ON THE WHITE DWARF COOLING SEQUENCE OF THE GLOBULAR CLUSTER ω CENTAURI

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ABSTRACT

We present deep and precise photometry (F435W, F625W, F658N) of ω Cen collected with the Advanced Camera for Surveys (ACS) on board the Hubble Space Telescope (HST). We have identified ≈6500 white dwarf (WD) candidates, and the ratio of WD to main-sequence (MS) star counts is found to be at least a factor of 2 larger than the ratio of CO-core WD cooling to MS lifetimes. This discrepancy is not explained by the possible occurrence of a He-enhanced stellar population, since the MS lifetime changes by only 15% when changing from a canonical (Y = 0.25) to a He-enhanced composition (Y = 0.42). The presence of some He-core WDs seems able to explain the observed star counts. The fraction of He WDs required ranges from 10% to 80% depending on their mean mass, and it is at least 5 times larger than for field WDs. The comparison in the color-magnitude diagram between theory and observations also supports the presence of He WDs. Empirical evidence indicates that He WDs have been detected in stellar systems hosting a large sample of extreme horizontal branch stars, thus suggesting that a fraction of red giants might avoid the He-core flash.

Subject headings: globular clusters: general — globular clusters: individual (ω Centauri)

1. INTRODUCTION

White dwarfs (WDs) in Galactic globular clusters (GGCs) represent the intersection of several theoretical and empirical astrophysical problems (Koester 2002; Hansen & Liebert 2003; Hansen 2004). They play a crucial role in constraining the correctness of the physical assumptions adopted to construct WD evolutionary models (Prada Moroni & Straniero 2007). Cluster WDs possess several advantageous features. (1) Homogeneous sample. Cluster WDs are located at the same distance and generally have about the same reddening. Moreover, at all luminosities the colors of cluster WDs are systematically bluer than main-sequence (MS) stars. This means that to properly identify cluster WDs we can use a color-magnitude diagram (CMD) instead of a color-color diagram. Therefore, cluster WDs are not affected by the color degeneracy with MS stars that affects field WDs (Hansen & Liebert 2003). (2) Statistics. Evolutionary predictions indicate that in a GC with an age of 12 Gyr and a Salpeter-like initial mass function the number of WDs should be 3 orders of magnitude larger than the number of horizontal-branch (HB) stars (Brocato et al. 1999). This together with the high stellar concentration implies that the expected density of WDs in GCs is several orders of magnitude larger than in the Galactic field. (3) Origin. For cluster WDs we can trace back the evolutionary properties of the progenitors, since both the cluster age and the chemical composition are well known (Kalirai et al. 2007, hereafter K07).

However, cluster WDs also present a few drawbacks. (1) Crowding. They are faint objects severely affected by crowding problems (Moepler et al. 2004). (2) Cluster versus field. Current data do not allow us to establish definitively whether cluster WDs are the analogs of field WDs. The impact that the high-density environment of GCs may have on the formation and evolution of cluster WDs is still poorly known (Monelli et al. 2005, hereafter M05).

In a previous investigation based on three out of nine ACS pointings we have already addressed the properties of WDs in ω Cen (M05). In the meantime, deep photometric investigations called attention to the occurrence of a split along the MS of ω Cen (Bedin et al. 2004). Spectroscopic data have indicated that the stars distributed along the bluer MS (30% of the entire population) are more metal-rich than the typical population and probably also He-enriched (Y ∼ 0.42; Piotto et al. 2005).

2. OBSERVATIONS AND DATA REDUCTION

We use archival multiband (F435W, F625W, F658N) photometric data collected with the ACS on board the HST. The current data set includes eight out of the nine pointings located across the cluster center that have already been discussed by Castellani et al. (2007, hereafter C07; see their Fig. 1). The central pointing of the 3 × 3 mosaic was omitted due to the severe crowding of the innermost regions. For each field, the F435W- and F625W-band data consist of one shallow (8 s) and three deep (340 s each) exposures, while the F658N-band data consist of four exposures of 440 s each. The raw frames were prereduced by the standard HST pipeline. The entire set of
images was reduced simultaneously with DAOPHOT IV/ALLFRAME, and the final catalog includes more than one million stars. The photometry was kept in the Vega system (Sirianni et al. 2005).

