Evolutionary stellar population synthesis at 2Å spectral resolution

A. Vazdekis

Institute of Astronomy, School of Science, University of Tokyo, Osawa 2-21-1, Mitaka, Tokyo 181-8588, Japan
e-mail: vazdekis@mtk.ioa.s.u-tokyo.ac.jp

ABSTRACT

In this paper we develop an evolutionary stellar population synthesis model to predict spectral energy distributions, SED’s, for single-age, single-metallicity stellar populations, SSP’s, at resolution \(\sim 1.8\text{Å}\) in two narrow, but very important spectral regions around 4000Å and 5000Å. The input stellar database is composed of a subsample of \(\sim 550\) stars, selected from the original KPNO coude feed stellar spectral library of Jones. Therefore, this is the first time that an evolutionary model employs such an extensive empirical stellar spectral library, at such high resolution, for supporting its SED’s predictions.

A spectral library corresponding to simple old stellar populations with metallicities in the range \(-0.7 \leq [\text{Fe/H}] \leq +0.2\) is presented here, as well as an extensive discussion about the most popular system of absorption indices at intermediate resolution, the Lick system, showing the advantages of using the new model predictions. Also, for the first time is shown the behavior of the system of indices of Rose, at higher resolution, as a function of the age and metallicity of the stellar population.

The newly synthesized model spectra can be used to analyze the observed galaxy spectrum in a very easy and flexible way, allowing us to adapt the theoretical predictions to the characteristics of the data instead of proceeding in the opposite direction as, for example, we should do when transforming the observational data for using model predictions based on a particular instrument-dependent system of indices at a specific resolution. The synthetic SSP spectra, with flux-calibrated response curve, can be smoothed to the same resolution of the observations, or to the measured galaxy internal velocity dispersion, allowing us to analyze the observed spectrum in its own system. Therefore we are able to utilize all the information contained in the data, at their spectral resolution. After performing this step, the entire observational spectrum can be compared at once, or the analysis can be done measuring a particular set of features in the two, the synthesized and the observational spectrum, rather than trying to correct the latter from broadening or instrumental effects.

The SSP model spectra were calibrated at relatively high resolution with two well studied metal-rich globular clusters in our galaxy, 47 Tuc and NGC 6624, providing very good fits and being able to detect well known spectral peculiarities such as the CN anomaly of 47 Tuc. The model was also confronted to an early-type galaxy, NGC 3379, revealing its well known magnesium over iron overabundance, and showing how appropriate are the new model predictions, as well as the way in which they can be used, for...
studying the elemental ratios of these stellar systems. In fact, different models of different metallicities provide equal approaches to the galaxy spectrum: once H$_\beta$ is properly constrained, either we are able to fit the iron features (with a metallicity somewhat in the range -0.4$\leq$[Fe/H]$\leq$0) or the magnesium features (with a metallicity in the range 0$\leq$[Fe/H]$\leq$+0.2), but never the two set of indices simultaneously.

*Subject headings:* galaxies: abundances — galaxies: elliptical and lenticular, cD — galaxies: stellar content — globular clusters: individual (47 Tuc, NGC 6624) — stars: fundamental parameters
1. INTRODUCTION

The stellar population studies of galaxies, in particular the most simple ones, i.e., the early-type galaxies, have been performed originally by using photometric information (e.g., broad band filters in the Johnson system) with different types of stellar population synthesis methods (e.g., Tinsley 1980). These models try to find a combination of stars for which the integrated colors agree with the observed ones. This has been done either using a few physical constraints, the so-called empirical population synthesis models (e.g., O’Connell 1986), as opposed to the evolutionary, which, by means of a theoretical isochrone or H-R diagram convert isochrone parameters to observed ones, assuming empirical or theoretical prescriptions, and finally integrate along the isochrone assuming an initial mass function, IMF, e.g., Arimoto & Yoshii (1986). These studies showed that there is an age-metallicity degeneracy, i.e., the two effects cannot be separated simultaneously (Worthey 1994; Arimoto 1996).

Analyzing the galaxy spectra is possible to obtain more information. This analysis can be done by evolutionary stellar population synthesis models which provide spectral energy distributions, SED’s, at low dispersion, either using theoretical stellar atmospheres, e.g., Kurucz 1992 (e.g., Bressan et al. 1994; Kodama & Arimoto 1997) or empirical stellar spectral libraries (e.g., Bruzual & Charlot 1993). Also, on the basis of empirical stellar libraries, SED’s predictions are predicted by empirical population synthesis approaches (e.g., O’Connell 1980; Pickles 1985; Bica 1988). In particular, Bica (1988), used as units of population distributions of stars observed in clusters of our Galaxy, instead of individual stars.

Recently, more accurate spectral information have been addressed by predicting absorption line-strengths at intermediate resolution (~9Å FWHM) for the strongest atomic and molecular absorption features in the visible, mainly those of the extended Lick system (Worthey et al. 1994). These new generation of models (e.g., Worthey 1994; Vazdekis et al. 1996, hereafter Paper I) calculate the line-strengths of the integrated populations by means of empirical fitting polynomials which relate the stellar atmospheric parameters (T_{eff}, log g and [Fe/H]) with the measured index equivalent widths (Gorgas et al. 1993; Worthey et al. 1994). Some of these absorption indices are also predicted on the basis of other approaches than the Lick fitting functions (e.g., Peletier 1989; Buzzoni 1995). Models of this kind have shown that solar neighborhood elemental ratios are not universal in external galaxies (Peletier 1989; Worthey et al. 1992; Vazdekis et al. 1997, hereafter Paper II). In this paper we combined the information provided by almost the whole set of indices of the extended Lick system, together with optical and near-infrared broad band photometry. We found the metallicity as the main parameter causing the observed color and absorption feature gradients when going outward in giant ellipticals. These intermediate spectral resolution indicators were found very useful for studying the S0 galaxies (e.g., Bender & Packet 1995; Fisher et al. 1996; Jablonka et al. 1996; Vazdekis & Peletier 1997; Kuntschner & Davies 1998). This kind of model predictions, in particular those based on the Lick system, became very popular and widely used in most of the recent works that attempted to understand the stellar populations of the galaxies and globular clusters (e.g., Trager et al. 1998 and references therein).

However, for a correct comparison of these absorption line-strength predictions with the ones measured on the galaxy data, a number of serious problems must be solved in advance. In particular, since the stars of the Lick database are not flux-calibrated, the use of the Lick system model based predictions requires a proper conversion of the observational data to the characteristics of the instrumental response curve of this system (see the extensive analysis of Worthey & Ottaviani 1997, hereafter WO97). This is usually done by observing a number of Lick stars, with the same instrumental configuration as the one used for the galaxy. Then, comparing with tabulated Lick measurements for the same stars, the authors find some empirical corrections factors for each individual absorption feature. Another important step to be followed, is to prebroaden the observational spectra to match the resolution of that system (i.e., in most cases neglecting the higher resolution allowed by the original data), which is strongly dependent on the wavelength. From this step, a new set of empirical corrections factors for each individual feature is found on the basis of the observed common stars. Finally, the authors place their line-strength measurements on to the Lick system by applying these two types of correction factors. Thus, the analysis of the observed galaxy spectrum requires a very careful work, and do not allow to achieve all the potential offered by the data because the fixed requirements of the adopted system.
The higher the spectral resolution the higher the constraining power. However predicting such high dispersion SED’s for stellar populations is very difficult due to the non-availability of the required input stellar spectra. Among the problems the theoretical stellar spectra require heavy and non-available calculations while the empirical ones usually do not cover all the desired atmospheric parameters. There are a few studies that have attempted to include spectral features at higher resolution (e.g., Rose 1994, hereafter R94; Jones & Worthey 1995). The first author used empirical stellar spectra and Tripicco & Bell (1992, 1995) used theoretical model atmospheres to synthesize stellar population spectra for analyzing metal-rich globular clusters providing acceptable fits. R94 showed that the answer obtained from high spectral resolution analysis would be different from the one obtained by, e.g., taking into account colors. Despite the fact that 47 Tuc and M 32 show very similar colors, he found significant differences in their stellar populations on the basis of higher resolution spectra. Jones & Worthey (1995) showed the potential of their H$_{γ_{HR}}$ high resolution index to separate the metallicity and the age effects. WO97 have shown the importance of the increasing resolution when working with Balmer lines.

