & Meiksin 2004; Zwitter, Castelli & Munari 2005; Frémaux et al. 2006). Many of these libraries were created with refined and updated line lists, state of the art model atmospheres and spectral synthesis codes and a very extensive parameter coverage. A qualitative comparison of some of the recent high-resolution synthetic libraries is given by Bertone (2006).

The major concern when using synthetic libraries for high-resolution stellar population models is to know whether a synthetic library can safely replace an empirical one. These libraries are based on model atmospheres and therefore are limited to the approximations adopted in the computations. Ideally, one would like to generate model that accounts for all the effects taking place across the HR diagram: non-local thermodynamic equilibrium (LTE), line blanketing, sphericity, expansion, non-radiative heating, convection etc. Such an approach is unfeasible at present time, even if the astrophysical models were available. What is usually done is to take some of these effects into account where they matter the most. The hardest stars to reproduce in this sense are the very hot and very cool stars, where extreme scenarios take place (e.g. non-LTE effects for very hot stars, and sphericity for cool giants). Additionally, computing reliable high-resolution synthetic spectra is a very challenging task, since it requires building an extensive and accurate list of atomic and molecular line opacities.

Nevertheless, synthetic libraries overcome limitations of empirical libraries, for instance their inability to cover the whole space in atmospheric parameters, and in particular abundance patterns that differ from that of the observed stars (mainly from the solar neighbourhood, and in some few cases from the Magellanic Clouds). Therefore, population models based solely on empirical libraries cannot reproduce the integrated spectra of systems that have undergone star formation histories different than the solar neighbourhood.

With so many different choices for the stellar library, the stellar population modeller might feel lost about which library should be used. It is certain that each of these libraries has its own strengths and weaknesses, but identifying them is not always trivial. We propose in this work to make a detailed comparison between some of the major synthetic stellar libraries available, comparing them against empirical libraries.

This paper is organized as follows: in Section 2 we present an overview of theoretical libraries. In Section 3 the model predictions of three sets of model atmospheres (Castelli & Kurucz 2003, hereafter ATLAS9; MARCS; PHOENIX) for broad-band colours are compared to the empirical $UBVRIJHK$ relation from Worthey & Lee (2007, hereafter WL07). In Section 4 we compare model spectral indices predicted by three recent high-resolution libraries (Coelho; Martins; Munari) to indices measured in the empirical libraries by Valdes et al. (2004), Sánchez-Blázquez et al. (2006) and Prugniel & Soubiran (2001).

For the purpose of the present work, we focus our comparisons on the solar metallicty regime, where the completeness of the empirical libraries is higher, as well as the accuracy of the stellar atmospheric parameters. Our conclusions and discussions are presented in Section 5.

2 OVERVIEW OF THE THEORETICAL LIBRARIES

The nomenclature used by atmosphere and synthetic spectra modellers are sometimes confusing for the stellar population models users.

By model atmosphere we mean the run of temperature, gas, electron and radiation pressure, convection 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 flux distribution or synthetic spectra is the emergent flux predicted by a model atmosphere, and is required for comparison with observations.

It is convenient from the computational point of view to split the calculation of a synthetic spectra in two major steps: the calculation of the model atmosphere, commonly adopting opacity distribution function (ODF) technique (Strom & Kurucz 1966) – and the calculation of the emergent flux with a spectral synthesis code.

Alternatively, model atmosphere codes that use an opacity sampling (OS) method to account for the line absorption (e.g. Johnson & Krupp 1976) can directly produce as output a well sampled flux distribution. The OS technique is more time consuming from the computational point of view then the ODF technique, but allows for a much larger flexibility in modelling. For example, peculiar chemical compositions can be easily considered that.

The majority of model atmospheres available are one-dimensional (1D) and hydrostatic, assume LTE and treat convection with the mixing-length theory. The mixing-length theory was introduced in ATLAS6 code by Kurucz (1979), and is a phenomenological approach to convection in which it is assumed that the convective energy is transported by eddy ‘bubbles’ of just one size. t requires an adjustable parameter $\alpha_{ML}$, which represents the ratio between the characteristic length (distance travelled by an element of fluid before its dissolusio) and the scaleheight of the local pressure ($H_L$). The parameter $\alpha_{ML}$ has to be set at different values to fit different types of observations (Steffen & Ludwig 1999), and no single value works well in all classes. An alternative convective model is Full Spectrum Turbulence, introduced by Canuto & Mazzitelli (1991) and adopted, for example, by NeMo grid of atmospheres (Henter et al. 2002).

Throughout this paper we further distinguish a flux distribution from a synthetic spectrum. The flux distribution is the spectral
energy distribution predicted directly by a model atmosphere, and is commonly available together with the model atmospheres. This is the case, for example, of the synthetic libraries by ATLAS9, MARCS and PHOENIX.

By synthetic spectrum we mean the flux calculated by a line profile synthesis code, using as input a model atmosphere and a refined atomic and molecular line list, that can be at some extend different from the line list adopted in the model atmosphere computation. It can also adopt different chemical compositions than the model atmosphere in order to account for small variations in the abundance pattern (as long as the difference is not enough to produce important changes in the structure of the atmosphere). This is the method commonly used in high-resolution stellar spectroscopy studies, and it is the case of the libraries from Coelho, Martins and Munari. A synthetic spectrum is usually computed at a higher resolution than a model atmosphere flux distribution, given that it aims at resolving individual line profiles.

Additionally, a theoretical library that is intended to produce accurate high-resolution line profiles is not generally a library that also predicts good spectrophotometry. That happens because usually only the lower lying energy levels of atoms have been determined in laboratory. If only those transitions are taken into account in a model atmosphere, the line blanketing would be severely incomplete. To avoid this deficiency and to improve both the temperature structure of the model atmospheres and the spectrophotometric flux distributions, the computation requires accounting for lines where one or both energy levels have to be predicted from quantum mechanical calculations. These so-called ‘predicted lines’ (hereafter PLs; Kurucz 1992) are an essential contribution to the total line blanketing in model atmospheres and flux distribution computations. However, as the theoretical predictions are accurate to only a few per cent, wavelengths and computed intensities for these lines may be largely uncertain. As a consequence the PLs may not correspond in position and intensity to the observable counterparts (Bell, Paltoglou & Tripicco 1994; Castelli & Kurucz 2004), ‘polluting’ the high-resolution synthetic spectrum. Therefore, synthetic libraries that are aimed at high-resolution studies do not include the PLs, and thus they provide less accurate spectrophotometric predictions when compared to the flux distributions libraries.

