A population of binaries in the Asymptotic Giant Branch of 47 Tucanae?¹

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ABSTRACT

We have used a set of archived Hubble Space Telescope/ACS images to probe the evolved populations of the globular cluster 47 Tucanae. We find an excess of Asymptotic Giant Branch (AGB) stars in the cluster core. We interpret this feature as the signature of an extra-population likely made by the progeny of massive stars originated by the evolution of binary systems. Indeed the comparison with theoretical tracks suggests that the AGB population of 47 Tuc can be significantly contaminated by more massive stars currently experiencing the first ascending Red Giant Branch.

Subject headings: Globular clusters: individual (47Tuc); stars: evolution – binaries: close - blue stragglers

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1. INTRODUCTION

In recent years it became clear that stellar evolution and stellar dynamics cannot be studied independently: in fact, physical interactions between single stars and binaries, as well as the formation and evolution of binary systems can significantly alter the properties of the overall stellar populations. This is particularly true for dense stellar systems such as the Globular Clusters (GCs), where dynamical encounters between stars (especially those involving binaries) are most probable. In particular, such a dynamical activity can generate exotic stellar populations, like Blue Straggler Stars (BSSs), Millisecond Pulsars (MSPs), low-mass X-ray binaries (LMXBs), Cataclysmic Variables (CVs), etc. (see Bailyn & Pinsonneault 1995), that cannot be explained by the standard single-mass stellar evolution theory, and are thought to be originated by the evolution of binary systems. For instance, BSSs consist (or will consist, once the mass transfer or the merge event is completed) in a progeny of mass-enhanced single stars (possibly with a He white dwarf companion), with masses typically ranging between 1 and 2 times the cluster Turn Off (TO) star mass. Then, these objects will evolve along the characteristic paths of a rejuvenated mass-enhanced population, and are therefore expected to "contaminate" the post-main sequence (MS) evolutive sequences of normal cluster stars. However, when considering all possible by-products of the binary evolution, a variety of different exotic objects could be originated (depending on the mass, the evolutionary state of the donor star, the mass ratio and the physical parameters of the binary system), and their identifications in the Color Magnitude Diagram (CMD) may be not obvious. The detection of surface chemical anomalies also seems to be a quite promising tool for identifying by-products of binary evolution, but high-resolution spectroscopic studies of this kind have just started to become feasible (see Ferraro et al. 2006, and references therein).

Indeed, 47 Tucanae has been found to harbor a large population of exotic objects in its core (see Grindlay et al. 2001; Ferraro et al. 2001; Knigge et al. 2002), confirming that stars have experienced (and are experiencing) dynamical interactions involving single stars or primordial binaries, leading to mass transfer phenomena and mergers (see Ferraro et al. 2004, hereafter F04; Mapelli et al. 2004; Ferraro et al. 2006). In particular, the large population of BSSs found in the cluster (Paresce et al. 1991; Guhathakurta et al. 1992; Ferraro et al. 2001, F04) represents the major reservoir of binary by-products currently experiencing the MS stage. Their bimodal radial distribution, discovered by F04, suggests that most of the BSSs strongly segregated in the cluster center have a collisional origin, while those lying in its periphery are mainly originated by the evolution of primordial binaries (see Mapelli et al. 2004, 2006). Also the detection of chemical anomalies via high-resolution spectroscopy has recently provided a number of interesting results in the case of 47 Tuc: (i) Ferraro et al. (2006) have detected a population of carbon-oxygen depleted BSSs and interpreted this feature as the signature of the mass-transfer activity during the BSS formation processes;
Wylie et al. (2006) have detected peculiar $s$ and $r$-process elements enhancement on the surface of 7 Asymptotic Giant Branch (AGB) stars in the external region ($r > 10'$) of the cluster. They proposed that at least part of these AGB stars might be formed through mass transfer along the evolutionary path of a $1.4 + 0.5M_\odot$ binary system.

