

THE RADIAL EXTENT OF THE DOUBLE SUBGIANT BRANCH IN NGC 1851 *

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ABSTRACT

Recent HST-ACS observations revealed the presence of a double subgiant branch (SGB) in the core of the Galactic globular cluster NGC 1851. This peculiarity was tentatively explained by the presence of a second population with either an age difference of about 1 Gyr, or a higher C+N+O abundance, probably due to pollution by the first generation of stars.

In the present Letter, we analyze VLT-FORS V, I images, covering 12.7′ × 12.7′, in the southwest quadrant of the cluster, allowing us to probe the extent of the double SGB from ~1.4 to ~13 arcmin from the cluster center. Our study reveals, for the first time, that the “peculiar” population is the one associated to the fainter SGB. Indeed, while the percentage of stars in this sequence is about 45% in the cluster core (as previously found on the basis of HST-ACS data), we find that it drops sharply, to a level consistent with zero in our data, at ~2.4 arcmin from the cluster center, where the brighter SGB, in our sample, still contains ~100 stars. Implications for the proposed scenarios are discussed.

Subject headings: globular clusters: individual (NGC 1851) — Hertzsprung-Russell diagram

1. INTRODUCTION

Until 2004, ω Centauri (NGC 5139) and M54 (NGC 6715) used to be the only two globular clusters (GCs) with clear evidence of multiple stellar components, based on the presence of a complex red giant branch (RGB) in their color-magnitude diagrams (CMDs; Pancino et al. 2000, Siegel et al. 2007). Thanks to the exquisite image quality of the ACS camera on board HST, complex CMD features such as splitings and multimodalities were confirmed in these clusters, and even subtler features have been detected in other GCs. Bedin et al. (2004) discovered that the main sequence (MS) of ω Cen is also bimodal (see also Villanova et al. 2007), and Piotto et al. (2005) demonstrated that the blue MS was more metal-rich than the red one, and suggested that an exceptionally high helium content (Y ∼ 0.38) could explain its bluer color. A triple MS was discovered in NGC 2808 (Piotto et al. 2007), while NGC 1851, and possibly NGC 6388, have double subgiant branches (SGB; Milone et al. 2008a, Piotto 2008). In addition, several LMC clusters show evidence of multiple sequences, mostly along their SGBs (Milone et al. 2008b).

Interestingly, the CMD sequences in these GCs tend to be discrete, pointing to multiple, but separated, generations of stars (as opposed to extended star formation periods) or to multimodality in the chemical composition (as opposed to metallicity spreads). However, each of the clusters mentioned shows a different CMD peculiarity, resulting from a different enrichment/formation history (see Piotto 2008, for a review).

Some of the observed features, such as the double SGBs, could be explained in terms of age differences between the subpopulations (Milone et al. 2008a). However, a star formation history consisting of two bursts with an age gap but identical composition would be unlikely, due to the winds of massive stars and core-collapse supernovae (SNs) of the first generation quickly enriching the medium, hence altering the initial composition of the material from which the second generation is born. Therefore, the most plausible scenarios involve multiple populations born at different times with different abundances (Cassisi et al. 2008, Salaris et al. 2008, Renzini 2008). The presence of two coeval populations with different chemistry might be possible, in principle, in the pollution scenario, where some of the stars have their surfaces contaminated by the winds of stars belonging to the same burst (e.g., D’Antona et al. 1983). However, as discussed by Renzini (2008), this would lead to spreads rather than multimodalities, given that the amount of contamination would be a continuous function of mass, velocity, and orbit for each star inside the cluster.

In the present paper we use ground-based data to analyze the radial behavior of the double SGB identified by Milone et al. (2008a) in NGC 1851. This is a massive cluster (3 × 105 M⊙; McLaughlin & van der Marel 2005), previously studied from the ground (e.g., Walker 1992, Saviane et al. 1998, Bellazzini et al. 2001), whose main known peculiarity is a bimodal horizontal branch (HB). The ACS study by Milone et al. (2008a), confined to the cluster core, showed that the SGB splits into two similarly populated sequences, with 45% of the stars in the fainter SGB and 55% in the brighter one. Cassisi et al. (2008) proposed a different C+N+O content as a possible explanation for the double SGB, while Salaris et al. (2008) and Catelan et al. (2009) claimed that such a difference should not be coupled with a variation in the helium content Y, or else the observed HB cannot be reproduced. By means of high-resolution spectroscopy of 8 giants in NGC 1851, Yong & Grundahl (2008) claimed the absence of any spread or bimodality in [Fe/H], together with the presence of large, correlated star-to-star variations in the abundances of O, Na, and Al.