For this reason we divided the comparisons of the present paper in two different sections. Section 3 studies the flux distributions given by some model atmosphere grids in order to assess the ability of those models in predicting broad-band colours. In Section 4 we change our focus to libraries that aim at high-resolution studies, testing their ability to reproduce higher resolution spectral features. The grids evaluated in the present work are briefly described below.

2.1 Model atmosphere flux distributions

Amongst several model atmosphere grids available in literature (e.g. Kurucz 1993; Hauschildt et al. 1996; Pauldrach, Hoffmann & Lennon 2001; Lanz & Hubeny 2003), we selected three grids that cover a large parameter space in effective temperatures $T_{\text{eff}}$ and superficial gravities $g$: ATLAS9, MARCS and PHOENIX.

Based on Kurucz (1993) codes, the ATLAS9 model atmospheres follow the classical approximations of steady state, homogeneous, LTE, plane-parallel layers that extend vertically through the region where the lines are formed. In its more recent version (ATLAS9), $\alpha_{\text{ML}}$ is assumed to be 1.25 to fit the energy distribution from the centre of the Sun. All models are computed with the convection option switched on and with the overshooting option switched off. The convective flux decreases with increasing $T_{\text{eff}}$ and it naturally disappears for $T_{\text{eff}} \sim 9000$ K. The models are available in the range $3500 \leq T_{\text{eff}} \leq 50000$ K.

Plane-parallel LTE models will fail wherever sphericity (especially important for giant stars) and non-LTE effects (for very hot stars) are evident. Two models that take sphericity into account are PHOENIX and MARCS.

PHOENIX (Hauschildt et al. 1996) is a multipurpose stellar model atmosphere code for plane-parallel and spherical models. The original versions of PHOENIX were developed for the modelling of novae and supernovae ejecta (Hauschildt, Allard & Baron 1999, and references therein). The most recent grid is presented in PHOENIX.2 The equilibrium of PHOENIX is solved simultaneously for 40 elements, with usually two to six ionization stages per element and 600 relevant molecular species for oxygen-rich ideal gas compositions. The chemistry has been gradually updated with additional molecular species since the original code. The convective mixing is treated according to the mixing-length theory, assuming $\alpha_{\text{ML}} = 2.0$. Both atomic and molecular lines are treated with direct OS method. PHOENIX models cover the range $2000 \leq T_{\text{eff}} \leq 100000$ K.

MARCS models have undergone several improvements since the original code by Gustafsson et al. (1975), the most important ones being the replacement of the ODF technique by OS technique, the possibility to use a spherically symmetric geometry for extended objects and major improvements of the line and continuous opacities (Plez 1992). The common assumptions of spherical or plane-parallel stratification in homogeneous stationary layers, hydrostatic equilibrium and LTE are made. Energy conservation is required for radiative and convective flux, where the energy transport due to convection is treated according to the mixing-length theory by Henyey, Vardy & Bodenheimer (1965). The mixing-length $l$ is chosen as $1.5H_p$, which is a reasonable quantity to simulate the temperature structure beneath the photosphere (Nordlund & Dravins 1990). The most recent version of the MARCS grids is presented in MARCS.3 The models cover $4000 \leq T_{\text{eff}} \leq 80000$ K and adopt plane-parallel geometry for the dwarfs ($\log g \geq 3.0$) and spherical geometry for the giants ($\log g \leq 3.5$; both geometries are available for $\log g$ values of 3.0 and 3.5).

The three sets of models adopt a microturbulent velocity of $2$ km s$^{-1}$ and are computed for $1$ M$\odot$.

### 2.2 High-resolution synthetic spectral libraries

Amongst the higher resolution synthetic libraries, we selected three of the most recent ones which are publicly available, each of them with an outstanding improvement compared to previous ones. Munari4 have an impressive coverage of the HR diagram. Their models are based on Kurucz (1993) codes and ATLAS9 grid, covering 2500–10500 Å in wavelength range at a maximum resolution of $R = 20000$. They range from 3500 to 475 00 K in $T_{\text{eff}}$, with $\log g$ varying between 0.0 and 5.0 dex, for different values of metallicity, $\alpha$ enhancement, rotational velocity and microturbulent velocity.

1 ftp://ftp.hs.uni-hamburg.de/pub/outgoing/Phoenix/GAIA
2 http://marcs.astro.uu.se/
3 http://archives.pd.astro.it/2500-10500/
4 http://wwwuser.oat.ts.astro.it/castelli/grids.html
The library by Coelho, also based on ATLAS9 model atmospheres, had a special care for low-temperature stars, employing a detailed and calibrated line list that has been improved along the years (see the original paper for a list of references). Their models cover from 3000 Å to 1.8 μm spanning from 3500 to 7000 K, with log g varying between 0.0 and 5.0 dex, also covering different metallicities and α enhancement.

Martins searched the literature for the best available codes for each range of temperatures and used them to build the models. They used Hubeny (1988), Hubeny & Lanz (1995), Lanz & Hubeny (2003) model atmospheres considering non-LTE for hot stars, ATLAS9 models for intermediate temperature stars and PHOENIX line-blanketed models for very cool stars. The library covers from 3000 to 7000 Å, with temperatures ranging from 3000 to 55 000 K and log g from −0.5 to 5.5 dex, for four different metallicities (but no α enhancement).

3 EVALUATING THE FLUX DISTRIBUTIONS: BROAD-BAND COLOURS

A convenient way of comparing the flux distributions given by the model grids with observations is through broad-band colours, which are likely to be the first observables expected to be predicted by spectral stellar population models.

In order to do this comparison, we selected pairs of $T_{\text{eff}}$ and log g that are representative of an isochrone of a young and an old population (10 Myr and 10 Gyr). The pairs were selected to uniformly cover $T_{\text{eff}}$, respecting the spacing of each set of models (ATLAS9 and MARCS have steps of 250 K, and PHOENIX has steps of 200 K). The isochrones adopted are the ones by Girardi et al. (2002), for solar metallicity composition. The transformation to observed colours were done adopting the $UBVRI$HJKG empirical calibration by WL07. In that work, the authors used stars with measured photometry and known metallicity [Fe/H] to generate colour–colour relations that include the abundance dependence. They further added colour–temperature relations until the whole parameter range was covered, taking medians in regions where more than one relation applied. The colour–$T_{\text{eff}}$ relations were obtained from several sources in literature, mainly from empirical work, but also from theoretical work. At both ends of the $T_{\text{eff}}$ range, the relations were taken purely from empirical sources; in the middle range, the theoretical relations by VandenBerg & Clem (2003) for $V − J$ were added, and behaved well compared to empirical ones. Any other theoretical relation employed was used with a lesser weight (G. Worthey, private communication; see also figs 7 and 8 in WL07). Therefore, we expect the relations by WL07 to be a close match to observations, and that the theoretical relations, which could bias our comparisons, do not have an important weight.

