EVIDENCE FOR BLUE STRAGGLER STARS REJUVENATING THE INTEGRATED SPECTRA OF GLOBULAR CLUSTERS

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ABSTRACT

Integrated spectroscopy is the method of choice for deriving the ages of unresolved stellar systems. However, hot stellar evolutionary stages, such as hot horizontal branch stars and blue straggler stars (BSSs), can affect the integrated ages measured using Balmer lines. Such hot, “noncanonical” stars may lead to overestimation of the temperature of the main-sequence turnover, and therefore underestimation of the integrated age of a stellar population. Using an optimized $\text{H}\beta$ index in conjunction with HST WFPC2 color-magnitude diagrams (CMDs), we show that Galactic globular clusters exhibit a large scatter in their apparent “spectroscopic” ages, which does not correspond to that in their CMD-derived ages. We find for the first time that the specific frequency of BSSs, defined within the same aperture as the integrated spectra, shows a clear correspondence with $\text{H}\beta$ in the sense that, at fixed metallicity, higher BSS ratios lead to younger apparent spectroscopic ages. Thus, the specific frequency of BSSs in globular clusters sets a fundamental limit on the accuracy with which spectroscopic ages can be determined for globular clusters, and perhaps for other stellar systems such as galaxies. The observational implications of this result are discussed.

Subject headings: blue stragglers — galaxies: star clusters — galaxies: stellar content — globular clusters: general

1. INTRODUCTION

A common method for estimating the ages of unresolved stellar systems is to measure Balmer lines and metal lines from integrated spectra, and compare them to stellar population models. The method relies on the fact that Balmer lines are mostly sensitive to the effective temperature ($T_{\text{eff}}$) of the main-sequence turnoff, and therefore underestimation of the internal age of a stellar population. Using an optimized $\text{H}\beta$ index in conjunction with HST WFPC2 color-magnitude diagrams (CMDs), we show that Galactic globular clusters exhibit a large scatter in their apparent “spectroscopic” ages, which does not correspond to that in their CMD-derived ages. We find for the first time that the specific frequency of BSSs, defined within the same aperture as the integrated spectra, shows a clear correspondence with $\text{H}\beta$ in the sense that, at fixed metallicity, higher BSS ratios lead to younger apparent spectroscopic ages. Thus, the specific frequency of BSSs in globular clusters sets a fundamental limit on the accuracy with which spectroscopic ages can be determined for globular clusters, and perhaps for other stellar systems such as galaxies. The observational implications of this result are discussed.

1. INTRODUCTION

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In order to shed light on the above issue, in this letter we describe our findings within the context of estimating ages for unresolved stellar populations.

2. THE DATA

Integrated optical spectra for 41 GGCs were taken from S05. These data were obtained by drift-scanning the core diameter of each GGC, with a spectroscopic aperture equal to this diameter, in order to construct a representative integrated spectrum. The spectra cover a wavelength range of $\sim3350$–$6430\ \AA$, with a FWHM of $\sim3.1 \AA$ and typical signal-to-noise ratios (S/N) of $\sim250\ \AA^{-1}$ in the continuum of the $\text{H}\beta$ line. We refer the reader to S05 for more details on these data.

In Figure 1 we present the indices $\text{H}\beta_{\text{o}}$, $\text{H}\beta_{\text{str}}$ (Worthey et al., 1994), and [MgFe] (González 1993) measured for the 41 GGC spectra at the S05 spectral resolution. Uncertainties in the index measurements (1 $\sigma$ error bars) account for the S/N spectra and the typical radial velocity error provided by S05 for each GGC. To guide the eye, based on the MILES stellar library (Sánchez-Blázquez et al. 2006b; Cenarro et al. 2007a), an extension of the simple stellar population (SSP) models in Vazdekis (1999) are overplotted at $3.1\ \AA$ spectral resolution. The fact that most GGCs lie below the model grids arises from the well-known zero-point problem of SSP models (e.g., Vazdekis et al. 2001; Schiavon et al. 2002), although this does not affect our results, which are based on relative differences.

