Stellar Populations - Planning for the Next Decade
Proceedings IAU Symposium No. 262, 2009
Gustavo Bruzual & Stéphane Charlot, eds.

doi:10.1017/S174392131000253X

MILES SSP Models

A. Vazdekis[1,2]†, P. Sánchez-Blázquez[1,2], J. Falcón-Barroso[1,2], A. J. Cenarro[1,2,3], M. A. Beasley[1] N. Cardiel[4], J. Gorgas[4] & R. Peletier[5]

[1]Instituto de Astrofísica de Canarias, La Laguna, E-38200 Tenerife, Spain
[2]Departamento de Astrofísica, Universidad de La Laguna, E-38205 La Laguna, Tenerife, Spain
[3]Centro de Estudios de Física del Cosmos de Aragón, C/ General Pizarro 1, E-44001, Teruel, Spain
[4]Dept. de Astrofísica, Fac. de Ciencias Físicas, Universidad Complutense de Madrid, E-28040 Madrid, Spain
[5]Kapteyn Astronomical Institute, University of Groningen, Postbus 800, 9700 AV, Groningen, Netherlands

Abstract. We present SEDs for single-age, single-metallicity stellar populations (SSPs) covering the full optical spectral range at resolution (FWHM = 2.3Å). These SEDs can be regarded as our base models, as we combine scaled-solar isochrones with an empirical stellar spectral library (MILES), which follows the chemical evolution pattern of the solar neighbourhood. The models rely as much as possible on empirical ingredients as also employ extensive photometric libraries. Thanks to the unprecedented parameter coverage of the MILES library we synthesize SSP SEDs from intermediate- to very-old age regimes, and the metallicity from super-solar to [M/H] = −2.3, all for a suite of IMF shapes and slopes. We propose a new Line Index System (LIS), based on flux-calibrated spectra, to avoid the intrinsic uncertainties associated with the Lick/IDS system and provide more appropriate, uniform, spectral resolution.

Keywords. galaxies: abundances, galaxies: star clusters galaxies: dwarf galaxies: elliptical and lenticular, cD galaxies: evolution galaxies: stellar content

1. Introduction

We present SSP SEDs based on the MILES library (Sánchez-Blázquez *et al.* 2006) and Cenarro *et al.* (2007). These models represent an extension of the Vazdekis (1999) SEDs to the full optical spectral range providing better predictions for intermediate- and old-stellar populations. MILES is composed of 985 stars covering the spectral range $\lambda\lambda$ 3540-7410 Å at 2.3 Å (FWHM). The stellar parameters ($T_{\rm eff}$, $\log g$, [Fe/H]) coverage of MILES represent a significant improvement over previous libraries.

As we employ an empirical library the newly synthesized SEDs are imprinted with the chemical composition of the solar neighbourhood, which is the result of the star formation history experienced by our Galaxy. As the stellar isochrones (Girardi *et al.* 2000) – i.e. the other main ingredient feeding the population synthesis code – are solar-scaled, our models are self-consistent, and scaled-solar for solar metallicity. In the low metallicity regime, however, our models combine scaled-solar isochrones with stellar spectra that do not show this abundance ratio pattern (e.g., Edvardsson *et al.* 1993; Schiavon 2007). However our (base) models, can be used to obtain a good proxy for the [Mg/Fe] abundance ratio, if appropriate line indices are employed (Yamada *et al.* 2006; de la Rosa *et al.* 2007).

† E-mail: vazdekis@iac.es

Table 1. MILES SSP SED properties

Spectral properties	
Spectral range	$\lambda\lambda$ 3540.5-7409.6 Å
Spectral resolution	FWHM $= 2.3$ Å, $\sigma = 54$ km s^{-1}
Linear dispersion	0.9 Å/pix (51.5 km s^{-1})
Continuum shape	Flux-scaled
Telluric absorption residuals	Fully cleaned
Units	$F_\lambda/L_\odot Å^{-1} M_\odot^{-1}$, $L_\odot = 3.826 \times 10^{33}$ erg.s^{-1}
SSP parameter coverage	
IMF type	Unimodal, Bimodal, Kroupa universal, Kroupa revised
IMF slope (for unimodal and bimodal)	0.3 – 3.3
Stellar mass range	0.1 – 100 $M_\odot$
Metallicity	−2.32, −1.71, −1.31, −0.71, −0.41, 0.0, +0.22
Age ([M/H] = −2.32)	$10.0 < t < 18$ Gyr (only for IMF slopes $\leqslant 1.8$)
Age ([M/H] = −1.71)	$0.07 < t < 18$ Gyr
Age ($-1.31 \leqslant$ [M/H] $\leqslant +0.22$)	$0.06 < t < 18$ Gyr

