THE DOUBLE SUBGIANT BRANCH OF NGC 1851: THE ROLE OF THE CNO ABUNDANCE

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ABSTRACT

We explore the possibility that the anomalous split in the subgiant branch (SGB) of the Galactic globular cluster NGC 1851 is due to the presence of two distinct stellar populations with very different initial metal mixtures: a normal $\alpha$-enhanced component, and one characterized by strong anticorrelations among the CNONa abundances, with a total CNO abundance increase by a factor of 2. We test this hypothesis taking into account various empirical constraints, and conclude that the two populations should be approximately coeval, with the same initial He content. More high-resolution spectroscopic measurements of heavy elements—and in particular of the CNO sum—for this cluster are necessary to prove (or disprove) this scenario.

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

1. INTRODUCTION

Recent accurate spectroscopic and photometric observations of stars in Galactic globular clusters (GCs) have shown that surface abundance variations of C, N, O, Na, and often also of Mg and Al exist in stars within individual clusters (see, e.g., Gratton et al. 2004), and that these elements display a pattern of abundance variations that is constant along the red giant branch (RGB) and down to the turnoff (TO) (see, e.g., Gratton et al. 2001; Carretta et al. 2005). This pattern shows anticorrelations between CN and ONa (and, when observed, MgAl) superimposed on a “normal” $\alpha$-enhanced heavy-element distribution ([Fe/Fe] $\sim$ 0.3–0.4), in the sense that negative variations of C and O are accompanied by increased N and Na abundances. The generally accepted explanation is that these stars were born with the observed CNONa abundance patterns. Winds of intermediate-mass asymptotic giant branch (AGB) stars or winds of fast-rotating massive stars have been invoked as sources of the necessary heavy-element pollution (see, e.g., Ventura et al. 2001; Decressin et al. 2007; D’Antona & Ventura 2007 and references therein). Provided that a significant fraction of this material is not lost from the GC, new stars can form directly out of this matter (within $10^6$–$10^8$ yr after the formation of the first generation, the exact time depending on the nature of the pollution sources) or from preexisting matter polluted to varying degrees by the stellar ejecta. The iron abundances would be constant among the different subpopulations, as is actually observed in almost all GCs (see, e.g., Suntzeff 1993).

A prediction of both scenarios is that the second stellar generation in a GC must have an enhanced initial He content, compared to the first generation with a “normal” $\alpha$-enhanced heavy-element distribution. A spread in the initial He content of GC stars allows us to interpret the morphology of the horizontal branch (HB) in a number of GCs (see, e.g., D’Antona & Caloi 2004; Caloi & D’Antona 2008 and references therein). Recent accurate photometries of GCs obtained with the Advanced Camera for Surveys (ACS) on board the HST have given direct photometric evidence of multiple populations with varying He content in $\omega$ Centauri (Anderson 1997; Bedin et al. 2004; Piotto et al. 2005). Given that this cluster has since long been known to harbor multiple populations with different [Fe/H] values, it may not be a typical GC, but rather a small galaxy. More remarkable, from the point of view of studying “normal” GCs, is the recent detection of a triple MS in NGC 2808 (Piotto et al. 2007). This is a clear sign of populations with distinct initial He abundances (as earlier suggested by D’Antona et al. 2005) in a typical GC with no sign of spread in [Fe/H], hence no sign of metal enrichment due to supernovae ejecta. An even more recent result is the discovery by Milone et al. (2008, hereafter M08) that the SGB of NGC 1851 is split into two distinct branches. This is, to date, the third GC for which there is direct photometric evidence of multiple stellar populations.