In this Letter, we further investigate the issue of identifying possible by-products of binary evolution in 47 Tuc, by reporting on the detection of anomalies (both in terms of star counts and radial distribution) along the canonical evolutionary sequences in the cluster CMD. In particular, we have found a significant enhancement of AGB stars in the core and we discuss the possibility that this is due to a contamination by a progeny of massive stars originated by the evolution of binary systems, and now sunk to the cluster center by mass segregation processes.

### 2. Observations and data reduction

In this paper we use high-resolution photometric data obtained with the Advanced Camera for Survey (ACS) on board the Hubble Space Telescope (GO-9453). Observations were performed with the *ACS-Wide Field Channel*, which employs a mosaic of two 4096 × 2048 pixels CCD, providing a plate-scale of 0.05''/pixel and a total field of view (FoV) of 3.4' × 3.4'. In these images the core of the cluster is fully contained in chip#1 of the ACS CCD mosaic. Since we were interested in deriving an accurate photometry of the cluster giant population, only images with very short exposure times ($t_{\text{exp}} = 0.5$ s) obtained through the filters F606W and F814W were retrieved from the ESO/ST-ECF Science Archive. All the images were properly corrected for geometric distortions and effective flux (over the pixel area) following the prescriptions of Sirianni et al. (2005). The photometric analysis was performed independently in the two drizzled images by using the aperture photometry code SExtractor (*Source-Extractor*; Bertin & Arnouts 1996), and adopting a fixed aperture radius of 2 pixels (0.1''). The two magnitude lists were cross-correlated in order to obtain a combined catalog. A sample of bright isolated stars has been used to transform the instrumental magnitudes to a fixed aperture of 0.5'', and the extrapolation to infinite has been performed by using the values listed in Table 5 of Sirianni et al. (2005). The magnitudes were finally transformed into the VEGAMAG photometric system by adopting the synthetic Zero Points from Table 10 of Sirianni et al. (2005).

An additional data-set of public short-time exposure ($t_{\text{exp}} = 20$ s) images in $V$ and $I$ bands, obtained with the *Wide Field Imager* (WFI) mounted at the 2.2m telescope at ESO, were also retrieved from the ESO/ST-ECF Archive. The raw WFI images were corrected for
bias and flat field, and the over-scan region was trimmed using standard IRAF\textsuperscript{2} tools. The PSF fitting procedure was performed independently on each $V$ and $I$ image, using DoPhot (Schechter, Mateo & Saha 1993).

Each WFI catalog was referred to the absolute astrometric system by adopting the procedure described in F04. The astrometric Guide Star Catalog GSCII was used to identify astrometric standards in the WFI FoV. More than thousand stars were used to find an astrometric solution for each of the eight WFI chips, with an accuracy of the order of $\sim 0.2''$ in both right ascension and declination. Then, we used $\sim 1000$ stars in common between WFI and ACS catalogs as \textit{secondary astrometric standards} to transform the ACS catalog into the WFI astrometric system. Since the two data sets have the $I$ passband in common (F814W filter corresponds to the $I$ band), we used the stars in common to photometrically homogenize the two samples.

In order to avoid spurious effects due to incompleteness of the ground based observations in the most crowded region of the cluster, we restricted the WFI dataset to the outer region ($r > 224''$; hereafter the \textit{WFI sample}). In the inner region only stars observed with ACS have been considered. However, since the ACS FoV was not centered on the cluster center, the most external region ($r \sim 170 - 224''$) was only marginally sampled by the high-resolution observations; for this reason we decided to exclude it from the analysis. Hence in the following we consider in the \textit{ACS sample} only stars with $r < 170''$ from the cluster center.