As expected, in the $\text{H}\beta_{\text{str}}$ plot (Fig. 1a) GGCs follow, on average, an old sequence in metallicity. However, by simple visual inspection they seem to separate into two groups, particularly at the high-metallicity end ([MgFe] $\gtrsim 1.2$). Hence, filled and open symbols are employed to indicate, respectively, GGCs with high and low $\text{H}\beta_{\text{str}}$ values at fixed [MgFe]. Henceforth, these are referred to as GGCH and GGCL, respectively.

When using the $\text{H}\beta_{\text{str}}$ definition (Fig. 1b), both GGC groups are still distinguished, although the greater age–metallicity degeneracy of $\text{H}\beta_{\text{str}}$ would make their differentiation less clear to detect if the distinct symbol codes were not present. Even so,
Puzia et al. (2002) already pointed out the existence of unexpected Hβ$_{ins}$ differences among certain metal-rich (MR) GGCs. It therefore appears that some property differs between the two groups, leading to different Balmer-line strengths at a given metallicity. In fact, since the effect seems to increase with increasing metallicity, we focus our analysis on those 25 GGCs from S05 with [Fe/H] > −1.35 ([MgFe] ≥ 1.2) among which clear differences in Hβ at fixed metallicity are observed.

Together with the indices in Figure 1, the adopted CMD-derived parameters for the 25 GGCs are listed in Table 1. The HB morphology, as measured by the HBR parameter (Lee et al. 1994), and the specific frequency of RR Lyrae variables, $S_{RR Lyrae}$, are taken from the Harris (1996) catalog (February 2003 revision; hereafter H03). We adopted the relative age estimates from De Angeli et al. (2005) and Recio-Blanco et al. (2006), whose applied the so-called vertical method on the GGC HST WFPC2 snapshot catalog of Piotto et al. (2002). Also based on that catalog, Recio-Blanco et al. (2006) estimated the maximum $T_{eff}$ along the HB, $T_{eff}$ HB, considered as an HB morphology parameter, whereas Moretti et al. (2008; hereafter M08) measured the logarithm of the number of BSSs inside the core radius, $r_c$, normalized to the sampled luminosity (in units of $10^4 L_\odot$) in the F555W HST band within the same aperture. The last quantity can be considered as a logarithmic specific frequency of BSSs inside the GGC $r_c$, hereafter $S_{bss}$, and is representative of the spectroscopic data in S05, as they are both computed within the same aperture.

3. ANALYSIS

With the aim of constraining the origin of the intrinsic scatter in the Balmer line strengths of our GGC subsample, in Figure 2 we show the CMD-derived parameters of § 2 (where available) as a function of the GGC metallicity from H03. Symbols are as in Figure 1, except that the MR GGCs NGC 6388 and NGC 6441, which being well-known “second parameter” clusters (Rich et al. 1997), are plotted with open stars rather than filled squares to facilitate further discussion.

In Figure 2a, we see that there is no dependence of the group location on the CMD-derived age. The difference in Hβ strengths between the two groups is therefore not due to age differences among the GGCs, as would normally be inferred from a classical SSP index-index analysis. Note also that the typical dispersion of $\sim$1 Gyr quoted by De Angeli et al. (2005) among the CMD-derived ages of intermediate metallicity GGCs could never explain the large scatter in Hβ. We also rule out the possibility that the number of RR Lyrae stars in the instability strip plays a significant role, as the two GGC groups are well mixed (Fig. 2b). In addition, we find that there is no obvious dependence on the HB morphology, as measured by either the HBR parameter or the maximum $T_{eff}$ of the HB (Figs. 2c and 2d, respectively).

As expected, the second-parameter clusters NGC 6388 and NGC 6441 (open stars) do stand out of the general trends in both panels. Their high Hβ strengths are naturally explained by the addition of hot HB stars in their integrated spectra.

Besides basic properties of the GGC CMDs, literature estimates of [α/Fe] for the GGCs in S05 (where available) show a high degree of homogeneity (e.g., Pritzl et al. 2005), so differing levels of α-elements cannot account for the observed differences.