The magnitudes predicted by ATLAS9, MARCS and PHOENIX grids were measured using the Image Reduction and Analysis Facility (IRAF) task SBANDS, adopting the filter transmission curves of the photometric systems adopted in WL07. Zero-point corrections were applied to the model magnitudes using the Vega model by Castelli & Kurucz (1994), and adopting Vega magnitudes:

$$U_{\text{Johnson}} = 0.02, B_{\text{Johnson}} = 0.03, V_{\text{Johnson}} = 0.03, R_{\text{Cousin}} = 0.039, I_{\text{Cousin}} = 0.035, J_{\text{Bessell}} = 0.02, H_{\text{Bessell}} = 0.02, K_{\text{Bessell}} = 0.02.$$}

The comparison between the empirical relation and the model predictions are given in Figs 1 and 2 for the 10 Myr and 10 Gyr isochrones, respectively. The empirical relation is presented as black circles. ATLAS9 predictions are given in red diamonds, blue squares are predictions for MARCS models and green triangles for PHOENIX. Filled and open symbols represent dwarfs (log g $\geq$ 3.0) and giant stars (log g $< 3.0$), respectively.

The results are presented in colour–colour relations where on the x-axis is shown the $(V − K)$ colour, which is a good tracer of $T_{\text{eff}}$ (higher values of $T_{\text{eff}}$ correspond to lower values of $V − K$). The six panels in each figure show different colours in the y-axis. The residuals (model minus empirical) between the model colours and the WL07 calibration for each $T_{\text{eff}}$, log g pair is shown below each colour–colour panel, where the error bars indicate the uncertainties of the WL07 calibration.

For stars 4000 $< T_{\text{eff}} < 8000$ K, which is the interval that is common to all sets of models, we present in Tables 1 and 2 the average absolute differences between model and empirical relations, for the 10 Gyr and 10 Myr populations, respectively.

It can be seen from Figs 1 and 2 that the three set of models show a similar behaviour among themselves for a large range in $T_{\text{eff}}$ ($V − K$), and are a good reproduction of the empirical relation for the colours $V − I$, $V − R$ and $J − K$. The residuals are larger for cooler stars ($V − K \gtrsim 3$), for all colours. There is a tendency in all models to underpredict the $B − V$ and $H − K$ colours. The colour where the models differ more strongly is $U − B$; in the case of Fig. 2 (10-Gyr isochrone), we note that in the range $1 \lesssim V − K \lesssim 3$ (which mainly represents the turn-off stars) ATLAS9 models reproduce considerably better the observations than either PHOENIX or MARCS. The situation is more complex for the same colour in the young population (Fig. 1) and all residuals are larger, specially for the giants. In the case of the dwarfs, ATLAS9 is still the set of models that best reproduces the empirical relation. The differences are typically smaller for the visual colours, and for $V − I$ and $V − R$ colours ATLAS9 presents on average higher residuals than MARCS or PHOENIX, likely due to the different implementations of molecular opacities. For the near-infrared (IR) colours, the behaviour is quite similar for the three sets of models.

The reason for the large difference in the $U − B$ colour is unclear to the present authors. Differences in the implementation of both line blanketing and continuum opacities, and also differences in calibration of the convection treatment might be playing a role. The effect of both line blanketing and continuum opacities in the near-ultraviolet (UV) and UV fluxes is a long-standing (and sometimes confusing) problem. Each set of models has its particular implementation, and we refer the reader to Allende Prieto & Lambert (2000), Houdashelt, Bell & Sweigart (2000), Peterson, Dorman & Rood (2001); Allende Prieto & Lambert (2003), Castelli & Kurucz (2004) and García-Gil et al. (2005) and references therein for appropriate discussions on the subject. The effect of the convection treatment on broad-band colours have been discussed, for example, in Heiter et al. (2002), and indeed we note that the three sets of models present different values of the mixing-length parameter $\alpha_{\text{ML}}$. However, Kuçinskas et al. (2005) have shown that the effect of different $\alpha_{\text{ML}}$ is not significant, and important effects appear only when more realistic three-dimensional (3D) computations take place. Nevertheless, they focused their analysis in late-type giants, and therefore it remains an open question if different $\alpha_{\text{ML}}$ could explain the differences we see here for the parameters typical of turn-off stars.
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Concerning the cooler stars, usually around $V-K \sim 3 (T_{\text{eff}} \sim 4250 \text{ K})$ the models start to deviate from the empirical relation. It is interesting to see that the model predictions are not strikingly different among the sets of models analysed here (at least for $T_{\text{eff}} \geq 3500 \text{ K}$), even though ATLAS9 models are computed in plane-parallel geometry and PHOENIX models in spherical geometry (MARCS models present both geometries). Kučinskas et al. (2005) present a very detailed analysis of broad-band colours for late-type giants, and test the effect of several model parameters on the broad-band colours predictions (namely molecular opacities, microturbulent velocities, stellar mass and treatment of convection). Those authors note that it is possible that spherical models may not be sufficient, and additional effects as convection, variability and mass loss become increasingly important for cooler stars.

4 EVALUATING THE HIGH-RESOLUTION FEATURES: SPECTRAL INDICES

A convenient way to evaluate the theoretical spectra is to measure widely used spectral indices and compare them with the observed values. This approach will not evaluate the quality of the model spectrum at its full wavelength coverage, but allows a presentation of the results in a scale that is familiar to the user of stellar population models.

We compared Coelho, Martins and Munari libraries with three of the most complete empirical libraries available: Indo-US, MILES and ELODIE.

4.1 Overview of the empirical libraries

The first empirical stellar library that provided flux calibrated spectra was presented in Jones (1998). With moderately high resolution (1.8 Å), this library was used by Vazdekis (1999) to produce for the first time spectral stellar population models at high resolution. However, Jones library is limited to two narrow wavelength regions (3820–4500 and 4780–5460 Å), and it is sparse in dwarfs hotter than about 7000 K and metal-poor giants.

