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The MIUSCAT stellar population models: constraints from optical photometry

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Abstract

We present the spectral extension of our stellar population synthesis models based on the MILES and CaT empirical stellar spectral libraries. For this purpose we combine these two libraries with the Indo-US to construct composite stellar spectra to feed our models. The spectral energy distributions (SEDs) computed with these models and the originally published models are combined to construct composite SEDs for single-age, single-metallicity stellar populations (SSPs) covering the range $\lambda\lambda 3465 - 9469$ Å at resolution FWHM = 2.51 Å. We also show a comprehensive comparison of the MIUSCAT models with photometric data of globular clusters and early-type galaxies. The models compare remarkably well with the integrated colours of Milky Way globular clusters in the optical range. On the other hand we find that the colour relations of nearby early-type galaxies are still a challenge for present-day stellar population synthesis models. We investigate a number of possible explanations and establish the importance of $\alpha-$enhanced models to bring down the discrepancy with observations.

1 Introduction

Stellar population synthesis (SPS) models are commonly used for solving a great variety of studies, from age/metallicity estimates in globular clusters to the reconstruction of the star formation history (SFH) in galaxies. The modeling of the spectral energy distribution emitted by evolving stellar populations requires at least three main ingredients: stellar evolutionary tracks, a spectral or photometric library with well-established atmospheric parameters for each library star, and an initial mass function (IMF). In particular, the adoption of the spectral library used to convert physical quantities in observed flux turned out to be critical in the

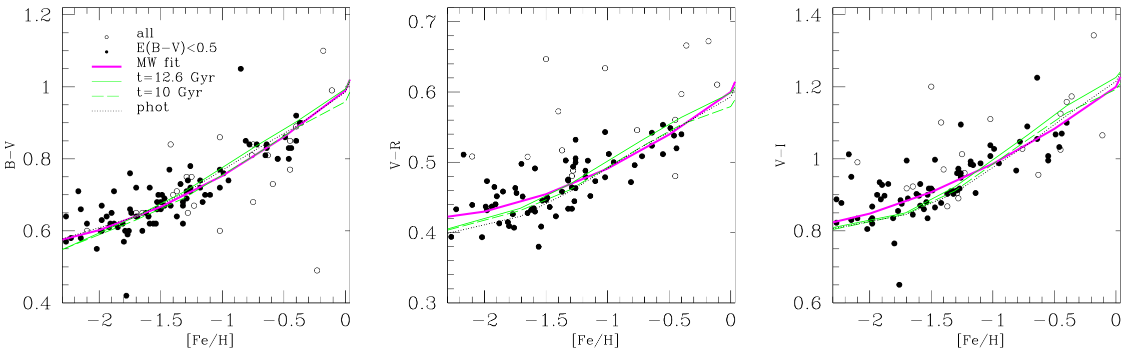

Figure 1: Optical colours in several bands as a function of metallicity for the MW globular clusters [4]. Filled (open) circles represent globular clusters with reddening $E(B-V) \leq 0.5$ (> 0.5). The magenta line shows a second order polynomial fit to the data with $E(B-V) \leq 0.5$. The black dotted lines show the photometric predictions of the MILES models. The synthetic colours derived from the MIUSCAT SSP spectra for models with age of 12.6 and 10 Gyr, for different metallicities and Kroupa Universal IMF, are shown in solid and dashed green lines, respectively.

comparison with observations. Although theoretical libraries are widely used among the most popular SPS models (e.g. [1] and [5]) because they are easier to handle, given the wide stellar parameter and spectral coverages and the arbitrary wavelength resolution, empirical-based libraries represent an advantage as the stars are real. The adoption of empirical spectra allows to overcome the uncertainties in the underlying model atmosphere calculations, giving more reliable predictions when compared with both spectroscopic [13, 14] and photometric data [7]. Broadband colours are among the simplest predictions of population synthesis models, thus comparing the model predictions to observed colours is the natural zeroth- order test of compatibility between models and observations. Therefore, in the present work we assess the reliability of the MIUSCAT models by comparing the model predictions to photometric data of globular clusters and quiescent galaxies. For a full description of the models and the photometric calibration we refer the reader to [15] and [10]. The MIUSCAT models are available at: http://miles.iac.es.