We have also ruled out the possibility that the Balmer lines of GGCs are systematically filled-in by emission. In fact, emission was found and corrected by S05 for only NGC 6171 and NGC 6553 (GGCHs), and NGC 6352 (GGCL). Interestingly, the fact that NGC 6532 has the weakest Hβ line of the sample may suggest that a residual emission could still be present.

Having rejected the above mechanisms from being responsible for the observed differences in Hβ between GGCHs and GGCLs, except in the obvious case of NGC 6388 and NGC 6441, in Figure 2e we show the GGC metallicities plotted against $S_{bss}$. Interestingly, GGCHs and GGCLs (which were identified spectroscopically) separate cleanly into two groups in terms of their BSS specific frequencies. At a given metallicity, GGCs with higher $S_{bss}$ values exhibit stronger Hβ lines, suggesting that BSSs are indeed affecting their integrated spectra.

To reinforce this result, we quantify the impact of BSSs on the integrated spectrum of NGC 6342, the GGCH with the highest $S_{bss}$. Based on photometric data from H03 and M08 for this GGC and its BSS population, we find that 13% of the GGC flux in V band within $r_c$ comes from a population of seven BSSs with $0.22 \leq B - V \leq 0.52$, and a luminosity-weighted $B - V$ of 0.33. For each BSS, assuming [Fe/H] = −0.65 and its $B - V$, we
TABLE 1

