The helium spread in the globular cluster 47 Tuc

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ABSTRACT
Spectroscopy has shown the presence of the CN band dicothomy and the Na-O anti-correlations for 50–70% of the investigated samples in the cluster 47 Tuc, otherwise considered a "normal" prototype of high metallicity clusters from the photometric analysis. These anomalies are also found the Main Sequence stars, suggesting that a consistent second generation is present in 47 Tuc. Very recently, the re-analysis of a large number of archival HST data of the cluster core has been able to put into evidence the presence of structures in the Sub Giant Branch: it has a brighter component with a spread in magnitude by ~0.06 mag and a second one, made of about 10% of stars, a little fainter (by ~0.05 mag). These data also show that the Main Sequence of the cluster has an intrinsic spread in color which, if interpreted as due to a small spread in helium abundance, suggests ΔY~0.027.

In this work we examine in detail whether the Horizontal Branch morphology and the Sub Giant structure provide further independent indications that a real –although very small–helium spread is present in the cluster. We re–analyze the HST archival data for the Horizontal Branch of 47 Tuc, obtaining a sample of ~500 stars with very small photometric errors, and build population synthesis based on new models to show that its particular morphology can be better explained by taking into account a spread in helium abundance of 2% in mass. The same variation in helium is able to explain the spread in luminosity of the Sub Giant Branch, while a small part of the second generation is characterized by a small C+N+O increase and provides an explanation for the fainter Sub Giant Branch. We conclude that three photometric features concur to form the paradigm that a small but real helium spread is present in a cluster that has no spectacular evidence for multiple populations like those shown by other massive clusters. This work thus shows that multiple populations in Globular Clusters are more and more confirmed to be ubiquitous.

Key words: stars: globular clusters; stars:evolution; stars: horizontal branch; stars: subgiant.

1 INTRODUCTION

NGC 104, better known as 47 Tuc, is the second largest and brightest globular cluster (GC) in the sky and for this reason it is one of the most studied old associations of the Milky Way. Although not so extreme as the other two GCs of similar metallicity, NGC6441 and NGC6388, this cluster shows some chemical anomalies, that deserve investigation. On the spectroscopic side, studies in the last 30 years show CN variations along the Red Giant Branch (RGB) of 47 Tuc down to the Turn Off (TO) and along the Main Sequence (MS). In particular Briley (1997) verified the existence of a bimodal distribution of CN band strengths. An examination of the location of Horizontal Branch (HB) stars on the color-magnitude diagram reveals that the CN-strong HB stars are on average, about 0.05 mag more luminous in V, and tend to be bluer, than their CN-weak counterparts. Briley (1997) found also a radial gradient of the relative fraction of stars with strong and weak CN bands. In the inner part of the cluster there is a higher fraction of stars with strong CN absorption. The existence of this gradient had been first noted by Norris & Freeman (1979) and further documented by Paltaglos (1990). Cannon et al. (1998) showed that the bimodal distribution of CN band strengths is present also on the upper MS. Recently, with the availability of 8 to 10 m class telescopes and the capability of multiobject spectroscopy, Harbeck et al. (2003) have shown that the
bimodality in CN strength still exists 2.5 mag below the TO.

These results indicate that the abundance spread in 47 Tuc is not due to an evolutionary effect, rather to the presence of an original stellar population (first generation, FG) and of a second generation (SG). Stars in the SG formed from material processed through the hot CNO cycle in the progenitors, belonging to the FG, but not enriched in the heavy elements expected in supernova ejecta, according to todays’ new paradigm for the formation of galactic GCs (Gratton et al. 2001; Carretta et al. 2009b; D’Ercole et al. 2008).

It is not definitely settled what kind of stars produced this material. The two most popular candidates are the intermediate mass stars during the Asymptotic Giant Branch (AGB) phase (Ventura et al. 2001) or fast rotating massive stars (Decressin et al. 2007), and is not clear yet if the material came entirely from the wind ejected from these objects or it is a mixture of processed gas and pristine matter of the initial star forming cloud.

The analysis of the Na-O anticorrelation among the stars of 47 Tuc performed by Carretta et al. (2009) gives results compatible with this interpretation: about 70 % of stars belong to what they call “intermediate” population, i.e. they are oxygen depleted and sodium enhanced.

