FAKE STAR FORMATION BURSTS: BLUE HORIZONTAL BRANCH STARS MASQUERADE AS YOUNG MASSIVE STARS IN OPTICAL INTEGRATED LIGHT SPECTROSCOPY

P. Ocvirk
Astrophysikalisches Institut Potsdam, an der Sternwarte 16, D-14482 Potsdam, Germany
Received 2009 June 23; accepted 2009 November 10; published 2009 December 29

ABSTRACT

Model color–magnitude diagrams of low-metallicity globular clusters (GCs) usually show a deficit of hot evolved stars with respect to observations. We investigate quantitatively the impact of such modeling inaccuracies on the signiﬁcance of star formation history reconstructions obtained from optical integrated spectra. To do so, we analyze the sample of spectra of galactic globular clusters of Schiavon et al. with STECKMAP (Ocvirk et al.), and the stellar population models of Vazdekis et al. and Bruzual & Charlot, and focus on the reconstructed stellar age distributions. First, we show that background/foreground contamination correlates with $E(B-V)$, which allows us to deﬁne a clean subsample of uncontaminated GCs, on the basis of an $E(B-V)$ ﬁltering. We then identify a “conﬁusion zone” where fake young bursts of star formation pop up in the star formation history although the observed population is genuinely old. These artifacts appear for 70%–100% of cases depending on the population model used, and contribute up to 12% of the light in the optical. Their correlation with the horizontal branch (HB) ratio indicates that the confusion is driven by HB morphology: red HB clusters are well ﬁtted by old stellar population models while those with a blue HB require an additional hot component. The confusion zone extends over $[\text{Fe/H}] = [-2, -1.2]$, although we lack the data to probe extreme high and low metallicity regimes. As a consequence, any young starburst superimposed on an old stellar population in this metallicity range could be regarded as a modeling artifact, if it weighs less than 12% of the optical light, and if no emission lines typical of an H II region are present. This work also provides a practical method for constraining HB morphology from high signal to noise integrated light spectroscopy in the optical. This will allow post-asymptotic giant branch evolution studies in a range of environments and at distances where resolving stellar populations is impossible with current and planned telescopes.

Key words: galaxies: evolution – galaxies: formation – galaxies: stellar content – globular clusters: general – stars: horizontal-branch – techniques: spectroscopic

Online-only material: color ﬁgures

1. INTRODUCTION

Spectroscopy is a major tool for the study of galaxy formation and evolution. The analysis of the spectrum of galaxies provides constraints on their star formation activity, past and present. However, the accuracy of these constraints depends on the quality of the data, but also critically on the quality of the models used to interpret these spectra, as shown for example in Koleva et al. (2008). Since spectral models of stellar populations rely on stellar evolution models, it is vital the latter models be able to account for most of the observed stellar evolution stages, or at least the most luminous ones (e.g., turnoff, red giant branch (RGB), and horizontal branch (HB) stars). While thermally pulsing asymptotic giant branch (TP-AGB hereafter) stars are fundamental for NIR spectral modelling, hot evolved stars are crucial in the UV for intermediate and old populations. The latter have been proposed as the origin of the UV-upturn of elliptical galaxies (Han et al. 2007; Yi 2008). In this paper, we will focus on these hot HB stars. They are fairly luminous for their mass: while weighing only about 0.5 $M_{\odot}$, they have a typical absolute magnitude $M_V = -0.7$ (Cox 2000). Their He-burning core tends to be hotter with decreasing metallicity, making the HB of low-Z galactic globular clusters bluer (Lee et al. 1994), although the morphology of the HB also depends on a second parameter, so far elusive.

Accurate modeling of the HB morphology of globular clusters (GCs) is a difficult problem. For instance, it is strongly sensitive to mass-loss on the RGB (Dotter 2008). Moreover, accurate fitting of blue HB in GCs usually requires a fine tuning of He abundance dispersion, as shown in NGC 2808 by Lee et al. (2005). This clashes with the general treatment of spectral synthesis for galaxies, where a single stellar population (hereafter SSP) is chemically homogeneous. In effect, the parameter space allowed by popular full spectrum SSP models (as opposed to those predicting indices) such as Bruzual & Charlot (2003, hereafter BC03) or Le Borgne et al. (2004) is strictly (age, metallicity), and the abundances are solar-scaled, with no intrinsic dispersion. With only these parameters, it is expected that the isochrones adopted in these SSP models are not appropriate for the whole range of HB morphology. Indeed, Figure 7 of BC03 shows that the “Padova 1994” and “Padova 2000” tracks do not fit well the color–magnitude diagrams (hereafter CMD) of GCs with blue HB. In particular, the HB of the models does not extend enough toward the blue. These very tracks are nonetheless used for the computation of spectral SSP models. What can be the impact of this lack of hot evolved stars when interpreting the spectra of stellar populations? Their effect can be readily seen in the integrated colors of GCs (Smith & Strader 2007). Moreover, recent works indicate that space observations in the GALEX NUV and FUV are required to differentiate between blue HB stars and young hot stars (Kaviraj et al. 2007; Schawinski et al. 2007). However, although GALEX has been successful at securing data for a fair fraction of the sky, a large corpus of past, present, and ongoing extragalactic studies still rely on optical spectra only (e.g., Reichardt et al. 2001; Panter et al. 2003; Heavens et al. 2004; Tojeiro et al. 2007a, 2007b; Koleva et al. 2009b; Michielsen et al. 2008).
It is now well known that HB morphology makes age-dating stellar populations from optical spectra only troublesome, using indices (Beasley et al. 2000; Puzia et al. 2005), but also using full spectrum fitting techniques (Koleva et al. 2008; Sharina & Davoust 2009): the age inferred spectroscopically can be several Gyr younger than that measured from the turnoff. The effect on star formation history (hereafter SFH) reconstructions could be even more dramatic: do the missing hot stars show up as an additional fake burst as suggested in Coelho et al. (2009), or do they simply shift the whole age distribution to younger ages? At the moment, no studies have been published specifically on the effect of HB morphology on the significance of SFH reconstructions from full spectrum fitting in the optical.

