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ABUNDANCES FOR A LARGE SAMPLE OF RED GIANTS IN NGC 1851: HINTS FOR A MERGER OF TWO CLUSTERS?*

E. Carretta[1], R. G. Gratton[2], S. Lucatello[2,3,4], A. Bragaglia[1], G. Catanzaro[5], F. Leone[6], Y. Momany[2,7], V. D'Orazi[2], S. Cassisi[8], F. D'Antona[9], and S. Ortolani[10]
[1] INAF, Osservatorio Astronomico di Bologna, via Ranzani 1, 40127 Bologna, Italy; eugenio.carretta@oabo.inaf.it, angela.bragaglia@oabo.inaf.it
[2] INAF, Osservatorio Astronomico di Padova, vicolo dell'Osservatorio 5, 35122 Padova, Italy; raffaele.gratton@oapd.inaf.it, sara.lucatello@oapd.inaf.it, valentina.dorazi@oapd.inaf.it
[3] Excellence Cluster Universe, Technische Universität München, Boltzmannstr. 2, D-85748 Garching, Germany
[4] INAF-Osservatorio Astrofisico di Catania, Via S.Sofia 78, I-95123 Catania, Italy
[5] Max Planck Institute for Astrophysics, Postfach 1317, 85741 Garching, Germany
[6] Dipartimento di Fisica e Astronomia, Università di Catania, Via S.Sofia 78, I-95123 Catania, Italy
[7] European Southern Observatory, Alonso de Cordova 3107, Vitacura, Santiago, Chile
[8] INAF, Osservatorio Astronomico di Collurania, via M.Maggini, 64100, Teramo, Italy
[9] INAF, Osservatorio Astronomico di Roma, via Frascati 33, 00040, Monteporzio Catone (Roma), Italy
[10] Dipartimento di Astronomia, Università di Padova, Vicolo dell'Osservatorio 2, 35122 Padova, Italy
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ABSTRACT

We present the abundance analysis of a sample of more than 120 red giants in the globular cluster (GC) NGC 1851, based on FLAMES spectra. We find a small but detectable metallicity spread. This spread is compatible with the presence of two different groups of stars with a metallicity difference of 0.06–0.08 dex, in agreement with earlier photometric studies. If stars are divided into these two groups according to their metallicity, both components show Na–O anticorrelation (signature of a genuine GC nature) of moderate extension. The metal-poor stars are more concentrated than the metal-rich ones. We tentatively propose the hypothesis that NGC 1851 formed from a merger of two individual GCs with a slightly different Fe and α-element content and possibly an age difference up to 1 Gyr. This is also supported by number ratios of stars on the split subgiant and on the bimodal horizontal branches. The distribution of *n*-capture process elements in the two components also supports the idea that the enrichment must have occurred in each of the structures separately and not as a continuum of events in a single GC. The most probable explanation is that the proto-clusters formed into a (now dissolved) dwarf galaxy and later merged to produce the present GC.

Key words: globular clusters: general – globular clusters: individual (NGC 1851) – stars: abundances – stars: evolution – stars: Population II

Online-only material: color figures

1. INTRODUCTION

The idea that massive Galactic globular clusters (GCs) may be formed within dwarf galaxies is not new (e.g., Bekki & Freeman 2003). Recently, theoretical considerations and new observations demonstrated that massive GCs like ω Cen or M 54 probably had their origin in dwarf spheroidal galaxies (dSphs), which are currently either lost or still surrounding the cluster (Böker 2008; Bellazzini et al. 2008; Carretta et al. 2010c). This idea was extended by Carretta et al. (2010b) to practically all GCs, sketching a scenario that unifies the view of GCs and dSphs. The ancestral progenitors of both kinds of systems started as cosmological fragments, but the evolution of dSphs proceeded undisturbed in near isolation from the distant main Galaxy. In contrast, strong interaction with the Galactic main body triggered a chain of events in the so-called precursor of current GCs, whose final products are the systems we are seeing (see Carretta et al. 2010b for a detailed description). The same mechanism may also work within a single dSph, as in the case of Fornax or Sagittarius.