Although other clusters also show evident photometric indications that multiple population are present, 47 Tuc did not show any clear photometric sign, until Anderson et al. (2008) which exploiting the large number of archival HST data have found, in the cluster core, a splitted sub giant branch (SGB) with at least two distinct components: a brighter one with a small and real spread in magnitude (∼0.06 mag) and a second one containing about 10% of star a little (∼0.05mag) fainter.

Recently Bergbusch & Stetson (2009) have published a color magnitude diagram, based on ground-based data, covering all evolutionary sequences of 47 Tuc. They also looked at the possible presence of multiple sequences, in particular for star brighter than the turn off. They could not reach any conclusive evidence of a multiple SGB, which is not surprising, because of the lower quality of the ground-based data, and, most importantly, because of the fact that, because of crowding, they could concentrate only on the outer part of cluster. Small number statistics, and the possible presence of a radial gradient in the multiple population distribution (as in ω Cen, Bellini et al. 2009) may be at the basis of their failure to find the features so clearly identified in the cluster core by Anderson et al. (2009).

A splitting of the SGB was also observed in NGC 1851 (Milone et al. 2008). Cassisi et al. (2008) explained this result with a difference in the overall C+N+O content of the two group of stars, and negligible spread in helium, whereas Ventura et al. (2008) in the framework of a self-enrichment process by which a second generation of stars formed from the gas ejected by massive AGBs, assumed that stars in the faint SGB were not only enriched in the CNO by a factor ∼3, but also slightly enriched in helium, in agreement with the yields of the intermediate masses. If we make the same hypothesis for 47 Tuc, a contradiction emerges because only the 10% of stars belong to faint SGB, not enough to explain the percentage of SG inferred by the spectroscopic data.

To explain the formation and constitution of 47 Tuc stars, in this work we build a homogeneous framework to reconcile the spectroscopic and photometric results by Anderson et al. (2009). For this aim, we will use both HB and SGB data (Section 3), interpreted on the basis of the models described in Section 2. A discussion of the results and conclusions close the paper.

2 EVOLUTIONARY MODELS AND POPULATION SYNTHESIS

We computed stellar models with the code ATON2.0, described in Ventura et al. (1998) and updated in Ventura et al. (2003). We adopted a metallicity Z = 0.006 and an α-enhanced mixture with [α/Fe]=0.4. As standard helium content we have adopted Y=0.25, but different initial Y (=0.28, 0.32, 0.40) were investigated. Models cover the mass range ∼0.40M⊙-1.2M⊙ from the pre main sequence until the He ignition at the RGB tip.

In the case of HB stellar models, the He-core mass and envelope He-abundance values were taken from the RGB progenitors for an age of ∼12Gyr.

In order to reproduce the faint SGB we followed the
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Figure 2. Comparison between observed (filled circle) and two different synthetic HB simulations (open squares-magenta in the electronic version of the paper) Upper panels: synthetic population is built under the hypothesis that a unique generation of stars with $Y=0.25$ is present. Even using a large value of $\sigma$ it is not possible to reproduce at the same time the spread in color and magnitude. We also show the HB evolutionary tracks of stars with masses $M=0.63, 0.66, 0.70$ and $0.80$ solar masses and the ZAHBs for normal populations with respectively $Y=0.25$ (low luminosity) and $Y=0.28$ (high luminosity) shifted as described in the caption of Fig.1. Lower panel: The synthetic population is built under the hypothesis that $70\%$ of stars has $Y$ randomly chosen between $Y=0.25$ and $Y=Y_{\text{UP}}=0.27$ (see text). The dashed histograms refer to synthetic populations, while the solid ones are those relative to observations.

line of interpretation adopted for the double SGB in NGC1851 (Ventura et al. 2009), and considered C+N+O enriched models. Concerning the choice of the element mixture, we make the hypothesis that this population is born from matter mixed with hot-CNO processed ejecta of massive AGBs and look at the abundances computed by Ventura & D'Antona (2009) (Table 2). Extending their results for the metallicity of 47 Tuc we see that the 5M$_{\odot}$ AGB evolution provides a C+N+O increase by a factor $\sim 1.4$, with C depleted by $-0.55$ dex, N enhanced by 1.44 dex and O depleted by 0.31 dex (i.e $[O/Fe]=0.09$ dex for our $\alpha$-enhanced mixture). We computed evolutionary tracks and isochrones for this composition (mixture CNO↑↑) and also for a compositions obtained by diluting these abundances with 50% of matter having the starting standard composition (we call this mixture CNO↑). The idea below
3 THE RESULTS

