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Testing evolutionary synthesis models: Empirical feedback to model makers

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Abstract. Integrated spectra of star clusters are the best test beds for predictions of evolutionary synthesis models. We present spectral fits of star cluster using a variety of recent models. All models allow good spectral fits, but newer ones tend to be better. Ages estimated through spectral fits are not strongly model dependent, but metallicities can differ a lot from one model to another. For some clusters, multi-population fits suggest a combination of very old (10^{10} yr) and very young ($<10^{8}$) populations, an artifact of the lack of old and blue stars in the models.

Keywords. galaxies: star clusters

1. Context and motivation

High spectral resolution models of simple stellar populations (SSPs) appeared in the literature in the past $\sim$ half decade and have been constantly improving. It took a long time for these models to be produced, but a very short one for them to spread through the extragalactic community, who had tons of galaxy spectra crying for a detailed λ-by-λ analysis. In particular, the 2003 models published by our chairmen became an instant best seller, and are now an integral part of so many studies of galaxies that just listing these publications would take up more than these 4 pages. Undeniably, these studies have advanced tremendously our understanding of galaxy properties, their star formation and chemical enrichment histories. However, one should not loose sight of the fact that this progress is heavily dependent of the accuracy of the spectral predictions for SSPs.

Direct tests of these models, on the other hand, received much less attention in the recent literature (Wolf *et al.* 2007; Koleva *et al.* 2008). Despite all the evidence for complex stellar populations and the effects of hard-to-model phenomena (like blue stragglers) presented in this meeting, star clusters are still the closest thing in the sky to actual SSPs. They therefore provide the best test-beds for models whose basic prediction are integrated spectra of SSPs. This contribution and its sister paper (González Delgado & Cid Fernandes, in the proceedings of IAU Symposium 266) summarize work which uses star clusters to test evolutionary synthesis models for the integrated spectra of SSPs.

2. Data, models, and spectral fits

Medium resolution (FWHM = 5.7 Å) 3650–4600 Å spectra 27 well studied clusters from Leonardi & Rose (2003) were used in this exercise. These clusters, most (20) of which live in the LMC, span a wide range of ages and metallicities, as determined through spatially resolved data (CMDs or spectroscopy of individual stars).

We fit these spectra with different versions of evolutionary synthesis models, with the general goal of testing them and evaluating their pros and cons. By doing so we may be able to provide some useful feedback to model makers and all those involved in the arduous tasks of building ever more complete libraries of evolutionary tracks and stellar spectra. The models employed in this study are: (1) Four variants of the Bruzual & Charlot (2003) models, all based on STELIB, but with 2 versions of evolutionary tracks (Padova 1994 and 2000) and 2 versions for the IMF (Salpeter and Chabrier), (2) the Granada models (Martins *et al.* 2005; González Delgado *et al.* 2005), built with theoretical stellar spectra, (3) the models by Vazdekis and collaborators (presented elsewhere in this volume), based on the MILES library by Sánchez-Blázquez *et al.* (2006), and (4) preliminary models by Charlot & Bruzual which mix the MILES and Granada libraries, for "Padova 1994" tracks and a Chabrier IMF. These models are used in their original form, without any interpolation.