In this paper, we propose to investigate quantitatively this very issue. To do so, we first need a sample of objects with well known, simple star formation histories, and a variety of well constrained HB morphologies. From this point of view, GCs are advantageous since they are mostly believed to arise from a single star formation episode, and display a whole range of HB morphologies. We will focus on the library of integrated spectra of galactic GCs published by Schiavon et al. (2005)1 with STECKMAP (Ocvirk et al. 2006a, 2006b), a Bayesian method for reconstructing the star formation history of galaxies using full spectrum fitting, and a collection of popular SSP models based on MILES (Sánchez-Blázquez et al. 2006) and also BC03. For each GC, the CMD is available from the literature, so that we can relate HB morphology to possible departures of the SFH reconstructions from a unique star formation burst. We recall that the aim of the paper is not to propose a new spectral model for the sample of GCs: it is well established that interpreting HB morphology in globular clusters requires more parameters than the simple SSP population models used here (Bedin et al. 2004; Ferraro et al. 2004; Norris 2004). Instead, our goal is to understand how the unknown HB morphology in galaxies may complicate the interpretation of their spectra. That is why our setup reproduces the prevailing regime in which most extragalactic stellar populations studies in optical integrated light spectroscopy are carried out and therefore uses SSPs or combinations of SSPs. The plan of the paper is as follows: Section 2 presents the data, the SSP models and the method, and Section 3 presents the recovered stellar age distributions and their dependence on HB morphology. In Section 4, we discuss the implications of our results for spectroscopic extragalactic studies.

2. METHODOLOGY

2.1. Data

We consider the sample of integrated spectra of galactic globular clusters published by Schiavon et al. (2005).1 It consists of 40 Galactic globular clusters, obtained with the Blanco 4m telescope and the R–C spectrograph at the Cerro Tololo Inter-American Observatory. The spectra cover the range ≈3350–6430 Å with ≈3.1 Å (FWHM) resolution. The spectroscopic observations and data reduction were designed to integrate the full projected area within the cluster core radii in order to properly sample the light from stars in all relevant evolutionary stages. The signal-to-noise values of the flux-calibrated spectra range from 50 to 240 per Å at 4000 Å and from 125 to 500 per Å at 5000 Å. The selected targets span a wide range of cluster parameters, including metallicity, horizontal-branch morphology, Galactic coordinates, Galactocentric distance, and concentration. We dropped NGC 6569, NGC 6388, and NGC 6441, which have rather peculiar HB morphology. We are then left with 37 GCs. The parameters relevant to this study are listed in Table 1, and are taken from Table 1 of Schiavon et al. (2005). In order to characterize HB morphology, we use the Horizontal Branch Ratio (HBR) indicator, defined as in Lee et al. (1994):

\[
\text{HBR} = (B - R)/(B + V + R),
\]

where \(B\), \(V\), and \(R\) are the number of blue, variable, and red HB stars, respectively. GCs with a blue HB have HBR ≈ 1, while GCs with a red HB have HBR ≈ −1. For NGC 5946 and NGC 6284, we assign HBR = 1 (no value is provided in Schiavon et al. 2005). Since the GCs we study here have masses of the order \(10^3–10^6\) \(M_\odot\) (see Chernoff & Djorgovski 1989 for

\[\text{Table 1} \]