2 MIUSCAT models

The MIUSCAT models represent an extension of the [13] and [14] models, based on the CaT [2] ($\lambda\lambda$8350-9020 Å) and MILES [11] ($\lambda\lambda$3525-7500 Å) libraries. To fill-in the spectral range around 8000 Åwe have added 537 stars of the Indo-US stellar library [12] ($\lambda\lambda$3465-9426 Å). As

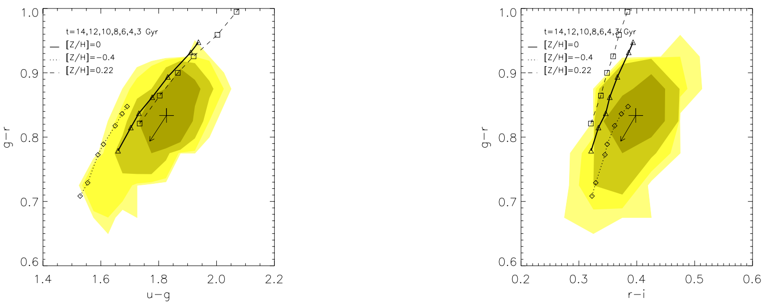

Figure 2: Observed colour distributions in the SDSS bands for the ETG sample at $z \simeq 0.04$. The contours enclose 20%, 40%, 60% and 95% of the galaxies and the cross indicates the median colours ($u - g = 1.83$, $g - r = 0.83$, $r - i = 0.40$ mag). The arrow indicates the colour de-reddening when an internal extinction of $A_V = 0.2$ mag is assumed. Synthetic colours derived from the MIUSCAT SEDs for a Kroupa Universal IMF are overplotted. The different lines join models with the same metallicities for ages ranging from 3 to 14 Gyr.

the flux-calibration quality of the Indo-US is not as accurate as in the other two libraries, a procedure was applied to correct the spectrum shape in the region $\lambda\lambda \approx$ 7400-8350 Å to match the MILES and CaT stellar spectra. Moreover the Indo-US spectrum was used to extend the spectral range blueward the MILES and redward the CaT spectral ranges without applying any correction to the Indo-US spectrum. The MIUSCAT spectra were then smoothed to match the resolution of MILES, i.e. 2.5 Å (FWHM). Finally the MIUSCAT composite library was implemented in the models as described in [14]. The relevant spectral ranges of the resulting SSP SEDs were extracted and plugged to the original model SEDs computed on the basis of the MILES and CaT libraries. For the latter step a further correction, similar to that described above for the individual stellar spectra, was applied to the model SEDs to obtain a unique spectrum, which is identical to the MILES and CaT based models in the corresponding spectral ranges, respectively.

3 Comparison with globular clusters

Globular clusters are the ideal benchmark to test the accuracy of the models, as they are an almost coeval and mono-metallic population of stars. In Fig. 1 we use the catalogue of [4] (150 clusters with spectroscopic metallicity, extinction and integrated Johnson-Cousins

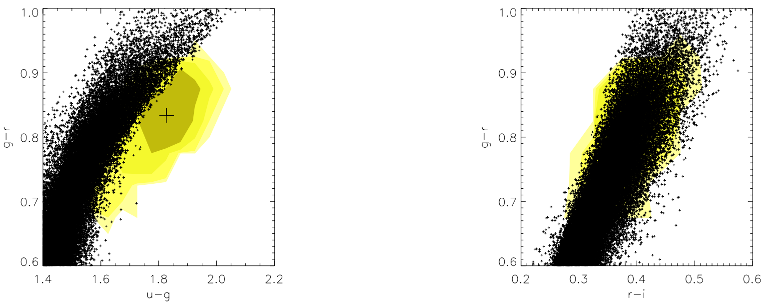

Figure 3: The observed colour-colour distributions are compared with simulated points derived from the three-bursts Montecarlo SFHs described in the text.

photometry) as a reference for the Milky Way (MW) globular clusters. The integrated colours of MW globular clusters can be remarkably reproduced by the MIUSCAT models in all the visible bands. Note that the $V-I$ colour is particularly relevant to test the reliability of our models. This colour is heavily sensitive to the details the three libraries (MILES, Indo-US and CaT) have been joined to build-up the MIUSCAT models. The good match to the observed colours shows the robustness of the method and the flux-calibration of the MIUSCAT SEDs. It is also remarkable the ability of our models to reproduce the $B-V$ colour, that has always challenged models based on theoretical stellar libraries, which fail at matching the range covered by the V filter. Here we have shown that the problem can be solved by the use of empirical stellar libraries (see also [6]).