2. The MILES base models

We use the scaled-solar isochrones of Girardi *et al.* (2000), which cover a wide range of ages and metallicities including an updated version of the models published in Girardi *et al.* (1996) for $Z = 0.0001$. The theoretical parameters of the isochrones are transformed to the observational plane by means of empirical relations between colours and stellar parameters, instead of using theoretical atmospheres. We mostly use the relations of Alonso, Arribas & Martínez-Roger (1996, 1999; respectively, for dwarfs and giants). We apply the metal-dependent bolometric corrections of Alonso *et al.* (1995, 1999). For the Sun we adopt $BC_\odot = -0.12$ and a bolometric magnitude of 4.70. We use the Unimodal and Bimodal IMFs of Vazdekis *et al.* (1996) with varying slopes (0.3–3.3; 1.3 for Salpeter), and the Universal and Revised IMFs of Kroupa (2001).

We use MILES for computing the SSP SEDs. The stellar spectra of this library were properly flux-calibrated and the telluric absorption fully cleaned. For its implementation each star of the library has been compared with other MILES stars with similar atmospheric parameters, using the same interpolation algorithm used in the synthesis code (see Vazdekis *et al.* 2003). From these tests and other considerations (e.g., spectroscopic binaries, anomalous variability) we removed, or decreased the weight with which a given star contributes to the synthesis of a stellar spectrum, of 135 (out of 985) stars of MILES. A quantitative analysis, which basically takes into account the parameter coverage of the input stellar library feeding the models, clearly shows that our SSP SEDs can be safely used in the age range 0.06–18 Gyr, and the metallicity coverage from supersolar ([M/H] = +0.22) to [M/H] = −2.32. For the latter metallicity only SSPs with ages above ∼10 Gyr are safe, being very useful for globular cluster studies. For comparison, line indices predicted on the basis of the Lick/IDS fitting functions (Worthey *et al.* 1994) should not be considered safe for [M/H] < -1.3. This limit is set to [M/H] ~ -0.7 for models based on STELIB (e.g. Bruzual & Charlot 2003). Table 1 summarizes the spectral properties of the model SEDs and the SSP parametric regions where they can be safely used. For a full description of these models we refer the reader to Vazdekis *et al.* (2010).

With these models the stellar population analysis is straightforward and can be done in a very flexible manner. Our favourite approach is to analyze a galaxy spectrum at the resolution imposed by its velocity dispersion (and its instrumental resolution), which require us to smooth the SSP SEDs to match the observed total resolution. Thus the analysis is performed in the system of the galaxy, either by focussing on selected line indices or by full spectrum fitting approaches.

https://doi.org/10.1017/S174392131000253X Published online by Cambridge University Press

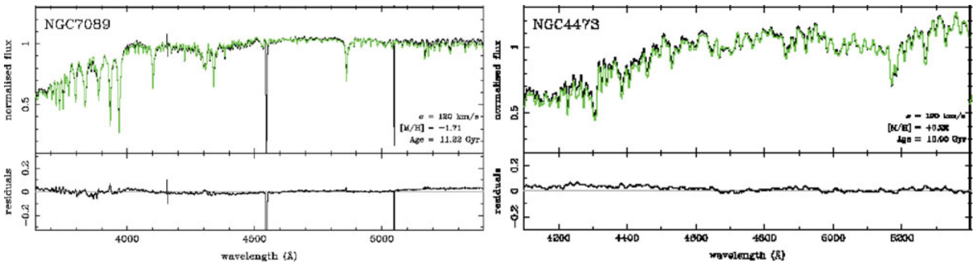

Figure 1. Left: the spectrum of a representative metal-poor Galactic globular cluster from Schiavon *et al.* (2005) is plotted in black. We overplot in green the best fitting SSP SED, which has been smoothed to match the instrumental resolution of the observation (i.e. $\sigma = 120\,\mathrm{km\,s^{-1}}$). Right: A Virgo elliptical galaxy from the sample of Yamada *et al.* (2006) is plotted in black. We overplot in green the SSP SED corresponding to the age and metallicity, which have been derived by these authors via the $H\gamma_\sigma$ vs. [MgFe] diagnostic diagram. The model spectrum was smoothed to match the total resolution (indicated within the panel). We adopt for the models a Kroupa Universal IMF. The age and metallicity of the SSPs are indicated within the panels. The obtained residuals are plotted using the same scale. Note that no continuum removal was applied when performing the fits.

