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Stellar populations as a test for the stellar evolution

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Abstract. The understanding of complex stellar populations and their star formation histories relies on the stellar evolution theory as much as the improvement of our knowledge of the stellar evolution relies on the study of stellar populations. In this context, testing stellar evolution models is fundamental to properly evaluate the reliability of the results of the analysis of observational data and also as a way to improve the models themselves.
Here we present a few examples among the several ones that could have been selected showing strengths and weakness of the stellar evolution models. They include direct comparison of predictions of different libraries; relevant properties of stellar populations which interpretation depends on not well established results of stellar evolution, and comparison of solutions of the star formation history of complex stellar populations using different sets of models.
We have adopted the observer point of view, but our review is intended both for observers and theoreticians with the aim of stimulating the former to provide stronger observational constraints where they are needed and to encourage the latter to isolate the input physics responsible for the different behavior between models and the reasons for the discrepancies with data.

Key words. Stars: evolution – Stars: horizontal-branch – Hertzsprung-Russell (HR) and C-M diagrams – Galaxy: Globular Clusters – Galaxies: stellar content – Galaxies: Local Group

1. Introduction

In the last several years there has been growing interest on the determination of the star forma-

Send offprint requests to: A. Aparicio tion history (SFH) of composite stellar populations. The HST has offered new opportunities of extending the kind of studies done for the most nearby Milky Way satellites. The key source of information is the color-magnitude diagram (CMD), and new specific software has been developed for the analysis of the new data of increasing accuracy and complexity. But this analysis strongly relies on stellar evolution models. For this reason, on the one hand, new stellar evolution libraries of increasing quality have been produced. On the other hand, the observational data and dedicated software provide, in turn, valuable material for testing the theory. These test must go beyond the classical ones based on the CMD of Milky Way globular clusters and have to include other scenarios, like young, low metallicity systems or short time evolutionary phases. Rather than intending to be exhaustive, which is impossible in this paper short space provided for this paper, we will concentrate on a few examples among those that may be considered representative of the current state of stellar evolution testing. For a more comprehensive review, see Gallart et al. (2005). Also, we will present some tests showing the influence that stellar evolution models have on the results of the SFH of complex populations derived with state of the art software. We have written this paper from the point of view of the stellar evolution library user. Readers looking for the models internal details should refer to other works. This kind of *qualitative* presentation will allow us to highlight the results of the comparison between the models and the data, as well as the disagreements between different libraries among the most commonly used ones.

2. The Main Sequence Turn-off

2.1. Life-times

Although determination of the SFH of complex stellar populations require the global analysis of the CMD, the magnitude of the main sequence (MS) turn-off is a key characteristic of each stellar generation and the key information to retrieve the age of stellar clusters. Estimating relative ages for them is quite independent of stellar evolution models (Rosenberg et al. 1999; De Angeli et al. 2005; Marin-Franch et al. 2008), but this is not the case of absolute ages. Figure 1 shows a significant example of the problem. A track and an isochrone are plotted from two of the currently most used stellar evolution libraries: Teramo-BaSTI (Pietrinferni et al. 2004) and Padua-Girardi (Girardi et al. 2000). Tracks correspond to a 1.9 $M_\odot$ star. Isochrones correspond, for each library, to the age at turn-off of a 1.9 $M_\odot$ star, which are 1.75 Gyr for the Teramo-BaSTI library and 1.25 Gyr for the Padua-Girardi library. Track loci are very similar, indicating a similar mass-luminosity-temperature relation in both libraries. But ages differ by a factor of 1.4 from each other, showing how model dependent absolute age estimates can be. This is however an extreme case and other age ranges and libraries show smaller discrepancies (Gallart et al. 2005).