### 3. RESULTS

In Figure 1 we show the brightest portion of the CMD obtained from the analysis of the ACS sample. Thanks to the high quality of the data, all the sequences are well populated and clearly separable one from the others. In particular the AGB-clump is clearly visible at $I \sim 12$. This feature, which flags the beginning of the AGB evolutionary phase, has been observed in other clusters (Ferraro et al. 1999) and it is well predicted by theoretical models (e.g., Castellani, Chieffi & Pulone 1991). In fact the beginning of the AGB phase is characterized by a slowing down of the stellar evolutionary rate, just after the very fast evolution at the end of the Horizontal Branch (HB) phase (see Figure 1 by Castellani et al. 1991). This is nicely confirmed by the star distribution in the CMD shown in Figure 1, where only a few stars can be found between the HB-clump at $I \sim 13.1$ and the AGB-clump. We

\textsuperscript{2}IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
therefore selected samples of stars in different evolutionary stages as marked in Figure 1 by different symbols: Red Giant Branch (RGB; crosses), HB\(^3\) (open circles), and AGB (open squares), respectively.

In panel (a) of Figure 2 we show the cumulative radial distribution of the selected populations in the innermost region of the cluster (\(r < 100''\)). Surprisingly AGB stars turn out to be significantly more centrally segregated than HB and RGB stars. In order to check the statistical significance of this result we applied a Kolmogorov-Smirnov test, that yields a \(\sim 99\%\) probability that the radial distribution of AGB stars is genuinely different from that of both HB and RGB stars. An analogous test has been performed for the WFI sample, and no significant difference in the radial distribution of the three populations has been detected in the outer regions of the cluster.

In order to further investigate this unexpected result, we followed the approach proposed by F04 for the study of BSSs in this cluster: we divided the surveyed area (ACS and the WFI FoVs) into a set of 9 concentric annuli. Thus, HB and AGB stars has been counted in each annulus (see Table 1) and the population ratio \(N_{\text{AGB}}/N_{\text{HB}}\) have been computed. Accordingly with the definition by Ferraro et al. (1993), we also computed the double normalized specific frequency \(R_{\text{AGB}}\)^4:

\[
R_{\text{AGB}} = \frac{(N_{\text{AGB}}/N^\text{tot}_{\text{AGB}})}{(L^\text{sample}/L^\text{sample}_\text{tot})}
\]

where the fraction of AGB stars observed in each annulus \((N_{\text{AGB}}/N^\text{tot}_{\text{AGB}})\) is normalized to the fraction of luminosity sampled by each annulus \((L^\text{sample}/L^\text{sample}_\text{tot})\), as computed from the surface brightness profile. Figure 3 shows the radial distribution of the calculated ratios.

As can be seen, AGB stars turn out to be significantly overabundant in the innermost annulus \((r < 20''\), roughly corresponding to 47 Tuc core radius): in fact, while in the outer regions \((r > 20'')\) the \(N_{\text{AGB}}/N_{\text{HB}}\)^5 ratio is roughly constant with a mean value \((0.13 \pm 0.03)\) which is in full agreement with what expected on the basis of the evolutive time scales (see Renzini & Fusi Pecci 1988, for a review), the same ratio in the cluster core is \(\sim 0.30 \pm 0.06\), suggesting that AGB stars are twice more abundant there than in the external regions. Also

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\(^3\)We considered “fiducial HB” only stars belonging to the HB-clump, while those lying in the HB extension toward brighter magnitudes have been considered as a different population and labeled as bright-HB (hereafter bHB) stars (they are marked with triangles in Figure 1), since they can be sensibly contaminated by a progeny of binaries currently experiencing the Helium-burning phase (see the discussion in Section 4).

\(^4\)Note that this ratio is expected to be equal to unity for any post-MS evolutionary stage, since the observed number of stars is expected to scale linearly with the sampled luminosity following equation 1 of Renzini & Fusi Pecci (1988).

\(^5\)Note that the same result has been obtained by using the RGB as reference population.
the $R_{\text{AGB}}$ ratio, which turns out to be $\sim 1.5$ in the central bin, suggests the presence of $\sim 10$ contaminating stars (mimicking low-mass AGB).