STELIB\(^9\) (Le Borgne et al. 2003) represents a substantial improvement over previous libraries. It consists of 249 stellar spectra in the range of 3200 to 9500 Å, with a spectral resolution of about 3 Å ($R = 2000$). This is the base library for the widely used Bruzual & Charlot (2003) stellar population models.

Following this work, Valdes et al. (2004) published Indo-US,\(^10\) a library with resolution down to FWHM (full width at half-maximum) $\sim 1$ Å and a good coverage of the colour–magnitude diagram. Indo-US has a much higher number of stars (1273), with

\(^9\)http://www.ast.obs-mip.fr/users/leborgne/stelib/index.html
\(^10\)http://www.noao.edu/ctlib
spectra ranging from 3460 to 9464 Å. They cover a fair range in atmospheric parameters. The main concern on this library regards its spectrophotometry, which was obtained by fitting each observation to a standard spectral energy distribution with a close match in spectral type, using the compilation of Pickles (1998).

Prugniel & Soubiran (2001) published the ELODIE library,\footnote{http://www.obs.u-bordeaux1.fr/m2a/soubiran/elodie_library.html} which has been updated since then. In its current version (Elodie.3) there are 1388 stars, in the wavelength range 4000 to 6800 Å. Although it has a more limited wavelength coverage with respect to the others, it has a very high spectral resolution ($R = 10000$ for flux calibrated spectra and $R = 42000$ for flux normalized to the pseudo-continuum). However, the flux calibration of this library might be compromised by the use of an echelle spectrograph.

Another library that became available recently is MILES\footnote{http://www.ucm.es/info/Astrof/miles/miles.html} (Sánchez-Blázquez et al. 2006; Cenarro et al. 2007). The spectra range from 3525 to 7500 Å, at a 2.3 Å (FWHM) resolution. This library, with 985 stars, was carefully created trying to fill the major gaps that existed in other empirical libraries.

The Next Generation Stellar Library (NGST; Gregg et al. 2004) is yet another library soon to be publicly available, which is a UV/optical (from 1660 to 10200 Å) stellar spectral atlas using Space Telescope Imaging Spectrograph-Hubble Space Telescope (STIS-HST; PID 9786). The advantage of this library is that, being obtained with STIS at HST, it presents an unprecedented internally consistent flux calibration across all wavelengths.

Fig. 3 shows the coverage in temperature and gravity of four empirical libraries (STELIB, Indo-US, MILES and ELODIE), overplotted on isochrones from Girardi et al. (2002) for ages 10, 100 Myr.

### Table 1. Mean absolute residuals for the broad-band colours. These values were obtained for the 10-Myr isochrone and for the interval $4000 \leq T_{\text{eff}} \leq 8000$ K.

| Colour | ATLAS9 | MARCS | PHOENIX | Mean error |
|--------|--------|-------|---------|------------|
| $U - B$ | 0.370  | 0.695 | 0.611   | 0.073      |
| $B - V$ | 0.070  | 0.145 | 0.066   | 0.020      |
| $V - I$ | 0.041  | 0.029 | 0.010   | 0.015      |
| $V - R$ | 0.022  | 0.045 | 0.026   | 0.012      |
| $J - K$ | 0.049  | 0.056 | 0.079   | 0.013      |
| $H - K$ | 0.018  | 0.016 | 0.019   | 0.004      |

### Table 2. Mean absolute residuals for the broad-band colours. These values were obtained for the 10-Gyr isochrone and for the interval $4000 \leq T_{\text{eff}} \leq 8000$ K.

| Colour | ATLAS | MARCS | PHOENIX | Mean error |
|--------|-------|-------|---------|------------|
| $U - B$ | 0.105 | 0.440 | 0.309   | 0.073      |
| $B - V$ | 0.146 | 0.235 | 0.126   | 0.020      |
| $V - I$ | 0.048 | 0.015 | 0.009   | 0.015      |
| $V - R$ | 0.038 | 0.017 | 0.016   | 0.012      |
| $J - K$ | 0.023 | 0.027 | 0.034   | 0.013      |
| $H - K$ | 0.024 | 0.022 | 0.018   | 0.004      |
libraries. The closest model was chosen based on the smaller distance \( d \) to the \( T_\text{eff} \) \( \log g \) plane, defined in equation (1), where \( T_\text{eff} \) and \( \log g \) are parameters of the models, and \( T_\text{obs} \) and \( \log g_\text{obs} \) are parameters of the empirical libraries:

\[
d = \sqrt{\left( \frac{T_\text{eff} - T_\text{obs}}{T_\text{obs}} \right)^2 + \left( \frac{\log g - (\log g)_\text{obs}}{(\log g)_\text{obs}} \right)^2}.
\]

The typical parameter spacing of the models (250 K in \( T_\text{eff} \) and 0.5 dex in \( \log g \)) is of the same order of the accuracy of the atmospheric parameters in the empirical libraries. Therefore, we believe the closest model is a reasonable approach. The theoretical libraries were degraded to the resolution of each empirical library prior to the measurements of the indices. The exception was the ELODIE library, whose superior resolution could only be matched by Coelho library. In this case the theoretical libraries and ELODIE were degraded to a common resolution of FWHM = 0.3 Å.

Figures for all the comparisons are presented in the appendix (online material). Figs 4 to 10 show the results for some of the indices. The data points on the figures are the median values for each \( T_\text{eff} \) and \( \log g \) bin in the empirical libraries, and the error bars are the correspondent 1\( \sigma \) dispersion of the empirical measurements for that parameter bin. A point with no error bar implies that there was only one star for that \( T_\text{eff} \) and \( \log g \). We colour coded the stars in three \( T_\text{eff} \) intervals: blue squares are stars with \( T_\text{eff} > 7000 \) K, green diamonds are stars with \( 4500 < T_\text{eff} < 7000 \) K and red asterisks are stars with \( T_\text{eff} < 4500 \) K. The black crosses are stars with \( T_\text{eff} < 3500 \) K, but they are really rare. We also separated them by gravity: dwarf stars (\( \log g < 3.0 \)) are represented by filled symbols and giant stars (\( \log g > 3.0 \)) are represented by open symbols. The black line in each plot shows the one to one relation. The thick black symbols indicate the location of a Sun-like dwarf (cross; \( T_\text{eff} = 5750 \) K and \( \log g = 4.5 \)), and a typical K1 giant (diamond; \( T_\text{eff} = 4250 \) K and \( \log g = 1.5 \)). The K1 giant have all parameters but metallicity close to the star Arcturus. We show the position of these particular stars on the plots because line lists are usually calibrated based on their high-resolution spectra. Also shown in each plot is the adev value for each temperature range, a statistical measurement of how much each model is representing the stars in that range. Adev takes into account the distance of each theoretical point from the one-to-one line in the index plots, and is defined as

\[
\text{adev} = \frac{1}{N} \sum \left| \frac{I_e - I_i}{I_e} \right|,
\]

where \( N \) is the number of stars, \( I_i \) is the measure of the index on the theoretical library and \( I_e \) is the measure of the index on the empirical library.