2.2. The effect of He abundance

Luminosity and T_{eff} on the MS and, in particular, at turn-off are dependent on the He abundance. The dependence is small and usually overlooked, but it could be quite relevant in particular situations. In general, current stellar evolution libraries do not offer model sets computed with different He fractions, for which stellar population analysis can not be done with He abundance as a test parameter. A paradigmatic, although not yet fully confirmed, case of the relevance of the He fraction is the multiple MS of the globular cluster ωCen. Piotto et al. (2005) have shown that, contrary to what would be expected, the bluest MS in ω Centauri is populated by stars more metal-rich than the bulk population. A way to account for this is that bluer and higher metallicity MS stars have also extremely high He content. A simple mechanism to account for such He excess in dwarf galaxies (ωCen could be the remnant of a dwarf galaxy) is that these galaxies would be unable to retain most metal rich SN ejecta, but they would manage to retain significant amounts of He rich AGB winds (Piotto et al. 2005; Moles, Aparicio, & Masegosa 1989).

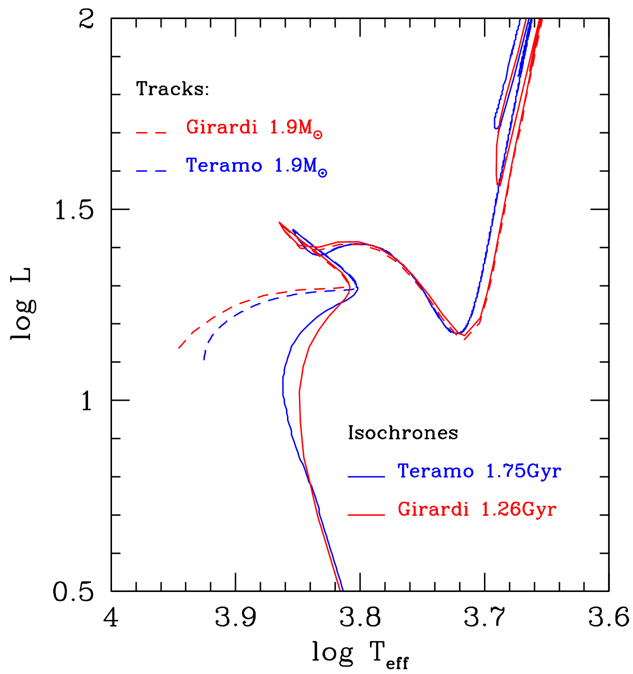

Fig. 1. Dashed lines: tracks of identical mass from Teramo-BaSTI and Padua-Girardi libraries. Solid lines: isochrones of ages corresponding to the lifetimes of each track at the turn-off. For both libraries, models with overshooting are considered

Table 1. Effect of age on metallicity derivations from RGB colors

	[Fe/H]=–1.79		[Fe/H]=–1.27		[Fe/H]=–0.66	
age (Gyr)	Δ(V-I)	[Fe/H]'	$\Delta(V-I)$	[Fe/H]'	$\Delta(V-I)$	[Fe/H]'
10	0.02	–1.98	0.03	–1.44	0.05	–0.67
6	0.05	–2.21	0.07	–1.69	0.12	–0.80
4	0.08	–2.47	0.10	–1.90	0.17	–0.96
2	0.13	–2.90	0.15	–2.30	0.25	–1.33
1	0.17	–	0.20	–2.75	0.32	–1.76

Whatever the mechanism to produce higher He contents, the point that we want to stress here is the need for stellar evolution libraries including different He fractions.