The CMD by M08 displays a very narrow MS and RGB, which puts strong constraints on the possible interpretations of the SGB splitting. M08 discuss at length this issue and conclude that two populations with the same age but with either a different initial He content or a different [Fe/H] can be excluded. Another possibility they considered is to have the second population with both increased He ($Y \sim 0.30$) and higher [Fe/H] (by $\sim 0.2$ dex). Given the opposite effect of metals and He on the colors of the MS and RGB, this combination would preserve the narrowness of the MS and RGB and also reproduce the split of the SGB while keeping the age constant. The very recent results from high-resolution spectroscopy of eight bright cluster giants (an admittedly small sample) by Yong & Grundahl (2008) exclude the presence of a bimodal Fe abundance. The same conclusion can be reached by considering the Walker (1998) estimate of [Fe/H] from the Fourier decomposition of the light curves of nine cluster RRab variables. As an alternative scenario, M08 suggest that the SGB splitting could be simply due to the age effect: the two SGBs would correspond to two distinct star formation bursts separated by $\sim 1$ Gyr.

Here we propose a connection between this photometric evidence of multiple populations in NGC 1851, and the pattern of CNONa abundance anomalies typical of several GCs. This
Hesser et al. (1982) obtained 4 resolution spectra of bright AGB stars compared to the value of the first stellar generation. In case of AGB pollution, and with their best choice for the convection treatment they obtain CNO sums that can increase by a factor of 2 compared to the normal α-enhanced distribution. We discuss whether this is consistent with existing photometric constraints, from both HST and ground-based photometry. The next section briefly presents our new model calculations, while the subject of § 3 is the comparison with photometric data. A discussion follows in § 4.

2. STELLAR MODELS

We consider as representative of the “normal” stellar population in NGC 1851 models computed with the α-enhanced mixture ([Fe/H] = 0.4) employed by Pietrinferni et al. (2006), a metal mass fraction Z = 0.002, and Y = 0.248, corresponding to [Fe/H] = −1.3 (Yong & Grundahl 2008) have determined a mean abundance [Fe/H] = −1.27 ± 0.03. We have then computed additional models for a second heavy-element mixture, with abundances representative of the extreme CNONa anticorrelations (hereafter “extreme” mixture) detected in GCs. This mixture is the same as adopted by Salaris et al. (2006) and displays a 1.8 dex increase of the N abundance, a 0.6 dex decrease of C, a 0.8 dex increase of Na, and a 0.8 dex decrease of O, with respect to our “normal” α-enhanced heavy-element distribution. We have taken into account the effect of this new mixture in both the radiative opacity (see Salaris et al. 2006 for more details) and nuclear burning network, and use the same evolutionary code and physical inputs adopted for the BaSTI stellar library (Pietrinferni et al. 2004, 2006; Corder et al. 2007). To ensure the same [Fe/H] in both populations, this set of stellar models and isochrones has been computed by using a value of Z equal to 0.0037 and two different He contents: Y = 0.248 and 0.28. The reduction in the hydrogen abundance implied by this increase in Y affects the [Fe/H] value by less than 0.02 dex. The sum of the CNO element abundance in the isochrones with the extreme composition is a factor of 2 larger than in the case of the normal α-enhanced counterpart.

As a working scenario we assume the presence of two distinct stellar populations in this cluster, one with a “normal” α-enhanced metal distribution, and a second one with a pattern of CNONa anticorrelations superimposed on the normal α-enhanced distribution. For a given Fe content, the latter distribution has a larger CNO abundance (by a factor of 2) compared to the normal α-enhanced mixture. We discuss whether this is consistent with existing photometric constraints, from both HST and ground-based photometry. The next section briefly presents our new model calculations, while the subject of § 3 is the comparison with photometric data. A discussion follows in § 4.

3. COMPARISON WITH OBSERVATIONS

To fix the cluster distance modulus we fit the theoretical zero-age HB (ZAHB) of the normal population to the lower envelope of the HB in the M08 photometry, and adjust the reddening by fitting the theoretical ZAHB to the vertical part of the observed HB, as displayed in the top panel of Figure 1. It is important to note that M08 photometry includes only magnitudes and colors of the RR Lyrae population taken at random phases; therefore the portion of the observed HB crossing the instability strip cannot be used to put any constraint on the ZAHB fitting.