4. DISCUSSION

We have found evidences of a significant overabundance of AGB stars in the core of 47 Tuc. This finding is in agreement with the preliminary detection of an "enhancement in the frequency of stars about 1 mag brighter than the HB" already noted by Bailyn (1994). As shown in Figure 3 this enhancement is present only in the cluster core. Such a strong radial segregation is not expected to result from dynamical processes (mass segregation) acting on genuine AGB stars\textsuperscript{6}. Hence the combination of these observational facts (overabundance and central segregation) suggests the presence along the AGB of 47 Tuc of an extra-population of massive (not-genuine AGB) stars, possibly related to the evolution of binary systems, i.e., generated either by mass transfer (or coalescence) between binary companions, or by mergers of single/binary stars due to collisions. Indeed previous multiband observations (Camilo et al. 2000; Grindlay et al. 2001; Ferraro et al. 2001; Knigge et al. 2002) have demonstrated that the core of 47 Tuc hosts a large population of centrally segregated exotic objects (BSSs, LMXBs, CVs, MSPs, etc.), that can be originated by a variety of interacting binaries. In particular, the large population of BSSs, having masses between 1 and $1.6\, M_\odot$, are the natural progenitors of any anomalous high-mass evolved object that can be currently found in the cluster. In this respect, Bailyn (1994) first suggested that (at least part of) the excess AGB stars might be evolved BSSs currently experiencing the HB evolutionary stage. However an appropriate comparison with theoretical tracks (see Figure 4) clearly demonstrates that, in a metal rich cluster as 47 Tuc, the Zero Age Horizontal Branch (ZAHB) magnitude level of stars in the mass range $1.1 - 1.5\, M_\odot$ is significantly fainter than the observed AGB-clump. Instead, the CMD region populated by the lower mass AGB is fully consistent with the RGB sequence of such massive stars: hence, the observed AGB population can be significantly contaminated by high-mass binary by-products currently ascending for the first time the RGB. Also the evolutionary time-scales suggest that this could be the case: in fact, a $1.3\, M_\odot$ star spends $\sim 2.4 \times 10^7$ yr evolving along the RGB in the magnitude portion covered by the low-mass AGB extension ($12.2 < I < 10.2$). This time-scale is more than twice the AGB evolutionary time ($\sim 10^7$ yr) of a genuine $0.8\, M_\odot$ star.

From the inspection of Figure 4 we also note that the ZAHB level of a $1.1 - 1.5\, M_\odot$

\textsuperscript{6}AGB stars are expected to be even less massive than the current TO stars because they have experienced significant mass-loss during previous evolutionary stages.
star is fully consistent with the brightest extension of the observed HB-clump (i.e., stars labeled as bHB and plotted as empty triangles in Figure 1). Hence (at least part) of the bHB stars observed between the HB and the AGB clumps could be the progeny of the binary systems currently experiencing the He-burning phase. Interesting enough the radial distribution of these stars turns out to be significantly different (at more than 3σ level) from that of genuine HB (or RGB) stars, and similar to that of AGB stars (panel b of Figure 2). To further investigate the possibility that the canonical sequences are contaminated by binary populations, we studied the radial distribution of stars at the base of the RGB. In particular, we found that ~30 faint (13.7 < I < 14.7) blue (V − I ≲ 0.7) RGB stars (fRGB) show a radial distribution which is significantly different (at 3σ level) from that of the other RGB within the same magnitude limits, and nicely similar to that of AGB and bHB stars (panel b of Figure 2). Moreover, the radial distribution of AGB, bHB and fRGB stars in the innermost region of 47 Tuc nicely agrees with that of BSSs (Ferraro et al. 2001, 2004). This seems to indicate a common evolutionary scenario for these four populations, suggesting that all these objects have been segregated in the cluster core by dynamical processes. As demonstrated by appropriate dynamical simulations computed to model the BSS peculiar radial distribution (Mapelli et al. 2004, 2006), dynamical friction processes can generate the observed central peak of the BSS distribution. Accordingly to these findings, the dynamical friction time-scale here specifically computed for 47 Tuc (by using an appropriate model of the cluster) suggests that all the objects with masses of 1.2 − 1.5M⊙ generated within ~10rc (corresponding to ~4′) from the cluster center are expected to sink into the cluster core in a time comparable to the cluster age (t = 12Gyr); hence they could generate the segregated populations detected in the core.