| GGC     | Group | Hβ                  | Hβ_{BBG} | [MgFe] | [Fe/H] | Age_{norm} | S_{RRLyr} | HBR | log(T_{eff, HB}) | S_{BSS} |
|---------|-------|---------------------|----------|--------|--------|------------|-----------|-----|-----------------|---------|
| NGC 0104 | L     | 2.30 ± 0.02         | 1.55 ± 0.01 | 2.31 ± 0.02 | −0.76 | 0.99 | 0.2 | −0.99 | 3.756 | 1.03 |
| NGC 1851 | H     | 2.99 ± 0.03         | 2.27 ± 0.02 | 1.32 ± 0.02 | −1.22 | 0.81 | 13.5 | −0.36 | 4.097 | 1.48 |
| NGC 2808 | L     | 2.69 ± 0.01         | 2.01 ± 0.01 | 1.32 ± 0.02 | −1.15 | 0.76 | 0.3 | −0.49 | 4.568 | 0.94 |
| NGC 5904 | L     | 3.06 ± 0.01         | 2.42 ± 0.01 | 1.18 ± 0.01 | −1.27 | 0.81 | 37.7 | +0.31 | 4.176 | 1.07 |
| NGC 5927 | L     | 2.43 ± 0.03         | 1.38 ± 0.03 | 2.87 ± 0.02 | −0.37 | 0.92 | 0.0 | −1.00 | 3.724 | 1.40 |
| NGC 6121 | H     | 3.12 ± 0.03         | 2.28 ± 0.03 | 1.34 ± 0.02 | −1.20 | 0.91 | 52.7 | −0.06 | 3.377 | 1.68 |
| NGC 6171 | H     | 2.81 ± 0.05         | 2.08 ± 0.05 | 1.76 ± 0.03 | −0.04 | 0.99 | 31.0 | −0.73 | 3.875 | 0.96 |
| NGC 6266 | H     | 2.88 ± 0.02         | 2.09 ± 0.02 | 1.41 ± 0.02 | −1.29 | 0.92 | 15.6 | +0.32 | 4.477 | 1.97 |
| NGC 6284 | H     | 3.13 ± 0.04         | 2.33 ± 0.04 | 1.31 ± 0.03 | −1.32 | 0.87 | 3.9 | ... | 4.279 | 0.97 |
| NGC 6304 | L     | 2.41 ± 0.05         | 1.47 ± 0.04 | 2.63 ± 0.03 | −0.59 | ... | 0.0 | −1.00 | 3.724 | 1.51 |
| NGC 6316 | L     | 2.47 ± 0.04         | 1.46 ± 0.04 | 2.13 ± 0.02 | −0.55 | ... | 0.0 | −1.00 | 3.724 | 1.51 |
| NGC 6342 | H     | 2.92 ± 0.11         | 2.07 ± 0.09 | 2.00 ± 0.06 | −0.65 | 0.94 | 1.4 | −1.00 | 3.724 | 1.51 |
| NGC 6521 | L     | 1.98 ± 0.05         | 1.33 ± 0.04 | 2.37 ± 0.03 | −0.70 | ... | 0.0 | −1.00 | 3.724 | 1.51 |
| NGC 6536 | L     | 2.40 ± 0.04         | 1.58 ± 0.03 | 2.42 ± 0.02 | −0.50 | 0.97 | 0.0 | −1.00 | 3.756 | 1.12 |
| NGC 6626 | L     | 2.53 ± 0.06         | 1.99 ± 0.05 | 1.56 ± 0.03 | −0.95 | 0.92 | 55.1 | −0.58 | 3.954 | 1.47 |
| NGC 6638 | H     | 2.89 ± 0.02         | 1.86 ± 0.02 | 2.14 ± 0.02 | −0.60 | ... | 2.4 | −0.70 | 4.255 | 1.01 |
| NGC 6441 | H     | 2.91 ± 0.03         | 1.80 ± 0.02 | 2.38 ± 0.02 | −0.53 | ... | 0.3 | −0.70 | 4.230 | 1.10 |
| NGC 6658 | H     | 3.00 ± 0.04         | 1.59 ± 0.03 | 3.32 ± 0.02 | −0.04 | ... | 0.0 | −1.00 | 3.377 | 1.73 |
| NGC 6553 | H     | 2.94 ± 0.05         | 1.52 ± 0.04 | 3.25 ± 0.03 | −0.21 | ... | 1.6 | −1.00 | 3.377 | 1.73 |
| NGC 6569 | L     | 2.53 ± 0.08         | 1.73 ± 0.07 | 1.79 ± 0.04 | −0.86 | ... | 0.0 | ... | 3.954 | 1.12 |
| NGC 6624 | L     | 2.55 ± 0.03         | 1.66 ± 0.02 | 2.23 ± 0.02 | −0.44 | 0.88 | 0.0 | −1.00 | 3.771 | 1.73 |
| NGC 6637 | L     | 2.35 ± 0.03         | 1.55 ± 0.03 | 2.11 ± 0.02 | −0.70 | 0.91 | 0.0 | −1.00 | 3.748 | 1.41 |
| NGC 6638 | L     | 2.54 ± 0.05         | 1.77 ± 0.04 | 1.79 ± 0.03 | −0.99 | 0.87 | 18.3 | −0.30 | 4.097 | 1.14 |
| NGC 6652 | L     | 2.86 ± 0.03         | 2.03 ± 0.02 | 1.73 ± 0.02 | −0.96 | 0.92 | 0.0 | −1.00 | 4.000 | 2.14 |
| NGC 6723 | L     | 2.64 ± 0.05         | 2.15 ± 0.04 | 2.16 ± 0.03 | −1.12 | 0.97 | 20.5 | −0.08 | 4.130 | 1.05 |

*GGCs with high (H) and low (L) Hβ indices at fixed metallicity.

b Measured at FWHM = 3.1 Å spectral resolution.

c From the Harris (1996, February 2003 revision) catalog.

d Relative GGC ages from De Angeli et al. (2005) and Recio-Blanco et al. (2006).

e Maximum T_{eff} along the HB, from Recio-Blanco et al. (2006).

f S_{BSS} = log (N_{BSS}/L_{total}) inside the core radius, L_{total}, in units of 10^4 L_{0}. Taken from Moretti et al. (2008).

4. DISCUSSION

Based on the close correspondence between the specific frequency of BSSs in GGCs with [Fe/H] > −1.35 and their integrated Hβ strengths at fixed metallicity, we conclude that BSSs are primarily responsible for the Hβ variations observed in the integrated spectra of GGCs of intermediate-to-high metallicity. Far from discussing on the origin for the distinct S_{BSS} values among GGCs (see M08 for a thorough study on this topic), we here analyze the implications of the above result in the context of age-dating unresolved stellar populations.

