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On the age and metallicity estimation of disc galaxies using optical and near-infrared photometry

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We have investigated the robustness of stellar population models in order to address the age and metallicity estimation of disc galaxies. We note that the scatter among simple stellar population models by different groups is surprisingly large at ages $t < 2$ Gyr. The dominant uncertainties in stellar population models arise from convective core overshoot assumptions and the treatment of the thermally pulsing asymptotic giant branch phase and helium abundance may play a significant role at higher metallicities. It is also emphasized that the current composite stellar population models need some implementation of chemical enrichment histories for the proper analysis of the observational data.

Keywords: Galaxies: evolution; Galaxies: photometry; Galaxies: disc; Galaxies: stellar content

1 Introduction

Many recent works on age estimation of disc galaxies have used the surprisingly orthogonal color–color grids that combine optical and near-infrared colors (e.g., [1, 2]). The "surprise" comes from a long list of previous works starting with [3] that showed that age effects and metallicity effects in old stellar populations are very similar on colors, i.e. the age-metallicity degeneracy problem. Age and metallicity vectors projected onto color–color diagrams from simple stellar populations are not orthogonal, but lie nearly parallel to each other so that age effects and metallicity effects are nigh indistinguishable. We have investigated whether this seemingly successful method to break the age-metallicity degeneracy is convincingly robust or not. The benefits of near-IR photometry combined with optical photometry have been addressed by many groups and applied to wide variety of stellar systems (e.g., [2, 4, 5]). The basic claim is that age-sensitive main-sequence turnoffs (MSTO) dominate the visible band while metallicity-sensitive giant branches dominate the near-IR, and that the photometric behavior of these two evolutionary regions is sufficiently different to provide diagnostic power in terms of deriving average ages and metallicities.

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It is important to note, however, that the orthogonal grids that appear in the literature are not simple stellar population (SSP) models, but composite stellar population (CSP) ones. The CSP models that we study here are different from the SSP ones in that CSP models are made by convolving SSPs with some plausible *star formation histories* (SFHs) at *fixed* metallicity and *fixed* initial mass function. Obviously, SSP models that consist of a single age and a single metallicity are not good representations of the protracted and ongoing star formation history of disc galaxies. We have adopted an exponentially declining star formation rate (often called a τ model) in order to make composite models.

2 Stellar population models

Many integrated-light models are now available for those interested in interpreting galaxy spectra and colors. Since we employ the observational studies of [1] and [2], we include the stellar evolution upon which the models of Bruzual & Charlot [6] (hereafter BC03) are based. Besides BC03 models*, we also examine the works [7] (the Teramo group's SPoT†), and [8] (hereafter M05)‡.

Both HR diagram behavior and SSP photometric models have been examined in [4]. Of key interest are the effects from convective core overshooting and from the thermally-pulsing asymptotic giant branch phase at relatively young ages (100 Myr to 2 Gyr).

3 Results and discussion

Composite stellar population models from three different groups (BC03, M05, SPoT) are shown in Fig. 1. BC03 (black) and M05 (red) are compared in the top panel and BC03 and SPoT (blue) are contrasted in the bottom panel. We have generated each model grid using *identical* star formation rates (SFR). The simple exponential SFR that we use in this study is $\Psi_{\rm exp}(t)$,

$$\Psi_{\rm exp}(t) = \frac{c_{\rm exp}}{\tau} e^{-t/\tau}, \tag{1}$$

where

$$c_{\rm exp} = \frac{1}{1 - e^{-A/\tau}} \tag{2}$$

and $A = 13$ Gyr. The average age by which they are labeled is a *mass-weighted* average age and at a given τ, computed as:

$$\langle A \rangle = A - \tau \frac{1 - e^{-A/\tau}(1 + A/\tau)}{1 - e^{-A/\tau}}. \tag{3}$$

For example, a constant star formation rate over 13 Gyr yields an average age of 6.5 Gyr. If weights by luminosity rather than mass, one arrives at much younger ages.