In Paper II we showed the necessity of using as much observational constrains as possible for increasing our discriminating power between the number of possible solutions obtained when trying to fit early-type galaxies by only taking into account colors. With the new model developed here we hope to increase even more our constraining power synthesizing spectral energy distributions in two narrow wavelength ranges around 4000Å (blue) and 5000Å (red) but at higher resolution (~1.8Å FWHM). This method is different from the previous studies because is the first time where SED’s at such resolution are predicted under the evolutionary stellar population synthesis machinery on the basis of an extensive empirical stellar spectral library of Jones (1997, hereafter J97). This model differs, e.g., from the one of Jones & Worthey (1995) in, e.g., the fact that SED’s corresponding to single-age single-metallicity stellar populations (SSP’s) are calculated, instead of predicting just a number of features at relatively high resolution via the use of empirical fitting functions of the type of those calculated by Worthey et al. (1994). It also differs from the model of Tripicco & Bell (1995) because uses an extensive empirical stellar spectral library, instead of theoretical stellar atmospheric calculations.

Section 2 explains the main points regarding the empirical stellar spectral library to be suitable for the stellar populations synthesis purpose. Section 3 explains in detail how our population synthesis model (Paper I) has been developed for synthesizing SED’s at 1.8Å FWHM for old SSP’s. In section 4 the intermediate resolution indices of the Lick system are measured on the synthetic spectra and compared with previous model predictions, showing the advantages of the use of the new SSP spectral library. For the first time is shown the behavior of the high resolution indices introduced by R94 as a function of the metallicity and age of the stellar population. In section 5 the model spectral library is calibrated with observational data of two well known metal-rich globular clusters. We discuss how these predictions can be used for analyzing the data. In section 6 we test the potential utility of the new model spectra and how they must be applied when studying an early-type galaxy. Finally, in section 7, the conclusions are presented.

2. Treatment of the empirical stellar spectral library

2.1. The stellar library

In this paper our evolutionary population synthesis model (Paper I) is extended on the basis of the empirical stellar library of J97. The stars were selected to cover the most important evolutionary phases of a wide variety of spectral types (O - M), luminosity classes (I - V) and metallicities (-2.5≤[Fe/H]≤+0.5), on the basis of the availability of their atmospheric stellar parameters. This library is composed of 684 stars for which the spectra were obtained using the coude feed telescope and spectrograph at KPNO with grating RC-250 and the TI5 800×800 pixel CCD. The spectra cover two windows, 3820-4500Å and 4780-5460Å, at a resolution of 1.8Å FWHM. The reader is referred to J97 and Leitherer et al. (1996) for more details about the library. In the present paper these two spectral ranges will be called blue and red, respectively. These two wavelength regions provide a large number of well studied absorption line indices: 14 of the 21 absorption features of the extended Lick system (Worthey et al. 1994), the new Balmer indices of WO97, the high resolution indices introduced by R94, and 3 Lick-style Balmer indices by Jones & Worthey (1995).
Since the purpose here is to use this empirical library as a stellar spectral database for our stellar population synthesis model, those stars which were peculiar were removed from the original sample. In fact, 137 stars were removed from the sample because the following reasons: spectroscopic binaries, those stars that, after checking their spectra, were found to be quite different from what expected on the basis of the given atmospheric stellar parameters and those stars with high signal of variability (except for very late or very early spectral types). However, for some parametrical regions, for which only a few stars are present, we have chosen to keep some of these anomalous stars for completeness, e.g., very hot or very low metallicity stars with $[\text{Fe/H}]<-1.0$.

2.2. Reddening

To account for the reddening affecting the colors of these stars we found in the literature around $\sim 350$ for which extinction values were given by different authors. In particular we are very greatful to V. Vansevičius (private communication) who provided the $E_{B-V}$ values for the largest number of stars. Other papers from where we took large number of extinction values were McClure (1970), Neckel et al. (1980), Bond (1980), Savage et al. (1985), Beers et al. (1990), Blackwell et al. (1990), Carney et al. (1994), Blackwell & Lynas-Gray (1994) and Alonso et al. (1996). Finally, we assumed zero extinction for nearby stars, closer than $\sim 50pc$, for which we did not find any value in the literature.

2.3. Absolute magnitude

The absolute magnitude for each star was derived using the paralaxes measured by Hipparcos. Because the stellar fluxes are going to be assigned by our population synthesis model (this point is extensively discussed in section 3), the derived distances were kept even for the farthest stars to have an estimation for the $M_V$ as a reference, rather than obtaining an accurate value. For a small number of stars for which no paralaxes were given, we either used the absolute fluxes of Bond (1980), V. Vansevičius (private communication), or we just assigned the expected values following their given atmospheric parameters.

2.4. Adopted stellar atmospheric parameters

For each star of the sample we searched in the literature for a number of sets of atmospheric stellar parameters ($T_{eff}$, $\log g$, $[\text{Fe/H}]$) provided by different authors. The main sources were J97, Cayrel et al. (1997), Edvardsson et al. (1993), Carney et al. (1994), Alonso et al. (1996), Worthey et al. (1994), Borges et al. (1995), Pilachowski et al. (1996), Axer et al. (1995) and Bonifacio & Molaro (1997). On the basis of these different sets of stellar atmospheric parameters we derived the corresponding B-V and V-I colors following the prescriptions given in Paper I (see also Section 3), and then compared with the observed ones after dereddening (using the values found in section 2.2). The set of atmospheric parameters that provided the smallest sum of squared residuals for these two colors were selected. However for those stars for which no extinction values were given we just kept the most recent values given by Cayrel et al. (1997) or by J97. At this step, we removed those stars for which the predicted colors were very different from the observed ones. In conclusion, for each of the remaining stars we kept the adopted $T_{eff}$, $\log g$, $[\text{Fe/H}]$, $M_V$ and the corresponding blue and red spectrum, as a database for our stellar population synthesis code.

The adopted parameters for this final subsample composed of 547 stars are plotted in Fig. 1. The full list of stars and parameters can be found in Vazdekis (1998). From these diagrams it can be seen that all type of stars are well represented for solar metallicity. Normal giants with metallicities in the range $-0.7 \leq [\text{Fe/H}] \leq +0.4$ are also well covered. However this is not the case for giants cooler than $\sim 3800$ K, where mainly solar metallicity stars are present. The situation is the same for dwarfs cooler than $\sim 5000$ K and hotter than $\sim 6800$ K. Unfortunately, we do not see many metal-rich dwarfs with metallicities larger than $[\text{Fe/H}]=+0.2$, preventing to build very high metal-rich models. Finally, we see that there is an acceptable surface gravity coverage. In general, we can conclude that the metallicities for which we are safe are in the range $-0.7 \leq [\text{Fe/H}] \leq +0.2$. With respect to the limitations arising from the temperature coverage of the stellar sample, we will limit the present models to cover ages larger than 6 Gyr for $[\text{Fe/H}]=-0.7$, 3 Gyr for $[\text{Fe/H}]=-0.4$ and 1.5 Gyr for models of higher metallicities.

