The influence of the C+N+O abundances on the determination of the relative ages of Globular Clusters: the case of NGC 1851 and NGC 6121 (M4) * †

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ABSTRACT

The color magnitude diagram (CMD) of NGC 1851 presents two subgiant branches (SGB), probably due the presence of two populations differing in total CNO content. We test the idea that a difference in total CNO may simulate an age difference when comparing the CMD of clusters to derive relative ages. We compare NGC 1851 with NGC 6121 (M4), a cluster of very similar [Fe/H]. We find that, with a suitable shift of the CMDs that brings the two red horizontal branches at the same magnitude level, the unevolved main sequence and red giant branch match, but the SGB of NGC 6121 and its red giant branch “bump” are fainter than in NGC 1851. In particular, the SGB of NGC 6121 is even slightly fainter than the the faint SGB in NGC 1851. Both these features can be explained if the total CNO in NGC 6121 is larger than that in NGC 1851, even if the two clusters are coeval. We conclude by warning that different initial C+N+O abundances between two clusters, otherwise similar in metallicity and age, may lead to differences in the turnoff morphology that can be easily attributed to an age difference.

Key words: globular clusters; chemical abundances; relative ages

1 INTRODUCTION

The ages of Globular Clusters (GCs), the oldest systems populating our Galaxy for which an age estimate is feasible, provide a lower limit to the age of the Universe, and therefore constitute one of the important subjects of stellar astrophysical research. Unfortunately, absolute age measurements are still affected by a large number of uncertainties, in particular due to significant uncertainties in GC distances and reddening values (e.g. Gratton et al. 2003). Attention is then mostly devoted to the determination of relative ages. These can be obtained with much higher precision, by measuring the position of the main-sequence (MS) turnoff (TO) –which is the most-used age indicator– relative to some other feature in the color–magnitude diagram (CMD), whose location has little or no dependence on age, like the horizontal branch (HB) (Stetson et al. 1996; Sarajedini et al. 1997). Relative ages provide fundamental information on the formation and early evolution of the Galaxy.

Several procedures, and better and better data sets have been employed to derive relative ages (Buonanno et al. 1998; Salaris & Weiss 1998; Rosenberg et al. 1999; VandenBerg 2000; De Angeli et al. 2005; Marín-Franch et al. 2009a). The latest work by Marín-Franch et al. (2009a) employs the homogeneous photometric database achieved for 64 GCs in the ACS Survey of Galactic GCs (the HST Treasury program [Sarajedini et al. 2007]), and compares the relative positions of the clusters’ MS TOs, using MS fitting to cross-compare clusters within the sample. According to the authors, the method provides relative ages to a formal precision of 2% – 7%. One of the problems of the Marín-Franch
et al. study is that it does not include any consideration of possible systematic elemental abundance differences among GCs that apparently have the same [Fe/H]. This problem is clearly to be attacked, now that we know that GCs may harbour different stellar populations, whether because of differences in the helium content (D’Antona & Caloi 2004; Norris 2004; D’Antona et al. 2005; Piotto et al. 2003, 2007), differences in α-element abundances in general (Ivans et al. 1999); or differences specifically in total C+N+O, as will be discussed below. Limited helium content differences (in mass fraction, $\delta Y \sim 0.04 – 0.05$) do not seem to affect the TO luminosity at a given age (D’Antona et al. 2002), and so in principle do not affect the relative age determination. In contrast, stellar modelling shows that an increase in the total C+N+O content shifts the isochrone turnoffs to lower luminosity (Bazzano et al. 1982; Cassisi et al. 2008; Ventura et al. 2009a), without significantly changing the position of the unevolved MS, giant branch or HB.