The idea we want to test in this work is that the two separated SGBs found by [Anderson et al. 2009] are due to the presence of two stellar populations with different initial mixtures of elements heavier than helium, mainly C+N+O. In particular, we explore the possibility that CN strong stars all belong to the SG, and were formed from gas showing the signature of CNO processing, and a helium enrichment, but that only a small percentage of SG stars are increased in the overall CNO content.

Following the suggestion of [D’Antona & Caloi 2008] we decide first to investigate this hypothesis using the morphology of the HB of 47 Tuc, where a population with a larger helium abundance should emerge, and then test the results using the data of the SGB by [Anderson et al. 2009]. First we review previous literature concerning the HB of 47 Tuc and the features of metal rich HBs.

3.1 Previous analysis of the HB data for 47 Tuc and of the HB morphology of metal rich clusters

Already [Dorman, Vanderberg & Laskarides, 1989] attempted to derive information on the evolution in the HB of 47Tuc, by comparing the (B,V) data by [Hesser et al. 1977] (~50 HB stars) with evolutionary models computed for different chemistry. This work shows that the appropriate helium content for the gas out of which these stars formed had ~24% helium by mass, a value consistent with the (previous) estimates of primordial helium abundance. No population synthesis was attempted, and in any case the sample was too small to draw any inference on possible helium spread among the stars in this HB but they argued for the first time that the bluest HB stars should be somewhat brighter than the ZAHB, due to evolution. Population synthesis for metal rich compositions was extensively used by [Catelan & de Freitas Pacheco 1996] who show that some clump simulations have a wedge-shaped structure, due to the population of the long loops of the evolutionary tracks they adopt, but no quantitative comparison with 47Tuc data is available. Other works have studied the tilted morphology of several metal rich clusters attributing it as a natural outcome of standard evolutionary theories (for example see the case of NGC 6362 in [Brocato et al. 1994], or the consequence of the presence of a differential reddening [Raimondo et al. 2002]. Anyway, 47Tuc does not fall among the clusters having a “tilted” clump, as shown, for example, in the Fig.9 of the last mentioned paper. In fact, [Carney et al. 1993] suggested that the 47Tuc HB is “wedge-shaped”, based on the data by Hesser et al. 1977.

3.2 A new analysis of the Horizontal Branch

In the top panel of Fig.1 we report a zoom of CMD of 47 Tuc at HB level, including ~500 stars, and based on images of 5sec in F606W and F814W from ACS (GO-10775, PI Sarajedini). The photometric reduction of the ACS/WFC data was carried out using the software presented and described in detail in [Anderson et al. 2008]. It consists in a package which allowed us to analyze all the exposures simultaneously to generate a single star list. Stars are measured independently in each image by using a spatially varying 9×10 array of empirical “library PSFs” from [Anderson & King 2006], plus a spatially constant perturbation for each exposure, to account for variations in the telescope focus. This routine was designed to work well in both crowded and uncrowded fields, and it is able to detect almost every star that can be detected by eye. Calibration of ACS photometry into the Vega-mag system was performed following recipes in [Bedin et al. 2006] and using the zero points given in [Sirianni et al. 2005]. Unfortunately, the hybrid PSF model above is not able to account for all of the effects of telescope breathing, which can introduce a small spatial dependence of the shape of the PSF, which is not compensated for in our PSF model and can cause small systematic photometric errors that depend on position on the detector. The typical variation is small (about 1% in the fraction of light in the core). To account for these variations, we used the method adopted in [Milone et al. 2008].