Figure 1 (left) shows the F435W, F435W − F625W CMD for selected cluster stars. From this catalog we selected all the stars systematically bluer than MS stars and fainter than extreme HB (EHB) stars (B ≤ 20; see solid black lines in the left panel of Fig. 1). We ended up with a sample of ≈60,000 stars. The photometry of these stars was performed once again using ROMAFOT, but only for the deep exposures. Individual stars have been interactively checked in every image, and the WD candidates were measured either as isolated stars or together with neighbor stars. A significant fraction of the originally selected detections turned out to be either cosmic rays or spurious detections close to saturated stars, or detections too faint to be reliably measured on individual images. Figure 1 also shows the F435W, F435W − F625W (middle) and the F435W, F435W − F658N (right) CMDs based, this time, on the ROMAFOT photometry. Data plotted in these panels show that the candidate cluster WDs (~6500) are distributed along a well-defined star sequence fainter than EHB stars and bluer than MS stars (M05). To our knowledge this is the largest sample of cluster WD candidates ever detected. The current sample is ≈40% of the WDs identified in all GGCs combined (Hansen et al. 2004, 2007) and ≈50% of all spectroscopically confirmed field WDs (Eisenstein et al. 2006).

3. RESULTS AND FINAL REMARKS

In order to compare theory and observation we have adopted the cooling sequences for CO-core and H-rich envelopes (DA WDs) by Althaus & Benvenuto (1998), for CO-core and He-rich envelopes (DB WDs) by Benvenuto & Althaus (1997), and for He-core (He WDs) by Serenelli et al. (2002). The theoretical predictions were transformed into the observational plane by adopting the pure H and pure He WD atmosphere models computed by Koester et al. (2005). Predicted magnitudes in the Vega system were computed using the ACS bandpasses,12 while their zero points are based on the Vega spectrum (Bohlin & Gilliland 2004). Figure 2 shows the comparison, in the F435W, F435W − F625W CMD, between the candidate cluster WDs and predicted cooling sequences for DA (top; CO-core + H envelope), DB (middle; CO-core + He envelope), and He (bottom; He-core) WDs. Note that in this figure we have plotted only stars with σ(F435W − F625W) ≤ 0.3, i.e., objects above a 5σ detection threshold. Predicted cooling sequences were plotted for a true ω Cen distance modulus μ₀ = 13.70 ± 0.06 (Del Principe et al. 2006) and a reddening E(B − V) = 0.11 ± 0.02 (Calamida et al. 2005). Using the reddening law from Cardelli et al. (1989) and Rv = 3.1, we find A_F435W = 0.46, E(F435W − F625W) = 0.17, and E(F435W − F658N) = 0.18. Data plotted in this figure further

\[ \text{Available at ftp://ftp.stsci.edu/cdbs/cdbs1/comp/acss.} \]

\[ \text{Available at ftp://ftp.stsci.edu/cdbs/cdbs2/calspec.} \]
the conclusions of that investigation.

...the latter is less contaminated by spurious detections in the catalog, while the WD star counts are based on the ROMAFOT problems. The MS star counts are based on the ALLFRAME this magnitude range is minimally affected by completeness when considering fainter magnitudes. We did not apply any selection criteria to estimate the star counts, apart from the magnitude limits. We found that the observed ratios in the two different CMDs (see rows 1 and 2 in Table 1) agree quite well in the brighter magnitude bin (0.052 ± 0.002 vs. 0.050 ± 0.002) while they steadily decrease in the diagram based on the narrow F658N bandpass when moving toward fainter magnitudes (0.163 ± 0.004 vs. 0.147 ± 0.004). This effect is due to the difference in the completeness between the wide F625W and the narrow F658N band, the latter obviously being shallower. In order to constrain the dependence on the adopted MS sample, we counted MS stars once again in the box 19.025 mag ≤ B ≤ 19.275 mag. Ratios listed in Table 1 show that the difference in the brighter bin is on average ≈16%.