First thing to notice in these plots is that the error bars are non-negligible, specially for the low temperature stars. This is a consequence of the large uncertainties in the atmospheric parameters of these stars. The determination of those parameters in cool stars is known to be a real challenge. For the high-temperature stars it is clear that the spread between each point is very small for most of the indices. This is somewhat expected, since there are fewer metallic lines as you go up in temperature, and therefore many of these indices will give essentially no information in this case.

We organized the analysis grouping the results in four categories, related to the chemical species that dominate the index. It is worth remember that no index is sensible to only one element (see e.g. tables at Serven et al. 2005), but we attempted to categorize the indices by its main element.
Balmer lines. Include the indices Hβ, Hγ A and Hδ A. In general the hydrogen indices are well reproduced by all models down to 4500 K. For the very low temperature stars, models start to deviate from observational libraries, clearly subestimating the indices, as shown in Fig. 4 for Hγ A. It is known that hydrogen lines computed in LTE match well the wings, but cannot reproduce the core of the lines. Fine-tuned microturbulence velocities or mixing-length to pressure scaleheight ratio ℓ/H p were suggested in literature to improve the match in the solar spectrum (e.g. Fuhrmann, Axer & Gehren 1993; Van’t Veer-Mennert & Megessier 1996), but the same parameters would not necessarily improve the results for other spectral types. A realistic match would require non-LTE computations of H lines, only available for very hot stars. Besides, the bottom of the hydrogen lines form in the chromosphere, not included in the model atmospheres grids. Another point to note is that although these indices are aimed at measuring H lines, in low-temperature stars the actual hydrogen lines are considerably weak, and the metallic lines can be dominating the index. In this case, it is not clear if the main reason why the models are failing in reproducing the observed values is because of the non-satisfactory line core modelling, or because the dominance of uncalibrated metallic lines.

C and N indices. Include the indices CNO3862, CN1, CN2 and G4300. According to Tripicco & Bell (1995) calculations, the indices Ca4227 and Fe4668 are also highly sensitive to carbon abundance variations, and therefore these two indices could be possibly included in this group. From these indices, the subsample that is sensitive to both C and N abundances (CNO3862, CN1, CN2) show significant larger error bars, but the overall behaviour seem to be well matched by the models. Fig. 5, that shows the CN2 index, illustrates this effect. On the other hand, indices that are mainly sensitive to C abundance variations (G4300, Ca4227 and Fe4668) systematically deviate from the one to one line for stars cooler than T eff = 4500 K. Fig. 6 shows the G4300 index, which measures the G band of CH at 4300 Å. One possible reason for this effect is that the C and N abundances relative to Fe were assumed to be solar for all synthetic stars, but it is well known that the CNO cycle lowers the C abundance and enhances the N abundance in giants (e.g. Iben 1967; Charbonnel 1994). The same effect on the indices CN1 and CN2 would not be so clearly seen if the variations of C and N somewhat compensate each other. Nevertheless, we could not clearly attribute all the differences in these indices to the unmodelled CNO mixing. If the modelling of the CNO cycle was to be the only or major problem affecting the cool giants, we would expect the dwarfs (filled symbols; see e.g. Fig. 6) to be a closer match to the observations than the giants (open symbols). This is not the case, both presenting similar patterns. Interestingly, for temperatures between 4500 and 7000 K, Coelho models reproduce considerably better the observations, while the cool end deviates more strongly than the other synthetic libraries. This is probably because the CH lines adopted by Coelho models were computed with LIFBASE code (Luque & Crosley 1999) while Martins and Munari models adopt Kurucz (1993) molecular lines. This is a first indicative of how working on the line lists might impact the model results in significant ways.

Iron peak elements. Many of the iron indices are good examples suggesting that working on the line lists might improve the model results significantly. Fig. 7 shows the behaviour of the index Fe4383, where this effect is evident. Martins and Munari models have similar line lists, modified from the same Kurucz (1993) original work, while Coelho models employed its independent line list, based on high-resolution stellar spectroscopy studies. The effect of the different line lists is clearly seen.

α elements. Include all the indices sensitive to Mg, Ca, Ti and O. In this case there is not a general pattern. Fig. 8 shows the Mg2 index

Figure 4. Comparison of the index Hγ A measured in the empirical and theoretical libraries. Different symbols and colours represent three intervals of temperature: blue squares are stars with T eff < 7000 K, green diamonds are stars with 4500 < T eff ≤ 7000 K and red circles are stars with T eff ≤ 4500 K. Filled and open symbols represent dwarfs (log g ≥ 3.0) and giant stars (log g < 3.0), respectively. The black crosses are stars with T eff < 3500 K. The solid line is the one to one relation. The thick black symbols represent a Sun-like dwarf (cross) and an Arcturus-like giant (diamond).
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Figure 5. Comparison of the index CN2 measured in the empirical and theoretical libraries. This index measures the strength of the CN\ ASS 4150 absorption band, in magnitudes. Symbols and colours are the same as in Fig. 4.