Recently we have obtained observational evidence of the influence of such an additional parameter. In fact, two well separated subgiant branches (SGB) are present in the CMD of the cluster NGC 1851 (Milone et al. 2008). The faint SGB may be interpreted as being populated by stars either older by $\sim$1Gyr, or having equal (or slightly younger) age and an increase in the total C+N+O content (Cassisi et al. 2008; Ventura et al. 2009a). Formation models for multiple populations in GCs are still very much in their infancy (Bekki & Norris 2006; Bekki et al. 2007; D’Ercole et al. 2008), but no current model can easily accommodate a second stellar generation younger by 1 Gyr. On the other hand, a total C+N+O spread among the stars in NGC 1851 does have an independent observational basis (Yong & Grundahl 2008; Yong et al. 2009). An interpretation based on a different total C+N+O content is a variant of the “two stellar generations” models for GC formation that have already been investigated for the case of multiple main sequences, possibly showing differences in helium content. In this scheme, the second stellar generation forms out of matter polluted by the stellar winds of massive asymptotic giant branch stars of the first generation (Cottrell & Da Costa 1981; Ventura et al. 2001), although many details of such a model still need to be worked out (D’Ercole et al. 2008).

Now that we have such observational evidence, we can pose the question whether relative age indicators already present in the literature can be interpreted differently. In the following, we explore the case of the relative ages of the two clusters NGC 1851 and NGC 6121 (M4), that have always been considered twins from the point of view of metal abundance (e.g. Zinn & West 1984; Rutledge et al. 1997; Rosenberg et al. 1999; Marin-Franch et al. 2009a), with NGC 1851 somewhat younger if age is the only second parameter.

The influence of varying the CNO abundances in stellar models is well documented in the astrophysical literature (e.g. Simoda & Iben 1970, Bazzano et al. 1982; see also VandenBerg & Bell (2001) and references therein). In the last decade, however, the attention was mainly devoted to the effect of variations in oxygen – and in the other α-elements, following the discovery that population II stars had a larger than solar $\alpha$/Fe (e.g. McWilliam 1997). An increase by 0.3 dex in $\alpha$/Fe implies a 1 Gyr reduction in age for a fixed turnoff luminosity. Recently the attention has been focused on the possible differences in total C+O derived from the presence of multiple stellar generations, so different mixtures of these elements have been considered established. Cassisi et al. (2008) adopt an enhanced mixture based on a combination derived from some observations of abundance anomalies, while Ventura et al. (2009a) resorted more on the

![Figure 1](image_url)
chemical yields provided by theoretical massive AGB models. In any case, we are still far from a complete investigation of the relative role of the three elements, that may become more necessary following the results of the present work. We base our considerations mainly on the models computed to explain the double subgiant branch in NGC 1851. This problem is very timely, as it is also confirmed by the very recent exam by Marín-Franch et al. (2009b) of the influence, of CNO and helium variations, on the relative age determination of GCs, purely from a theoretical point of view.

### Table 1. Relative ages for NGC 1851 and NGC 6121

| Name       | [Fe/H]_{CGG} | relative ages | relative ages |
|------------|--------------|---------------|---------------|
|            |              | De Angeli 2005 | Marín-Franch 2009 |
| NGC 1851   | −1.03        | 0.82 ± 0.07   | 0.78 ± 0.04   |
| NGC 6121   | −1.05        | 0.91 ± 0.04   | 0.98 ± 0.05   |

### Relative ages of the Globular Clusters NGC 1851 and M4

2. **THE TWO CLUSTERS NGC 1851 AND NGC 6121**

In this analysis we exploit the archive of homogeneous CCD photometry maintained by one of us (see, e.g., Stetson et al. 1993; Stetson 2000, 2003). The photometry of NGC 1851 has already been described in Milone et al. (2009); their CMD is reproduced here as the blue points in Fig. 1. Note that the ground-based photometry confirms the split of the SGB into faint and bright branches, as originally found from HST data (Milone et al. 2008). In addition, the fit by Ventura et al. (2009a) of the bright SGB with a standard isochrone of 12 Gyr, and the fit of the corresponding faint SGB with the same isochrone and C+N+O abundances increased by a factor three (CNO×3 mixture) is consistent with the observations in the V vs. B−I plane (see Fig. 2).

The photometry of NGC 6121 to be discussed here is similarly obtained from analysis of 1,199 individual CCD images resulting from 814 exposures (55 of the exposures had been taken with the eight-CCD WFI camera on the ESO/MPE 2.2m telescope) made during ten observing seasons on six telescopes (ESO/Dutch 0.9m, CTIO 0.9m, Jacobus Kapteyn 1m, ESO/Danish 1.5m, and Nordic Optical 2.6m Telescope, in addition to the aforementioned ESO/MPE 2.2m). Any given star may have been measured in as many as 255 B-, 202 V-, and 253 I-band images. The results have been transformed to the photometric system of Landolt (1992) following methodology described in Stetson et al. (1998); Stetson (2000, 2003).