The ACS data cover only the cluster core, while the quoted ground-based photometries for NGC 1851 did not allow to constrain the shape of the SGB with the precision required to detect an SGB split. The present paper is the first attempt at

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constraining the radial extent of the two populations associated with the double SGB.

![Diagram of FORS Fields](image)

**Fig. 1.** — DSS image of NGC 1851 with the position of the VLT-FORS 2' × 2' mosaic. The HST-WFPC2 and HST-ACS fields are also indicated. North is up and east to the left.

2. OBSERVATIONS AND DATA ANALYSIS

Our data comes from the pre-imaging run of a spectroscopic survey for CN-CH anticorrelations in several GCs. The NGC 1851 images were acquired on September 28th, 2001, in service mode, using the FORS2-VLT 2k × 2k SiTe CCD. The 4-field mosaic in the SW quadrant of the cluster (Fig. 1) contains a short (2s) and a long (15s) exposure taken with each of V and I at each position. There is ∼15% overlap between adjacent fields, yielding a total imaged area 12.7' × 12.7'. The average seeing was 1.3''.

The images were de-biased and flat-fielded by the ESO FORS pipeline. PSF-fitting photometry was carried out with DAOPHOTII, ALLSTAR, and ALLFRAME (Stetson 1987, 1994), using a constant PSF across the field—which empirically yielded the best results. Though no standard fields were observed, the photometry was calibrated by means of the ∼1200 stars in common with the Bellazzini et al. (2001) catalogue, for a 8'' × 8'' field centered on the cluster. Only the innermost FORS field had stars in common with this catalogue; the other three fields were calibrated thanks to the relatively large overlap with the central one, and amongst themselves (Fig. 1). While crucial to calibrate our data to the standard Johnson-Cousins system, the photometry by Bellazzini et al. does not reach the required precision to assess the presence or absence of a double SGB.

In order to improve the definition of the SGB, a selection was applied based on the photometric errors, as well as the CHI and SHARP parameters, obtained in the PSF fitting process (Stetson 1987). The smallest photometric error for each star is the Poisson error associated to its flux. Indeed, the lower envelope of the distribution of photometric errors yielded by DAOPHOT is always a smooth function of the magnitude. In order to select stars with unusually large errors for their magnitude, we fitted the lower envelope of the error distribution, and rejected stars having an error in excess of 0.03 mag in V or I with respect to this envelope. In addition, selection limits of CHI < 2.5 and −1 < SHARP < 1 were imposed on all stars. The procedure is similar to the one used in, e.g., Zorotovic et al. (2009, their Fig. 5). We emphasize that these selection criteria are very relaxed: only a small percentage of the stars in the turnoff-SGB region were rejected.

![CMD plots](image)

**Fig. 2.** — Bottom: three radial selections on the FORS CMD (see labels, with numbers in arcmin) corresponding to the stars marked in gray in the maps above each panel. The solid lines are two isochrones for 10 and 11 Gyr, with normal α-enhanced composition, and metallicity Z = 0.002. Formal photometric errors, as given by DAOPHOT are shown on the right side (middle and right panels).

3. THE SPATIAL DISTRIBUTION OF SGB STARS

Figure 2 shows the error-selected and mosaic-ed FORS photometry, in three radial annuli. The photometry in the innermost annulus, at a distance between 1.35' and 2.35' from the center, is rather poor, due to the high stellar density and the rather poor seeing. Also shown are the two isochrones used by Cassisi et al. (2008) to fit the HST-ACS SGB, having Z=0.002, standard α-element enhancement and helium content (Y = 0.25), and ages of 10 and 11 Gyr. The adopted distance modulus [(m−M)0 = 15.40] and reddening [E(B−V)=0.06] are constrained by the middle and right panels, assuming (rather arbitrarily at this point) that the SGB seen in those CMDs corresponds to the brighter one (see below).

Although the SGB in the innermost region is poorly defined, its appearance is compatible with the presence of two sequences, approximately matched by the isochrones. All the stars above the younger isochrone with colors V−I ≤ 0.8 are likely blends (see below). The middle and right panels show the CMD relative to the region between 2.35' and 4', and outside 4', respectively. Only one of the two SGBs is well populated in both. If the SGB were double, this would be readily apparent in this plot, given that the spread in magnitude, likely due entirely to photometric errors, is smaller than the
expected separation between the two sequences.\textsuperscript{6}