Figure 6. Comparison of the index G4300 measured in the empirical and theoretical libraries. Symbols and colours are the same as in Fig. 4.

where the line list from Coelho reproduces significantly better the observed values, specially in the low-temperature regime. However, it is interesting to point out that for stars cooler than $T_{\text{eff}} \sim 4250$ K, this index is heavily contaminated by TiO or molecular features (see fig. 13 in Coelho). The calcium and TiO indices, on the other side, are examples of how things can be complex. Fig. 9 shows the index Ca4455. Coelho models tend to predict slightly lower values than the observed. Munari models seem to show the same trend, to a lower level. At first order we could conclude that both models are underpredicting this index, but Bensby et al. (2005) studied F and G dwarfs from the thin and thick disc of our galaxy and found that the [Ca/Fe] tend to be slightly supersolar for stars with [Fe/H] solar. In the likely case that the stars in the empirical libraries show a similar behaviour than the one found by Bensby et al. (2005), we should not expect the models, calculated with solar mixture ([Ca/Fe] = 0), to actually match the observations. In this case, the behaviour of both Coelho
and Munari models are consistent with the observations. Martins models show a more complex behaviour: intermediate-temperature stars, which were computed with SPECTRUM synthesis code and line lists and ATLAS9 models, are overestimated; low-temperature stars, calculated with PHOENIX models and line lists, are underestimated. Fig. 10 shows the TiO index. This index has no meaning for stars with temperatures higher than $\sim 4500$ K, where there is no TiO in the spectrum to be measured. For lower temperature stars the values raise rapidly, being extremely sensitive to temperature. This implies that uncertainties in the $T_{\text{eff}}$ adopted for stars in the empirical libraries (usually considerably higher for low-temperature stars) make the comparison with models hardly reliable. Given the large uncertainties, models are not failing completely to reproduce this index.

4.3 Dependence on the atmospheric parameters

It is worth to keep in mind that errors on the empirical libraries, the most important one being uncertainties in the atmospheric parameters, hamper the comparison with the models.
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**Figure 9.** Comparison of the index Ca4455 measured in the empirical and theoretical libraries. Symbols and colours are the same as in Fig. 4.

**Figure 10.** Comparison of the index TiO2 measured in the empirical and theoretical libraries. Symbols and colours are the same as in Fig. 4.

ELODIE library is the only of the empirical libraries that provides, for each star, a flag that indicates the accuracy of each atmospheric parameter. In order to evaluate how much the accuracy might affect our comparisons, Figs 11 and 12 show the same comparisons as before for the indices G4300 and Fe4531, but filtering the observed stars by the quality flag of the atmospheric parameters. On the first line of the figures all stars are plotted. On the second line, only stars with good and excellent flags for the atmospheric parameters. On the third line, only the ones with excellent determination. It is clearly noticeable how much the agreement between models and observations can change, based only on stars with very good parameter determinations. The drawback, on the other hand, is that this filter limits drastically the number of points.

### 4.4 Dependence on the flux calibration

A second issue that can complicate the comparison between model and observations is related to flux calibrations uncertainties. One of...
the advantages of using spectral indices is that they were designed to be, as much as possible, insensitive to flux calibration issues. That implies that when using these indices to study the properties of stellar populations, the continuum shape is not used to extract information from the spectra. This is particularly useful when it is not possible to accurately flux calibrate the observations.

In order to test how sensitive to flux calibration issues are the indices studied here, we employed a modified version of Coelho library. As explained in Section 2, a library focused on spectroscopic use is not suitable to predict broad-band colours because it does not generally include the full line blanketing. As the libraries stand now, our note to the stellar population modeller – which might be inter-

Figure 11. Comparison of the index G4300 measured on the ELODIE library, filtering by the accuracy flags. First line has all the stars, second line shows only stars with good and excellent atmospheric parameters and the third line only stars with excellent flags. Symbols and colours are the same as in Fig. 4.

Figure 12. The same as Fig. 11 for the index Fe4531.
testing in using any of the synthetic libraries currently available – is that one has to find a compromise between a library which is good for spectrophotometric predictions or one which is good for spectroscopic studies. Until the accuracy of the predicted energy levels lines is significantly improved (see e.g. Kurucz 2006), the only way of achieving reasonable predictions for both broad-band colours and high-resolution indices is by correcting the pseudo-continuum of current high-resolution libraries to better match observed colours. In order to use the high-resolution library to build stellar population models, Coelho et al. (2007) applies a correction to the original library presented in Coelho in order to compensate for the mentioned missing line opacity. In a few words, this correction was done by comparing each star in Coelho library to the correspondent flux distributions by ATLAS9 grid. Smooth corrections to the continuum shape were applied to the stars in Coelho library in order to better match the continuum shape of its correspondent flux distribution by ATLAS9. Therefore, the modified Coelho library kept the high-resolution features of the original library, but presents a flux distribution which is closer to that predicted when including all blanketing (ATLAS9).

The effect of this correction is shown in Fig. 13, in a similar fashion of the broad-band colours figures in Section 3. ATLAS9 flux distributions are shown as red diamonds, Coelho original library stars are shown as green triangles and the blue squares are the flux corrected stars (the modified Coelho library by Coelho et al. 2007). The effect of the missing line opacity is clear, specially in the blue part of the spectrum.

The spectral indices were then measured in the modified Coelho library and compared to the original measurements. These comparisons can show how smooth changes in the stellar pseudo-continuum can affect the measurement of the indices used in the present work. As expected, for most of the indices the differences between the two measurements are smaller than 3 per cent. Among the classical Lick indices, only Ca4455 and Mg1 are slightly more sensitive (~5 per cent).

The notable exceptions are the indices D4000 and the three Ca indices in the near-IR that showed a considerable sensitivity to the modifications of the continuum shape (reaching above 10 per cent in the most extreme cases). In Fig. 14 we show the comparisons between the indices calculated with the original library (x-axis) and the flux corrected one (y-axis), and the residuals in the bottom panels. This high sensitivity of D4000 index to flux calibrations issues has also been noticed by G. Bruzual, V. Wild & S. Charlot (private communication).

### 4.5 The profile of the H lines in high-temperature stars

Balmer lines play a crucial role in the quantitative spectral analysis of hot stars. The Stark broadened wings depend on the photospheric electron density and, consequently, the stellar gravity log g. The line cores on the other hand are more sensitive to the effective temperature $T_{\text{eff}}$. Thus, the complete Balmer line profiles contain information about both fundamental atmospheric parameters, $T_{\text{eff}}$ and log g. The effects of non-LTE were demonstrated to be of drastic importance since the pioneering work of Auer & Mihalas (1972), and have to be considered in order to reproduce these lines. Martins already showed that this effect becomes more important with increasing $T_{\text{eff}}$, making a real difference for O and early B stars.

