THE DISCOVERY OF MORE THAN 2000 WHITE DWARFS IN THE GLOBAL CLUSTER $\omega$ CENTAURI

M. MONELLI,1 C. E. CORSI,2 V. CASTELLANI,3,4 I. FERRARO,2 G. IANNICOLA,2 P. G. PRADA MORONI,5,6 G. BONO,2 R. BUONANNO,7 A. CALAMIDA,7,8 L. FREYHAMMER,8,9 L. PULONE,2 and P. B. STETSON10

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ABSTRACT

We present deep multiband (F435W, F625W, and F658N) photometric data of the globular cluster $\omega$ Cen collected with the Advanced Camera for Surveys on board the Hubble Space Telescope. We identified in the (F435W − F625W, F435W)-plane more than 2000 white dwarf (WD) candidates using three out of nine available pointings. Such a large sample appears to be in agreement with predictions based on the ratio between WD and horizontal-branch evolutionary lifetimes. We also detected $\approx$1600 WDs in the (F658N − F625W, F625W)-plane, supporting the evidence that a large fraction of current cluster WDs are $\text{H}_\alpha$-bright.

Subject headings: globular clusters: general — globular clusters: individual ($\omega$ Centauri)

1. INTRODUCTION

Among Galactic globular clusters (GGCs), $\omega$ Cen is the most massive one ($M = 5 \times 10^5 M_\odot$; Meylan et al. 1995) and the only one that clearly shows a well-defined spread in metallicity. According to recent estimates based on sizable samples of evolved red giant branch (RGB) and subgiant branch stars, the metallicity distribution shows three peaks around $[\text{Fe}/\text{H}] = \approx -1.7, -1.5$, and $\approx -1.2$, together with a tail of metal-rich stars approaching $[\text{Fe}/\text{H}] \approx 0.5$ (Norris et al. 1996; Hilker et al. 2004). During the last few years it has also been suggested that $\omega$ Cen harbors multiple stellar populations (Lee et al. 1999) characterized by different ages (Ferraro et al. 2004; Hughes et al. 2004), He abundances, and distances (Bedin et al. 2004; Norris 2004; Freyhammer et al. 2005). More recently, Sollima et al. (2005) suggested that RGB stars present five peaks because of different stellar populations. Moreover, Piotto et al. (2005) found that the bluer main sequence (MS) detected by Bedin et al. (2004) is more metal-rich than the red MS. To account for this feature they suggested a possible variation of the He content among MS stars.

Although $\omega$ Cen presents properties that need to be properly understood, its stellar content is a gold mine for investigating several open problems concerning stellar evolution and its dependence on the metallicity. This applies not only to evolved stars such as RR Lyrae, hot horizontal-branch (HB) stars, and AGB stars and fainter than extreme HB stars. We ended up with a sizable sample of white dwarfs (WDs). The search for WDs in GGCs has already been successful, and several WD samples have been identified (Hansen et al. 2003; Moehler et al. 2004). So far, the richest sample of cluster WDs (222) was detected in M4 by Hansen et al. (2004). The detection of WDs in $\omega$ Cen dates back to Ortolani & Rosino (1987), who selected two dozen WD candidates on the basis of ground-based data, and to Elson et al. (1995), who detected four WD candidates using Hubble Space Telescope (HST) data. In this Letter, we present preliminary results concerning the identification of more than 2200 WDs in $\omega$ Cen on the basis of $B$, $R$, and $H\alpha$ data collected with the Advanced Camera for Surveys (ACS) on board HST and available on the HST archive. The reader interested in thorough reviews concerning recent theoretical and empirical results is referred to Fontaine et al. (2001), Koester (2002), Prada Moroni & Straniero (2002), Hansen & Liebert (2003), and Hansen (2004, and references therein).

2. OBSERVATIONS AND DATA REDUCTION

Current data were collected with nine pointings of the ACS camera across the center of the cluster. The $\approx 3 \times 3$ mosaic covers a field of view of $\approx 9' \times 9'$. Four images per field have been acquired in three different bands, namely, F435W, F625W, and F658N (hereafter $B$, $R$, and $H\alpha$). Three deep (340 s) exposures were secured for the $B$ and $R$ bands, respectively, while the exposure time for the $H\alpha$ images was 440 s each. The nine fields were independently reduced with the DAOPHOTII/ALLFRAME (Stetson 1994). An individual point-spread function has been extracted for each frame by adopting, on average, $\approx 200$ bright isolated stars. The individual catalogs were rescaled to a common geometrical system with DAOMATCH/DAOMASTER. The final catalog includes approximately $10^4$ stars, and the $B$, $B-R$ color-magnitude diagram shows a well-populated cluster MS together with a sizable sample of stars covering a wide region to the left of the MS (Bono et al. 2005).

From this catalog we selected all the stars bluer than MS stars and fainter than extreme HB stars. We ended up with a sample of approximately 45,000 stars distributed over the nine pointings. Among them we selected three pointings ($2$, $7$, and $9$) that include $\approx 14,000$ WD candidates. These stars have been identified in individual deep $B$, $R$, $H\alpha$ images, and we performed once again the photometry using ROMAFOTtwo. Individual stars have been interactively checked in every image, and the WD candidates were measured either as isolated stars or together with neighbor stars, where crowding affects the photometric accuracy. Note that a substantial fraction of the stars located close to WD candidates are truly MS stars, i.e.,
they did not belong to the original sample of stars located on the blue side of the MS. Note that the 80% of the selected stars were revealed to be cosmic rays, or spurious identifications of faint stars located close to saturated stars, or too faint objects to be safely measured on individual images. The photometric calibration was performed in the Vega System.\textsuperscript{11}

3. RESULTS AND DISCUSSION

In this investigation we present preliminary results based on three out of the nine pointings. Figure 1 shows the current sample of \( \omega \) Cen stars in the \((B - R, B)\)-plane. Interestingly enough, the original sample splits into two well-defined sequences, the redder one made by MS stars and the other one made by 2212 blue objects that range from \( B \approx 22, B - R \approx 0 \) down to \( B \approx 27, B - R \approx 0.8 \), covering the expected region of cluster WDs.