*http://www.cida.ve/∼bruzual/bc2003 (based on Padova 1994 isochrones)
†http://193.204.1.79:21075 (based on the earlier version of Teramo isochrones)
‡http://www-astro.physics.ox.ac.uk/∼maraston

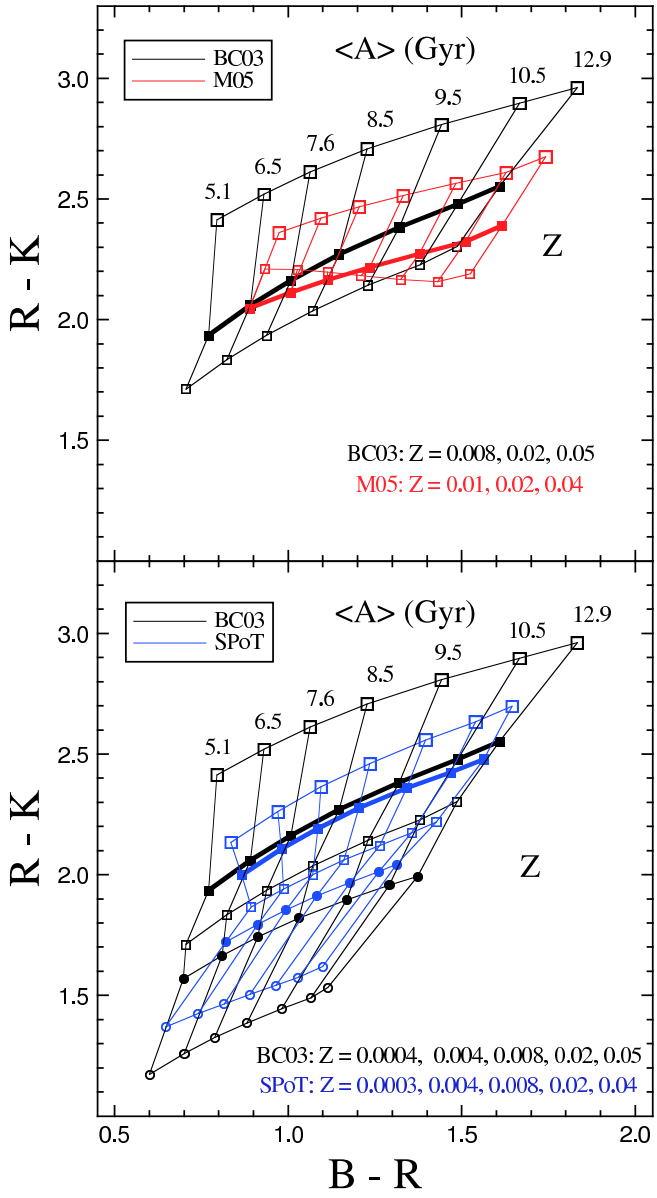


Figure 1 Three different groups' *composite* stellar population models are generated as identical SFHs are employed. BC03 (black) and M05 (red) are compared in the top panel and BC03 and SPoT (blue) are contrasted in the bottom panel. Same symbols are used for similar metallicities. To guide the eye, solar metallicities are depicted with thicker lines.

The models illustrated in Fig. 1 are clearly different from one another, although they seem to agree to a certain degree at solar metallicity (delineated with thick lines to guide the eye). The differences arise from the original dissimilarities of simple stellar

populations. In fact, the averaging process for the τ model CSPs smooths over many of the angularities present in the SSP grids to yield something more regular. It is also worthwhile to note that these composite grids are built *at fixed metallicity*, without any chemical evolution. The behavior of the CSP models echoes that of the SSP ones, and especially that of the younger components because younger subpopulations are brighter and tend to dominate the light. In the case of M05 CSP models, the iso-metallicity lines of $Z = 0.01$ and 0.02 even cross over, echoing their corresponding SSP models at 100 Myr and at 1 Gyr. The SPoT's CSP grids are much more compact in $R-K$ colors compared to BC03 both at the metal-poor and at the metal-rich side, also echoing their original SSP models.

We have used the same symbols for similar metallicities in Figure 1 in order to make the comparisons easy. The highest metallicities of three models are almost the same: the highest metallicity in BC03 is $Z = 0.05$ with $Y = 0.352$ while the two other are $Z = 0.04$ with $Y = 0.303$ (SPoT), and 0.340 (M05). The thick lines in Fig. 1 are solar iso-metallicity lines for each CSP models. We hope that the fact that different models become similar at this rather critical metallicity is a robust result and not a coincidence. Reading from Figure 1, a galaxy with colors $B - R = 0.97$ and $R - K = 2.37$ would, in the M05 τ models, have an age of 5.1 Gyr and $Z = 0.04$, or [Fe/H] $= +0.3$ where $[\alpha/\mathrm{Fe}] = 0$. The same galaxy would have $(\mathrm{Age}, Z, [\mathrm{Fe/H}]) = (7.0, 0.037, 0.27)$ according to BC03, or $(6.7, 0.052, 0.41)$ according to SPoT. Taking another galaxy as an example, with $B - R = 1.61$ and $R - K = 2.39$, M05 would indicate $(\mathrm{Age}, Z, [\mathrm{Fe/H}]) = (13, 0.02, 0.00)$, while BC03 indicates $(15, 0.008, -0.40)$ and SpoT indicates $(16, 0.012, -0.22)$. The uncertainties appear to be in line with those tabulated in [9], about 30% in age. The scatter in abundance may be a bit larger than the 0.1 dex predicted by Charlot et al. [9]. In terms of relative, $\Delta Z/\Delta\mathrm{Age}$ measurements, such as would be applied to spatial gradient data, Fig. 1 yields similar percentage scatter.