Fig. 15 shows a comparison between three hot stars from the ELODIE library (which is more complete for hot stars) and the theoretical libraries from Martins and Munari (Coelho library stops at 7000 K). The hot stars in Munari library are also limited to log g equal to 4.5 or 5.0, while in the empirical libraries the hotter stars have 3.5 < log g < 4.0. The top line of the figure shows three Balmer lines for a star with $T_{\text{eff}} \sim 21{,}000$ K. In this case, both

![Figure 13](https://example.com/figure13.png)

**Figure 13.** Comparison between the colours predictions from two versions of Coelho library, with and without the empirical correction of the continuum as described in Section 4.4 (blue squares and green triangles, respectively). Red diamonds are the predictions by ATLAS9 models, for comparison.

![Figure 14](https://example.com/figure14.png)

**Figure 14.** Comparison between indices calculated for two versions of Coelho library, with and without the flux correction due to missing line opacity.
models are LTE. On the Hβ profile this might be the reason for not reproducing the very bottom of the line. The middle and bottom lines show two hotter stars (spectral type O), only represented in Martins library. For this temperature range Martins library consider non-LTE computations, and all Balmer profiles are very well reproduced.

4.6 Summary

The overall performance of the high-resolution synthetic libraries is summarized in Fig. 16. This figure shows the variation of adev for each theoretical library, split in the three $T_{\text{eff}}$ intervals. We did not considered observed stars that were significantly deviating from the other stars with similar $T_{\text{eff}}$ and $\log g$. For each theoretical library and each index, the adev shown is the average of the adev values obtained by the comparison to the three empirical libraries (the results for each of the empirical libraries are given in the appendix).

The indices are shown on the $x$-axis, in order of increasing wavelength. The dotted lines are linear fits of the adev values for each of the synthetic libraries (this fit does not take into account the near-IR indexes, since the only empirical library that covers this region is Indo-US). Although this figure cannot be seen as a precise measure of the quality of the models, it can highlight interesting patterns.

First, all models are systematically deviating more in the blue part of the spectrum, where the blending of lines is considerably larger. To improve the quality of the line list, specially in the blue region and further in the UV is the aim of the HST Treasury Program 9455 by Ruth Peterson (see e.g. Peterson et al. 2001, 2003), and we confirm here that this is clearly the part of the spectrum that needs more work.

Second, Coelho library is the one that has the best average performance. This is likely a consequence of their line list, which was calibrated along the years in several high-resolution stellar studies (e.g. Erdelyi-Mendes & Barbuy 1989; Castilho et al. 1999; Meléndez et al. 2003). For stars hotter than 7000 K Martins and Munari have similar results, but again, these indices are very weak and provide almost no information on these hot stars. A visual comparison of the Balmer lines profiles shows, nevertheless, that above $T_{\text{eff}} \sim 30\,000$ K, non-LTE modelling is crucial.

The values of adev are tabulated in Table A1 in Appendix A.

5 CONCLUSIONS

With this work we aimed at pointing strengths and weaknesses of current theoretical stellar libraries, focusing on the observable values that are mostly used in stellar population models.

We divided our comparisons in two parts. In the first part, presented in Section 3, we measured broad-band colours predicted by three of the most used model atmospheres grids currently available: ATLAS9, MARCS and PHOENIX. We compared the model predictions with the recent empirical colour–temperature relation by WL07, for the stars that are representative of a young and an old simple stellar population. The empirical relation is fairly well reproduced by the models for the colours $V - I$, $V - R$ and $J - H$. All models are a little too blue in the $B - V$ and $H - K$ plane. The biggest differences among the models, and also where they most deviate from the empirical relation, is seen in the $U - B$ colour. ATLAS9 is the model grid that best represents the empirical relation (although a considerable improvement is still required), but presents slightly higher residuals in the visual bands. All colours of the cooler stars ($T_{\text{eff}} \lesssim 4500$ K) also need improvements.

The second part of our comparisons, presented in Section 4, focus on the high-resolution synthetic libraries that are aimed at spectroscopic studies. We measured 35 spectral indices defined in the literature on three recent high-resolution synthetic libraries: Coelho, Martins and Munari. We compared the model indices with the observed measurements given by three high quality empirical libraries by Prugniel & Soubiran (2001), Valdes et al. (2004) and Sánchez-Blázquez et al. (2006). Our first result is that it is not trivial to compare model and empirical libraries because errors in the
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would be the best way to test how much models are indeed able to reproduce these lines.

As suggestions to the next generation of theoretical stellar libraries, we think that concerning the model atmospheres grids and flux distributions, a better reproduction of the blue flux (particularly important in the studies of young populations or any population at high redshift) and of the cool giants (that dominates the integrated spectra of old populations) are still required. It is unclear to the present authors (none of us being a stellar atmosphere modeller) if this is to be achieved by more sophisticated physics modelling (3D computations, non-LTE, non-spherical effects etc.), or improvements in the molecular, atomic and continuum opacities, or yet by adjusting model parameters (like mass, mixing-length parameter and microturbulent velocities) as a function of spectral type. Concerning the high-resolution libraries, we believe that significant improvement can still be made by fine tuning the atomic and molecular line lists, through their calibration against high-resolution stellar spectra whose atmospheric parameters – Teff, log g and detailed abundance ratios – are known very accurately.

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Definition of metallic indices calculated for each stellar library.

**APPENDIX A: DEFINITION AND REFERENCE OF THE INDICES MEASURED IN THE PRESENT WORK**

**Table A1.** Definition of metallic indices calculated for each stellar library.

| Name of the feature | Blue cont.       | Feature         | Red cont.       | Ref.
|---------------------|------------------|-----------------|-----------------|-----
| Cr3594              | 3586.600–3602.400| 3536.600–3560.500| 3625.200–3641.500| 2   |
| Ca H&K              | 3899.500–4003.500| 3806.500–3833.800| 4020.700–4052.400| 2   |
| Mn3794              | 3744.900–3769.600| 3780.900–3805.100| 3847.900–3865.300| 2   |
| CNO3862             | 3768.100–3812.300| 3840.300–3883.400| 3896.400–3916.200| 2   |
| Hα                  | 4041.600–4079.750| 4083.500–4122.250| 4128.500–4161.000| 2   |
| CN1                 | 4085.125–4097.625| 4143.375–4178.375| 4243.375–4285.375| 1   |
| CN2                 | 4129.400–4161.000| 4143.375–4178.375| 4243.300–4284.200| 2   |