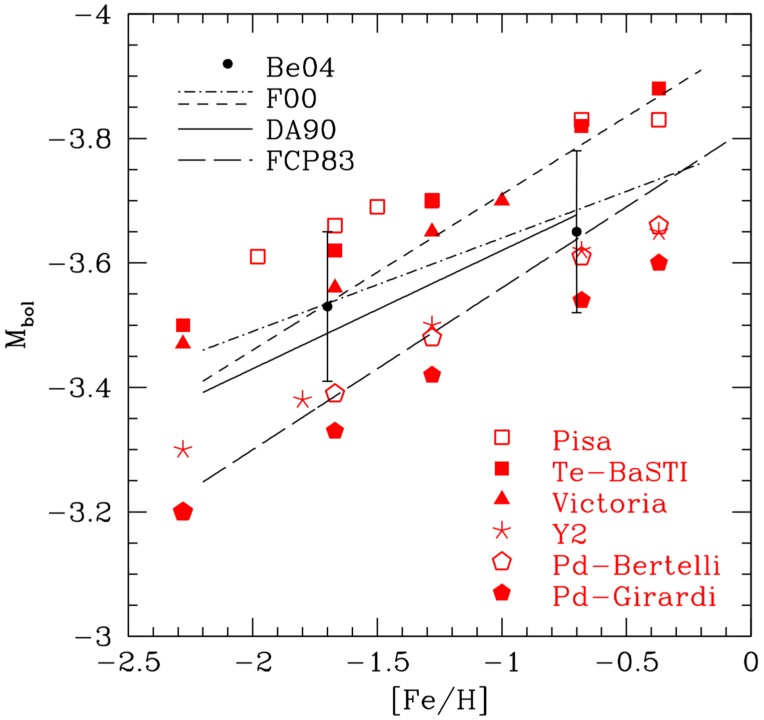

Fig. 2. Comparison between $M_{bol,TRGB} - [Fe/H]$ as predicted by current models (large dots) and empirically determined by different authors (black lines and small dots). Reference key: Empirical data: Be04: Bellazzini et al. (2004); F00: Ferraro et al. (2000); DA90: Da Costa & Armandroff (1990); FCP83: Frogel et al. (1983). Theoretical data: Pisa: Cariulo et al. (2004); Te-BaSTI: Pietrinferni et al. (2004); Victoria: VandenBerg et al. (2000); Y2: Yi et al. (2001); Pd-Bertelli: Bertelli et al. (1994); Pd-Girardi: Girardi et al. (2000).

3. Red Giant Branch

3.1. Problems estimating the metallicity

The large metallicity dependence and comparatively low age dependence of the RGB color justifies using the latter as a metallicity indicator (Da Costa & Armandroff 1990; Saviane et al. 2000). The dependency of RGB color on metallicity has been empirically determined for old populations, so model uncertainties are not a concern here. However, since ages are not known, the effect of age is usually neglected and models show that this produces significant deviations from the actual metallicity when intermediate-age stars are present.

Table 1 shows the differences between input and estimated $[Fe/H]$ for different ages when the age is wrongly assumed to be 13.0 Gyr. Models from Teramo-BaSTI have been used (Gallart et al. 2005). It can be seen that differences between the real and the estimated metallicity can be very large if a significant intermediate age population is populating the RGB.

3.2. Problems estimating distance

The tip of the RGB (TRGB) corresponds to the fast He ignition in the electron degenerate cores of low-mass stars. It is produced at almost constant He-core mass. As a consequence, the TRGB shows a sharp morphology, its I-Cousin band magnitude, $M_{TRGB,I}$, being almost constant and only weakly dependent on metallicity. For this reason and because the TRGB magnitude is relatively easy to measure, it is frequently used as a distance estimator. However, the determination of the $M_{TRGB,I}-[Fe/H]$ or the $M_{TRGB,bol}-[Fe/H]$ relations is challenging. From the empirical calibration side, the TRGB may be affected by incompleteness, which would produce a wrong zero-point for the $M_{TRGB,I}-[Fe/H]$ relation. It is also possible to use theoretical model results to determine the $M_{TRGB,bol} - [Fe/H]$ relation, which is connected to the $M_{TRGB,I} - [Fe/H]$ through the bolometric corrections. However, significant differences from one library to other are found. Figure 2 shows a comparison between $M_{TRGB,bol} - [Fe/H]$ as predicted by current models (large dots) and empirical determined by different authors (black lines and small dots). This figure indicates that errors affecting distances estimated by this method should be set at least to ±0.1 in any case or, to be more conservative, ±0.15.

4. The HB and the second parameter problem

The star location in effective temperature along the Zero Age HB (ZAHB) depends on almost all stellar parameters (composition, age, rotation, etc). The wide colour distribution of the HB, or HB morphology, is strongly driven by large differences in the envelope mass of stars having the same core mass, at the same evolutionary stage. The HB phase behaves as an amplifier, reflecting both initial conditions and any variations and perturbations in the evolution of the star from its birth up to the HB stage. Therefore, properly interpreting HB morphologies would yield a better understanding of Population II stellar evolution in general, and of the specific stellar systems, stellar clusters or galaxies, in particular.