In order to better quantify the visual impression provided by Figure 2, we analyze the distribution of stars around the mean ridgeline in Figure 3. Following a procedure similar to that in Piotto et al. (1999), a coordinate transformation is applied to the x-axis, in order to give equal weight to color and magnitude and thus correctly project each star on the fiducial line. The distribution of the distances of SGB stars from the ridgeline is shown in the figure insets. A strong selection on CHI and SHARP applied to the photometry of the inner region confirmed our suspicion that the bright blue stars above the turnoff are blends.\textsuperscript{7} In the inner region there are indications of the presence of two SGBs, separated by 0.1 mag, as seen with ACS. Two Gaussians fit this distribution better than a single one, with 88.2% confidence, according to the KMM test (Ashman et al. 1994). However, the same test indicates, at better than the 99.99% confidence level, that a single Gaussian provides a better fit to the SGB distribution further out. The sigma of the latter Gaussian (0.03 mag) is a realistic estimate of the errors of our photometry, and is significantly smaller than the expected separation between the two SGBs (0.1 mag).

Clearly, the present photometry in the inner region is not comparable with the ACS one. However, if a double SGB were present in the SW quadrant beyond 2.7′, we would certainly have been able to detect it. In what follows, we will carry out two more tests to further examine this conclusion.

3.1. Could the double SGB show up only in the F606W filter?

Our CMD was obtained using $V, I$, unlike Milone et al.’s, which used F606W, F814W. Since F606W is significantly broader than Johnson $V$, it could in principle include some spectral feature (e.g., the red CN band) not included in $V$. If this feature differed markedly between the two SGBs, one might see the SGB splitting only in F606W (ACS), and not in $V$ (FORS).

This possibility can be rejected based on the following arguments. First, if the SGB splitting were due to either age or CNO overabundance, it would be present also in luminosity, as easily verified in the isochrones computed by Cassisi et al. (2008). This means that the splitting would be due to a different evolutionary path, and not to different line blanketing. While the latter could be present preferentially in the filter including CN bands, the former affects all filters in a similar way. Second, while the CMD in the left panel of Figure 3 has too few stars to firmly establish the presence of a double SGB, the CMD from the HST-WFPC2 Snapshot Project\textsuperscript{8} (Piotto et al. 2002) does show it rather unambiguously. Figure 4 shows a zoom of the CMD of NGC 1851, as obtained with HST-WFPC2, in a region outside 1′ from the cluster center. This demonstrates that, whatever the cause of the SGB splitting, it is visible in the F555W filter, which is very similar to Johnson $V$.

3.2. Which of the two SGBs disappears in the outer region?

The CMD in Figure 4 also shows that the fainter SGB is significantly less populated than the brighter one, the former including $\sim 40\%$ as many stars as the latter. This strongly suggests that the “peculiar” population, intended here as the less numerous one, corresponds to the fainter SGB.

\textsuperscript{6} Note that the lower RGB is not well matched by the isochrones. This is a known problem, due to an improper transformation to the observational plane in these bands (Cassisi, private communication). Indeed, the isochrone fit shown in Figure 2 of Cassisi et al. (2008) does not include the lower RGB.

\textsuperscript{7} The different CHI,SHARP selection criteria in the two panels of Figure 3 are justified by the argument that in the inner region a double SGB remains even after a strong selection, hence it is not due to the presence of blends. On the contrary, no double SGB is seen in the outer part, even with a very loose selection.

\textsuperscript{8} The data are publicly available from http://dipastro.pd.astro.puc.cl/globulars/databases/snapshot/snapshot.html.
To further check this, we shifted the FORS CMD vertically by 0.08 mag, so that its red HB matches the WFPC2 one (Fig. 5). This removes the small zero point difference between the Johnson V and HST F555W filters, while the color term is negligible given the similarity between the two filter passbands. The single SGB visible in the FORS CMD can be identified in the WFPC2 CMD by means of its magnitude at a fixed (arbitrary) color. Since the colors on the x-axis are different in the two panels, we need to select a reference position on the CMD, instead of an absolute color value. The color in the “middle” of the SGB, i.e., the average between the color of the MS at V = F555W = 19.5 and the color of the RGB at V = F555W = 18.6, was selected as reference. Figure 5 clearly shows that, at this reference color, the brighter SGB has V = 18.87 in both CMDs, while the fainter one has V = 19.01 in the WFPC2 data, and is not visible in the FORS CMD.

This exercise clearly demonstrates that the “peculiar” population corresponds to the fainter SGB, which in our data is present only in the central ∼ 2′ – as already hinted by Figure 2. Further support to this idea comes from the fact that Milone et al. (2008a) also found the fainter SGB to be more centrally concentrated than the brighter SGB (see their Fig. 6). However, having data only for the cluster core, they concluded that the difference was compatible with the two groups of stars sharing the same spatial distribution. Instead, our study clearly shows that the fainter SGB is much more centrally concentrated.