This scenario, although not entirely new (e.g., Searle & Zinn 1978), may explain several characteristics of GCs, including the multiple stellar generations, found in all objects investigated so far (Carretta et al. 2009b, 2009c; Gratton et al. 2004 for a review). It is currently well assessed that the second-generation stars (presently constituting the bulk of the cluster population) should have formed from the ejecta of only a fraction of the first-generation (primordial) stars (e.g., Gratton et al. 2001; Prantzos & Charbonnel 2006). To account for the present chemical composition, a precursor baryonic mass about 20–50 times larger than the current mass of the GCs is required (Carretta et al. 2010b). However, the proposed scenario is still qualitative; for instance, it is not obvious that only one GC should be the final output of an individual precursor. Examples of binary and multiple clusters are frequently observed in the Large Magellanic Cloud (e.g., Dieball et al. 2002).

To clarify these issues, we added NGC 1851 to our ongoing FLAMES survey studying the Na–O anticorrelation in GCs (Carretta et al. 2006). NGC 1851 has a bimodal horizontal branch (HB) and several other peculiarities. The color–magnitude diagram (CMD) shows a double subgiant branch (SGB; Milone et al. 2008). Two distinct red giant branch (RGB) sequences were discovered by Lee et al. (2009b) with Ca *uvby* photometry and confirmed by Han et al. (2009) using broadband filters. In Carretta et al. (2010a), we challenged the hypothesis advanced by Lee et al. (2009a) of Ca variations in GCs, ascribed to a possible pollution by core-collapse Type II supernova (SN II). However, the case of NGC 1851 was left open, since we had not yet adequate data.

A photometric approach alone is probably not enough to understand the complex nature of multiple populations in

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GCs. The most striking photometric feature in NGC 1851, the split SGB, has been explained in terms of either an age/metallicity/helium effect or a different total CNO content between the two populations (e.g., Cassisi et al. 2008; Ventura et al. 2009). A mix of two or more factors cannot be excluded. Furthermore, the spatial distribution of these sub-populations is still controversial (Zoccali et al. 2009; Milone et al. 2009). Only a precise chemical tagging allows the accurate separation of different stellar generations and helps provide a first relative ranking in age between them. The only existing abundance analysis from high-resolution spectroscopy in this GC is the one by Yong & Grundahl (2008), on eight RGB stars. That analysis (complemented by Yong et al. 2009) showed a number of additional interesting features: a possible small metallicity spread, correlations between abundances of *p*-capture elements and elements produced in *s*-processes, and possibly a variable value of the total C+N+O sum. However, these data are only available for a frustrating small number of stars.

In this Letter, we partially fill this gap, presenting the results on the chemical composition of more than 120 red giants. We think that our results support the hypothesis that NGC 1851 formed from two clusters (likely born within a single dSph), an idea already circulating in the literature for GCs with composite CMDs, in particular for NGC 1851 (e.g., van den Bergh 1996; Catelan 1997). These two clusters have slightly different metallicity, and later underwent a merger, leaving however detectable traces of that past event.

2. DATA AND ANALYSIS

The FLAMES spectra (GIRAFFE and UVES) of 124 RGB members of NGC 1851 were obtained in 2009 April, August, and September. The stellar parameters were determined using the same techniques described, e.g., in Carretta et al. (2010c). A full description of the analysis will be presented elsewhere (E. Carretta et al. 2010, in preparation); here we only show abundances of some interesting species: Fe, Na, O, Ca, a few *s*-process elements, such as Ba, La, Ce, and the *r*-process element Eu. Details of our abundance analysis trace as closely as possible the homogeneous procedures adopted for other GCs (Carretta et al. 2009b, 2009c and references therein).[11]

3. METALLICITY SPREAD IN NGC 1851

Our first result is that there is a small but real spread in metallicity in NGC 1851. We find an average [Fe/H] I $= -1.179 \pm 0.019$ ($\sigma = 0.067$ dex) from 13 stars with UVES spectra. The analysis of the GIRAFFE spectra yields [Fe/H] I $= -1.158 \pm 0.005$ ($\sigma = 0.051$ dex; 121 stars), after correcting the equivalent widths to the system defined by the higher resolution UVES spectra (Carretta et al. 2007a). The observed dispersions in [Fe/H] I for UVES spectra are statistically significant when compared to internal errors in [Fe/H], which are estimated to be 0.017 dex (internal errors for GIRAFFE spectra, 0.060 dex, are too large to be used in this context).[12]

There are additional ways to show that the spread in [Fe/H] is real. First, Yong & Grundahl (2008) also found some range in [Fe/H], although they did not expand on this due to the small size of their sample. Second, in Figure 1, we compare the metallicity distribution function (MDF) in NGC 1851 with the MDFs of M 4 and M 5, GCs of similar metallicity analyzed through an identical procedure (Carretta et al. 2009a). The metallicity spread in NGC 1851 is clearly larger. The MDF of M 4 would reproduce the one of NGC 1851 if we split it into two equal components with a difference in metallicity of 0.06–0.08 dex; the same is obtained for M 5. Finally, we also find a spread in [Ca/H], similar to the one in [Fe/H], confirming photometric results by Lee et al. (2009b) and Han et al. (2009).