![Figure 2](image_url)
First, caution must be employed in Balmer-line-based age-metallicity studies of unresolved extragalactic globular clusters (EGCs). Cenarro et al. (2007b) already reported the existence of EGCs with strong Balmer lines that were consistent with hosting an additional population of either blue HB stars and/or BSSs. Since the BSS fraction of EGCs is generally not known, the findings in this letter set a fundamental limit to the reliability with which ages may be determined for EGCs using Balmer lines and SSP models. Taking the S05 data as a representative old GC system, we can estimate this limit from the averaged offsets in the measured H$\delta$ lines of GGCHs and GGCLs. Since the offsets seem to vary with metallicity, linear fits to all GGCHs and GGCLs in Figure 1 with $\langle [\text{MgFe}] \rangle > 1.5$ ([$\text{Fe/H}] \approx -1.0$) have been performed. For instance, at the location of 47 Tuc (NGC 0104; $\langle [\text{MgFe}] \rangle \sim 2.31$), we obtain $\Delta H\beta = 0.46 \pm 0.03 \, \AA$ and $\Delta H\beta_{\text{SSP}} = 0.33 \pm 0.04 \, \AA$ (at the S05 resolution), with uncertainties accounting for the standard errors of the means. Thus, assuming that GGCLs are $\sim 14$ Gyr old (the largest SSP age in Fig. 1), the two offsets can be consistently misinterpreted on the basis of SSP models as GGCHs being $\sim 6-7$ Gyr old, that is, as a rejuvenation of up to $\sim 8$ Gyr. Differences between GGCHs and GGCLs also exist for the Lick H$\gamma$ and H$\delta$ indices (Worthey & Ottaviani 1997), although they are not so apparent, probably due to their limited age-disentangling power for old SSPs. For these indices, the above test leads to rejuvenations of up to $\sim 4-5$ Gyr.

The role of metallicity in the present discussion is worthwhile considering. Although the relation between $S_{\text{BSS}}$ and metallicity is not statistically significant (but marginally positive) over the entire GGC sample (in agreement with M08), we find clear correlations for GGCHs and GGCLs separately, as illustrated by the solid lines in Figure 2e. The different slopes seem to indicate that, when BSSs are important, their relative contributions are larger at high metallicities. Note that the fading with metallicity expected in the F555W band for the most MR GGCs only accounts for up to $\Delta S_{\text{BSS}} \sim 0.2$, so the above trends are irrespective of this effect.

These results may also have important consequences for EGC studies. To understand the origin of color bimodality in GC systems within a context of galaxy formation, age-dating GC subpopulations, through the analysis of their integrated Balmer lines, is a common practice (see Brodie & Strader 2006, and references therein). Interestingly, some papers have reported that the MR GC subpopulation of certain galaxies show on average a smaller mean age and a larger age scatter than their metal-poor (MP) counterparts (e.g., Puzia et al. 2005). Although the present finding does not rule out the existence of true age differences between MP and MR GC subpopulations, the increasing importance of BSSs with metallicity might, at least, partially affect the results of previous work.

Whether all the above results can compromise the integrated ages of other stellar systems, such as galaxies, may rely on the mechanism that dominates the formation of BSSs. If stellar encounters were driving the BSS population, then one should not expect a major effect in galaxies, because of their much lower stellar densities. However, this would not apply if mass-transfer binaries were the progenitors of most BSSs. In fact, Momany et al. (2007) and Mapelli et al. (2007) support the last scenario to explain the large BSS populations of dwarf spheroidal galaxies, and Han et al. (2007) have demonstrated the importance of binary interactions to understanding the UV-upturn of elliptical galaxies (Es). It therefore seems that BSSs could play a nonnegligible role in the integrated spectra of galaxies as long as they host an important fraction of binary stars. If this were the case and the potential increasing importance of BSSs with metallicity were still to hold for massive Es, then BSSs could contribute to the age scatter reported for massive Es and to the fact that younger Es have higher metallicities than older Es (e.g., Trager et al. 2000; Sánchez-Blázquez et al. 2006a). This picture, however, requires further investigation which is beyond the scope of this paper.