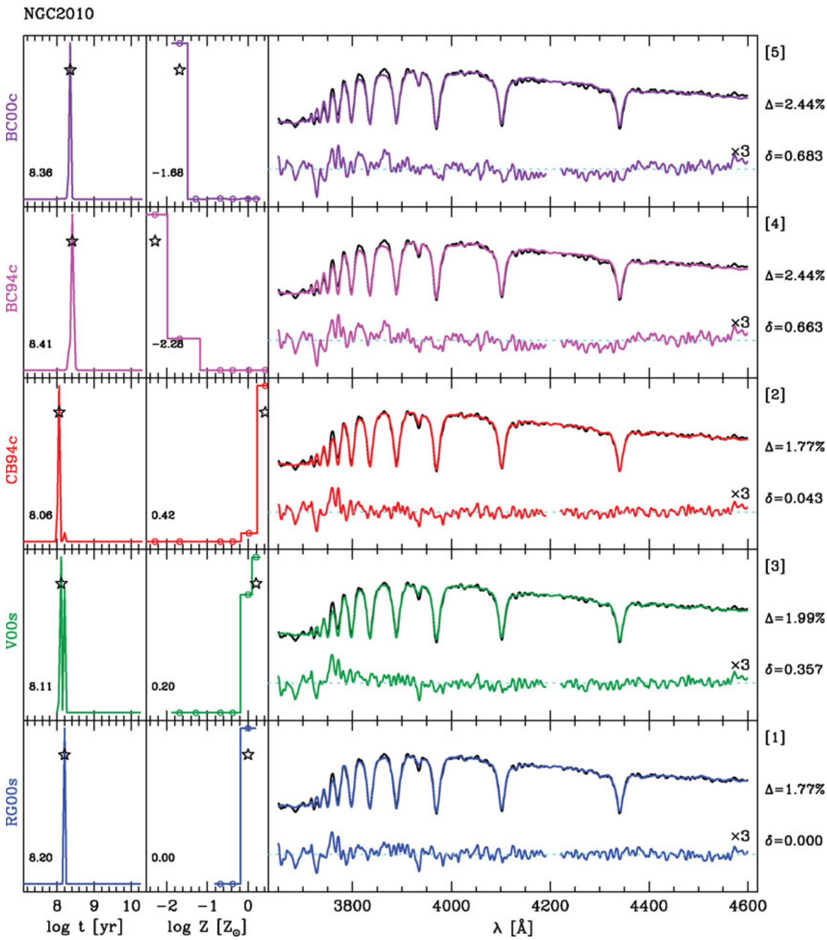

Figure 1. Comparison of spectral fits of NGC 2210 obtained with different SSP models. The top 2 panels correspond to BC03 models with Padova 2000 or 1994 tracks, while the middle one is for the preliminary CB models. Then come results obtained with the Vazdekis and Granada models. Right panels show the observed, best fit, and residual spectra (*multiplied by 3* for clarity), all normalized at 4020 Å, and the dashed line marks the zero flux level. Values of the mean percentage residual ($\overline{\Delta}$) are listed to the right, where the number in brackets indicate the χ^2 fit quality ranking, and $\delta = (\chi^2 - \chi^2_{best})/\chi^2_{best}$. The left panels show the probability distribution functions of t and Z. Best fit values of $\log t$ and $\log Z$ are listed and also marked by a star. In the middle panel, open circles are plotted in each of the metallicities available in the base. Notice how all models yield similar ages, but that the STELIB-based ones suggest very low metallicities.

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The spectral synthesis code STARLIGHT was used to fit all spectra with all models. STARLIGHT is better known as a tool to analyze composite stellar populations (i.e., galaxies), but given a base of SSP spectra, it also finds the best fit single SSP, along with the corresponding extinction. This output is post-processed to derive Bayesian estimated of the star cluster's age (t), metallicity (Z) and extinction (A_V), as well as covariance maps. Details on the methodology and its results are presented in a couple or upcoming articles.

3. Results & some lessons

Figs. 1 and 2 illustrate the results. Visual inspection shows that all models provide good spectral fits, but a closer look shows that fits with STELIB-based models tend to produce larger residuals than those based on the MILES and/or Granada libraries. This is true as long as one does not extrapolate the nominal range of validity of the models. We see this as good news: Things seem to be progressing in the right sense.