2.5. The flux-calibration quality

In order to check the flux-calibration quality of the stellar spectra of J97, we asked Cardiel & Gorgas (private communication) to provide us with some of their
intermediate resolution, but very well flux-calibrated, stellar spectra of the stars in common with the J97 library. Twelve of these $\sim$120 common stars were selected, taking into account the fact of having different spectral types and air masses at the time of observation. Next, four well separated spectral regions, covering $\sim$300 Å each, not very crowded by absorption features were defined for the red and blue spectra. For this purpose the pseudocontinua spectral regions given by Worthey et al. (1994) were taken into account. Then the stellar spectra of J97 were smoothed to match the Cardiel & Gorgas resolution. Next, the fluxes at these spectral intervals were measured in order to derive colors for the two sample of stellar spectra. The comparison of these colors showed that the J97 flux-calibration quality is reasonably good when the colors are composed from nearby spectral regions. However for larger wavelength baselines colors, i.e. composed of spectral regions separated by more than $\sim$300 Å, we obtain differences that can be slightly larger than 0.1 magnitudes. Therefore this test confirms that the the stellar spectra of J97 are nearly flux-calibrated, and we conclude that the flux-calibration quality is acceptable within $\sim$300 Å.

3. The model

This section explains how our evolutionary stellar population synthesis model (Paper I) is used for calculating SED’s, at relatively high spectral resolution, for SSP’s on the basis of the empirical stellar library described in section 2. The reader is referred to Paper I for a complete model description, however we briefly summarize here its main aspects. The model makes predictions for the optical and IR colors and 29 absorption line indices of the extended Lick system (Worthey et al. 1994; WO97) and the Ca II triplet features in the near infrared as defined by Díaz et al. (1989). It uses the homogeneous set of the theoretical isochrones of Bertelli et al. (1994) (calculated with solar abundance ratios) and the stellar tracks of Pols et al. (1995) for the very low-mass stars. We converted to the observational plane (e.g., fluxes; colors) on the basis of the relations inferred from extensive observational stellar libraries rather than by implementing theoretical stellar atmospheric spectra. In particular, for normal dwarfs we used the metal dependent empirical relations given in Alonso et al. (1996) (obtained from their sample composed of $\sim$500 stars) to obtain each color as a function of the $T_{\text{eff}}$ and metallicity. For stars above 8000 K we performed the $T_{\text{eff}}$-color transformation of Code et al. (1976) and the color-color relation from Johnson (1966). For normal giants we used the empirical calibration of Ridgway et al. (1980) to obtain the V-K color from $T_{\text{eff}}$, after which we applied the color-color conversions of Johnson (1966) (for giants) and the empirical stellar library of Fluks et al. (1994). For the very cool giants we used the models of Bessell et al. (1989, 1991) and the Fluks et al. (1994) empirical stellar library. Finally, for predicting the line-strengths of the Lick system of indices, the model uses the empirical fitting functions obtained by Worthey et al. (1994) and Gorgas et al. (1993), while for predicting the Ca II triplet features we produced our own empirical fitting functions. As can be inferred from the above description, this model is an evolutionary stellar population synthesis code which employs, as far as possible, extensive observational stellar libraries rather than theoretical stellar atmospheric spectra to support its photometric predictions. This fact differentiates this model from most of the present day evolutionary stellar population synthesis models, which are heavily based on, e.g. the theoretical stellar spectra of Kurucz (1992), from which the colors are calculated. The code is also able to produce more complex stellar populations if we use its full chemo-evolutionary option (see Paper I).

Despite the fact that this model provides spectral information in the form of line-strengths, there is a lack of SED predictions. In this paper the model is extended to predict SED’s at two narrow spectral regions but at 1.8 Å FWHM resolution, always keeping our criterion to give the priority to the use of the empirical stellar libraries. Following, we explain how to make such predictions starting at the point when the code yields a stellar distribution for an SSP of age $T_G$ and metallicity $Z$ (we refer the interested readers to Paper I for details regarding previous steps of the model calculation). To obtain the high resolution spectrum corresponding to a SSP, $S_{\lambda}(T_G, Z)$, we integrate in the following way:

$$S_{\lambda}(T_G, Z) = \int_{m_i}^{m_f} S_{\lambda}(m, T_G, Z)F_{\lambda_{ref}}(m, T_G, Z)N(m, T_G)dm$$

where $S_{\lambda}(m, T_G, Z)$ is the empirical spectrum corresponding to a star of mass $m$ and metallicity $Z$ which is alive at the age assumed for the stellar population $T_G$, $F_{\lambda_{ref}}(m, T_G, Z)$ is its corresponding abso-
lute flux at certain wavelength reference point, and 
$N(m, T_G)$ is the number of this type of stars. The 
spectrum to be assigned to each of these stars is se-
lected from the empirical stellar database, while the 
corresponding total flux is assigned following the pre-
scriptions of our code. Therefore we need to find a 
common reference wavelength point, $\lambda_{ref}$, from where 
to scale $S_\lambda(m, T_G, Z)$. We selected a $\sim$30Å wide spec-
tral range, not very crowded by absorption lines along 
the stellar spectral type, around the peaks of the B 
and V bands filters. These regions are (4421-4451Å) 
for the blue, and (5415-5443Å) for the red. The two 
regions fall almost at the red edge side of each spectrum 
(blue and red). We divided the stellar spectra 
of the whole empirical stellar sample by the average 
value at the selected regions, so that we obtain a value 
of 1 at 4436Å for the blue and at 5429Å for the red. To calculate the absolute flux at the selected refer-
ence points, $F_{\lambda_{ref}}(m, T_G, Z)$, for each of the stars 
requested by the code, we first used equation (6) of 
Code et al. (1976), which provides a relation between 
the absolute V flux and the calibrated bolometric cor-
rection, to infer the following relation:

$$\frac{F_V}{F_{bol}} = 10^{-0.4(M_V - 3.762)}$$

where $F_V$ is the absolute V flux, and the absolute 
magnitude is provided by the code. The predicted 
model color B-V is used to calculate the absolute B 
flux by:

$$\frac{F_B}{F_{bol}} = \frac{F_V}{F_{bol}} 10^{-0.4(B-V)}$$

Finally, the absolute V and B fluxes are divided by 
their effective equivalent widths to obtain the absolute 
flux per Angstrom, in order to be assigned to the two 
selected reference wavelength points.

The empirical stellar spectrum $S_\lambda(m, T_G, Z)$, to be 
assigned to a requested star for which the model pro-
vides $T_{eff}, \log g, [\text{Fe/H}]$ and $M_V$, is selected from the 
whole sample of 547 stars according to the following 
method:

- Depending on whether the required star is gi-
  ant ($\log g < 3.5$) or dwarf ($\log g \geq 3.5$), the 
  model selects from the sample all these stars 
  with temperatures in the range ($T_{eff} - \Delta T_{eff}$, 
  $T_{eff} + \Delta T_{eff}$).

- Next, the remaining stars are discriminated 
taken into account their metallicities, which 
must be in the range ($[\text{Fe/H}] - \Delta[\text{Fe/H}], [\text{Fe/H}] + \Delta[\text{Fe/H}]$).

- In the last step, the code selects those stars that 
simultaneously satisfy the conditions of hav-
ing $\log g$ and $M_V$ in the ranges ($\log g - \Delta \log g$, 
$\log g + \Delta \log g$) and ($M_V - \Delta M_V, M_V + \Delta M_V$), re-
spectively.