In order to define the typical stellar mass of MS turnoff stars we adopted two cluster isochrones for t = 12 Gyr (Fig. 2, top) with canonical primordial helium content Y = 0.25 (Spergel et al. 2007) and metal abundances (Z = 0.0004, Z = 0.0015) that bracket the observed spread in metallicity of α Cen stars (Sollima et al. 2005; Villanova et al. 2007). These isochrones were transformed into the observational plane using the atmosphere models provided by Brott & Hauschildt (2005). The above isochrones are based on evolutionary tracks computed with an updated version of the FRANEC evolutionary code (Chieffi & Straniero 1989) including microscopic element diffusion (Cariulo et al. 2004; C07). In order to estimate the lifetime spent by MS stars in crossing the specified magnitude bin we constructed two evolutionary tracks with M/M_☉ = 0.75 (Z = 0.0004) and M/M_☉ = 0.78 (Z = 0.0015). We found that the average crossing time for these two tracks is ≈950 Myr. The predicted lifetime ratios between DA/DB WD (M_{WD} = 0.5–0.9 M_☉) and MS (M_{MS} = 0.75–0.78 M_☉) stars attain, within the uncertainties, similar values (see rows 3–6 in Table 1). The errors in the lifetime ratios include an uncertainty of ≈10% in the adopted input physics (C07). The ratios for He WDs are, as expected, larger, and in the brighter

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**TABLE 1**

| F435W | Ratio 1  | Ratio 2  | F435W | Ratio 1  | Ratio 2  | F435W | Ratio 1  | Ratio 2  |
|-------|---------|---------|-------|---------|---------|-------|---------|---------|
|       | 24.0 mag|         | 24.5 mag|         | 25.0 mag|         |
| N_{WD}/N_{MS} | 0.052(2)^a | 0.044(2)^a | 0.095(2)^a | 0.080(2)^a | 0.163(4)^a | 0.137(3)^a |
| DA[0.5]^f | 0.021(3)^f | 0.020(2)^f | 0.057(8)^f | 0.047(7)^f | 0.13(2)^f | 0.13(2)^f |
| DA[0.9]^f | 0.004(5)^f | 0.0034(5)^f | 0.016(2)^f | 0.008(1)^f | 0.07(1)^f | 0.05(07)^f |
| DB[0.5]^f | 0.35(5)^f | 0.38(5)^f | 0.51(7)^f | 0.57(8)^f | 0.70(10)^f | 0.80(11)^f |
| DB[0.9]^f | 0.0040(5)^f | 0.040(6)^f | 0.18(3)^f | 0.17(2)^f | 0.33(5)^f | 0.34(5)^f |
| He[0.23]^f | 0.15(2)^f | 0.15(2)^f | 0.32(4)^f | 0.30(4)^f | 0.63(9)^f | 0.61(9)^f |
| He[0.45]^f | 0.019(3)^f | 0.024(3)^f | 0.044(6)^f | 0.057(8)^f | 0.11(2)^f | 0.14(2)^f |
| DB[0.5]^f | 0.019(3)^f | 0.012(6)^f | 0.052(7)^f | 0.067(9)^f | 0.12(2)^f | 0.16(2)^f |
| He[0.23]^f | 0.32(5)^f | 0.42(6)^f | 0.47(7)^f | 0.61(8)^f | 0.64(9)^f | 0.82(2)^f |
| He[0.3]^f | 0.07(1)^f | 0.08(1)^f | 0.17(2)^f | 0.21(3)^f | 0.30(4)^f | 0.39(5)^f |
| He[0.45]^f | 0.14(2)^f | 0.18(3)^f | 0.29(4)^f | 0.37(5)^f | 0.58(8)^f | 0.75(11)^f |