Properties of the Sample of GCs and Results

| GC    | \(E(B-V)\) | \(Z\) | HBR | \(f_{\text{hot}}\) | \(f_{\text{hot}}\) |
|-------|------------|------|-----|----------------|---------------|
| (1)   | (2)        | (3)  | (4) | (5)           | (6)           |
| 104   | 0.04       | −0.7 | −0.99 | 0 | 0 |
| 1851  | 0.02       | −1.21 | −0.36 | 0 | 0 |
| 1904  | 0.01       | −1.55 | −0.89 | 0 | 8 |
| 2298  | 0.15       | −1.97 | 0.93 | 3 | 11 |
| 2808  | 0.23       | −1.29 | −0.49 | 0 | 0 |
| 3201  | 0.21       | −1.56 | 0.08 | 1 | 0 |
| 5286  | 0.24       | −1.51 | 0.8 | 5 | 0 |
| 5904  | 0.03       | −1.26 | 0.31 | 8 | 6 |
| 5927  | 0.45       | −0.64 | −1 | 0 | 0 |
| 5946  | 0.54       | −1.54 | 1 | 4 | 2 |
| 5986  | 0.27       | −1.53 | 0.97 | 0 | 9 |
| 6121  | 0.4       | −1.15 | −0.06 | 0 | 0 |
| 6171  | 0.33       | −1.13 | −0.73 | 0 | 6 |
| 6218  | 0.19       | −1.32 | 0.97 | 7 | 8 |
| 6255  | 0.36       | −1.36 | 0.89 | 3 | 4 |
| 6254  | 0.28       | −1.51 | 0.98 | 4 | 8 |
| 6266  | 0.47       | −1.2 | 0.32 | 0 | 0 |
| 6284  | 0.28       | −1.27 | 1 | 8 | 6 |
| 6304  | 0.52       | −0.66 | −1 | 0 | 0 |
| 6316  | 0.51       | −0.9 | −1 | 1 | 1 |
| 6333  | 0.35       | −1.65 | 0.87 | 0 | 7 |
| 6342  | 0.46       | −1.01 | −1 | 0 | 0 |
| 6352  | 0.19       | −0.7 | −1 | 0 | 0 |
| 6356  | 0.28       | −0.74 | −1 | 0 | 0 |
| 6362  | 0.08       | −1.17 | −0.58 | 0 | 0 |
| 6522  | 0.48       | −1.39 | 0.71 | 8 | 7 |
| 6528  | 0.62       | −0.1 | −1 | 6 | 3 |
| 6544  | 0.73       | −1.38 | 1 | 5 | 2 |
| 6553  | 0.8       | −0.2 | −1 | 13 | 10 |
| 6624  | 0.28       | −0.7 | −1 | 0 | 0 |
| 6626  | 0.38       | −1.21 | 0.9 | 10 | 8 |
| 6637  | 0.16       | −0.78 | −1 | 0 | 0 |
| 6638  | 0.4       | −1.08 | −0.3 | 0 | 4 |
| 6652  | 0.09       | −1.1 | −1 | 0 | 0 |
| 6723  | 0.05       | −1.14 | −0.08 | 0 | 0 |
| 6752  | 0.04       | −1.57 | 1 | 0 | 9 |
| 7089  | 0.06       | −1.49 | 0.96 | 4 | 7 |

Notes:

(1) NGC name, (2) color excess, (3) Metallicity [Fe/H], (4): horizontal branch ratio, (5): Fraction of light in the hot component in %, computed from the SADs obtained with the Vazdekis et al. models, (6): same as (5) with BC03. Columns (1)–(4) are taken from Schiavon et al. (2005), and for (5)–(6), see Section 3.

\[1\] http://www.noao.edu/gcclib/description.html
instance for mass determinations), and the scanned area encloses a large fraction of the mass, we consider that our results should not be affected by stochastic fluctuations related to the finiteness of their stellar populations. According to Lanceron & Mouhcine (2000), the flux fluctuations for our sample should be smaller than a few percents.

2.2. Models

We consider two popular SSP models. The first one (A. Vazdekis et al. 2010, in preparation, hereafter Vazdekis et al.\(^2\)) is based on the MILES stellar library (Sánchez-Blázquez et al. 2006) and the isochrones from Girardi et al. (2000). The other one is (BC03), based on the STELIB stellar library (Le Borgne et al. 2003), and using the “Padova 1994” tracks (Bertelli et al. 1994). The corresponding isochrones for \([\text{Fe/H}]=[-0.7, -1.3, -1.7]\) are shown in Figure 1. Note that throughout the paper we will use the notation \([\text{Fe/H}]=\log_{10}(Z/Z_\odot)\) and \(Z_\odot=0.0189\) (Anders & Grevesse 1989).

The isochrones are very similar up to the beginning of the RGB. In the latter phase, the Girardi (2000) set is bluer, especially for \([\text{Fe/H}]=-1.3\). Then both sets develop a horizontal branch which extends further to the blue with increasing age and decreasing metallicity.

The spectral models we use thus include the HB contribution by construction. However, although the predicted position of the blue horizontal branch (BHB) in the CMD is rather satisfactory in these isochrone sets, the predicted number of stars in this phase is very small. For instance, a synthetic CMD obtained with IAC-STAR\(^3\) in the default setup using the Girardi et al. (2000) isochrones for a \([\text{Fe/H}]=-1.7, 17\) Gyr old population, produces a horizontal branch ratio HBR \(=0.2\), while most GCs of our sample have HBR \(=1\) at the same metallicity and an age of about 10 Gyr. In effect, we checked carefully the spectral evolution of the low-\(Z\) models from 10 to 20 Gyr in the optical and they show very little sign of the increasing BHB contribution with age: for the Vazdekis et al. models, a very slight blueness and deepening of the Balmer lines (about 1%) can be seen at these extreme ages, however for the BC03 models we see nothing at all. In any case, the contribution of the BHB to the optical spectrum even in 20 Gyr models is much smaller than the difference in GCs spectra induced by differences in HB morphology for clusters of similar metallicity, as shown for instance by Figure 3 of Schiavon et al. (2005). So even if the BHB is present in the isochrones, it is legitimate to say that there is almost no BHB contribution to the spectra in the optical within our set of SSP models.