The evidences reported in this Letter show the presence of an extra population contaminating the genuine AGB stars in 47 Tuc: these objects are significantly more centrally segregated than RGB and HB stars suggesting they are significantly more massive than the normal stars in the cluster. Hence, they possibly are the progeny of binary system evolution. Future high-resolution spectroscopic observations aimed to search for chemical anomalies (as those observed in 7 AGB stars in the outer region of the cluster and in a sub-sample of BSS by Wylie et al. 2006 and Ferraro et al. 2006, respectively), would identify the binary progeny and possibly confirm the scenario presented here.

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Note that ratio of the presumed contaminating population in the upper RGB (mimicking the AGB) and in the fRGB is ~3, in reasonable agreement with the expected evolutionary time-scale ratio (~4).
dell’Università e della Ricerca.

REFERENCES

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Table 1. Number of AGB and HB stars in concentric annuli at different distances from the cluster center.

<table>
<thead>
<tr>
<th>$r$ [arcsec]</th>
<th>$N_{AGB}$</th>
<th>$N_{HB}$</th>
</tr>
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<tbody>
<tr>
<td>0–21</td>
<td>30</td>
<td>101</td>
</tr>
<tr>
<td>21–58</td>
<td>23</td>
<td>195</td>
</tr>
<tr>
<td>58–110</td>
<td>15</td>
<td>104</td>
</tr>
<tr>
<td>110–224</td>
<td>6</td>
<td>45</td>
</tr>
<tr>
<td>224–350</td>
<td>19</td>
<td>145</td>
</tr>
<tr>
<td>350–550</td>
<td>18</td>
<td>152</td>
</tr>
<tr>
<td>550–730</td>
<td>8</td>
<td>61</td>
</tr>
<tr>
<td>730–1000</td>
<td>5</td>
<td>30</td>
</tr>
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</table>
Fig. 1.— CMD for the ACS sample. Stars marked with different symbols belong to different populations
Fig. 2.— The cumulative radial distribution of AGB stars (heavy solid line) in the innermost region of the cluster ($r < 100''$) as a function of the projected distance $r$ from the cluster center, is compared with those obtained for HB and RGB stars (panel a), and bHB, faint-blue RGB (fRGB), and BSS stars (panel b), respectively. AGB stars are significantly more centrally segregated than RGB and HB stars. The radial distribution of AGB, bHB and fRGB stars is nicely in agreement with that of BSS stars.
Fig. 3.— Relative frequency of AGB-to-HB stars (upper panel) and double-normalized specific frequency of the AGB stars (lower panel) as a function of the projected distance from the center, over the entire cluster extent. Horizontal grey regions in the lower panel show the double-normalized specific frequency of HB stars used as reference population. The dashed area marks the cluster region excluded from the analysis in order to avoid spurious effects due to incompleteness of the sample.
Fig. 4.— Theoretical tracks from Pietrinferni et al. (2006, http://www.te.astro.it/BASTI/index.php) for different masses (from 1.1 to 1.5$M_\odot$; solid lines) are overplotted to the ACS CMD of 47 Tuc. The theoretical tracks, with $\alpha$ - enhancement ([$\alpha$/Fe] = 0.4) and [Fe/H]=-0.66 (Z= 0.008), have been transformed in the ACS filters following Bedin et al. (2005). A distance modulus (m-M)$_0$ = 13.33 and reddening E(B-V)=0.04, have been adopted (Ferraro et al. 1999). The RGB phase for such massive stars turns out to occupy the same region of the CMD where ”normal” low-mass AGB stars are observed. The post-RGB evolutionary track for a 1.5$M_\odot$ star is also shown (dashed line). Note that the ZAHB level for such a massive star lies in the bright extension of the observed HB where the bHB sample has been defined. The evolutionary time needed by a 1.3$M_\odot$ star to cover the RGB portion between the two horizontal lines is also reported.