![Diagram](image-url)
An apparent distance modulus \((m - M)_{F606W} = 15.52\) together with a reddening \(E(F606W - F814W) = 0.038\), corresponding to \(E(B - V) = 0.04\) (according to the relationships by Bedin et al. 2005), enables us to fit the observed HB with models for both the normal population and the extreme one with \(Y = 0.248\). This reddening agrees with the standard estimates \(E(B - V) = 0.02 \pm 0.02\) in the literature (see, e.g., Walker 1998) The red part of the HB appears to be matched better by the ZAHB for the normal population, whereas the knee at the blue side of the HB can be matched better by the ZAHB for the extreme population. Along the vertical part of the HB the two ZAHB sequences practically overlap. On the other hand, it is difficult to accommodate the presence of an extreme population with \(Y = 0.28\) together with the normal \(\alpha\)-enhanced one. The ZAHB with \(Y = 0.28\) is largely overluminous, and is compatible with the observed CMD only at the fainter blue end of the observed HB.

In passing, we note that the ZAHB for the extreme population with \(Y = 0.248\) is mildly brighter that the ZAHB corresponding to the normal population. This occurrence could appear at odds with the fact that usually the ZAHB locus becomes fainter when increasing the global metallicity. However, in this case the extreme population has a larger CNO abundance, and a larger CNO abundance implies a more efficient H-burning shell and, in turn, a brighter ZAHB.

The top panel of Figure 2 displays the upper MS-TO-SGB part of the M08 CMD. A 10 Gyr isochrone for the normal population and a 9 Gyr isochrone for the extreme population with \(Y = 0.248\) both match very well the bright SGB, once shifted for the adopted distance modulus and reddening. The faint SGB is equally well matched by an 11 Gyr isochrone for the normal population and a 10 Gyr isochrone for the extreme population with \(Y = 0.248\). It is essentially the increased CNO abundance that affects the TO and SGB brightness in the isochrone computed with the extreme mixture, and causes a 1 Gyr age difference when matching either of the two SGBs. The lower MS and the RGB of the isochrones for the two heavy-element mixtures are practically coincident, thus satisfying the constraint posed by the narrow observed MS and RGB. We have therefore two possibilities. If the bright SGB is matched by the normal population, the two components will be essentially coeval, with an age of 10 Gyr. If the bright SGB is matched by the 9 Gyr extreme population with \(Y = 0.248\), the normal population has to be 2 Gyr older, in order to match the faint SGB. This comparison demonstrates that it is possible to reproduce the peculiar SGB morphology of NGC 1851 by considering two distinct stellar populations, with the same initial He content: a standard \(\alpha\)-enhanced one, and one with a pattern of CNO\(\alpha\) anticorrelations and a CNO sum increased by a factor of 2.

There is still a potential ambiguity regarding the ages of the two populations, depending on which one matches the bright SGB. In absence of direct spectroscopic measurements of CNO abundances, there is no reason to prefer either of the two solutions. Some help comes from the M08 comparison of the bright to faint SGB population ratio with the ratio of the HB stars redder than the RR Lyrae gap to the ones bluer than the gap. Taking into account the fact that, as discovered by previous studies, the RR Lyrae population in the cluster is <10% of the total HB population, the red-to-blue HB star ratio is close to the 55/45 ratio of bright to faint SGB populations. Based on this similarity, together with the fact that the ZAHB for the extreme composition \((Y = 0.25)\) fits better the blue side of the HB (see Fig. 1 and previous discussion), it is tempting to conclude that the extreme population corresponds to the faint SGB, and therefore it is coeval with the normal \(\alpha\)-enhanced population, both having an age of about 10 Gyr. We note also that this scenario in which the extreme population with \(Y = 0.25\) populates the blue side of the HB distribution requires a more efficient mass loss during the RGB stage, compared to the normal \(\alpha\)-enhanced population. The bottom panel of Figure 1 displays the value of the ZAHB mass as a function of the color \((F606W - F814W)\) for a fixed value of the \(h\) parameter in the Reimers (1975) mass-loss formula, according to our calculations the two distinct stellar populations would be expected to have approximately the same total stellar mass at the RGB tip. We postpone

\[\text{Fig. 2.—Top: } m_{F606W} - m_{F814W} \text{ diagram of NGC 1851 by M08 zoomed around the SGB. The solid lines represent the isochrones for the extreme population with } Y = 0.248 \text{ and ages of 9 and 10 Gyr. The dashed lines are isochrones for the normal population and ages of 10 and 11 Gyr. The isochrones are shifted by } (m - M)_{F606W} = 15.52 \text{ and } E(B - V) = 0.04 \text{ (see text for details). Bottom: As above, but this time the solid lines represent the extreme population with } Y = 0.280. \text{ The ages are again 9 and 10 Gyr.} \]
a more detailed investigation of this issue to a forthcoming paper.