Both models cover equally well the wavelength range of the data. We consider the metallicity set \([\text{Fe/H}]=[-1.7, -0.7, -0.4, 0, 0.4]\). Although BC03 covers a wider age range, we restrict ourselves to SSP sequences of age \(=10^8-2.10^{10}\) yr for both models, divided in 40 age bins. We include these extreme ages even though they are larger than the WMAP5 age of the universe of 13.7 Gyr (Hinshaw et al. 2009), because, as shown by Figure 1, really blue HBs develop only at ages larger than 12 Gyr in both sets of isochrones. We did not use PEGASE-HR (Le Borgne et al. 2004) coupled with the ELODIE 3.1 library (Prugniel et al. 2007), although it offers the highest spectral resolution \((R=10,000)\), because it does not cover the \(\lambda < 3900\) Å domain.

\(^2\) http://www.iac.es/galeria/vazdekis/vazdekis_models_ssp_seds.html
\(^3\) http://iac-star.iac.es/iac-star/

![Figure 1](image-url)  
**Figure 1.** Color–magnitude diagrams of the isochrones used for the Vazdekis et al. models (Girardi et al. 2000, black solid line) and BC03 (Bertelli et al. 1994, gray dashed line) for 3 metallicities \([\text{Fe/H}]=[-0.7, -1.3, -1.7]\). For each panel, the sequence spans the [4–20] Gyr age range by logarithmic increments of 0.1 dex.

2.3. Interpretation Software: STECKMAP

In order to analyze the observed spectra with SSP models as a reference, we use the interpretation code STECKMAP
We now present the results obtained by applying STECKMAP with the described setup to the sample of GCs. A very good fit to the data is obtained in all cases, as shown for NGC 1851 in Figure 2.

### 3.1. Two Families of Stellar Age Distributions

We find that the recovered SADs fall in two classes, as illustrated by Figure 3.

1. **Type I**: genuinely old SAD, with a single bump consisting only of $>10^{9.5}$ yr components (left panel).
2. **Type II**: two-component SAD, with most of the light provided by an old population, and a small light fraction (up to 12%) coming from the youngest bins (right panel).

While the first family of SADs is what one would actually expect for GCs, the second one comes as a surprise, since GCs are usually expected to consist of stars formed in one single short star formation event. We already pointed out that hot evolved stars such as BHB stars, if unaccounted for in the SSP models, could show up in the spectra by producing abnormally deep blue Balmer lines. In such cases, the model SSPs will be redder and display weaker Balmer lines than the observed spectrum. As a consequence, our interpretation code STECKMAP indicates that the best fitting combination of the SSP models provided consists of an old SSP plus a very young SSP that mimics the HB stars unaccounted for by the model isochrones.

We now test the relevance of this interpretation of type II SADs by investigating quantitatively their connection with HB morphology.

### 3.2. Hot Fraction and Horizontal Branch Morphology

We define the hot fraction $f_{\text{hot}}$ as the sum of the luminous weights of the young (age $< 10^{8.5}$ yr) components. We recall here that the SAD is normalized (the sum of all weights is 1). In Figure 4, we plot the hot fraction $f_{\text{hot}}$ versus the HBR for the whole sample. About half of the clusters have $f_{\text{hot}} = 0$, which was our initial expectation. Moreover, there seems to be a general trend of increasing $f_{\text{hot}}$ with HBR. About 10 of the GCs...
investigated the use of alternative indicators of contamination. Exposure time, and hence also on the distance to the GC. We thus filtered, since the likelihood of a contamination depends on galactic center direction. However, this does not provide a good proxy, since the color excess $E(B-V)$ is a good proxy for the likelihood of foreground/background contamination, and the left panel of Figure 5 tells us that GCs with $E(B-V) < 0.4$ should be relatively free from contamination. Therefore, for these objects, $f_{hot}$ should trace contamination. One could object that the large $f_{hot}$ found could also be a consequence of a strong contribution from blue stragglers (hereafter BS). Indeed, Zoccali et al. (2001) shows a clear “blue plume” in the CMD of NGC 6553. However, their kinematical cleaning shows that only half of the stars of the plume are indeed cluster members and therefore genuine BS. The other half of the plume consists of young disk stars in the foreground, and is hotter and more luminous than the BSs. Hence, even if BSs certainly partially contribute to the blue light excess, the latter is dominated by foreground disk contamination. The high $f_{hot}$ found for NGC 6553 thus effectively traces contamination rather than abnormal BSs frequency.

The left panel of Figure 5 shows $f_{hot}$ as a function of color excess for GCs with $HBR < 0$. Indeed, most of the red HB GCs are well fitted by genuinely old SSPs, without the need for any additional hot component. However, for $E(B-V) > 0.4$, $f_{hot}$ increases sharply, reaching a maximum for the two galactic center GCs NGC 6553 and NGC 6528. This correlation between $f_{hot}$ and extinction lends support to our interpretation. In effect, a correlation between background/foreground contamination and extinction should naturally arise from the two following points.

1. If dust and stellar density correlates, then $E(B-V)$ increases with the integrated stellar density along the line of sight to the GC.
2. Young hot contaminating stars are more likely to live in dusty environments.