Fig.1 shows the HR diagram. As the photometric errors are

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Figure 3. The same as Fig. 2 but in this case the SGB region is shown. Crosses (cyan color in the electronic version) are used to mark those 10% of simulated stars obtained from CNO↑ models using the same N(Y) and ∆M used for the rest of population (see text). 13 Gyr isochrones calculated from normal and enhanced C+N+O models with primordial helium abundance (solid lines) and Y=0.28 (dashed lines) are shown. Down from bright luminosity we have respectively CNO normal, CNO↑, CNO↑↑ isochrones. Histograms show the comparison between observed and simulated distributions of magnitude of stars confined in two box drawn in the CMD in order to isolate the two components of SGB. It is evident from the lower panels that the case of a mixed population with a 70% of total stars belonging to a SG, a part of which (∼10%) have also a little increase of C+N+O elements, fit better the observations. On the right panels the comparison is shown at the level of MS for the same set of data, in order to explain the method used to choice the photometrical errors included in our simulations (∼0.008 mag, see text).

very small (∼ 0.01 mag on each filter), we can see that the “wedge-shaped” morphology is in fact reduced to the presence of a small dent in luminosity, at color mF606W-mF814W ∼0.675 mag, between the blue (and brighter) side and the red (and dimmer) side. Figure 8 in Briley (1997) shows that the brighter HB stars (including the bluer ones) are preferentially CN strong, while the dimmer ones are all CN weak. This is the strongest hint that we are looking at a population effect and not at an evolutionary effect as first suggested by Dorman, Vanderberg & Laskarides (1989).

The theoretical zero age HB (ZAHB) for two different values of Y (0.25 and 0.28) are shown, reported on the observational plane using a reddening E(606-814)=0.038 mag, corresponding to the E(B-V)=0.04 mag given in literature according to the relationships by Bedin et al. (2005). The apparent distance modulus (m-M)F606W =13.09 mag was chosen in order to fit a ZAHB of pristine Y=0.25 to the lower envelope of the observed HB.

We see from Fig.1 that the ZAHB with Y=0.25 provides a good fit of the reddest stars observed, whereas the bluer part is not fit and appears to require a larger helium. This supports our idea that a SG of stars is present in 47 Tuc, with an higher abundance of helium. In Fig. 1 we also show the ZAHBs with CNO↑ (dashed line) which are little fainter than the ZAHBs corresponding to the normal CNO abundance, in agreement with the fact that the total metallicity of the new mixture is a little higher.

To compute a synthetic population of the HB of 47 Tuc we adjusted the mean mass loss on the RGB and its dispersion in order to reproduce the feature we attribute to the FG, in particular the dent described before. We assume that 30% of the stars (the FG) formed with the primordial helium abundance Y=0.25. We find that the best choice is ∆M⊙=0.27M⊙ and σ=0.010M⊙ for an age of 12 Gyr. The
same distribution of mass loss is used for the remaining 70% of stars, a population with Y randomly distributed between Y=0.25 and Y=YUP, and YUP is chosen to reproduce both the color and magnitude distributions of the observed HB. The choice of 30% of stars for the FG is consistent with both the CN strength sample (e.g. Briley 1997) and the [Na/O] anticorrelation sample (Carretta et al. 2009).

Fig. 2 shows that the choice YUP=0.27, coupled with the same distribution of mass loss assumed for the FG stars, allows to nicely reproduce both the color and magnitude distributions observed on the HB. On the other hand, any attempt to model the observed HB with a single population proved much less satisfactory, independently of the choices concerning mass and the distance modulus. We show as an example (upper panel of Fig. 2) the synthetic population obtained when a larger dispersion in the mass loss (σ=0.017 Ms⊙): an acceptable fit of the color dispersion is accompanied by a poorer match of the magnitude spread. Tracks having loops more extended towards the blue, for a given chemical composition, would reduce the value of mass dispersion, but leave the problem unchanged. Of course such a detail of behavior would remain hidden if the observations were of lower quality. In addition, the spectroscopic confirmation that the bluer and brighter stars are CN strong (and thus belonging to the SG, and possibly helium rich) is fundamental to give weight to this interpretation.