As can be seen above, the first criterion taken into 
account was the effective temperature and the condi-
tion of giant or dwarf. The metallicity was the sec-
ond constraint applied. The final step is performing a 
more fine tuning for the luminosity class. The subse-
quient step is only followed when having found at least 
one star from the sample after applying the present 
step. At a certain step, when no stars are found, 
the range is gradually increased in a much more fine 
tuning until at least one star is found. In spite of 
the fact that our starting minimum box is very small 
(of the order of typical error stellar atmospheric pa-
rameter determinations) in most of the cases, after 
this selection procedure, remain more than just a sin-
gle star because our stellar database is quite large. 
Therefore, usually, the code averages the surviving 
stellar spectra. However, in no case is performed 
any interpolation between stars with different atmo-
spheric stellar parameters. Bruzual & Charlot (1993) 
showed that only in 5% of the cases the situation im-
proved when interpolating (also, their stellar library 
is in fact around 5 times smaller than ours). When 
dealing with a parametrical region not covered by any 
star, the code chooses the closest one. For the most 
important cases the minimum box described above 
was: $\Delta T_{eff}=90$ K, $\Delta [\text{Fe/H}]=0.13$, $\Delta \log g=0.6$ and 
$\Delta M_V=0.75$. Of course, this selection worked very 
well for the solar metallicity as inferred from Fig. 1. 
However, to account for the fact that always are found 
more number of stars at the half part of the box 
which is closer to $[\text{Fe/H}]=0.0$, for $[\text{Fe/H}]=-0.7$ and 
$[\text{Fe/H}]=+0.2$ (see below) we left our starting metallic-
ity ranges asymmetrical, being the less crowded side 
two times greater. Also more generous ranges were 
established for those parametrical regions where not 
many stars can be found (e.g., for cool and hot stars 
for metallicities different than solar). In this way we 
avoided the fact to, e.g., assign a very hot metal-poor 
star to a metal-rich one, because the $T_{eff}$ was the 
first criterion applied. This does not mean that the 
other of the steps explained above is changed, since
the accuracy of the given temperatures, e.g., above 7000 K, is in fact much lower.

Models of metallicity [Fe/H]=+0.2. The present stellar spectral library does not allow us to build very high metallicity models. However, since our effort is mainly devoted to study galaxies it is worth to show models for as higher metallicity as it allowed. Due to the fact that the limit imposed by our stellar library is [Fe/H]=+0.2 (see section 2.4) and because our stellar population synthesis model is based on the Padova isochrones (calculated for solar and 2.5 times solar metallicity, i.e., [Fe/H]=0.0 and [Fe/H]=+0.4, respectively), we need either to interpolate between the isochrones before using them for calculating the SSP synthetic spectrum, or to interpolate the final output spectra after calculating them on the basis of the closest isochrones. For simplicity, we followed the second approach: for each assumed age, we first calculated the spectrum for an SSP corresponding to [Fe/H]=+0.2 on the basis of the isochrones of metallicity [Fe/H]=0.0, and another spectrum on the basis of the isochrones of [Fe/H]=+0.4. Finally, the two resulting spectra are combined to obtain one which resembles a metallicity of [Fe/H]=+0.2. In fact we find this way safe enough since our method of selecting the stellar spectra is based on the desired metallicity ([Fe/H]=+0.2) rather than on the metallicity of the isochrones. Also, in order to ensure the participation of a larger number of metal-rich stellar spectra we selected an asymmetrical starting box in the metallicity range +0.1 ≤ [Fe/H] ≤ +0.4. Thus, all the stars involved in the two calculations do have metallicities around [Fe/H]=+0.2, while the main differences between the two resulting spectra arise from the fact that the average effective temperature of the SSP spectrum obtained on the basis of the solar metallicity isochrone is somewhat ~200 K higher (if we average between all the ages above 1.5 Gyr).

4. The synthetic SSP spectra at 1.8 Å

Instead of giving an extended list of the new model spectra and/or tables of different spectral indices as measured on the resulting spectra, in this paper we have preferred to study the behavior of the Lick system of indices, at intermediate resolution, when compared with model predictions based on the empirical fitting functions derived from the stellar Lick library (see section 1). Here we also show for the first time the behavior of the higher resolution indices of R94 as a function of the metallicity and age. For this purpose, synthetic spectra at 1.8Å FWHM (0.6Å/pix) corresponding to single-aged simple stellar populations of metallicities [Fe/H]=-0.7, -0.4, 0.0 and +0.2 were calculated. For each metallicity, the ages were varied from 1.6 to 17 Gyr, except for the lowest metallicity where we started at 6.3 Gyr and for [Fe/H]=-0.4 starting at 3.2 Gyr. The reason for not calculating younger ages arises from the limitations of the present library as already discussed in section 2.4. To be more general, in this section we used the Salpeter (1955) initial mass function. The resulting spectra cover the following wavelength ranges: 3856-4476Å for the blue and 4795-5465Å for the red.

The extended data set including the variation of the IMF, as well as a discussion regarding the behavior of these spectral indices at different resolution, i.e., at different galaxy velocity dispersions, will be published elsewhere.

4.1. The Lick indices

This section shows a comparison between the Lick indices as measured on the synthetic spectra and as calculated in Paper I, i.e., on the basis of the empirical fitting functions of Worthey et al. (1994) and Gorgas et al. (1993). However, transforming our line-strength measurements on the new spectra to the Lick system (i.e., the predictions in Paper I) is not so straightforward, because this system is based on an stellar library which is not flux-calibrated, and because its resolution FWHM depends on the wavelength range (see WO97 for an excellent review). Also, these authors tested very carefully, various methods with different stellar libraries, yielding to a large scatter regarding the resolution. Here, for simplicity, we prebroadened our SSP’s synthetic spectra by convolving with gaussians (see Table 2) which allowed us to match our measurements on the smoothed spectra for two strongly resolution sensitive indicators, the Ca4227 in the blue and the Fe5335 in the red, to the model predicted values calculated on the basis of the empirical fitting functions for the solar metallicity models. Table 1 shows the measured values for different metallicities and ages, while Table 2 provides the way for converting the new index values to the previous predictions of Paper I, i.e., on the Lick system instrumental response curve and resolution.

We perform here a comparison on absolutely similar model prescriptions (the code is the same one),
representing, in fact, a comparison of the Lick indices for SSP’s as derived from the Lick instrumental response curve and as measured on the Lick’s flux-calibrated spectra. The main difference is the different input stellar libraries, however, since the number of stars is quite large in the two samples the discussion presented here cannot be significantly affected. The results are summarized in Fig. 2.

As it was noted above, the Ca4227 and Fe5335 line-strengths are fully matched for solar metallicity. Good agreement is also found for the resolution sensitive indicators Fe5270 and Fe5406.

The Mg1 and the Mg2 show important differences which become larger as a function of the increasing metallicity. We attribute this to the fact that in their index definitions the two pseudocontinua are separated by around 470Å, being in this way very sensitive to the differences between the spectrum shape of our nearly flux-calibrated (very safe within ~300Å but smaller than the required range) model spectra and the instrument dependent Lick indicators, and because the characteristic Mg bump becomes more prominent as a function of the metallicity. The same effect is seen for the much narrower Mg6, but to a much less extent.

The observed model shifts for the CN are surprisingly small despite the fact that WO97 showed a rapid decrease of the resolution FWHM of the Lick system as a function of decreasing wavelength for the regions corresponding to our blue spectra, and because the large wavelength coverage of the CN indices. This fact was already pointed out by these authors on the basis of their comparison of various stellar samples.

The long wavelength coverage definitions must contribute in part to the observed differences for the Fe4383 and Fe5015. The latter also shows an increasing shift for a decreasing metallicity. However, in this case, the trend depends to some extent to the resolution adopted. The model differences for Fe4383 and Fe5015 are somewhat lower and higher, respectively, than the shifts given by WO97 in their Table 9. These authors performed a direct comparison of the spectra of the stars in common between the Lick and Jones samples, after broadening the latter stellar sample by their favorite values provided in their Table 8. These differences must be attributed in part to the differences in smoothing, i.e., if the applied broadening is quite different, this trend could well be reversed.

The behavior of the G band is slightly different from what expected from the calculations based on the empirical fitting functions. The G band tends to converge to the same level for old populations at different metallicities. Notice that, for this index, the dependence of the differences between the two kind of predictions increase with decreasing metallicities (in opposite direction to the Mg1 and the Mg2 indices). However, as for the Fe5015, this is in part determined by the applied smoothing.

Finally, the new strengths obtained for Hβ are slightly higher than those based on the empirical fitting functions for the oldest populations. The model differences are larger for increasing metallicity but the average value is very similar to the one given in WO97.