3. A new standard system for index measurements

As many authors choose to plot the line-strength measurements of their whole galaxy sample in a single index-index diagnostic diagram, or to compare their data to tabulated indices in the literature, we propose a new Line Index System (named LIS), which makes this method very eassy to apply. In fact we avoid the well known uncertainties inherent to the Lick/IDS system (see Worthey & Ottaviani 1997). The LIS system has a constant resolution as function of wavelength and a universal flux-calibrated spectral response. Data can be analyzed in this system at three different resolutions: 5 Å, 8.4 Å and 14 Å (FWHM), i.e. $\sigma = 127$, 214 and $357\,\mathrm{km\,s^{-1}}$ at 5000 Å, respectively. These resolutions are appropriate for studying globular cluster, low and intermediate-mass galaxies, and massive galaxies, respectively. Line-strength measurements given at a higher LIS resolution can be smoothed to match a lower LIS resolution.

4. Fitting stellar cluster and galaxy spectra

We use these model SEDs to fit a number of representative stellar clusters of varying ages and metallicities, obtaining good agreement with CMD determinations. It is remarkable the fit obtained for the scaled-solar, and solar metallicity, open cluster M 67 (Schiavon *et al.* 2004), which shows negligible residuals. Our SED fits to a sample of Galactic globular clusters (Schiavon *et al.* 2005) are also good, but show non negligible residuals blueward of 4300 Å (see Fig. 1), which mostly reflect the characteristic CN-strong features of these clusters among other deviations from the scaled-solar pattern.

We apply the models to a representative set of galaxies with very high quality spectra (Yamada *et al.* 2006), obtaining a good agreement with the detailed line-strength analysis performed by these authors. An example is shown in Fig. 1. It is worth noting that our base models can be used for studying line-strength indices of galaxies with α-enhanced element partitions. Examples of such a use can be found in, e.g., Vazdekis *et al.* (2001), Kuntschner *et al.* (2002), Carretero *et al.* (2004), Yamada *et al.* (2006). The method consists in plotting a highly sensitive age indicator, such as those of Vazdekis & Arimoto (1999), or the recently defined $H\beta_o$ index of Cervantes & Vazdekis (2009) versus Mg (e.g., Mgb) and versus Fe (e.g., Fe4383, $\langle\mathrm{Fe}\rangle$), obtaining a virtually orthogonal model grid where

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the estimated age does not depend on the metallicity indicator in use. Unlike the age, for a [Mg/Fe] enhanced galaxy the obtained metallicities differ when plotted against, for example, Mg*b* and ⟨Fe⟩ indices. This metallicity difference, $[Z_{Mgb}/Z_{<Fe>}]$, can be used as a good proxy for the abundance ratio determined with the aid of stellar population models that specifically take into account non-solar element partitions. Although this proxy yields larger [Mg/Fe] values, there is a linear relation between these two ways of estimating the abundance ratios (e.g., de la Rosa *et al.* 2007; Michielsen *et al.* 2008).

The fits shown in Fig. 1 also confirm the flux calibration quality of the SSP SEDs. Moreover the optical colours that we obtain from our SSP SEDs are consistent with the ones that we derive through the photometric stellar libraries feeding our models (Vazdekis *et al.* 1996), within typical zero point uncertaintes (i.e. 0.02 mag for the $B-V$ colour).

5. The web tool

We present a webpage (http://miles.iac.es) from which these models and the MILES stellar library can be downloaded. We provide a suite of user-friendly webtools to facilitate the use of these spectra. For example, once the user enters the details of the instrumental setup employed in the observations (e.g., PSF, sampling), it is possible to obtain their favourite line-strength indices and diagnostic diagrams, ready to plot their observational measurements. The webpage also provides predictions for a suite of observable quantities.

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