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REFERENCES

Alonso, A., Arribas, S., & Martínez-Roger, C. 1996, A&A, 313, 873
Brodie, J. P., & Strader, J. 2006, ARA&A, 44, 193
Buzzoni, A., Mantegazza, L., & Garibaldi, G. 1994, AJ, 107, 513
Cenarro, A. J., et al. 2007a, MNRAS, 374, 664
Cenarro, A. J., Beasley, M. A., Strader, J., Brodie, J. P., & Forbes, D. A. 2007b, AJ, 134, 391
Cervantes, J. L., & Vazdekis, A. 2008, MNRAS, in press (arXiv:0810.3240)
Davies, M. B., Benz, W., & Hills, J. G. 1994, ApJ, 424, 870
De Angeli, F., Piotto, G., Cassisi, S., Busso, G., Recio-Blanco, A., Salaris, M., Aparicio, A., & Rosenberg, A. 2005, AJ, 130, 116
González, J. J. 1993, Ph.D., Univ. California
Harris, W. E. 1996, AJ, 112, 1487
Harris, W. E. 2001, in Star Clusters, ed. L. Labhardt & Binggeli (Berlin: Springer), 223
Lee, Y., Demarque, P., & Zinn, R. 1994, ApJ, 423, 248
Lee, H. Y., Yoon, S., & Lee, Y. 2000, AJ, 120, 998
Mapelli, M., Ripamonti, E., Tolstoy, E., Sigurdsson, S., Irwin, M. J., & Batista, G. 2007, MNRAS, 380, 1127
McCrea, W. H. 1964, MNRAS, 128, 147
Momany, Y., Held, E. V., Saviane, I., Zaggia, S., Rizzi, L., & Gullieuszik, M. 2007, A&A, 468, 973
Moretti, A., De Angeli, F., & Piotto, G. 2008, A&A, 483, 183 (M08)
Piotto et al. 2002, A&A, 391, 945
Pritzi, B. J., Venn, K. A., & Irwin, M. 2005, AJ, 130, 2140
Puzia, T. H., Saglia, R. P., Kissler-Patig, M., Maraston, C., Greggio, L., Renzini, A., & Ortolani, S. 2002, A&A, 395, 45
Puzia, T. H., Kissler-Patig, M., Thomas, D., Maraston, C., Saglia, R. P., Bender, R., Goudreau, P., & Hempel, M. 2005, A&A, 439, 997
Rich, R. M., et al. 1997, ApJ, 484, 25
Recio-Blanco, A., Aparicio, A., Piotto, G., De Angeli, F., & Djorgovski, S. G. 2006, A&A, 452, 875
Rose, J. A. 1985, AJ, 90, 1927
Sánchez-Blázquez, P., Gorgas, J., Cardiel, N., & González, J. J. 2006a, A&A, 457, 809
Sánchez-Blázquez, P., et al. 2006b, MNRAS, 371, 703
Sandage, A. R. 1953, AJ, 58, 61
Schiavon, R. P., Faber, S. M., Rose, J. A., & Castillo, B. V. 2002, ApJ, 580, 33
Schiavon, R. P., Rose, J. A., Courteau, S., & MacArthur, L. A. 2004, ApJ, 608, 33
Schiavon, R. P., Rose, J. A., Courteau, S., & MacArthur, L. A. 2005, ApJS, 160, 163 (S05)
Trager, S. C., Faber, S. M., Worthy, G., & González, J. J. 2000, AJ, 120, 165
Trager, S. C., Worthy, G., Faber, S. M., & Dressler, A. 2005, MNRAS, 362, 2
Vazdekis, A., Salaris, M., Arimoto, N., & Rose, J. A. 2001, ApJ, 549, 274
Vazdekis, A. 1999, ApJ, 513, 224
Vazdekis, A., Cenarro, A. J., Gorgas, J., Cardiel, N., & Peletier, R. F. 2003, MNRAS, 340, 1317
Worthey, G., & Ottaviani, D. L. 1997, ApJS, 111, 377
Zoccali, M., Cassisi, S., Bono, G., Piotto, G., Rich, R. M., & Djorgovski, S. G. 2000, ApJ, 538, 289