The main parameter driving the temperature extension and morphology of the observed HBs is metal abundance. This is the so-called first parameter. Metal-rich clusters tend to have short red HBs, while metal-poor ones exhibit predominantly blue HBs. However, there are cases of clusters with nearly identical metallicities showing very different HB colour distributions. One classical example is the pair formed by M3 and M13, with very similar metallicities ([Fe/H] = −1.57 and [Fe/H] = −1.54 respectively), but very different HB morphologies (Rey et al. 2001). Therefore, some other parameter (or set of parameters) must be also at work. They are globally referred as the second parameter.

The variety of proposed candidates to second parameter ranges from cluster age to helium mixing, [CNO/Fe] abundance, cluster concentration, stellar rotation, planets, etc.

In the context of the Milky Way formation scenario, cluster age was suggested as a second parameter source (Searle & Zinn 1978; Chaboyer et al. 1998). However, Rosenberg et al. (1999), De Angeli et al. (2005) and Marin-Franch et al. (2008) have shown that cluster age dispersion cannot account for the observed HB morphology dispersion. Furthermore, through a multivariate analysis, Recio-Blanco et al. (2006) have shown that total cluster luminosity, hence total cluster mass, has the main contribution to second parameter. This is in agreement with the results by Fusi Pecci et al. (1993) and Buonanno et al. (1997).

In the context of the stellar populations as a test for stellar evolution, we would like to remark the fact that we are still far to fully understand the HB and to emphasize the importance of both experimental and theoretical researches on this evolutionary phase

5. Retrieving the SFH: the effects of the stellar evolution library

The CMD is the best tool to derive the SFH of a galaxy. Deep enough CMDs display stars born all over the life-time of the galaxy and are indeed fossil records of the SFH. But actually deciphering the information contained in a complex CMD and deriving a quantitative, accurate SFH is complicated and requires some relatively sophisticated tools. Although

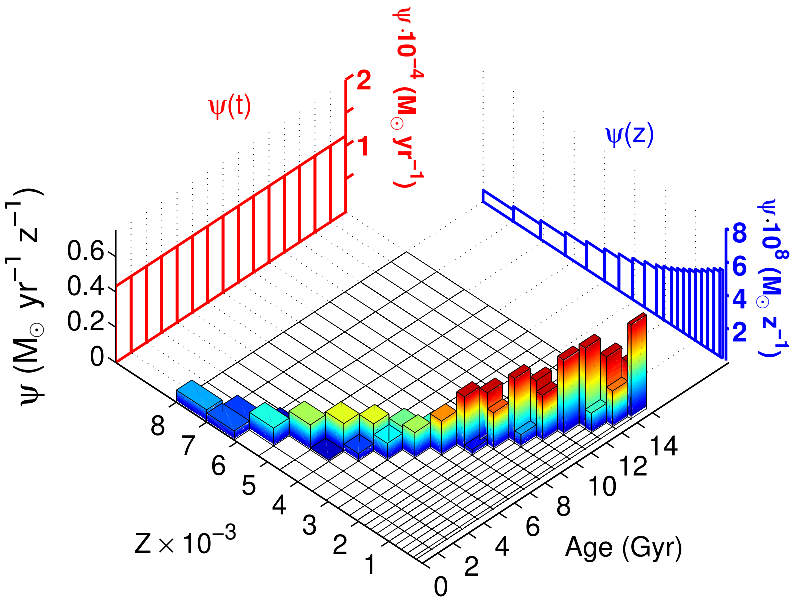

Fig. 3. The SFH of the mock stellar population with continuous star formation.