In Fig. 3 we perform the same kind of comparison as in Fig. 2 for the new Balmer indices defined in WO97. In this plot we have included their model predictions for solar metallicities. In general we see that our values, either as calculated on the basis of their empirical fitting functions or as measured on the new spectra, are lower than their predictions. These differences are attributed mainly to the fact that our respective models are based on different set of isochrones, being ours slightly cooler. The same explanation was given for the observed differences in Hβ for the model comparison performed in Paper I.

After analyzing Fig. 2 and Fig. 3 we should warn the users of the stellar population synthesis models to be aware of these differences, which can lead to different results when interpreting the observational data. For example, if we want to use the Mg2 or Hβ vs. age diagrams for interpreting some observed values that, e.g., fall onto a ~12 Gyr solar metallicity for the model predictions based on the empirical fitting functions (see thin solid line on Fig. 2), it can also be interpreted as a result of a stellar population of the same metallicity but ~17 Gyr old when using the flux-calibrated SSP model spectra (thick solid line). The situation can be even worse if the observed values are not properly transformed to the characteristics of the Lick system instrumental response curve and resolution(s). In this case, model predictions based on the empirical fitting functions can drive easily to erroneous interpretations. Also, Fig. 2 reveals to what extent can be difficult to perform a proper data conversion to the Lick system since the response could also depend on model parameters such as the metallicity or age. In fact, when looking at, e.g., the Mg2 plot, we see that a correct conversion to the Lick system can-
not be performed without knowing a priori the metallicity of the observed target which, in fact, is intended to be studied. It is rather clear that the model spectral library presented here represents a considerably more flexible tool, and overcomes most of the previous problems, when using the Lick indices for an easier and correct stellar population interpretation. For increasing the analyzing power, the interested users should first flux-calibrate their observational data or normalize in the same way the two, the observed and the synthetic SSP model spectra. Next, by smoothing the theoretical SSP spectra to the galaxy velocity dispersion or data resolution, we will be able to treat each galaxy spectrum in its own system and interpret the information at the highest spectral resolution allowed by the data. The present approach prevents for performing the heavy task of correcting the particular indices measured on the galaxy spectrum for the broadening and instrumental response curve effects, as it is required when applying the Lick-system based stellar population model predictions. Finally, if our purpose is to compare a group of galaxies of different internal velocity dispersions under absolute similar resolution conditions, then we always are able to smooth all the data as well as the model spectra to a common velocity dispersion value. Examples of how to use the new SSP spectral library and this approach for performing the analysis is given in sections 5 and 6.

4.2. Rose indices

Since our SSP’s spectra can be obtained for higher resolution than the one(s) required by the Lick system, it is worth to show the behavior of the R94 system of indices with model parameters. This system has the advantage to contain many indicators which are in some cases dominated by different elements from those of the Lick system, showing important dependences on ages, metallicities and luminosity type in a very reduced portion of the galaxy spectra around 4000Å. The way in which these indices have been defined differs considerably from the Lick style indicators. We refer the reader to R94 (and references therein) where the author has extensively discussed and applied this high resolution system of indices to observational data of globular clusters and galaxies.

Fig. 4 shows the dependence of these indices as a function of the metallicity and age of the stellar population. The indices were directly measured on the resulting spectra, without performing any degradation of the resolution (i.e., 1.8Å FWHM). Their dependence on the resolution will be fully addressed in another paper and in Vazdekis & Arimoto (1998). The three indices Fe\textsubscript{I}HR, Ca\textsubscript{II}HR and H\textsubscript{γ}HR were measured following the prescriptions given in Jones & Worthey (1995) who slightly changed the original definitions of R94.

In general, we see that most of the indices evolve smoothly in spite of the fact of the high resolution involved. Most of the indices behave like most of the Lick indices: higher values for higher metallicities and ages.

On the other hand, the 4384/4352 and H\textsubscript{γ}HR indices decrease with these two model parameters, however, the latter is much less affected by the metallicity effect around solar values. H\textsubscript{γ}HR has been claimed by Jones & Worthey (1995) as the strongest age discriminator. In particular they find that around 12 Gyr its derivative $d \log t / d \log Z$ is zero. We find that its dependence on the metallicity is not very important but is not negligible depending on the metallicity level. In fact their finding is fully true for solar and half a solar metallicity models. It is worth to note that these authors smoothed their spectra by 83 km s$^{-1}$. However we see a strong dropping of the values for models with [Fe/H]=-0.7. Also, our most metal-rich models of $\sim$17 Gyr show very similar values to those of solar models of $\sim$11 Gyr. A redefinition of this index by using the new SSP spectral library allowed us to increase substantially its already high discriminating power (Vazdekis & Arimoto 1998). In that paper we also address the problem of its behavior as a function of the resolution.

Finally, the remaining two indices, CaII and p4220/4208, are nearly constant within the covered range of ages despite the fact that the scale is considerably narrow. For a detailed discussion about these indices and their errors we refer the reader to R94 (and references therein).

5. Calibration with globular clusters

In principle, the globular clusters represent uniform stellar populations and therefore they can be used to test the new synthetic model spectra corresponding to single-age, single-metallicity populations. Two metal-rich clusters in our galaxy, 47 Tuc and NGC 6624, were selected for this purpose. J. Rose kindly provided his blue flux calibrated spec-
trum of 47 Tuc and the non flux calibrated one for NGC 6624, both at $\sigma \sim 83$ Kms$^{-1}$. Spectra that cover the two ranges analyzed in this paper at resolution 3.4Å FWHM were generously provided by S. Covino. We also used a flux-calibrated spectrum at 8.1Å FWHM covering the two spectral ranges for 47 Tuc and a non flux-calibrated one covering the red region at 2.1Å FWHM for NGC 6624, the two spectra provided by S. Covino. On the other hand, for performing a comparison between these observations and our predictions we have preferred to calculate model spectra using the bimodal IMF as defined in Paper I, which only differs from the Salpeter IMF in the fact that it decreases the number of stars with mass lower than 0.6M$_{\odot}$, while its slope is the same. This selection is favored because the present stellar database does not contain many of these stars, and since we showed in Paper II that it provided slightly better fits for a small number of standard early-type galaxies. Following, we provide two examples of how to study the collected data. First, we deal with the whole information contained in the spectrum at once. Next, we study some key individual spectral features at the highest resolution allowed by the data.

The height of the resulting peak when crosscorrelating the observed and synthesized spectra provides a rough but an overall overview of the similarities between them. Also, the height of this peak only provides us a relative idea of the goodness of the global spectra as they are, but not an absolute value when comparing the obtained peak heights between different objects or observations. To prepare the model spectra for this purpose, they were conveniently degraded by convolving with a gaussian function to match the resolution of the observed data. Then, the observational and the model spectra were rebinned logarithmically and normalized using a spline3 of a fixed low order to remove the continua. The continuum removal was performed with great care taking into account the peaks of the spectra. When the observed spectra would have been flux-calibrated, this task was considerably easier and safer. However if the spectrum still contains the instrumental response, large scale structure can be very difficult to remove and cause not only the lose of the information contained in indices with large wavelength coverage, but also narrower indicators contained within larger scales can be affected during the normalization step. Prior to the crosscorrelation, the spectra were adequately filtered to remove the highest frequencies and multiplied by a cosine-bell-like functions (see Tonry & Davies 1979 and González 1993 for details about this method). As an example of this application, Fig. 5 shows the height of the peak obtained after crosscorrelating the blue spectrum of 47 Tuc with model spectra of different metallicities and ages at $\sigma \sim 83$ Kms$^{-1}$. One sees a clear cut difference between the solar and the models of metallicity $[\text{Fe/H}]=-0.7$. A very similar plot is obtained when performing this test using the data provided by Covino at 3.4Å FWHM and the SSP spectral library prebroadened to match that resolution for the blue and red spectral ranges. Finally, the same results are obtained for the spectra at 8.1Å FWHM, in spite of the fact that this metallicity cut is less pronounced. For saving space we do not show any of these plots, as well as those performed for NGC 6624, for which the same results arise even when the red spectrum at 2.1Å FWHM is involved. Fig. 5 suggests that the most likely synthetic spectrum should be found among models of $[\text{Fe/H}]=-0.7$ and ages larger than 8 Gyr, or those of $[\text{Fe/H}]=0.4$ and ages around 6–8 Gyr, and also shows that the present fitting approach is more sensitive to the metallicity than to the age of the clusters. This application serves as an example of how to deal with the whole information contained in the spectra at once, irrespective of the spectral resolution involved.