4 Comparison with nearby early-type galaxies

A further insight into the capabilities of the models can be obtained by comparing them to a sample of nearby galaxies. For this purpose we select a homogeneous sample in the local Universe with a large number of SDSS galaxies with visual morphological classification [9]. Our sample includes 370 galaxies with early-type morphology at $0.035 < z < 0.045$.

In Fig. 2 we show the colour distribution of the early-type galaxies (ETG) sample compared to the MIUSCAT SSP models with ages ranging from 3 to 14 Gyr for three metallicity values: [Z/H] $= -0.4, 0$ and 0.22. We see that none of the SSP models is able to match the observed colour distribution. Irrespective of their metallicity, the old SSPs provide too red $u-g$ and $g-r$ colours and too blue $r-i$ colour. We also find that the SSP model predictions

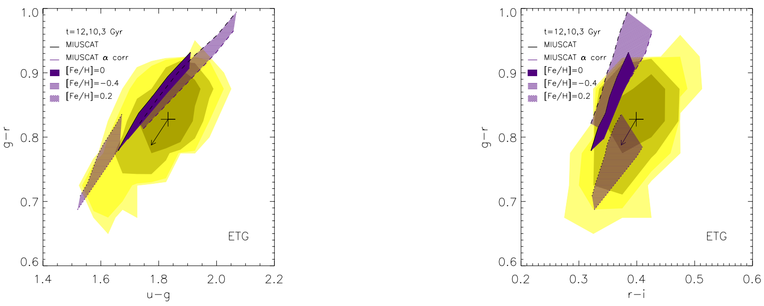

Figure 4: The observed colour-colour distributions are compared to the MIUSCAT SSP models once corrected from the α-enhancement effect. There are three shaded regions corresponding to each metallicity. For each of these regions the upper envelope indicate the MIUSCAT SSP models (same as in Fig. 2), whereas the lower envelope shows the resulting models once corrected from the α-enhancement effects with the aid of the models of [3]. For this purpose we estimate the colour difference obtained from comparing the scaled-solar and α-enhanced ($[\alpha/\mathrm{Fe}] = 0.4$ dex) models from these authors.

from different authors do not match these colour-colour distributions. Nonetheless, an important result drawn from such a comparison is that models based on empirical stellar libraries predict colours much closer to the observed distribution than models based on theoretical spectra (see [10] for further details).

An experiment done by simulating three-burst Montecarlo SFH confirmed the impossibility of the three model parameters (age, metallicity and IMF slope) to fairly match the color plane $g - r$ versus $u - g$. Fig. 3 shows the results for 100000 simulations. On one hand we see that the cloud of models can match the region enclosed by data in the $g - r$ versus $r - i$ plot (this is mainly due to steep IMF slopes, effective in reddening the $r - i$, while keeping almost unchanged the bluer colours). On the other hand the cloud does not properly match the observed galaxy distribution in the $u - g$ versus $r - i$ diagram. We are aware of the degeneracies affecting the optical colours, which do not allow us to properly constrain the solutions. It is beyond the scope of this work to fully constrain the SFHs, for which spectroscopic data or colors in other spectral range would be required, but the inability of these simulations to reproduce the observed colours suggests the need of another parameter to model the observations.

The MIUSCAT SSP SEDs employed here are computed on the basis of scaled-solar isochrones and stellar spectra with nearly scaled-solar abundance ratios for the high metallicity regime that is required to fit massive galaxies. However, it is well known that the spectra of these galaxies show an enhancement in [Mg/Fe]. To assess the effects of α-enhanced element partitions on the SSP colours we correct them, in a differential way, with the aid of the models of [3], by applying the difference in colour obtained from the scaled-solar and α-enhanced ($[\alpha/\mathrm{Fe}] = 0.4$ dex) models of [3] to the MIUSCAT SSP. The corrected SSP colours are shown for different metallicities in Fig. 4. Interestingly, the effect of α-enhancement tends to bluen the $u-g$ and $g-r$ colours and to redden $r-i$, as required by the data. Note that although this effect is relatively modest it certainly goes in the right direction for improving our fits to the most massive galaxies of our sample. Preliminary tests performed with our own version of the models constructed with α-enhanced mixtures based on the MILES library, making use of the [Mg/Fe] determinations of [8], lead to even larger differences with respect to the scaled-solar predictions in the same directions as with the models of [3].

Acknowledgments

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