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Table A1 – continued

| Name of the feature | Blue cont. | Feature | Red cont. | Ref. |
|---------------------|------------|---------|-----------|------|
| Cr4264              | 4246.800–4281.300 | 4179.300–4195.600 | 4310.700–4334.700 | 2 |
| Hγλ                 | 4283.500–4319.750 | 4319.750–4363.500 | 4367.250–4391.625 | 1 |
| Caλ4227             | 4212.250–4221.000 | 4223.500–4236.000 | 4242.250–4252.250 | 1 |
| G4500               | 4267.625–4283.875 | 4282.625–4317.625 | 4320.125–4336.375 | 1 |
| Fe4383              | 4360.375–4371.625 | 4370.375–4321.625 | 4444.125–4456.625 | 1 |
| Caλ4455             | 4447.125–4455.875 | 4453.375–4475.875 | 4478.375–4493.375 | 1 |
| Fe5451              | 4505.500–4515.500 | 4515.000–4560.500 | 4561.750–4580.500 | 1 |
| Fe5466               | 4612.750–4631.500 | 4635.250–4721.500 | 4744.000–4757.500 | 1 |
| Hβ                  | 4827.875–4847.875 | 4847.875–4876.625 | 4876.625–4891.625 | 1 |
| Fe55015             | 4964.500–4977.750 | 4977.750–5054.000 | 5054.000–5065.250 | 1 |
| Mg1                 | 4895.125–4957.625 | 5069.125–5134.125 | 5301.125–5366.125 | 1 |
| Mg2                 | 4895.125–4957.625 | 5154.125–5196.625 | 5301.125–5366.125 | 1 |
| Mgβ                 | 5142.625–5161.375 | 5160.125–5192.625 | 5191.375–5206.375 | 1 |
| Fe55270             | 5233.150–5248.150 | 5245.650–5285.650 | 5285.650–5318.150 | 1 |
| Fe55335             | 5304.625–5315.875 | 5312.125–5352.125 | 5353.375–5363.375 | 1 |
| Fe55406             | 5376.250–5387.500 | 5387.500–5415.000 | 5415.000–5425.000 | 1 |
| Fe55709             | 5674.625–5698.375 | 5698.375–5722.125 | 5724.625–5738.375 | 1 |
| Fe55782             | 5767.125–5777.125 | 5778.375–5798.375 | 5799.625–5813.125 | 1 |
| NaD                 | 5862.375–5877.375 | 5878.625–5911.125 | 5923.875–5949.875 | 1 |
| TiO1                | 5818.375–5850.875 | 5938.375–5995.875 | 6040.375–6105.375 | 1 |
| TiO2                | 6068.375–6143.375 | 6191.375–6273.875 | 6374.375–6416.875 | 1 |
| NaI8190             | 8167.400–8212.500 | 8081.800–8137.200 | 8231.600–8289.700 | 2 |
| CaII8498            | 8483.000–8513.000 | 8447.500–8462.500 | 8482.500–8587.500 | 3 |
| CaII8542            | 8527.000–8557.000 | 8447.500–8462.500 | 8482.500–8587.500 | 3 |
| CaII8662            | 8647.000–8677.000 | 8447.500–8462.500 | 8482.500–8587.500 | 3 |
| MgII8807            | 8799.500–8814.500 | 8775.000–8787.000 | 8845.000–8855.000 | 3 |

*1 – Worthey et al. (1994) and Worthey & Ottaviani (1997); 2 – Serven et al. (2005); 3 – Diaz et al. (1989).
Figure 32. Comparison of the index $\text{Mg}$ measured in the empirical and theoretical libraries. Symbols and colours are the same as in Fig. 17.

Figure 33. Comparison of the index Fe5270 measured in the empirical and theoretical libraries. Symbols and colours are the same as in Fig. 17.

Figure 34. Comparison of the index Fe5335 measured in the empirical and theoretical libraries. Symbols and colours are the same as in Fig. 17.

Figure 35. Comparison of the index Fe5406 measured in the empirical and theoretical libraries. Symbols and colours are the same as in Fig. 17.

Figure 36. Comparison of the index Fe5709 measured in the empirical and theoretical libraries. Symbols and colours are the same as in Fig. 17.

Figure 37. Comparison of the index Fe5782 measured in the empirical and theoretical libraries. Symbols and colours are the same as in Fig. 17.

Figure 38. Comparison of the index NaD measured in the empirical and theoretical libraries. Symbols and colours are the same as in Fig. 17.

Figure 39. Comparison of the index TiO1 measured in the empirical and theoretical libraries. Symbols and colours are the same as in Fig. 17.

Figure 40. Comparison of the index Na8190 measured in the empirical and theoretical libraries. Symbols and colours are the same as in Fig. 17.

Figure 41. Comparison of the index CaII8498 measured in the empirical and theoretical libraries. Symbols and colours are the same as in Fig. 17.

Figure 42. Comparison of the index CaII8542 measured in the empirical and theoretical libraries. Symbols and colours are the same as in Fig. 17.

Figure 43. Comparison of the index CaII8662 measured in the empirical and theoretical libraries. Symbols and colours are the same as in Fig. 17.

Figure 44. Comparison of the index Mg8807 measured in the empirical and theoretical libraries. Symbols and colours are the same as in Fig. 17.

Values of the adev obtained for the comparison between empirical and theoretical libraries

Figure 45. Values of adev from INDO-US library for each index and each theoretical library. The panels show three intervals of temperature, labelled in the plot. Black crosses, red stars and blue diamonds represent the values for Martins, Munari and Coelho libraries, respectively.

Figure 46. Values of adev from MILES library for each index and each theoretical library. The panels show three intervals of temperature, labelled in the plot. Black crosses, red stars and blue diamonds represent the values for Martins, Munari and Coelho libraries, respectively.

Figure 47. Values of adev from ELODIE library for each index and each theoretical library. The panels show three intervals of temperature, labelled in the plot. Black crosses, red stars and blue diamonds represent the values for Martins, Munari and Coelho libraries, respectively.

Table S1. Values of the adev obtained for the comparison between empirical and theoretical libraries and $T_{\text{eff}} \leq 4500$ K.

Table S2. Values of the adev obtained for the comparison between empirical and theoretical libraries and $4500 < T_{\text{eff}} \leq 7000$ K.

Table S3. Values of the adev obtained for the comparison between empirical and theoretical libraries and $T_{\text{eff}} > 7000$ K.

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