As cited above, the crosscorrelation technique allowed us a rough but global evaluation of the goodness of our fits, however, for a further understanding of the nature of the present crosscorrelation results and for utilizing the advantages of the higher resolution, which selectively emphasizes certain individual features that give unique information (R94; Jones & Worthey 1995), we have chosen to perform various key index-index diagrams of the type used in, e.g., Rose (1985), Rose & Tripicco (1986) or R94. Thus, we first measured the Rose system of indices (see section 4.2) on the blue spectra of the two clusters, and on the synthetic SSP library prebroadened to match the resolution of the former ones. Fig. 6 shows various of these diagrams selected on the basis of their ability to separate the effects of the metallicity and the age. We see that the previous crosscorrelation results are robust but now much strongly constrained, particularly, the first three plots indicate that the metallicity for the two clusters should be $[\text{Fe/H}]\sim-0.7$. The same diagrams also suggest ages in the range 10–15 Gyr. Our metallicity prediction for 47 Tuc is in agreement with Zinn (1985) and Webbink (1985), however our
estimation for NGC 6624 is lower than the value corresponding to the first author but more similar to the one tabulated in the second paper. Also, from the line-strengths of the Lick indices given in Table 3 of Covino et al. (1995) or those of Table 3 of Cohen et al. (1998), we do not find significant differences in the measured values between these two clusters suggesting similar metallicities, in agreement with our result here. Finally, in the Hα/4045 vs. Hδ/4045 plot of Fig. 6 we see that the observed values do not follow the model lines, showing the strong CN absorption feature for the two metal-rich clusters. This well known anomaly is present in both, their individual stellar spectra (e.g., Norris & Freeman 1979) or in their integrated light (e.g., Rose & Tripicco 1986). See also the discussion by R94 who built a synthetic spectrum for studying 47 Tuc. Tripicco & Bell (1992) also built a CN-strong SSP high resolution spectrum, based on the oxygen-enhanced theoretical isochrones of VandenBerg (1992), and varied the Carbon and Nitrogen abundances to fit the 47 Tuc CN feature in a satisfactory way. Our results here are in good agreement with their predicted age and metallicity.

Fig. 7 shows a 13 Gyr model spectrum of metallicity $[Fe/H]=-0.7$, conveniently smoothed, overplotted on the blue spectrum of 47 Tuc. This figure not only shows the quality of the fit, but also the quality of the flux-calibration of the model spectrum which is in excellent agreement with the observed cluster spectrum. As discussed above, the model spectrum, which is based on solar element ratios stellar spectra, is not able to fit the strong CN anomaly of this cluster but it is very sensitive in detecting such spectral peculiarities. Fig. 8 shows the normalized synthetic red spectrum (13 Gyr, $[Fe/H]=-0.7$) slightly broadened, overplotted on the observational spectrum of NGC 6624 at 2.1A FWHM.

The present section not only served for comparing our new model library with metal-rich globular clusters, but also showed how easily this library can be applied to study them, by first adapting the synthetic spectra to the characteristics of the observational data and, then, performing the comparison either using the whole spectrum at once, or studying a set of well defined indicators at the highest spectral resolution allowed by the data. The flux-calibration of the data helps in making even easier and safer this study, as well as to extract most the information provided by wider features. We provided excellent fits which allow to infer the ages and metallicities of these two metal-rich globular clusters. This study also showed the capacity of this new SSP spectral library to detect spectral anomalies in agreement with previous determinations.

6. An application to an early-type galaxy

Here we address the potential power of the new model predictions, as well as the way in which they can be used, for analyzing the galaxy data. In particular it will be shown that we can adapt our theoretical spectra to the characteristics of the observational galaxy spectrum and then performing a comparison in a consistent and very easy way. As an example, we have chosen an standard elliptical galaxy, NGC 3379, that we had studied in detail in Paper II by taking into account most of the spectroscopic absorption features of the Lick system and the broad band colors from U to K. The full chemo-evolutionary version of our code (see Paper I) predicted a very small spread in metallicity for the central regions of this galaxy, and that the bulk of the stars were formed at the very early stages of the galactic evolution (at lower ages than $\sim$1 Gyr) (see Paper II for details). Therefore single-age, single-metallicity stellar populations are suitable to provide reasonable fits to this galaxy. In fact, in that paper we found an acceptable fit at $5''$ of its center using an SSP of metallicity slightly larger than solar and $\sim$13 Gyr. These fits were found after excluding all the iron-dominated Lick features, because they were very weak when compared to most of the other Lick indices.

For studying this inner region of NGC 3379 (at $\sim$13% of its effective radius) using the new models, we first smoothen the synthetic spectra to match the velocity dispersion ($\sim 235 \text{ Kms}^{-1}$) obtained at this galactocentric distance. In this way it will be no longer necessary to calculate any velocity dispersion correction factors to analyze correctly certain absorption features (e.g, Davies et al. 1993). Since our observed galaxy spectrum is not flux-calibrated, we performed once again a very careful continuum removal to ensure a correct comparison, e.g., for using the crosscorrelation technique. The resulting peak heights are plotted in Fig. 9. One sees that the three models provide equally high values, but at slightly younger ages when increasing the metallicity from $[Fe/H]=-0.4$ to $[Fe/H]=+0.2$. This behavior differs from the ones that we obtained for the two globular clusters analyzed in section 5, where only the lowest
metallicities produced the largest heights in an appreciable way. Fig. 10 shows the galaxy spectrum with a representative model spectrum for each metallicity overplotted. Each of the three model spectra provide reasonable fits for Hβ, our most metal-rich model produces a reasonable Mgθ feature at 5175Å, but too strong iron features (e.g., Fe5015; Fe5270; Fe5335; Fe5406). The solar model spectrum almost fits the Mgθ feature, but still provides strong iron-dominated features. On the other hand, the half a solar metallicity spectrum does not provide enough depth to the iron features and not at all to the Mgθ feature. If we fix the age for the three metallicity models at, e.g., ∼15 Gyr (following Fig. 9), the half a solar model ([Fe/H]=-0.4) will produce slightly worse fits since the slightly younger age weakens the magnesium and the iron-dominated features. From this discussion it is now rather clear why different models of different metallicities can provide equal approaches to the galaxy spectrum: once Hβ is properly constrained, either we are able to fit the iron features (with a metallicity somewhat in the range -0.4≤[Fe/H]≤0) or the magnesium features (with a metallicity in the range 0≤[Fe/H]≤+0.2), but never the two set of indices simultaneously, in agreement with our deep analysis performed in Paper II. Thus, the new model spectra were able to identify the galaxy spectral peculiarities such as differences in the element ratios. A great advantage here is that the analysis has been done in a very simple way, and in particular avoiding the tedious and difficult task to match the spectrum shape of the observational data to the instrumental response curve of any system of indices (e.g., Lick), and without calculating the required velocity dispersion correction factor for each individual feature. In the present approach, we have utilized all the spectral information contained in the observational data, only limited by the galaxy internal velocity dispersion.