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* Star counts based on the F435W, F435W − F625W CMD and the MS box at B = 18.90.
* Numbers in parentheses are the uncertainties on the last decimal figure(s).
* Star counts based on the F435W, F435W − F625W CMD and the MS box at B = 19.15.
* Star counts based on the F435W, F435W − F658N CMD and the MS box at B = 18.90.
* Star counts based on the F435W, F435W − F658N CMD and the MS box at B = 19.15.
* Predicted cooling and lifetime ratios for CO-core (DA, DB) and He-core WDs. Numbers in square brackets are the WD masses in solar units.
* Estimates based on a distance modulus of D_M = 14.16.
* Estimates based on a distance modulus of D_M = 14.36.
* Estimates based on a cluster age of 10 Gyr.
* Estimates based on 70% He-normal (Y = 0.25) and 30% He-enriched (Y = 0.42) stars.

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...the preliminary evidence brought forward by M05 based on a smaller WD sample: DA and DB WD cooling sequences are, at fixed magnitude, systematically bluer (hotter) than the bulk of candidate cluster WDs. On the other hand, the predicted He WD cooling sequences are consistent with a substantial fraction of the observed candidate WDs. The discrepancy between predicted DA/DB WDs and observations can hardly be caused by the adopted WD atmosphere models. The difference in color at fixed magnitude between the same cooling sequences...
bin (F435W ≤ 24) they are at least a factor of 3 larger than CO-core ratios (see rows 7–9 in Table 1). To estimate possible uncertainties in distance and in the reddening correction, we adopted a larger apparent distance modulus (DMp = 14.36 vs. 14.16). The difference in the two sets of lifetime ratios for M WD = 0.5 is at most 18%.

This comparison between theory and observation indicates that the star count ratios in the brighter magnitude bin (see Fig. 3) are at least a factor of 2 larger than predicted by DA/DB WD cooling times. On the other hand, the observed ratios are at least a factor of 4 smaller than predicted by He WD cooling times. The discrepancy between the observed WD star counts and the predicted CO-core ratios can hardly be explained by incompleteness problems affecting the sample of candidate WDs, which would go in the direction of increasing the discrepancy between theory and observation. The same conclusion would apply for a putative increase in the mean mass of CO-core WDs, since the lifetime ratios on average decrease—as expected—by at least a factor of 2 (see rows 4 and 6 in Table 1). An increase in the mean mass of He WDs, on the other hand, does not imply a steady decrease in the cooling lifetime (see rows 7–9 in Table 1). This nonlinear behavior is due to the occurrence of CNO thermonuclear flashes in the mass range 0.22 ≤ M WD/⊙ ≤ 0.422 (Serenelli et al. 2002). The lifetime ratios quoted above indicate that predicted He WD lifetimes are at least a factor of 2 larger than observed.

The quoted discrepancies are also minimally affected by a decrease in the cluster age of 2 Gyr (Fig. 2, middle). We constructed two evolutionary tracks with M WD/⊙ = 0.77 (Z = 0.0004) and M WD/⊙ = 0.80 (Z = 0.0015) and found that the mean time they spend in crossing the specified magnitude bin is only 10% shorter than for the older models (see rows 10–14 in Table 1). Therefore, this decrease in the assumed age hardly affects the discrepancy between theory and observations. As another attempt to account for our findings we also considered a possible increase in the He content of MS stars. In particular, we adopted two cluster isochrones with same age and metal abundances as the canonical ones, but with a He-enhanced (Y = 0.42) composition (Fig. 2, bottom). In order to represent a possible spread in He content, we estimated the predicted ratios for a mix of stellar populations consisting of 70% stars with canonical He content (Y = 0.25) and 30% He-enhanced stars. We constructed two He-enhanced evolutionary tracks with M WD/⊙ = 0.55 (Z = 0.0004) and M WD/⊙ = 0.57 (Z = 0.0015) and found that the mean lifetime they spend in the specified magnitude bin is 460 Myr. Therefore, the MS lifetimes of the mixed-He population decrease by only ~15% (800 vs. 950 Myr) relative to the canonical population. Data plotted in Figure 3 (see also Table 1) indicate that the occurrence of a He-enhanced subpopulation in ω Cen cannot by itself explain the discrepancy between the star counts and the lifetime ratios.