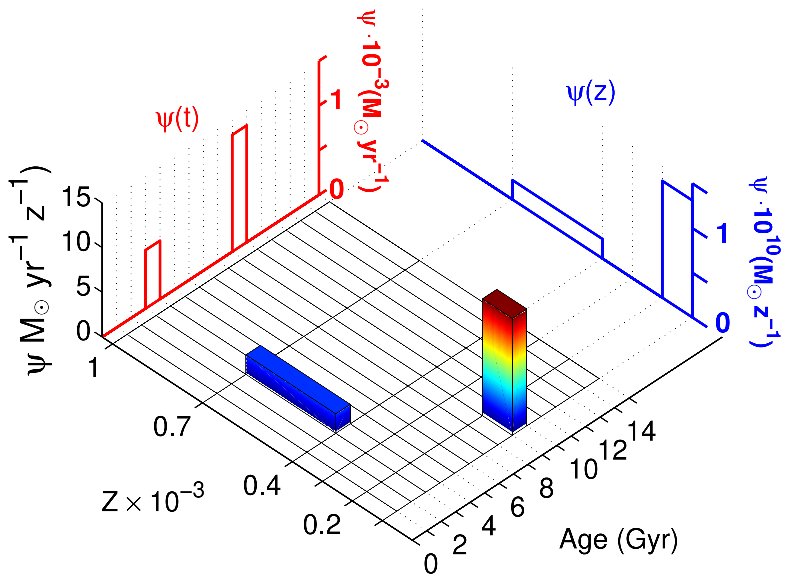

Fig. 4. The SFH of the mock stellar population consisting in two bursts.

other approaches are possible, the most extended and probably most powerful technique is the one based on synthetic CMDs analysis. Since synthetic CMDs are computed on the basis of stellar evolution models, these affect the final solution to some degree. Here we will show some of these effects by comparing the solution obtained for a mock synthetic

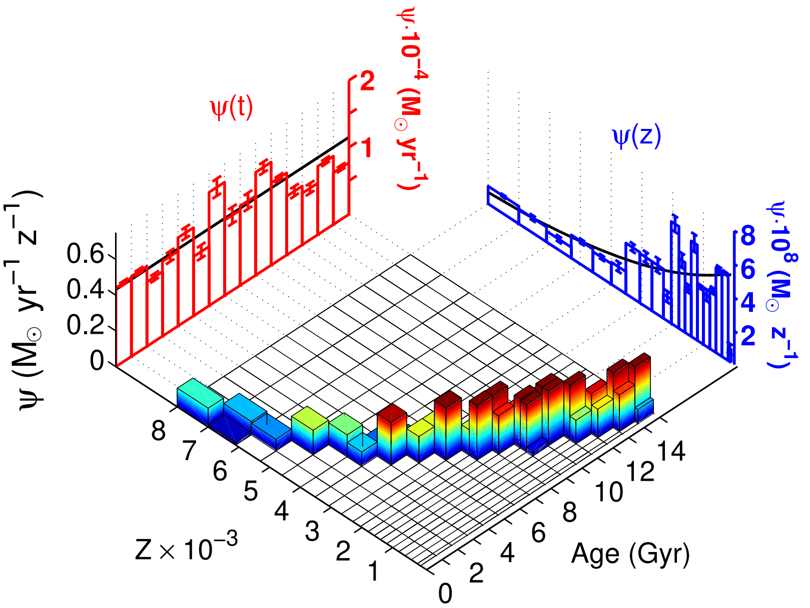

Fig. 5. Solution obtained for the SFH of the continuous star formation mock stellar population using IAC-pop and the stellar evolution library of Padua-Bertelli as input. Differences between the SFH shown in this figure and in Fig. 3 show intrinsic limitations of the method.