7. Conclusions

In this paper the evolutionary stellar population synthesis model of Vazdekis et al. (1996) is extended to predicts spectral energy distributions corresponding to SSP’s at resolution 1.8Å FWHM for two narrow, but very important wavelength ranges, around 4000Å and 5000Å. The new model uses as a database a subsample of 547 stars selected from the original Jones (1997) stellar spectral library, after a careful atmospheric parameters selection and removal of most of the peculiar stars (see also Vazdekis 1998). Therefore, this is the first time that an evolutionary model employs such an extensive empirical stellar spectral library, at such high resolution, for supporting its SED’s predictions.

A spectral library corresponding to simple old stellar populations with metallicities in the range −0.7 ≤ [Fe/H] ≤ +0.2 is presented here, as well as an extensive discussion about the most popular system of absorption indices at intermediate resolution, the extended Lick system (Worthey et al. 1994 and Worthey & Ottaviani 1997), showing the difficulties for a proper transformation of the observational data to that system. Also, for the first time is shown the behavior of the system of indices of Rose (1994) at higher resolution as a function of the age and the metallicity. The model spectral library can be retrieved from the web homepage of the author [http://www.ioa.s.u-tokyo.ac.jp/~vazdekis/].

The newly synthesized model spectra can be used to analyze the observed galaxy spectrum in a safe and flexible way, allowing us to adapt the theoretical predictions to the nature of the data instead of proceeding in the opposite direction as, for example, we should do when transforming the observational data to perform an analysis using model predictions based on a particular instrumental dependent system of indices at a specific resolution(s) (e.g., the Lick system). The synthetic SSP library, with flux-calibrated spectral response, can be smoothed to the same resolution of the observations or to the measured internal galaxy velocity dispersion, allowing us to analyze the observed spectrum in its own system and therefore utilizing all the information contained in the data, at their higher spectral resolution. After performing this step, the entire observational spectrum can be compared at once, or the analysis can be done measuring a particular set of features in the two, the synthetized and the observed spectrum, rather than trying to correct the latter from broadening or instrumental effects, e.g., which characterize the system at which we desire to transform. For a more correct and easy analysis the spectra should be normalized or they can be compared directly if the observational data are flux-calibrated. In fact, we strongly recommend to carry out this step (even before any normalization), which does not only places all the data at the same reference, but also for allowing to detect spectral peculiarities at larger scale, such as very strong Mgθ or CN absorption features.

The SSP model spectra were calibrated at rela-
tively high resolution with two standard metal-rich globular clusters, providing very good fits which not only allowed to predict their metallicity and age, but also to being able to detect well known spectral peculiarities such as the CN anomaly. The library was also confronted to an standard early-type galaxy, NGC 3379, revealing its well known magnesium over iron overabundance (Vazdekis et al. 1997), showing how appropriate are the new model predictions and the proposed methodology of analysis to study the elemental ratios. In fact, different models of different metallicities provide equal approaches to the galaxy spectrum: once H$\beta$ is properly constrained, either we are able to fit the iron features (with a metallicity somewhat in the range -0.4$\leq$[Fe/H]$\leq$0) or the magnesium features (with a metallicity in the range 0$\leq$[Fe/H]$\leq$+0.2), but never the two set of indices simultaneously.

As mentioned above, the predicted spectra offer the possibility to perform the study comparing any set of absorption indices (which falls in these spectral ranges) with the corresponding observed ones, after measuring them under the same conditions. An extensive set of tables and spectra corresponding to simple stellar populations with different model parameters, including the variation of the IMF, will be presented elsewhere. In that paper we explore the behavior of the different indicators as a function of the spectral resolution, i.e., the galaxy velocity dispersion. Vazdekis & Arimoto (1998) make use of the present SSP spectral library to redefine the H$\gamma$ index for increasing its unprecedented age discriminating power (Jones & Worthey 1995), and for studying its behavior as a function of the resolution and other factors.

The stellar population studies would strongly benefit from expanding the present stellar database to those parametrical regions not well covered by stars. Particularly, observations of metal-poor and metal-rich stars as well as very cool and hot stars are required to enlarge considerably the present range of predictions for the stellar populations of galaxies. This not only will allow to analyze a larger variety of galaxies, but also for performing more reliable predictions from more complex models which include, e.g., chemical evolution. Also, very important will be to extend the present wavelength coverage to account for the contributions from different stellar populations.

The author is indebted to L. Jones for making available his library, to V. Vansevičius for providing reddening values for the stellar sample, to J. Rose and S. Covino for providing their globular cluster spectra and to N. Cardiel and J. Gorgas for providing with a set of their stellar spectra before publication. The author is specially grateful to N. Arimoto, V. Vansevičius, R. Peletier and the non anonymous referee, J. Rose, for very useful comments and lots of suggestions which greatly improved this paper. My special thanks goes to my wife Sonia for lots of help and patience. The author thanks the Japan Society for Promotion of Science for financial support. This work was financially supported in part by a Grant-in-Aid for the Scientific Research (No.09640311) by the Japan Ministry of Education, Culture, Sports and Science.