4. DISCUSSION

We have demonstrated that the ratio between faint and bright SGB stars (fSGB/bSGB) in NGC 1851, which is 45/55 in the cluster core, drops dramatically in the outer region, to a level consistent with zero, at least in the cluster’s SW quadrant. We shall now use the central concentration of the “peculiar” population associated to the faint SGB to pose constraints on its origin.

Three hypotheses have been proposed to explain the SGB splitting in NGC 1851, namely: i) A pure age difference, by about ∼1 Gyr; ii) A CNO overabundance by about a factor of 2, associated with the brighter SGB – the latter also being ∼2 Gyr younger than the “normal,” fainter SGB; and iii) A CNO enhancement associated with the fainter SGB at a fixed age (i.e., coeval populations). Salaris et al. (2008) suggested that the progeny of the fainter SGB stars should be found both on the blue and red sides of the HB, while the brighter SGB should produce red HB stars only. By coupling the SGB shape with the constraints posed by star counts along the HB, they excluded the brighter SGB population as the extreme, CNO-enhanced one.

Pure age difference. If the fainter SGB corresponds to a population ∼1 Gyr older than the brighter one, its central concentration would imply something akin to an inside-out formation scenario, with a first episode of star formation, confined to the center and converting into stars only a small amount of the available gas, followed by a second burst 1 Gyr later, converting into stars all the remaining gas, and involving the whole cluster volume. This galaxy-like scenario seems rather unlikely for a low-mass stellar system; a specific dynamical model might confirm/disprove this hypothesis on more quantitative grounds.

CNO enhancement of the brighter SGB. If the brighter SGB stars are CNO-enhanced, then they should be ∼2 Gyr younger than the normal-abundance, fainter SGB ones. However, in this case the chemically normal population should be the minority one, located only in the center, but it should somehow have succeeded in enriching the second-generation stars throughout the cluster volume. Clearly this is not a plausible solution, because the relatively small total mass of the primordial population would not be able to enrich the more massive second generation. This scenario was also excluded by Salaris et al. (2008) on the basis of star counts along the HB.

CNO enhancement of the fainter SGB. If the fainter SGB is coeval with the brighter SGB, then it should have an extreme metal mixture, characterized by CNO enhancement, strong anticorrelations between C-N and O-Na, but the same Z and Y (Cassisi et al. 2008). The present data allow us to identify such a scenario as the most plausible one. The bulk of the stellar population in NGC 1851 would have been born ∼12 Gyr ago, and in the timespan between 20-30 Myr and 300 Myr after its birth, the winds from its massive AGB stars would accumulate enriched gas at the bottom of the potential well, i.e., at the cluster center (Renzini 2008). At some point during this time, the accumulated material could undergo a second episode of star formation, soon enough that the age difference would not be detectable with the current data.

The present analysis allowed us to identify the fainter SGB population as the “peculiar” one, being much more centrally concentrated than the brighter SGB, and either older or CNO enriched (and coeval within the errors, ∼0.4 Gyr). Both scenarios are compatible with the results of Salaris et al. (2008). However, in the middle (2.35 < R′ < 4.0) and outer (R > 4′) radial bins of the FORS data, the stars on the blue and red sides of the HB are in the proportion B : R = 2 : 8 and 2 : 3, respectively. If the progeny of the brighter SGB can evolve only to the red HB, as suggested by Salaris et al., then the blue HB should disappear in the outer region, together with the fainter SGB. Despite the small-number statistics, we do see 2 blue HB stars even out to R ∼ 4′, where the fainter SGB has disappeared in our data. Based on Walker’s (1992) data, covering a wider field than the SW quadrant studied here, we count B : R = 8 : 18 in the middle radial bin. If confirmed by statistically larger datasets, the presence of some blue HB
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stars over the whole cluster area would be in contradiction with the absence of fainter SGB stars outside 2.4 arcmin.

Before closing, we note that it is not obvious how multiple populations may remain radially segregated in an old GC such as NGC 1851. The central relaxation time of NGC 1851 is only $2.6 \times 10^7$ yr, whereas at the half-light radius it is still just $3.2 \times 10^8$ yr [Djorgovski 1993]. Thus, any differences in radial distribution among the different stellar components should have disappeared long ago. On the other hand, we estimate that, outside the half-light radius of NGC 1851 ($\approx 1.8'$), the relaxation time becomes longer than a Hubble time (eq. 2-61 in [Spitzer 1987]). Since our observations cover mostly regions further out, it is conceivable that the spatial distribution of distinct stellar populations in the cluster will only become more thoroughly homogeneized in the distant future. Further studies of the detailed spatial distribution of the stars associated with the different sub-populations, along with their chemical composition, are strongly encouraged.

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