Determination of relative ages requires complex procedures for determining observational parameters and for comparison with theoretical isochrones. Let us look at the final comparison between the two clusters under discussion in the analysis of De Angeli et al. (2005) and Marín-Franch et al. (2009a) summarized in Table 1. Both works make a very careful analysis, whose final results do not depend substantially on the adopted abundance scale and isochrones. Here we report the result for the Carretta & Gratton (1997) abundances, and for the models by Cassisi et al. (2004) in De Angeli, and by Dotter et al. (2007) in Marín-Franch.

The table shows that—according to the age interpretation of the observed differences—NGC 1851 is ∼10% younger than NGC 6121 in the De Angeli et al. (2005) analysis, and ∼20% younger in the analysis by Marín-Franch et al. (2009a). Assuming an age of 12 Gyr for NGC 6121, NGC 1851 turns out to be a bit less than 11 Gyr (De Angeli), or 9.5 Gyr (Marín-Franch) old, an age difference that is significant for models of the formation of the Galaxy.

In their Figure 7, De Angeli et al. (2005) compare the V vs. V−I CMDs of these two clusters, showing that, when the turnoffs are superposed, the HB of NGC 6121 turns out more luminous than the HB of NGC 1851, indicating indeed that NGC 6121 must be older. We make the reverse procedure. We use the metallicity information, to superpose the red parts of the HB: even in the presence of multiple populations, the red HB clumps are supposed to reflect the composition of the first stellar generation, so that their location is presumed to be unaffected, e.g., by altered helium. The match is made in the V versus B−I plane and is shown in Fig. 1 and in the enlarged view of Fig. 2. We use for this comparison the absolute magnitude $M_V$, by positioning the red clumps (RHB) of NGC 1851 and NGC 6121 on the zero-age horizontal branch (ZAHB) of our theoretical models (Ventura et al. 2009a), drawn in the figure. We selected by eye all the stars that, on the basis of their position in the CMD, belong very likely to the RHB and calculated their median $V$ magnitude. We find $V_{HB} = 16.19±0.01$ and $V_{HB} = 13.44±0.01$ for NGC 1851 and NGC 6121 respectively. The error associated to the HB position is calculated as $\sigma/\sqrt{N−1}$ where $N$ is the number of red HB stars and $\sigma$ is the 68.26th percentile of the absolute deviation from the average of their $V$ distribu-
apparent $V$ magnitudes of NGC 1851 are shifted by $\delta V \approx -0.08$ and the colors are shifted by $\delta(B-I) = -0.08$. The corresponding shifts for NGC 6121 are $\delta V \approx -1.27$ mag and $\delta(B-I) = -1$. On the blue side of the HB, the stars in M4 are slightly more luminous than in NGC 1851. This feature is not important for the present discussion, but remember that a slightly larger helium abundance in the blue HB of M4 may lead to greater blue HB luminosity, as shown by the (blue) ZAHBs with $Y = 0.26$ (dashed) and $Y = 0.28$ (dash-dotted) shown in Fig. 1. We see in the figure that the two MSs are well matched. The isochrones of 12 and 14 Gyr by Ventura et al. (2009a) for $Z = 10^{-3}$ and standard C+N+O abundances are also shown. The TO locations indicate an age difference of $\sim 2$ Gyr, as also concluded by Marin-Franch et al. (2009a). Since the SGB and TO of NGC 6121 appear fainter than the faint SGB of NGC 1851, another interpretation is possible: if NGC 6121 stars have total C+N+O abundance even larger than that of the stars on the faint SGB of NGC 1851, they could be coeval with the stars in NGC 1851. This is illustrated in Fig. 2 by the 12 Gyr isochrone by Ventura et al. (2009a) for a composition in which the total CNO is enhanced by a factor of five (CNO×5).