3.3 Sub Giant Branch

In Fig. 3 we show the SGB and a small portion of the MS of the inner region of 47 Tuc observed with WFC at HST’s Advanced Camera for Surveys. Two archive data set used here are: 1) GO-9028 for F475W photometrical band (20×60″) and 2) GO-10775 for F606W(4×50 s) and F814W (5×50 s). The reduction strategy is described in Anderson et al. (2009). In the figure also 13 Gyr isochrones calculated from normal and enhanced C+N+O models with primordial helium abundance (solid lines) and Y=0.28 (dashed lines) are shown. Down from bright luminosity we have respectively CNO normal, CNO↑ and models without the dilution described in previous section (CNO↑↑). It is important to note that for a fixed age and C+N+O content, the luminosity of SGB decreases by ∼ 0.02 mag by increasing the initial helium abundance by ΔY=0.02. We attribute the spread of the SGB of 47 Tuc found by Anderson et al. (2009) to this effect.

We adopt the same N(Y) distribution inferred to reproduce the HB, to simulate the TO and SGB and in Fig. 4 (lower panels) we show the results. In our simulations we use as photometric errors those which reproduce the width of the main sequence obtained from the same set of data as shown in the right panels in Fig. 3 since, as shown in Anderson et al. (2009) from the analysis of a less crowded region 6′ from the center of 47 Tuc, the intrinsic breadth of the MS is much more narrow (Δ(mF814W−mF606W )∼0.010 mag).

In this way we can reproduce the spread of the bright SGB and show that a simple population cannot do the same good job. This is shown in the upper panels of Fig. 4 where a single abundance of Y is considered with the right choice of the photometrical errors to reproduce the width of MS.

Finally to complete the analysis and to explain also the faint component of SGB we make the assumption that 10% of the total population belongs to a SG and has an higher CNO abundance (CNO↑↑ crosses in Fig. 4). This component is not recognisable in the HB, since ZAHBs calculated for a normal mixture and CNO↑ are substantially the same (Fig. 1).

4 DISCUSSIONS AND CONCLUSIONS

Our simulations show that the morphology of the HB of 47 Tuc needs a non negligible spread in the helium abundance (ΔY=0.02) to be explained, as originally suggested by Briley (1997). This spread is consistent with the value suggested by Anderson et al. (2009) from their analysis of the width of the MS (ΔY=0.027 especially if one take into account that the last one is obtained in the hypothesis that all the MS spread is due to helium, while there can be other color effects as suggested by the authors in their paper. The most interesting result is that the same variation in helium can also explain the spread of the bright SGB while the faint SGB is made of stars with higher C+N+O.

We interpret these results as the confirmation that SG in 47 Tuc consist of about 70 % of stars, as suggested by spectroscopic studies. Summarizing 47 Tuc is made up of three different sub-populations:

(i) FG: it consists in 30% of the cluster stars that we have recognized as first generation stars. In the CMD they are located on the red part of the HB and form the extreme upper part of the bright SGB.

(ii) SGI: formed by the 60% of stars belonging to a second generation characterized by the same C+N+O of FG but having a dispersion of Y between the primordial value (Y=0.25) e YUP=0.27. This population evolves in the bright part of the HB, including the bluer stars of the “step” and is responsible for the spread of the bright SGB. If the polluting matter is identified with the CNO processed gas ejected by AGB stars (Ventura et al. 2001) this population formed from material ejected from AGB progenitors so massive (>5 Ms⊙) that the chemistry of the ejecta is scarcely affected by third dredge up.

(iii) SGII: it is made up by 10% of stars wich are C+N+O enhanced, and emerge as faint SGB in the CMD but are not recognizable in the HB. We interpret this population as made up of stars born from material C+N+O enhanced by a factor 1.4 and diluted by 50 % with pristine material (mixture CNO↑). The presence of the faint SGB gives a lower limit to the AGB mass which have contributed to the formation of SG giving an indication on how long the phase of formation of SG last. Following our interpretation this time is ∼ 10⁸ yr after the formation of FG. Obviously this result depends on the dilution model used and on the models from which was calculated chemical yields. However the
spread we can see among the luminosities of the few stars belonging to the dimmer SGB (see Fig. 3) may also indicate an additional helium or C+N+O spread among the stars of this small population.

Concluding, we remember that, as shown in the hydrodynamic plus N–body simulations of the SG formation in globular clusters by D’Ercole et al. (2008) a larger concentration of these SG stars can be expected, in some cases at the center of the cluster. This result is compatible with our interpretation since Briley (1997) has shown that in the inner part of the cluster there is a higher fraction of stars with strong CN absorption (which we interpret as SG stars) than in the outer parts.

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