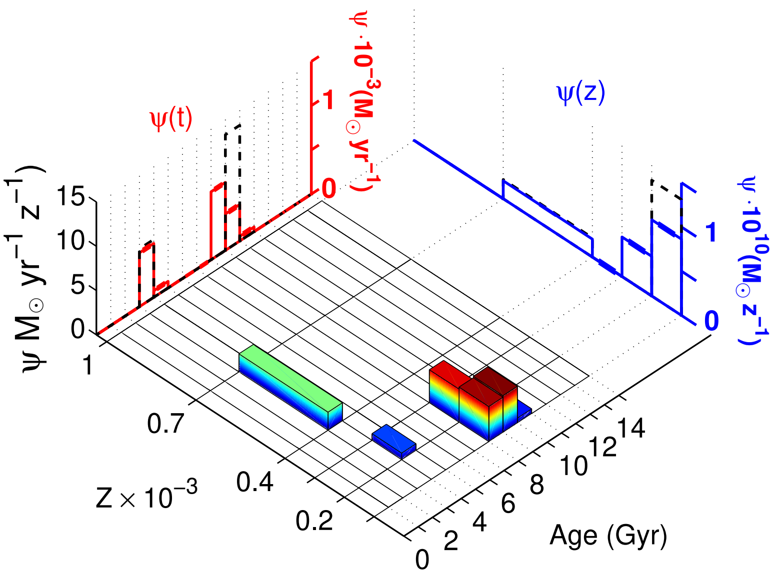

Fig. 6. Solution obtained for the SFH of the two bursts mock stellar population using IAC-pop and the stellar evolution library of Padua-Bertelli as input. Differences between the SFHs shown in this figure and in Fig. 4 show intrinsic limitations of the method.

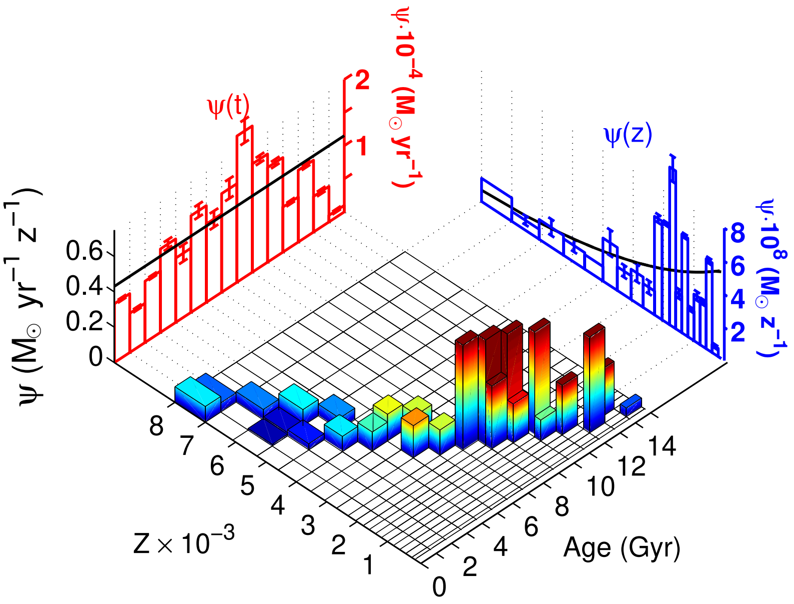

Fig. 7. Solution obtained for the SFH of the continuous star formation mock stellar population using IAC-pop and the stellar evolution library of Teramo-BaSTI as input. Since the CMD of the mock stellar population was computed using the Padua-Bertelli library, differences between the SFHs shown in this figure and in Fig. 3 show discrepancies in the stellar evolution libraries.