Are there any independent indications that this solution (same age and large difference in total C+N+O abundances) is to be preferred? A possible hint comes from Fig. 3, which shows the differential and cumulative red giant luminosity functions, and the location of the red giant “bump” due to the penetration of the hydrogen burning shell into the mean molecular weight discontinuity (or $\mu$-barrier) left by the maximum extension in mass fraction reached by the convective envelope at the beginning of giant-branch evolution. Standard theory and observations do not fully agree on the location of the bump. Many models—including the Ventura et al. (2009a) models—provide bumps $\sim 0.25$ mag more luminous than the observed ones (Zoccali & Piotto 2000). This may be due to uncertainties either in the metallicity scale (Zoccali & Piotto 1994, e.g.) or in the mixing below the convective envelope (Girardi et al. 2000), or to additional mixing caused by rotation (Palacios et al. 2006). Whatever the causes of this small discrepancy, here we are interested mainly in the relative positions of the bumps in the two clusters under discussion. Applying the distance moduli used to build up Fig. 1 to which we can assign a relative error not larger than $\pm 0.01$ mag, we see that the absolute magnitudes (median value) of the RG bump are $M_v = 0.65 \pm 0.01$ mag and $M_v = 0.79 \pm 0.01$ mag, respectively for NGC 1851 and NGC 6121. To determine the bump locations, we selected by hand stars that, according to their position in the CMD, have a high probability to belong to the RGB bump and calculated their median $M_V$ ($M_V$ bump). The error is calculated as: $\sigma / \sqrt{(N-1)}$, where $\sigma$ is the 68.26th percentile of the absolute deviation from the average of the $M_V$ distribution and $N$ is the number of selected stars. We see that there is a difference of $0.14 \pm 0.02$ mag in the bump level. Can we change the relative distance of the clusters in order to match the bumps? The red HB luminosity is indeed the best standard parameter for stars having the same [Fe/H]. Even if we assume that the HB red clump is populated by stars with similar [Fe/H] content but different C+N+O, the models by Ventura et al. (2009a) show that the ZAHB luminosity at the red side of the HB decreases only by $\sim 0.04$ mag, for a five-fold increase in C+N+O, so
the HB location can not explain this difference in the bump magnitude. An age increase of \(\sim 2\) Gyr can not explain the difference either: according to our models, the bump location becomes dimmer by only \(\sim 0.05\) mag. On the other hand, the models by Ventura et al. (2009a) for \(Z=10^{-3}\) and different C+N+O contents show that the bump luminosity decreases (almost) linearly with the C+N+O increase. It was already known that an increase in the oxygen abundance produces a lower bump luminosity (e.g., VandenBerg & Bell 2001). We obtain \(\Delta M_v(bump)\approx 0.037\) times the C+N+O abundance increase with respect to the “standard”, \(\alpha\)-enhanced, composition \((\text{CNO} \times 1)\). A difference of \(0.14 \pm 0.02\) mag, for a fixed age and helium abundance, corresponds to the difference between \(\text{CNO} \times 1\) and \(\text{CNO} \times (3.8 \pm 0.6)\) bumps. We conclude that the difference in absolute magnitude of the bumps is consistent with the hypothesis that M4 stars have a C+N+O content a factor of \(\sim 4\) larger than the bright SGB stars of NGC 1851.

Note also that the bump peak is more dispersed in NGC 1851 than in NGC 6752. This difference may indeed reflect the fact that NGC 1851 itself contains two populations with different C+N+O abundances.

3 DISCUSSION: A PLEA FOR CNO ABUNDANCE DETERMINATIONS AND FOR A WIDER THEORETICAL EXAM

The comparison in Figs. 1 and 2 has shown that the two clusters we are considering may differ in age by about 2 Gyr (as found by Marín-Franch et al. 2009a). However, now that we know that NGC 1851 harbours two SGBs, and that the faint SGB is very probably made up of coeval stars richer in total C+N+O than the bright SGB stars, it is tempting to propose that the stars of NGC 6121 are also coeval with “all” the stars of NGC 1851, but they have a global C+N+O abundance larger even than the stars on the fainter SGB in the latter cluster. An analysis of the magnitude difference of the RGB bump locations in the two clusters, and the relative location of their SGBs are consistent with the hypothesis that the global C+N+O in M4 stars is about a factor \(\sim 4\) larger than in the main population of NGC 1851. At present, this conclusion must be taken more as a working hypothesis for further discussions than as a proven fact. We need this conclusion must be taken more as a working hypothesis before the derived age spreads may be attributed to the modalities of formation of the Galaxy.

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