For the sake of the following discussion, we arbitrarily assume that NGC 1851 is made of a metal-poor (MP) and a metal-rich (MR) component. Since there is no obvious gap between these components, we simply assume that stars with [Fe/H] larger than the average -1.16 dex belong to the MR component, the others to the MP one. Figure 2 shows the RGB accordingly divided. If we fit the RGB with a line and compute the residuals in color between the individual stars and the line, the MR stars have average $B-V$ color redder by 0.02 $\pm$ 0.008 mag than the MP ones, in very good agreement with what is expected (Gratton et al. 2010) from the difference in metallicity.

One of our most striking results is shown in the right panel of Figure 1: these two metallicity components have a clearly different spatial distribution, with the MP one being more concentrated than the MR component. All of our stars are in the external regions, at more than 2 half-mass radii (Figure 1), where the relaxation time is very long so that mass segregation between the two components cannot be responsible, since the mass difference implied by the different metallicity and age (see Section 6) is about 0.04 $M_\odot$. Our new result, statistically very robust, is fully independent from any claimed radial distribution of SGB stars.

4. THE Na–O ANTICORRELATION IN NGC 1851

We find the familiar Na–O anticorrelation also in NGC 1851. Interestingly, this signature remains visible even considering the MR and MP populations separately. In Figure 3, we show the Na–O anticorrelation for both components, together with the run of the [O/Na] ratios as a function of the metallicity. We use [Na/H] and [O/H] to account for the well-known metallicity dependence of Na as a function of the metal abundance for stars of the primordial (P) component (see the definition of primordial, intermediate I, and extreme E populations in Carretta et al. 2009c).

The Na–O anticorrelation is slightly different for the MR and MP components, but in both cases the extension is quite modest, more similar to that in M 4 than in NGC 2808. This suggests only a modest spread in He in NGC 1851 because a high *Y* fraction seems to be associated only with very long tails of very O-poor stars, not present in this GC. Our finding from a chemical approach confirms the claims by Salaris et al. (2008), based on the absence of a tilt along the HB and the lack of a splitting in the MS.

In addition, we observe a slight change of the mean value of O and Na abundances at the level of the bump on the RGB. We already showed (Carretta et al. 2007b; Bragaglia et al. 2010) that this variation is expected from theoretical models, which predict a change in the bump luminosity with He content

[11] For instance, the temperature is derived from a relation between $T_{\rm eff}$ (from $V-K$ and the Alonso et al. 1999 calibration) and K magnitudes, much more reliably measured than colors, leading to very small internal errors in the atmospheric parameters, hence in the derived abundances.

[12] For a detailed discussion of the larger scatter found among brighter and cooler stars, see Carretta et al. (2009a). The observed spreads we found are only lower limits, due to the way we derive the final temperatures, using a mean relation between $T_{\rm eff}$ $(V-K)$ and the K magnitude along the RGB, which tends to decrease real abundance spreads. Finally, the reddening is very low ($E(B-V) = 0.02$; Harris 1996) and not differential.