It seems therefore that the color excess $E(B-V)$ is a good proxy for the likelihood of foreground/background contamination, and the left panel of Figure 5 tells us that GCs with $E(B-V) < 0.4$ should be relatively free from contamination. In order to clean our sample from contaminated spectra, we will drop the high-extinction GCs, and keep only those with $E(B-V) < 0.4$. The right panel of Figure 5 shows that, within this new definition of the sample, there is no correlation between $E(B-V)$ and $f_{hot}$ for the blue HB GCs either, and the points are randomly distributed. It also shows that the $E(B-V)$ filtering have $HBR \approx 1$ and $f_{hot} > 0$, which supports our interpretation for the type II SADs, as explained in Section 3.1. There are however outliers with respect to this simple picture: 4 GCs with red HB have $f_{hot} > 0$, and another 3–4 have a blue HB but $f_{hot} \approx 0$. We checked that these were not secondary minima by using a family of single bursts populations centered on random ages as first guess. They all led to the same solution.

3.2.1. Background/Foreground Contamination

The two objects in the top left part of Figure 4 are NGC 6553 and NGC 6528, which are located in the direction of the galactic center. Because of their location, they are definitely the most likely to be contaminated.

Since we are interested in the effect of HB morphology on the spectra rather than contamination, we wish to work on a sample free from foreground/background contamination. One could define a subsample by removing the GCs too close to the galactic center direction. However, this does not provide a good proxy, since the likelihood of a contamination depends on the integrated stellar density inside the scanned volume and the exposure time, and hence also on the distance to the GC. We thus investigated the use of alternative indicators of contamination.
only removes four BHB GCs, and leaves us with a large enough sample to carry on with our investigation.

3.2.2. The $f_{\text{hot}}$–HBR Correlation

The left panel of Figure 6 shows the results for the cleaned sample. The correlation between $f_{\text{hot}}$ and blue HB morphology is now much clearer: spurious bursts of recent star formation are very likely to appear in GCs with HBR > 0, while $f_{\text{hot}} = 0$ for all the GCs with HBR < 0. The intensity of the spurious young burst can be as high as 10% of the total optical light of the cluster. The spurious recent bursts correlate with HB morphology.

However, we find that four (out of 13) GCs with BHB have an almost $f_{\text{hot}} \approx 0$. To check this last puzzling point and more generally the robustness of the $f_{\text{hot}}$–HBR correlation we investigated the influence of the theoretical error in the SSP models.

3.3. Model Dependence

We repeated the analysis of the sample using the BC03 models. The results are shown in the right panel of Figure 6. First of all, the correlation between $f_{\text{hot}}$ and HBR is recovered, and is therefore a robust result of our study. However, the frequency of spurious young bursts is higher in general with this model, both in GCs with BHB and RHB. In particular, the low-$Z$ GCs for which $f_{\text{hot}} = 0$ with the Vazdekis et al. models, now all have a measurable $f_{\text{hot}} > 0$. On the other hand, two of the red HB GCs, which previously had $f_{\text{hot}} = 0$ now have a non-zero hot fraction.

The overall consistency of the results obtained using the two models indicates that, for the regime studied here (sub-solar metallicity, age > 6 Gyr), the systematic error introduced by the uncertainties in the modeling of the HB are larger than the other error sources (differences in the underlying stellar libraries, accuracy of the stellar parameters and coverage of the latter, interpolation procedures).

3.4. Method Dependence

In Koleva et al. (2008), the authors performed a similar experiment, however with a different, parametric method (Chilingarian et al. 2007), where the young SSP was replaced with a hot star spectrum. They also found a correlation between the HBR and the luminous weight of the hot star, although much
Because of this agreement, we suggest that the clearer fHBL–HBR results to STECKMAP in the reconstruction of the star formation history of dwarf elliptical galaxies (Koleva et al. 2009a). Because of this agreement, we suggest that the clearer fHBL–HBR correlation we find here with respect to Koleva et al. (2008) is essentially the consequence of the wider wavelength range of the models we used. Indeed, the Vazdekis et al. models allow us to exploit the full coverage of the data into the blue, down to 3500 Å, while Koleva et al. (2008) used PEGASE-HR (Le Borgne et al. 2004), which starts at 3900 Å. This gives us good confidence in the fact that our results are robust to a change of method, as well as a change of SSP models, provided that the wavelength range are kept similar.

4. DISCUSSION

4.1. The Confusion Zone

We identified a range in metallicity ([Fe/H] < −1.2) where the analysis of the integrated spectra of stellar populations in the optical is highly likely (70%–100% probability depending on the model) to lead to the detection of a fake young burst of star formation, contributing up to 12% of the light. The luminosity of this spurious burst correlates with HB morphology, and increases toward bluer HB. This result is independent of the SSP model and of the method used.

The consequence for studies of stellar populations of galaxies is that any detection of a young burst of star formation superimposed on an old metal-poor population ([Fe/H] < −1.2) from analysis of the optical spectrum is possibly spurious if the contribution of the young populations is smaller than 12% and no emission lines typical of H II regions are seen. Moreover, since galactic stellar populations are composite in general, smaller young fractions can still be the signature of BHB stars even if the old component has a luminosity-weighted metallicity larger than −1.2. For example, following our results, an old composite population, with 50% of mass in solar metallicity stars and 50% of mass in [Fe/H] = −1.2 stars could still display 5% of the light in a fake young burst. What exactly does it mean for extragalactic studies? In the following, we discuss the implications of our result for spectroscopic studies of various objects in integrated light.