Let us assume, as a working hypothesis, that the current sample of candidate cluster WDs represents a mix of CO-core and He-core WDs. The aforementioned lifetimes suggest that the fraction of He WDs ranges from 80% (if we assume a mean mass of 0.5 M ⊙ for the CO-core and 0.3 M ⊙ for the He-core WDs) to 10% (for a mean mass of 0.5 M ⊙ for the CO-core and 0.23 M ⊙ for the He-core WDs). The latter fraction decreases further if we assume still smaller He-core WDs, but current empirical estimates indicate that the lower limit ranges from ~0.17 to ~0.2 M ⊙ (Moehler et al. 2004; Kepler et al. 2007). This evidence, if supported by independent spectrophotometric measurements, indicates that cluster WD samples might present different intrinsic properties when compared with field WDs. Current estimates based on the large SDSS sample of WDs indicate that only 2% of field DA WDs possess masses smaller than 0.45 M ⊙. Note that the current fraction of He-core WDs is different by only a factor of 2–3 from the global binary frequency in ω Cen (Mayor 1996) and in good agreement with the binary fraction (~10%) in GCs in general (Davies et al. 2006). A similar excess of He WDs in the old open cluster NGC 6791 was proposed by K07. They found that roughly 40% of the WDs in this system did not experience the expected core-helium flash at the tip of the red giant branch (RGB). These objects end their evolution as He-core WDs after having lost a significant fraction of their envelope. According to evolutionary prescriptions they are the aftermath of an extreme mass loss episode possibly caused either by stellar collisions or by close binary interactions (Castellani et al. 2006a, 2006b). However, Bedin et al. (2005), using deep ACS images, suggested that the color distribution of WDs in NGC 6791 does not support the occurrence of He WDs.

The available observations present, as suggested by the referee, puzzling empirical aspects. Detailed photometric investigation of WDs in GCs such as M4 (Hansen et al. 2004) and NGC 6397 (Hansen et al. 2007) do not show evidence for He-core WDs. On the other hand, Sandquist & Martel (2007) found a well-defined deficiency (~20%) of bright RGs in NGC 2808 and suggested that the missing giants might produce He-core WDs. An enhanced mass loss efficiency, driven by metal content, was suggested by K07 to account for He-core WDs in NGC 6791. However, the peak in the metallicity distribution of ω Cen (Kaysar et al. 2006) and the metallicity of NGC 2808 (Carretta 2006) are at least 1.5 dex more metal-poor than NGC 6791. A possible He enrichment has been proposed to account for EHB stars and the complex MS structure in ω Cen and in NGC 2808 (D’Antona et al. 2002; Piotto et al. 2007). If we assume a canonical helium-to-metal enrichment ratio (∆Y/∆Z ≈ 2.5) a similar enhancement could also be present in NGC 6791. However, WD/MS and HB/MS (C07) star count
ratios in $\omega$ Cen do not seem to support this hypothesis: for a canonical enrichment ratio, the putative He-rich stars in $\omega$ Cen should have above solar metallicities. A single simple hypothesis of stellar evolution driven by cluster structural parameters and dynamical evolution can hardly account for the quoted He WD identifications, since the central density in $\omega$ Cen and in NGC 2808 is significantly larger than in NGC 6791. Therefore, we are left with compelling evidence that He WDs have been detected/predicted in stellar systems that host sizable samples of EHB stars ($\omega$ Cen, C07; NGC 2808, Castellani et al. 2006a; NGC 6791, K07). However, the natural progeny of EHB stars are CO-core WDs. The He enrichment scenario can account for EHB stars, but does not explain, for canonical mass loss rates, the occurrence of He WDs. On the other hand, if a substantial fraction of RGs avoids the He-core flash, they will end their evolution, according to the residual envelope mass, either as EHB/CO-core WDs or as He-core WDs (Hansen 2005; Castellani et al. 2006b).

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