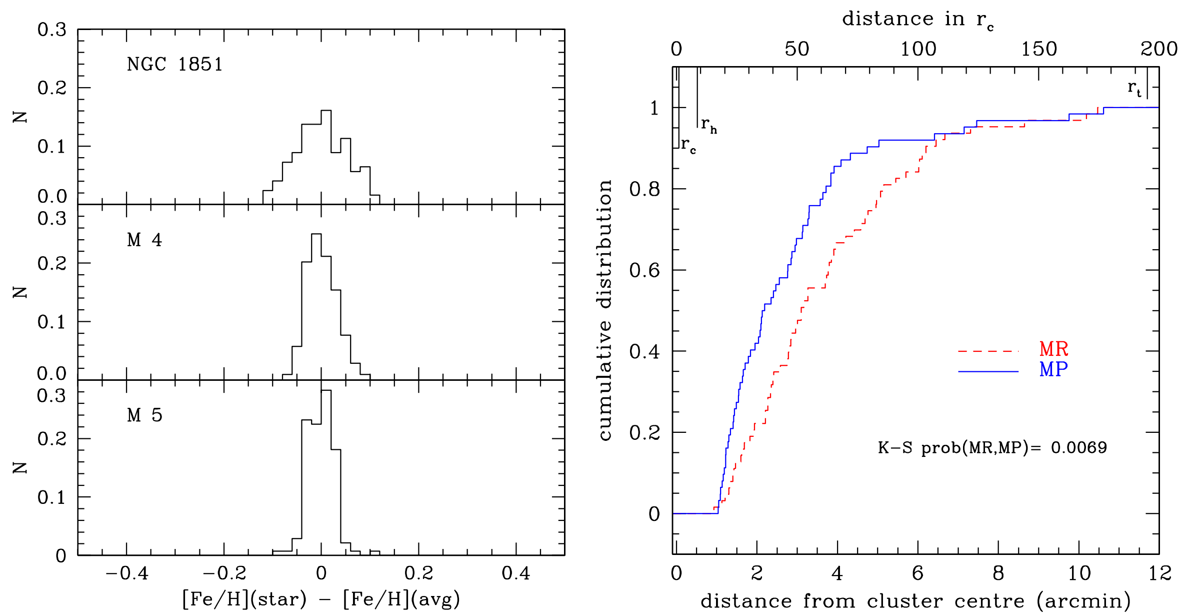

Figure 1. Left: MDF of NGC 1851 compared to those in M 4 and M 5 (Carretta et al. 2009c). All MDFs are normalized to the cluster average [Fe/H] value. Right: cumulative distributions of the radial distances for the MR and MP components in NGC 1851. A Kolmogorov–Smirnov test returns a negligible probability (∼0.007) that the two come from the same distribution. Our stars are all from ∼2 half-mass radii to the tidal radius.

(A color version of this figure is available in the online journal.)

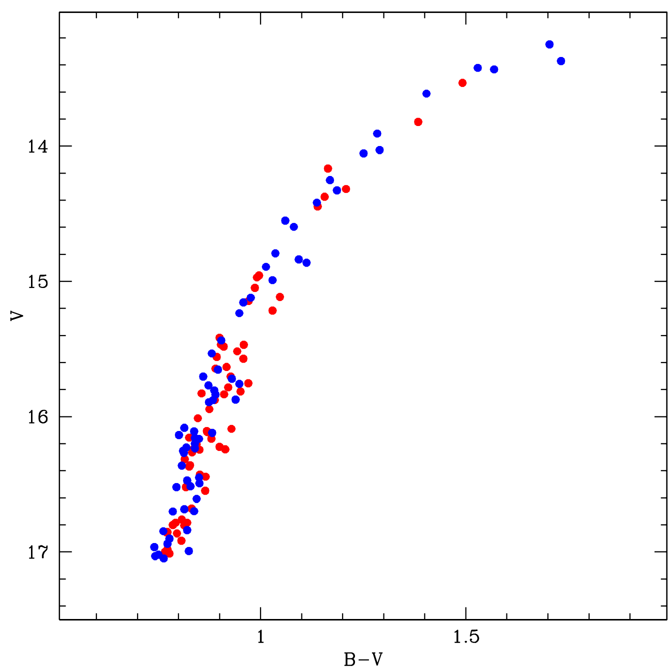

Figure 2. CMD V, $B-V$ indicating MP and MR stars in blue and red, respectively.

(A color version of this figure is available in the online journal.)

(Salaris et al. 2006), i.e., with elements involved in p-capture reactions. The presence of a mix of first- and second-generation stars results in a concentration of Na-poor/He-poor stars just before the bump accompanied by an accumulation of Na-rich/He-rich stars just above the bump level. This accounts for the observed abundance changes at the bump without resurrecting the internal mixing scenario for O and Na (e.g., Lee 2010) and then overcoming the unpalatable requirement of basic stellar structure differences between field and GC stars. For NGC 1851, where we hypothesize two distinct clusters (see below), we expect a further smearing of the bump in the RGB luminosity function (E. Carretta et al. 2010, in preparation).