4.2. Field and Cluster HB Stars

So far we have considered exclusively GCs. It is not obvious that our result also applies to integrated spectroscopy of field stars, which is the method of choice for extragalactic studies.

Indeed, some stages of stellar evolution seem to differ depending on membership to a GC or to the field, such as metal-rich RR Lyrae stars (Layden et al. 1999; Catelan et al. 2006; Matsunaga 2007). However, these differences seem to disappear at low Z (i.e., the regime of this work). Moreover, differences in the properties between field and GCs HB stars (other than RR Lyrae) have not been detected. It is not clear why some stages are affected by GC membership while others are not. Two processes at least are expected to be significantly more important in cluster environments than in the field. These are binary stellar evolution (higher binarity in clusters), and binary disruption (decreasing binary frequency), as shown for example in Guhathakurta et al. (1998) and Sollima et al. (2007).

As a matter of fact, blue HB morphology is indeed observed in the field as well: the CMDs of Dolphin (2002) show that the dwarf galaxies Leo I and especially Ursa Minor have a well defined BHB. In the absence of strong contrary evidence, we consider that the HB of the GCs analyzed here are representative of the HB morphologies of at least a fraction of the field stellar populations of galaxies.

4.3. Metal-rich Populations

The highest metallicity object of our clean sample is NGC 104, with [Fe/H] = −0.7. We were unable to use the higher metallicity part of the original sample because it happens to be also the most extincted, and thus the most contaminated. However, upon visual inspection of the CMDs of NGC 6528 and NGC 6553 ([Fe/H] = −0.1 and [Fe/H] = −0.2), no evidence for a blue HB is found, and these populations should therefore be well behaved with respect to star formation history reconstructions. This extends our results to quasi-solar metallicities. At even higher metallicities, we recall that spectroscopy of elliptical galaxies in the optical suggests small but recent star formation (Trager et al. 2000), in the form of a “frosting” of young stars, reminiscent of the artifacts we have observed for GCs with BHB. This is a very important aspect since the halt of star formation in massive galaxies, as inferred from their red colours, motivates a large amount of studies in the search for quenching mechanisms, either through hot shocks and the end of cold streams (Birnboim & Dekel 2003; Kereš et al. 2005; Ocvirk et al. 2008), or AGN feedback (Hopkins et al. 2007; De Lucia & Blaizot 2007). We note however that evidence for recent star formation in early-type galaxies is also found in IR data (Lyubenova et al. 2008), which is little sensitive to any EHB/BHB contribution. To probe such high metallicities, an integrated spectrum of NGC 6791, an old (8–9 Gyr), metal-rich (twice solar) open cluster, would be very useful. Interestingly, several extreme horizontal branch stars (EHB), even hotter than usual BHB stars, have been found in this object (Kaluzny & Udalski 1992; Liebert et al. 1994), although without any sizeable BHB counterpart. However, it is unlikely that this small population of very hot evolved stars can produce such strong artifacts in SFH reconstructions as we have seen from optical light. Their contribution peaks in the FUV and affects the optical light much less than the BHB studied here. As an alternative to NGC 6791, one could study old metal-rich extragalactic GCs, although we would then miss the accurate photometric determination of their HB morphology from a CMD.

4.4. M32

The rightmost panel of Figure 6 of Coelho et al. 2009 shows that except for the nucleus, a large fraction (about ≈50%) of the light of M32 is produced by a [Fe/H] < −1.2 old stellar population. Our study shows that in this regime, a spurious young burst accounting for ≈5% is indeed likely to appear. However, in the nucleus, the underlying stellar population is metal rich. Even though we do not constrain well the extent of the “confusion zone” in the high Z regime, the young component is stronger than the fake bursts we found: it accounts for 20% of the light (in a similar wavelength range) while we found maximum spurious contributions of 10%–12%. Hence, our result supports the claims of Coelho et al. (2009), mainly that there has been a recent burst of star formation in the center of M32, while the young component seen in the outskirts is also compatible with being an artifact due to the blue HB morphology of the system.
5. CONCLUSIONS

The analysis of integrated spectra of galactic GCs Schiavon et al. (2005) with STECKMAP yields two families of stellar age distributions.

1. Type I: genuinely old populations, with no contribution from components younger than $10^{9.5}$ yr.

2. Type II: old populations with a superimposed hot component younger than $10^{8.5}$ yr contributing a fraction $f_{\text{hot}}$ to the light of the GC.

GCs with red HB and a type II SAD are subject to background/foreground contamination. Since the latter correlates with color excess $E(B − V)$, we define a clean sample (with respect to contamination) by removing GCs with $E(B − V) > 0.4$. In this new sample, red HB GCs all have type I SADs, while blue HB GCs have mostly type II SADs, with up to 12% of the light in the hot component. This is the signature of inaccuracies in the modeling of the horizontal branch: in the model tracks used in Vazdekis et al. and BC03, the blue HB is often too short and/or under populated compared to observations. As a consequence, the observed integrated spectrum contains an additional hot component with respect to the corresponding model SSP, which gives rise to the $f_{\text{hot}}$–HB correlation. This is the main result of the paper, and it is found with both SSP models Vazdekis et al. and BC03.