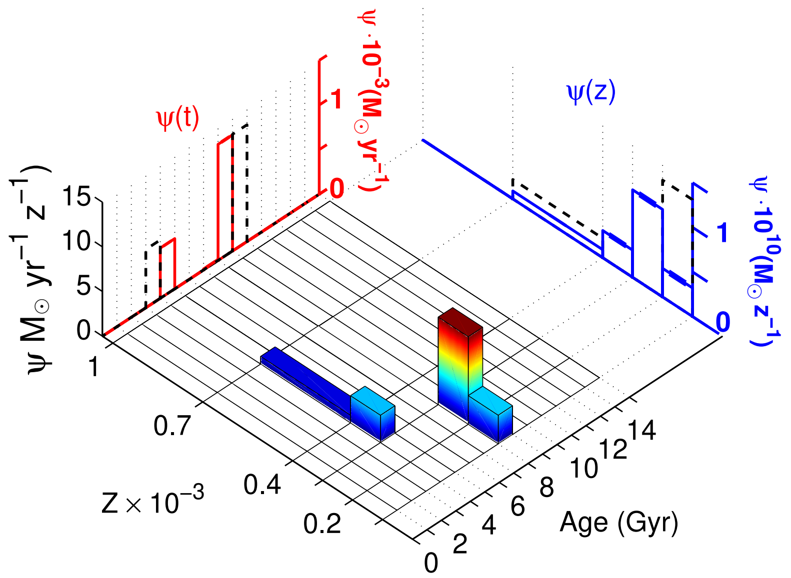

Fig. 8. Solution obtained for the SFH of the two bursts mock stellar population using IAC-pop and the stellar evolution library of Teramo-BaSTI as input. Since the CMD of the mock stellar population was computed using the Padua-Bertelli library, differences between the SFHs shown in this figure and in Fig. 4 show discrepancies in the stellar evolution libraries.

stellar population using two stellar evolution libraries as input to the solving software: the Teramo-BaSTI (Pietrinferni et al. 2004) and the Padua-Bertelli (Bertelli et al. 1994) ones.

IAC-star (Aparicio & Gallart 2004) to compute synthetic CMDs and IAC-pop (Aparicio & Hidalgo 2008) to solve the SFH have been used. Our method to obtain the SFH is explained in Aparicio & Hidalgo (2008) and an example of application to the real case of the dwarf galaxy of Phoenix can be seen in Hidalgo el al. (2008). It is enough to mention here that it uses as input the distribution of stars in the observed CMD and in a single synthetic CMD. The latter is divided into several simple population CMDs and the distribution of stars across the CMD in each one is computed. By *simple populations* we refer to populations containing stars with ages and metallicities within a narrow interval. A genetic algorithm is used to find the linear combination of the single populations which produce a distribution of stars in the CMD most similar to the observed one. This is performed by minimizing a merit function comparing the distributions of stars in the observed and synthetic CMDs. To perform the tests we show here, we have generated two mock stellar populations, one with continuous star formation and another with a bursting star formation. Their SFHs are shown in Figs. 3 and 4 and the corresponding CMDs have been computed using IAC-star and the Padua-Bertelli (Bertelli et al. 1994) stellar evolution library as input. Two tests are shown for each mock population. The first one consists in retrieving the SFH of such populations using IAC-pop and the Padua-Bertelli stellar evolution library as input. Solutions are shown in Figs. 5 and 6. Since the Padua-Bertelli library is the same one used to compute the CMDs associated to the mock population, these are self-consistency tests and differences between input and solution SFHs show intrinsic limitations of the method. In the continuous star formation case, a reasonable coincidence is seen between the mock and the solution SFHs. In the bursting case, it is seen that resolutions better than 1 to 2 Gyr are not attainable for old ages and also that metallicity resolution is limited for the intermediate age burst.

The second test consists in retrieving the SFH of the mock population, also with IAC-pop, but using the Teramo-BaSTI stellar evolution library as input. Solutions are shown in Figs. 7 and 8. Since now different libraries have been used to compute the CMD of the mock populations and to retrieve the solutions, this is a test of the influence of discrepancies in the stellar evolution models on the SFH solutions. It can be seen that, in the continuous star formation case, significant differences exist for the oldest population, which disappears from the solution (Fig. 7) and also on the stellar metallicity distribution for a wide age range. The lower SFH recovered for age$<$ 5 Gyr is an expected consequence of the fact that Teramo-BaSTI overshoot models predict longer lifetimes in the MS for stars of that age range, thus producing a more populated young and intermediate-age MS than the Padua-Bertelli models.

In the bursting case, it is put into evidence that beside the loss of resolution, old stars are recovered as if they were younger, while intermediate stars, are recovered as if they were older.

6. Summary

In summary, we have presented a few examples among the several ones that could have been selected to put into evidence two main points: (i) the need of continuous checking and feedback between theory and observations and (ii) the need of improving the consistency between different stellar evolution libraries. More details and a more exhaustive discussion can be found in the review by Gallart et al. (2005). We hope this contributes to stimulate observer to provide stronger observational constraints where they are needed and to encourage theoreticians to isolate the input physics responsible for the different behavior between models and the reasons for the discrepancies with data.

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