5. THE LOCATION OF STARS ON THE RGB IN NGC 1851

In Figure 4, we use the Strömgren $u, u-b$ CMD to test where stars of different components and populations are located on the RGB. This plane is optimally suited to separate first- and second-generation stars, probably because of N (enhanced in O-depleted, second-generation stars) via the formation of NH, CN, and their relevance on the $u-b$ (or the Johnson $U-B$), see Yong et al. (2008), Marino et al. (2008), and Carretta et al. (2009c).

Stars of the first generation (P; Carretta et al. 2009c) in NGC 1851 lie along a narrow strip to the blue of the RGB (Figure 4, bottom panel), as expected from their unprocessed chemical abundances. In contrast, the second-generation stars are spread out to the red, as in NGC 6752 (Carretta et al. 2009c): the I stars are in the middle, and the extreme E component, with the lowest O abundances, is located at the reddest edge. This segregation is also followed within each metallicity component, and it is "orthogonal" to the separation of MR and MP stars (Figure 4, top panel), which are well intermingled across all the RGB in this color. The same holds if we separate the RGB stars using the average value for Ca ([Ca/H] = −0.83): stars with low and high Ca are spread across the entire RGB (Figure 4, middle panel).

Therefore, the spread of Ca does not track the abundances of p-capture elements. A Kolmogorov–Smirnov test on the cumulative distributions of [Ca/H] for stars of the first and second generations in NGC 1851 indicates that they are indistinguishable. Instead, the Ca abundances closely track those of Fe. The cumulative distribution of [Ca/H] values for the MR and MP components on the RGB is definitively different. Moreover, also the radial distributions of Ca-rich and Ca-poor stars confirm the close correspondence with metallicity: the Ca-poor giants are more concentrated, while Ca-rich stars show a tendency toward more external regions.

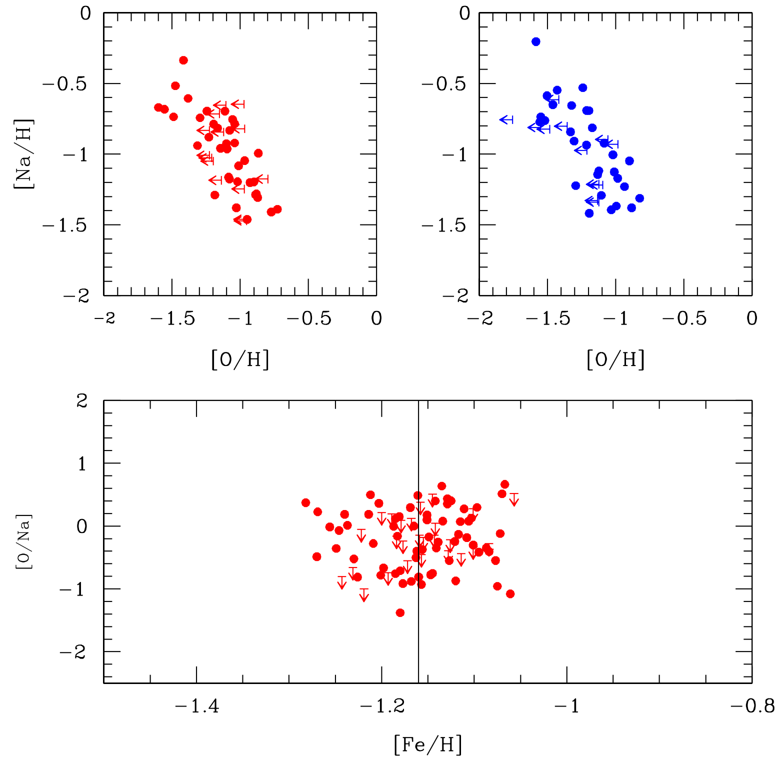

Figure 3. Na–O anticorrelation for the MR (upper left panel) and the MP component (upper right panel). The ratios [Na/H] and [O/H] are used to remove the dependence on metallicity of the Na abundances of P stars. Bottom panel: the [O/Na] ratio as a function of metallicity. Upper limits in O are indicated by arrows.

(A color version of this figure is available in the online journal.)

6. IS NGC 1851 A RELIC OF A MERGER OF TWO CLUSTERS?

Is there a comprehensive scenario able to account for all the evidence found here and in previous works in NGC 1851? In our view, the answer is affirmative if we consider NGC 1851 as the result of a chain of events that started with two distinct clusters. Several suggestions of duplicity come from the bimodal distribution of HB stars, the double SGB, and hints of double sequences on the RGB. Up to now, the main objection was the absence of a metallicity spread, owing to the lack of precise abundances for a statistically significant number of stars. This limitation has finally been overcome by our study.