These examples also show that, while estimated SSP ages tend to come out very similar, metallicities vary a lot from model to model. Values of Z estimated from spectral

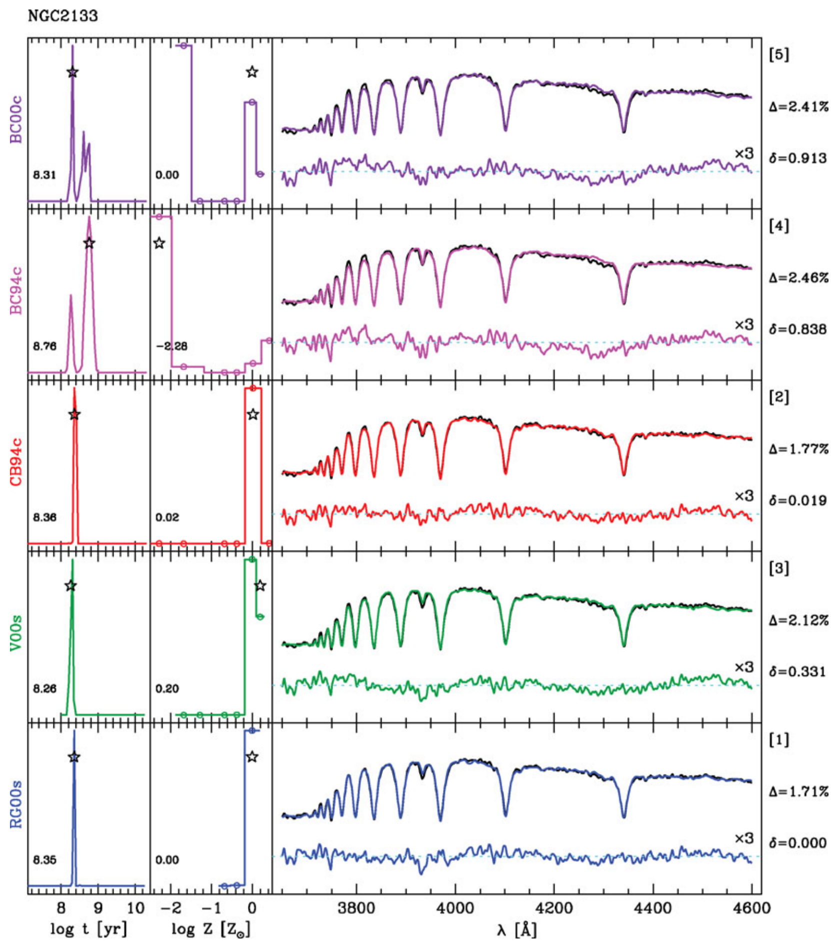

Figure 2. As Fig. 1, but for NGC 2133. Multiple peaks in the posterior probability distribution functions reflect different combinations of t and Z which fit the data $\sim$ equally well. More continuous distributions would be obtained if the Z-grids were less coarsely sampled.

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fits using STELIB-based models are systematically too low compared both to values derived with other models and independent estimates from the literature. The known mismatch between the nominal metallicity of these models and that of the stars actually used to build the spectra produces this and other side-effects, like multi-modal posterior probability distribution functions for t, Z and A_V (Fig. 2).

STARLIGHT also reports the output of multi-SSP fits. In principle, these should not be of interest for star clusters, but we in a few cases (NGC 2210, M15 and M79, "coincidentally" among the most metal poor clusters in our sample) the best-fit combination of SSPs had the peculiarity of mixing a very old component with a very young one. This pathological behavior is most certainly due to the lack of old blue stars in the SSP models. Koleva *et al.* (2008) attribute this to badly-modeled blue horizontal branch. Cenarro's contribution elsewhere in this volume talk about another possibility: blue stragglers.

Empirical tests in this same vein, but applied to galaxy spectra, were performed by Jean M. Gomes in his PhD thesis (2009). Galaxies are of course more complex than star clusters, but with thousands of objects from the SDSS, some clear trends can be identified. His study show that the MILES+Granada based models provide measurably better spectral fits than obtained with the "standard" BC03-STELIB models so widely used in the analysis of galaxy spectra. As for star clusters, not only the newer models provide better fits, but they also lead to differences in the derived physical properties, particularly those related to metallicity. Evidence of the lack of old blue stars is also present, not to mention large spectral residuals in bands sensitive to α elements, which cannot possibly be correctly modeled with models with solar-scaled abundances.

All in all, these empirical experiments reveal both reasons to celebrate progress and reasons to beware of model deficiencies yet to be fixed. Clearly, there are plenty of challenges for the next decade.

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