We have thus identified a “confusion zone,” where spurious starbursts are very likely to appear in star formation history reconstructions, even though the observed population is genuinely old. These fake starbursts are young (<$10^{10.5}$ yr) and occur in 70%–100% of cases depending on the SSP model, and can weight up to 12% of the light in the optical. This confusion is driven by HB morphology and is thus mainly a low-metallicity effect ([Fe/H] < −1.2). In this regime, any minor young burst of star formation can be an artifact, especially if no emission lines associated with star formation are seen. We expect this prediction to be independent of the interpretation method and models, as long as the evolutionary tracks used for the spectral synthesis are not tuned specifically to account for BHB morphology. The exact weight allowed for the fake starburst depends on the wavelength range considered. It should increase for domains bluer than the ones in this work, and decrease toward the red.

The highest metallicity of our clean sample is [Fe/H] = −0.7, which prevents us from properly probing the high-Z regime. We plan to do so by studying old metal-rich extragalactic GCs or an integrated spectrum of NGC 6791.

We wish to encourage the stellar evolution and extragalactic communities to consolidate the recent progresses made on HB morphology modeling by including the relevant tracks into future spectral synthesis models such as Vazdekis et al. However, we note that accurate fitting of blue HB morphology in GCs by fine tuning of He abundance dispersion such as in Lee et al. (2005) introduces additional parameters, and possibly new degeneracies in spectrum interpretation. Moreover, proper use of these tracks requires a stellar library, empirical or theoretical, for a range of non-solar abundance ratios, reliable everywhere on the CMD. Such models are still in their infancy, despite improvements such as Coelho et al. (2007).

This study is also an interesting sanity check for STECKMAP, which is found to behave very well. We propose that the exercise of analysing the $E(B − V)$-filtered sample and checking the results dependence on HBR as we have done be a test for all the star formation history reconstruction methods, such as MOPED (Reichardt et al., 2001), VESPA (Tojeiro et al., 2007), STARLIGHT (Cid Fernandes et al., 2005), ULySS (Koleva et al., 2009a, or Wild et al., 2007), and urge other authors to perform the same experiment.

Finally, the fact that STECKMAP associates BHB morphology with a type II SAD with a high success rate, shows that HB morphology can be determined in integrated light through full spectrum fitting, and in the optical domain, as was realized by Schiavon et al. (2004). This technique could thus become a valuable tool for extragalactic cluster studies: by removing the need for UV (i.e., space) observations and resolved populations (i.e., relatively nearby), it gives access to samples and environments otherwise unreachable.

The author thanks P. Coelho, A. Nebot Gomez-Moran, A. Lannon, D. Le Borgne, K. Freeman, P. Prugniel, and M. Koleva for useful comments, and M. Koleva again for providing accurate individual spectral masks for bad pixels and sky subtraction residuals. This work is supported by a grant from the Deutsche Luft und Raumfahrt (DLR). It has made use of the IAC-STAR Synthetic CMD computation code based on Aparicio & Gallart (2004). IAC-STAR is supported and maintained by the computer division of the Instituto de Astrofisica de Canarias. The author thanks D. Munro for freely distributing his Yorick programming language,5 and E. Thiebaut for sharing his Yorick optimization package OptimPack.

REFERENCES

Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Aparicio, A., & Gallart, C. 2004, AJ, 128, 1465
Beasley, M. A., Sharples, R. M., Bridges, T. J., Hanes, D. A., Zepf, S. E., Ashman, K. M., & Geisler, D. 2000, MNRAS, 318, 1249
Bedin, L. R., Piotto, G., Anderson, J., Cassisi, S., King, I. R.,Momany, Y., & Carraro, G. 2004, ApJ, 605, L125
Bertelli, G., Bressan, A., Chiosi, C., Fagotto, F., & Nasi, E. 1994, A&AS, 106, 275
Binhrnim, Y., & Dekel, A. 2003, MNRAS, 345, 349
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000 (BC03)
Catelan, M., Stetson, P. B., Pritzl, B. J., Smith, H. A., Kinemuchi, K., Layden, A. C., Sveigaart, A. V., & Rich, R. M. 2006, ApJ, 651, L133
Chernoff, D. F., & Djorgovski, S. V. 1989, ApJ, 339, 904
Chilingarian, I., Prugniel, P., Silchenko, O., & Koleva, M. 2007, in IAU Symp. 241, NBursts: Simultaneous Extraction of Internal Kinematics and Parametrized SFH from Integrated Light Spectra, ed. A. Vazdekis & R. F. Peletier (Dordrecht: Kluwer), 175
Cid Fernandes, R., Mateus, A., Sodre, L., Stasinska, G., & Gomes, J. M. 2005, MNRAS, 358, 368
Coelho, P., Bruzual, G., Charlot, S., Weiss, A., Barbuy, B., & Ferguson, J. W. 2007, MNRAS, 382, 498
Coelho, P., Mendes de Oliveira, C., & Cid Fernandes, R. 2009, MNRAS, 396, 624
Cox, A. N. 2000, Allen’s Astrophysical Quantities (4th ed.; Berlin: Springer)
De Lucia, G., & Blaizot, J. 2007, MNRAS, 375, 2
Dolphin, A. E. 2002, MNRAS, 332, 91
Dotter, A. 2008, ApJ, 687, L21
Ferraro, F. R., Origlia, L., Testa, V., & Maraston, C. 2004, ApJ, 608, 772
Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C. 2000, A&AS, 141, 371
GuhaThakurta, P., Webster, Z. T., Yanny, B., Schneider, D. P., & Bahcall, J. N. 1998, AJ, 116, 1757
Han, Z., Podsiajlowski, P., & Lynam-Gray, A. E. 2007, MNRAS, 380, 1098
Heavens, A., Panter, B., Jimenez, R., & Dunlop, J. 2004, Nature, 428, 625
Hinshaw, G., et al. 2009, ApJS, 180, 225
Hopkins, P. F., Bundy, K., Hernquist, L., & Ellis, R. S. 2007, ApJ, 659, 976
Kaluzny, J., & Udalski, A. 1992, Acta Astron., 42, 29
Kaviraj, S., et al. 2007, ApJS, 173, 619
Kereˇs, D., Katz, N., Weinberg, D. H., & Dav´e, R. 2005, MNRAS, 363, 2
Koleva, M., De Rijcke, S., Prugniel, P., Zeilinger, W. J ., & Michielsen, D. 2009a, MNRAS, 396, 2133
Koleva, M., Prugniel, P., Bouchard, A., & Wu, Y. 2009b, A&A, 501, 1269