As a tentative working hypothesis, we can think of two different clusters, born in a much larger system, perhaps a dSph. Being distinct, each one might have formed with a slightly different metallicity and with a different level of α-elements.[13] Each object is rightfully a GC, since each component show the Na–O anticorrelation, the classical signature of the processes ending in a GC (Carretta et al. 2010b). After a while, the two clusters underwent a merger, likely because both were dragged to the center of the dSph by dynamical friction (see Bellazzini et al. 2008) and the result is NGC 1851. Finally, the dSph merged with the Milky Way. We think that this is the simplest scenario, that with a minimum of hypothesis may account for many observational constraints.

The two MR and MP components do not show any significant difference in kinematics, the velocity dispersion being the same for both components. A comprehensive dynamical model would be very welcome, although we do not know when the merging occurred. We will rely on the observed chemistry.

[13] We find that Mg, Si, and Ti also track iron in the MR and MP components, as Ca does.

The observables include a double SGB, where the faint SGB (fSGB) includes 45% of the stars and the bright SGB (bSGB) the remaining 55% (Milone et al. 2008), and with controversial evidence of different concentration; the MR and MP components on the RGB, with a clear difference in radial concentration; a bimodal distribution on the HB, with ∼40% of the stars on the blue HB (BHB) and ∼60% on the red HB (RHB; Milone et al. 2008); the observed luminosity of HB stars and the moderate extension of the Na–O anticorrelation in both the MR and MP RGB components, which both suggests small He abundance variations.

We may explain these observables in different ways.

1. A single GC with two populations having a different total CNO abundance (but a similar He abundance). This may explain the SGB but fails to reproduce the number ratios on the HB (if the same efficiency for mass loss on the RGB is assumed for both sub-populations), because the minor fSGB component should be associated with the major RHB one.
2. A single GC with two populations having a different He and total CNO abundance. In this scenario, there is much more He in CNO-rich than in CNO normal stars. The CNO effect dominates on the SGB, and He effect on the HB. However, in this scenario the BHB should also be brighter than the RHB, which is not observed (e.g., Salaris et al. 2008).
3. A merging of two GCs differing in age (although this does not exclude a priori a difference in the total CNO). In this scenario, one of the GCs (including some 55%–60% of the stars) would be responsible for the bright, younger (possibly less concentrated) SGB, for the MR (less concentrated) RGB, and for the younger RHB. The other GC (including some 40%–45% of the stars) would be responsible for the

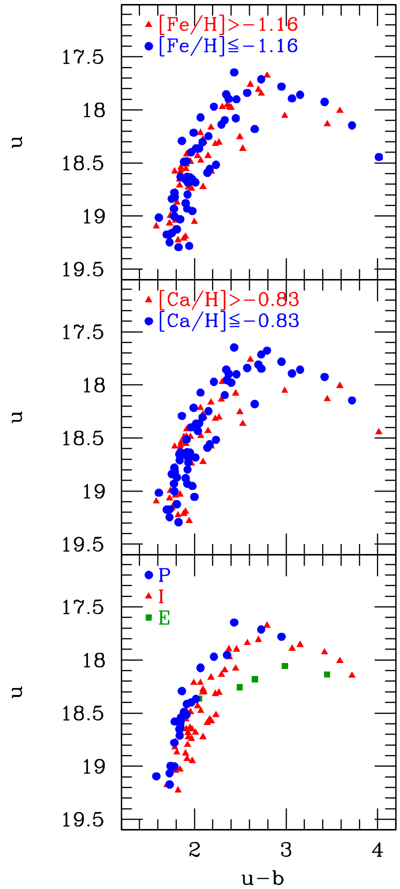

Figure 4. $u, u - b$ CMDs for stars analyzed in NGC 1851. Top: stars are separated at the average metallicity [Fe/H] = −1.16 in MR (red filled triangles) and MP (blue filled circles). Middle: the separation is made at the average [Ca/H] = −0.83 value (Ca-rich: red filled triangles; Ca-poor: blue filled circles). Bottom: stars are separated in P (blue filled circles), I (red filled triangles), and E (green filled squares) according to their Na, O abundances.

(A color version of this figure is available in the online journal.)

faint, older (possibly more concentrated) SGB, for the MP (more concentrated) RGB, and for the older BHB. In this case, the two SGBs can be fitted by isochrones differing in age by ∼1.5 Gyr, if the same CNO content is assumed for both GCs, and the difference in Fe is as derived from the MP and MR RGB components.