The bottom panel of Figure 2 displays a fit to the SGB region using the helium-enhanced extreme isochrones and the same distance modulus as before. Brighter and fainter SGBs can be matched with ages essentially equal to the case of \( Y = 0.248 \). Due to the higher He content, the displacement between the extreme and normal isochrones along both the MS and the RGB is of the order of \( (m_{\text{F606W}} - m_{\text{F814W}}) = 0.02 \) mag, still marginally consistent with the spread in M08 photometry. However, the two populations cannot coexist along the HB, unless the He-enhanced one is located at the extreme end of the blue HB, where there are very few objects. In this case the number ratios between the two populations along the HB would not match the SGB number ratios, for any of the two possible age combinations.

Irrespective of the choice of \( Y \), along the RGB the combination of the normal and extreme population produces a well-defined bump in the luminosity function (see Salaris et al. 2006) whose brightness is only marginally changed when considering an enhanced He abundance in the extreme component.

4. DISCUSSION

In the previous section we have shown that it is possible to reproduce the peculiar SGB morphology of NGC 1851, by considering the presence of two stellar populations with distinct initial chemical composition: a normal \( \alpha \)-enhanced population and one characterized by a CNO anticorrelation pattern with an increased CNO total abundance. The best agreement with the CMD and population ratios along SGB and HB is obtained for a coeval age of 10 Gyr, and an He abundance of the extreme population showing a negligible enhancement compared to the normal population. It is important to note that a consequence of the increased CNO sum in the extreme population is the negligible time delay between the formation of these two components, an occurrence consistent with current theoretical ideas about the sources of chemical pollution, as briefly mentioned in § 1. The peculiarity of this cluster is that there are possibly two subpopulations with very distinct element abundance ratios, not a wide range of abundance anomalies, as observed in other clusters. Also, the negligible enhancement of He in the extreme population puts additional severe constraints on the models of the origin of this component.

In absence of detailed spectroscopically determinations of the CNO sum in NGC 1851, our result cannot be a definitive proof that this interpretation of the SGB splitting is the one corresponding to reality, just a working hypothesis that we hope will stimulate further spectroscopic work to definitely prove (or disprove) this scenario. Yong & Grundahl (2008) have recently determined only oxygen abundances, and on a very small sample of stars. Our assumed metal mixtures imply a bimodality in the CNO abundance as a whole, but also in the individual abundances of these three elements. The Yong & Grundahl (2008) sample of eight stars is too small to determine with some significance whether the measured O abundances are bimodal or not. We conclude by mentioning an independent empirical result that may provide some additional support to our idea, coming from the Strömgren photometry of the RGB of NGC 1851, presented in Calamida et al. (2007). After a careful selection of the cluster members, Calamida et al. (2007) have shown that the RGB of NGC 1851 splits into two distinct and well-separated sequences in the Strömgren \( (m_1, u-y) \) diagram. At \( (u-y) \sim 3.0 \) the difference in \( m_1 \) between the two sequences is about 0.1 mag. From the empirical relationships between \( m_1, (u-y), \) and \([\text{Fe/H}]\) presented in Calamida et al. (2007), one derives that a \([\text{Fe/H}]\) difference of more than \( \sim 0.6 \) dex is necessary to produce this split. The observed narrow MS and RGB in the ACS CMD and the results by Yong & Grundahl (2008) do not support this interpretation. An alternative explanation is the presence of two separate populations with different CN ratios given that, as discussed by, e.g., Bell & Gustafsson (1978) and Dickens et al. (1979), variations in CN abundances affect strongly the \( m_1 \) index.

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