REFERENCES
Alonso, A., Arribas, S., Martinez-Roger, C., 1996, A&AS, 117, 227
Arimoto, N., 1996, ASP Conference Series, Vol. 98, From Stars To Galaxies, eds. C. Leitherer, U. Fritze-von Alvensleben & J. Huchra, p. 287
Arimoto, N., & Yoshii, Y., 1986, A&A, 164, 260
Axer, M., Fuhrmann, K., Gehren, T., 1995, A&AS, 300, 751
Beers, T.C., Preston, G.W., Shectman, S.A., Kage, J.A., 1990, AJ, 100, 848
Bender, R. & Paquet, A., 1995, IAU Symp. 164, Stellar Populations, eds. P.C. van der Kruit & G. Gilmore (Dordrecht: Kluwer), p. 259
Bertelli, G., Bressan, A., Chiosi, C., Fagotto, F., Nasi, E., 1994, A&AS, 106, 275
Bessell, M.S., Brett, J.M., Scholz, M., Wood, P.R., 1989, A&AS, 77, 1
Bessell, M.S., Brett, J.M., Scholz, M., Wood, P.R., 1991, A&AS, 89, 335
Bica, E., 1988, A&A, 195, 76
Blackwell, D.E., Petford, A.D., Arribas, S., Haddock, D.J., Selby, M.J., 1990, A&A, 232, 396
Blackwell, D.E. & Lymas-Gray, A.E., 1994, A&A, 282, 899
Bond, H.E., 1980, ApJS, 44, 517
Bonifacio, P. & Molaro, P., 1997, MNRAS, 285, 847
Borges, A.C., Idiart, T.P., de Freitas Pacheco, J.A., Thevenin, F., 1995, AJ, 110, 2048
Bressan, A., Chiosi, C. & Fagotto, F., 1994, ApJS, 94, 63
Bruzual, G. & Charlot, S., 1993, ApJ, 405, 538
Buzzoni, A., 1995, ApJS, 98, 69
Carney, B.W., Latham, D.W., Laird, J.B., Aguilar, L.A., 1994, AJ, 107, 2240
Cayrel de Strobel G., Soubiran C., Friel E.D., Ralite N., Francois P., 1997, A&AS, 124, 299
Code, A.D., Davis, J., Bless, R.C., Hanbury Brown, R., 1976, ApJ, 203, 417
Cohen, J.H., Blakeslee, J.P., Ryzhov, A., 1998, ApJ, 496, 808
Covino, S., Galletti, S. & Pasinetti, L.E., 1995, A&A, 303, 79
Davies, R.L., Sadler, E.M. & Peletier, R.F., 1993, MNRAS, 262, 650
Díaz, A., Terlevich, E., Terlevich, R., 1989, MNRAS, 239, 325
Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D.L., Nissen, P.E., Tomkin, J., 1993, A&A, 275, 101
Fisher, D., Franx., M. & Illingworth, G., 1996, ApJ, 459, 110
Fluks, M.A., Plez, B., Thé, P.S., de Winter, D., Westerlund, B.E., Steenman, H.C., 1994, A&AS, 105, 311
González, J.J., 1993, Ph.D. Thesis, Univ. of Lick, Santa Cruz, California
Gorgas, J., Faber, S.M., Burstein, D., González, J.J., Courteau, S. & Prosser, C., 1993, ApJS, 86, 153
Jablonka, P., Martin, P. & Arimoto, N., 1996, AJ, 112, 1415
Johnson, H.L., 1966, ARA&A, 4, 193
Jones, L.A, 1997, Ph.D. Thesis, Univ. of North Carolina, Chapel Hill (J97)
Jones, L. & Worthey, G., 1995, ApJ, 446, L31
Kodama, T. & Arimoto, Y., 1997, A&A, 320, 41
Kuntschner, H. & Davies., R., 1998, MNRAS, 295, 29
Kurucz, R.L., 1992, in The Stellar Populations of Galaxies, ed. B. Barbuy & A. Renzini (Dordrecht: Kluwer), 225
McClure, R.D., 1970, AJ, 75, 41
Neckel, Th., Klare, G., Sarcander M., 1980, A&AS, 42, 251
Norris, J., & Freeman, K.C., 1979, ApJ, 230, L19
Leitherer, C., et al. 1996, PASP, 108, 996
O’Connell, R., 1980, ApJ, 236, 430
O’Connell, R., 1986, in Stellar Populations, ed. C. Norman, A. Renzini and M. Tosi, Cambridge University Press, p. 167
Peletier, R.F., 1989, Ph. D. Thesis, Univ. of Groningen
Pickles, A.J., 1985, ApJ, 296, 340
Pilachowski, C.A., Sneden, C., Kraft, R.P., 1996 AJ, 111, 1689
Pols, O.R., Tout, C.A., Eggleton, P.P., Han, Z., 1995, MNRAS, 274, 964
Ridgway, S.T., Joyce, R.R., White, N.M., Wing, R.F., 1980, ApJ, 235, 126
Rose, J.A., 1985, AJ, 90, 1927
Rose, J.A., 1994, AJ, 107, 206 (R94)
Rose, J.A.& Tripicco, M.J., 1986, AJ, 92, 610
Salpeter, E.E., 1955, ApJ, 121, 161
Savage, B.D., Massa, D., Meade, M., Wesselius, P.R., 1985, ApJS, 59, 397
Tinsley, B.M., 1980, Fund. Cosmic Phys., 5, 287
Tonry, J. & Davis, M. 1979, AJ, 84, 1511
Trager, S.C., Worthey, G., Faber, S.M., Burstein, D., González, J.J., 1998, ApJS, 116, 1
Tripicco, M.J. & Bell, R.A., 1992, AJ, 103, 1992
Tripicco, M.J. & Bell, R.A., 1995, AJ, 110, 3035
VandenBerg, D.A., 1992, ApJ, 391, 685
Vazdekis, A., 1998, PASJ, submitted.
Vazdekis, A., Casuso, E., Peletier, R. F. & Beckman, J. E., 1996, ApJS, 106, 307 (Paper I)
Vazdekis, A., Peletier, R. F., Beckman, J. E. & Casuso, E., 1997, ApJS, 111, 203 (Paper II)
Vazdekis, A. & Peletier, R.F., 1997, IAU Symp. 187, Cosmic chemical evolution
Vazdekis, A. & Arimoto, N., 1998, ApJ, submitted.
Webbink, R.F., 1985, IAU Symp. 113, Dynamics of Star Clusters, eds. J. Goodman and P. Hut (Reidel, Dordrecht), p. 541.
Worthey, G., 1994, ApJS, 95, 107
Worthey, G., Faber, S.M. & Gonzalez, J.J., 1992, ApJ, 398, 69
Worthey, G., Faber, S., González, J. & Burstein, D., 1994, ApJS, 94, 687
Worthey, G. & Ottaviani, D.L., 1997, ApJS, 111, 377 (WO97)
Zinn, R., 1985, ApJ, 293, 424
The Lick indices measured on the obtained synthetic spectra for SSP’s of different metallicities and ages (in Gyr) and Salpeter IMF, after smoothing as indicated in Table 2. For the models of $[Fe/H]=-0.2$ we refer the reader to the last paragraph of section 3. All the indices are expressed in EW, except the CN1, CN2, Mg2 and Mg4 which are given in magnitudes. Colors and other predictions can be found in Paper I.
Table 2: Transformation factors between the model indices obtained on the basis of the empirical fitting functions (Lick system instrumental response curve, i.e., Paper I) and those measured on the new model SSP spectra (nearly flux calibrated) after convolving with a gaussian of $\sigma=5.7$ pixels (0.6 Å/pix) for the blue and $\sigma=5.9$ pixels for the red ($\sim 255$ and $\sim 215$ Kms$^{-1}$ respectively). The tabulated numbers are obtained averaging the differences between the two predictions for all the ages presented in Table 1. A negative value denotes that the index measured on the synthetic spectra is lower.
Fig. 1.— The adopted atmospheric stellar parameters for the final subsample composed of 547 stars.
Fig. 2.— The Lick system of indices. The thick lines represent the measurements obtained on the synthetic model spectra after smoothing to the Lick resolution: the high resolution synthetic spectra were convolved with a gaussian so that the strong resolution sensitive indices, the Ca4227 in the blue and the Fe5335 in the red, were fully matched to the predictions obtained on the basis of the empirical fitting functions for solar metallicity. Dot dashed lines mean models of $[\text{Fe/H}]=-0.7$, dotted lines are models of $[\text{Fe/H}]=-0.4$, solid lines are models of solar metallicity and the dashed lines correspond to the predictions for $[\text{Fe/H}]=+0.2$ (using the approach discussed in the latest paragraph of section 3). Finally, the thin lines are the Paper I model predictions based on the empirical fitting functions of Worthey et al. (1994). The thin dashed lines represents the predictions for $[\text{Fe/H}]=+0.2$, after interpolating between the values given in Paper I for solar and 2.5 times solar metallicity predictions.
Fig. 3.— The system of indices of WO97. The lines have the same meaning as in Fig. 2. Big solid dots correspond to the solar metallicity model predictions of these authors.
Fig. 4.— The system of indices of R94. The values were measured on the same synthetic spectra as in Fig. 2 and Fig. 3 but without performing any degradation of the resolution (1.8Å FWHM). The line types have the same meaning as in these two figures. Here we warn that the resolution plays an important role and we will address this problem elsewhere.
Fig. 5.— Peak height resulting from the crosscorrelation of the 47 Tuc integrated blue spectrum with different SSP model spectra of various metallicities and ages (see the text for details). Notice that old populations of $[\text{Fe}/\text{H}]=-0.7$ provide the best fits.
Fig. 6.— Plot of various index-index diagrams of the Rose system. The model lines have the same meaning as in Fig. 2. We have marked for each metallicity the lowest and highest ages (in Gyr)
Fig. 7.— The 47 Tuc blue spectrum and a representative good fit model spectrum selected on the basis of Fig. 6. We have marked the well known CN strong bands of this globular cluster which has been detected by the model
Fig. 8.— The normalized NGC 6624 red spectrum and a representative good fit model spectrum at \( \sim 2.1\Delta \) FWHM spectral resolution. Also plotted is the ratio between the cluster and the model spectra.
Fig. 9.— Peak heights resulting from the crosscorrelation of the NGC 3379 galaxy red spectrum at \( \sim 13\% \) of its effective radius with different model spectra of various metallicities and ages. Notice that models of different metallicities provide very similar peak heights varying slightly the age.
Fig. 10.— The normalized NGC 3379 red spectrum. Overplotted are three model spectra selected on the basis of Fig. 9. Notice that all of them give good H\textsc{\textbeta} ($\sim$4860Å) fits but no one provides acceptable fits to the magnesium ($\sim$5175Å) and iron features (e.g., Fe5015; Fe5270; Fe5335; Fe5406) simultaneously.