Should solution (3) be the right one, the age difference that we need (∼1–1.5 Gyr) is not unlikely if the clusters were born in a dSph (see, e.g., the case of the Fornax dSph GCs; Buonanno et al. 1998, 1999). As a consistency check, we explored Lee's diagram HB type versus [Fe/H] (see, e.g., Figure 9 in Rey et al. 2001) using the average values of metallicity [Fe/H]= −1.20 (σ = 0.03 dex) and [Fe/H]= −1.12 (σ = 0.03 dex) for the MR and MP components, respectively. If we tentatively adopt for the two components the HB type of NGC 288 (0.98) and NGC 362 (−0.87), the diagram shows that the MR component may easily be about 1–1.5 Gyr younger than the MP one.

An additional constraint comes from the ratio between the abundances of *s*- and *r*-process elements. Figure 5 shows the [Ba/Eu] ratio as a function of metallicity for the 13 stars with UVES spectra. This ratio is close to that expected from a pure-*r* component for MP stars, while it indicates a larger contribution by the *s* process for the MR ones. The trend with [Fe/H] is even cleaner when using the average from Ba, La, and Ce. It suggests a larger contribution of polluters of smaller masses

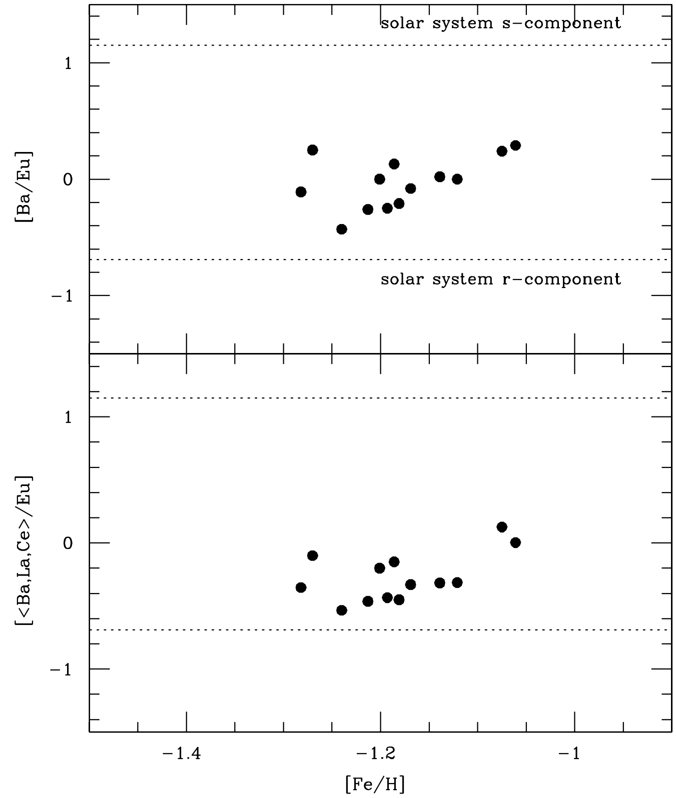

Figure 5. Ratio of [s/r] process elements for stars with UVES spectra, as a function of metallicity. Upper panel: [Ba/Eu] ratios. In the lower panel, the level of *s*-process elements is represented by the average of Ba, La, and Ce.

for the MR component, which fits well with the proposed age difference.

To conclude, we note that Carballo-Bello & Martinez-Delgado (2010) reported the existence of a distinct metal-poor main sequence around the GCs, NGC 1851 and NGC 1904, which they interpreted as a very low surface brightness stellar system. This is maybe consistent with the structure identified by Olszewski et al. (2009) in the form of a halo of main-sequence stars surrounding NGC 1851 up to a distance of 250 pc. Both of these observations suggest the existence of a residual structure that might be what is left by the destruction of the ancestral dwarf where the progenitor of NGC 1851 originated.

A really clear-cut test for the presence of two distinct GCs is to probe the Na–O anticorrelation among HB stars. If the merger hypothesis is correct, each one of the HB populations (coming from individual GCs) should present the Na–O anticorrelation, as we find in the MR and MP components of the RGB. In contrast, for a single proto-cluster scenario, we should expect the RHB stars to be almost all O-rich, with the O-poor stars only confined to the BHB. Specific proposals of observations aimed to perform this test have already been submitted.

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