Notwithstanding the incorporation of star formation history using the exponentially declining τ models, Fig. 1 is still far from a realistic description of stellar populations of disc galaxies. This is because even models like in Fig. 1 do *not* yet include any form of chemical evolution because they are built at *fixed* metallicity. In Fig. 2, we experiment the same exponential SFR that we have adopted in Fig. 1, but with one very simple and useful case of *chemical enhancement* where metallicity is varied along with age. For this experiment, $Z = 0.0001$ is assigned for the stars that formed at 13 Gyr ago, $Z = 0.0004$ for the stars formed at 11 and 12 Gyr ago, $Z = 0.004$ for the stars formed at 9 and 10 Gyr ago, $Z = 0.008$ for the stars formed at 7 and 8 Gyr ago, $Z = 0.02$ for the stars formed at 2, 3, 4, 5 and 6 Gyr ago, and $Z = 0.05$ is given for the stars that formed at 0.1 and 1 Gyr. These models are marked by big circles in Fig. 2, one for each *mass-weighted* average age, $\langle A \rangle$. In this case with strong age-metallicity relation, the CSP models with older *average* ages become considerably bluer in $R - K$ because of their (assumed) low metallicity as most star formation happens at very early cosmic time. Models with younger average ages, on the other hand, become progressively redder because recent star formation has high metallicity.

These models are clearly far from the observations of disc galaxies (roughly located near the thick line in Fig. 2 according to Fig. 11 in [2] suggesting that this toy model with a strong age-metallicity relation is incorrect. However, the toy model serves to

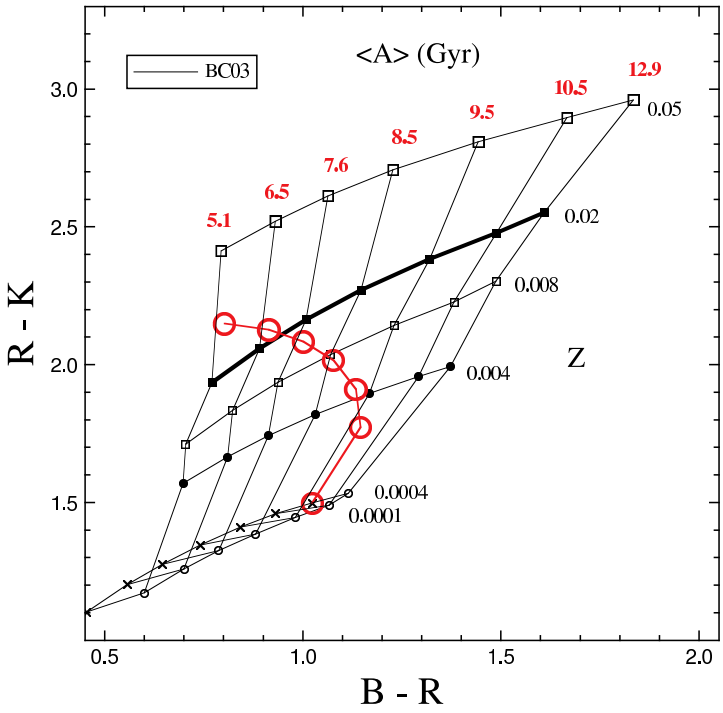


Figure 2 Similar to Fig. 1, with the BC03 models repeated (black), but *a chemical enrichment scheme with a monotonic age-metallicity relation* is incorporated in the BC03 composite stellar population models at given average ages (red circles).

illustrate that a general trend caused by *any* chemical evolution scheme with an age-metallicity relation will cause a *tilt* in the model grids. The toy model is an extreme case, but almost any chemical evolution scheme will share the characteristic that star formation starts at low metallicity at early times and works toward high metallicity at late times. This will, in every case, induce a bias in the CSP color-color plots. Clearly, future work should include chemical evolution if coherent age results are the goal.

Acknowledgments

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