5 http://www.maumae.net/yorick/doc/index.html
Koleva, M., Prugniel, P., Ocvirk, P., Le Borgne, D., & Soubiran, C. 2008, 
MNRAS, 385, 1998

Lançon, A., & Mouchine, M. 2000, in ASP Conf. Ser. 211, Massive Stellar 
Clusters, ed. A. Lançon & C. M. Boily (San Francisco, CA: ASP), 34

Layden, A. C., Ritter, L. A., Welch, D. L., & Webb, T. M. A. 1999, 
AJ, 117, 1313

Le Borgne, D., Rocca-Volmerange, B., Prugniel, P., Lançon, A., Fioc, M., & 
Soubiran, C. 2004, A&A, 425, 881

Le Borgne, J.-F., et al. 2003, A&A, 402, 433

Lee, Y.-W., Demarque, P., & Zinn, R. 1994, ApJ, 423, 248

Lee, Y.-W., et al. 2005, ApJ, 621, L57

Liebert, J., Saffer, R. A., & Green, E. M. 1994, AJ, 107, 1408

Lyubenova, M., Kuntschner, H., & Silva, D. R. 2008, A&A, 485, 425

Matsunaga, N. 2007, in ASP Conf. Ser. 378, Why Galaxies Care About 
AGB Stars: Their Importance as Actors and Probes, ed. F. Kerschbaum, 
C. Charbonnel, & R. F. Wing (San Francisco, CA: ASP), 86

Michielsen, D., et al. 2008, MNRAS, 385, 1374

Norris, J. E. 2004, ApJ, 612, L25

Ocvirk, P., Pichon, C., Lançon, A., & Thiébaut, E. 2006a, MNRAS, 365, 74

Ocvirk, P., Pichon, C., Lançon, A., & Thiébaut, E. 2006b, MNRAS, 365, 46

Ocvirk, P., Pichon, C., & Teyssier, R. 2008, MNRAS, 390, 1326

Panter, B., Heavens, A. F., & Jimenez, R. 2003, MNRAS, 343, 1145

Prugniel, P., Soubiran, C., Koleva, M., & Le Borgne, D. 2007, 
arXiv:astro-ph/0703658

Puzia, T. H., Kissler-Patig, M., Thomas, D., Maraston, C., Saglia, R. P., Bender, 
R., Goudfrooij, P., & Hempel, M. 2005, A&A, 439, 997

Reichardt, C., Jimenez, R., & Heavens, A. F. 2001, MNRAS, 327, 849

Sánchez-Blázquez, P., et al. 2006, MNRAS, 371, 703

Schawinski, K., et al. 2007, ApJS, 173, 512

Schiavon, R. P., Rose, J. A., Courteau, S., & MacArthur, L. A. 2004, ApJ, 608, 
L33

Schiavon, R. P., Rose, J. A., Courteau, S., & MacArthur, L. A. 2005, ApJS, 160, 
163

Sharina, M., & Davoust, E. 2009, A&A, 497, 65

Smith, G. H., & Strader, J. 2007, Astron. Nachr., 328, 107

Sollima, A., Beccari, G., Ferraro, F. R., Fusi Pecci, F., & Sarajedini, A. 
2007, MNRAS, 380, 781

Tojeiro, R., Heavens, A. F., Jimenez, R., & Panter, B. 2007a, MNRAS, 381, 
1252

Tojeiro, R., Wilkins, S., Heavens, A. F., Panter, B., & Jimenez, R. 2007b, 
MNRAS, 381, 1252

Trager, S. C., Faber, S. M., Worthey, G., & González, J. J. 2000, AJ, 120, 165

Wild, V., Kauffmann, G., Heckman, T., Charlot, S., Lemson, G., Brinchmann, 
J., Reichard, T., & Pasquali, A. 2007, MNRAS, 381, 543

Yi, S. K. 2008, in ASP Conf. Ser. 392, Hot Subdwarf Stars and Related Objects, 
ed. U. Heber, C. S. Jeffery, & R. Napiwotzki (San Francisco, CA: ASP), 3

Zoccali, M., Renzini, A., Ortolani, S., Bica, E., & Barbuy, B. 2001, AJ, 121, 
2638