Using Great Observatories Origins Deep Survey data collected with ACS in the bands F435W and F606W, we estimated that the expected number of field galaxies with \( 22 \leq B \leq 26 \) and \( 0.2 \leq B - R \leq 0.5 \)\textsuperscript{12} in the same area covered by current observations is \( \approx 60 \) (A. Grazian et al. 2005, private communication). The number of field stars is also negligible, because halo and disk stars peak around \( B - R = 0.7 \) and \( B - R = 1.8 \), respectively (King et al. 1990). More detailed estimates based on radial velocity (Suntzeff & Kraft 1996) or proper-motion (van Leeuwen et al. 2000) measurements in \( \omega \) Cen suggest that at most two dozen field stars might be located inside the area covered by current data. Finally, theoretical Galactic models (Castellani et al. 2002) suggest that in the same area covered by current observations are present at most 16 field WDs brighter than \( B = 25.5 \) and 55 field WDs brighter than \( B = 28 \).

This evidence suggests that we are faced with a bona fide sample of cluster WDs, including more than 2000 objects, thus the largest sample of WDs ever observed in a stellar cluster. Data plotted in Figure 1 clearly show that thanks to the sizable sample of \( \omega \) Cen stars, the cooling sequence shows up at \( B \approx 21 \). This bright limit, if we assume for \( \omega \) Cen an apparent distance modulus \( DM_0 \approx 14.21 \) (Thompson et al. 2001), implies that current data are tracing the cooling history of cluster WDs at least below \( M_p \approx 7 \). According to predictions by Althaus & Benvenuto (1998) for a 0.5 \( M_\odot \) WD with a CO core and pure H atmosphere models by Bergeron et al. (1995)\textsuperscript{13} the current WD sample provides the opportunity to investigate the WD cooling for luminosities ranging from 10 times the solar luminosity down to log \((L/L_\odot)\) \( \approx -3.1 \) \((B \approx 27, M_p \approx 12.8)\).

By adopting the same theoretical predictions, one can easily recognize that the huge number of WDs should not be a real surprise. As a matter of fact, the number ratio between WD and HB stars, for not too long of cooling times, is simply given by the ratio of the lifetimes spent during these two evolutionary phases. On the basis of the shallow ACS photometry in the \( B, R \) bands, recently presented by Freyhammer et al. (2005), we found in the same three fields the occurrence of \( \approx 630 \) HB stars. The typical evolutionary lifetime for HB stars is \( (1-2) \times 10^8 \) yr, depending on their zero-age HB effective temperature (Castellani et al. 2005), while for a WD with a CO core and \( M = 0.5 \ M_\odot \) at \( M_p \approx 11.3 \) \( \log (L/L_\odot) = -2.24 \) the lifetime is \( 3.5 \times 10^3 \) yr. This means that we expect to detect roughly twice as many WDs than HB stars brighter than \( B \approx 25.5 \).

Interestingly enough, we detected approximately 1200 WDs brighter than this magnitude limit. However, the current estimate should be considered as a robust lower limit, since preliminary artificial star experiments suggest that at this limiting magnitude the completeness is \( \approx 85\% \).

An unexpected observed feature in Figure 1 is the steady increase in color dispersion when moving toward fainter WD magnitudes. In order to assess whether this spread in color might be due to photometric errors, we performed an empirical test. We estimated the ridge line of WDs and the distance in color of individual objects from the ridge line. Figure 2 shows the color distribution of WDs in the magnitude interval \( B = 25 \pm 0.5 \) together with its Gaussian fit (solid line). Then we estimated standard deviation in color of the same selected WDs (intrinsics errors), and we found \( \sigma_B - R = 0.087 \). The dashed line plotted in Figure 2 shows the expected color distribution for the same sample of WDs (712) according to the assumption that their \( B, R \) magnitudes would only be affected by Gaussian intrinsic errors. Data plotted in Figure 2 indicate that the \( \sigma \) of the Gaussian fit to observed WDs is a factor of 2 larger than expected. On this basis, we estimated that the two distributions differ at 99% confidence level. This finding, taken at face value, indicates that the color dispersion might be real.

In order to investigate the WD location in the color-magnitude diagram, we adopted the WD cooling sequences for CO core and H envelopes constructed by Althaus & Benvenuto (1998). Theoretical predictions have been transformed into the observational plane by using pure H atmosphere models con-

11 See http://www.stsci.edu/hst/acs/documents.
12 Note that to perform this estimate we accounted for the difference in magnitude between AB and Vega systems and for the difference between the filter F606W and the filter F625W (see http://www.stsci.edu/hst/acs/documents).
13 See also http://www.ASTRO.UMontreal.CA/bergeron/CoolingModels.
The solid line shows the Gaussian fit to the observed distribution, while the dashed line shows the expected distribution for the same sample of WDs in the case that their colors would only be affected by Gaussian photometric intrinsic errors.

The comparison between theory and observations (see Fig. 3a) discloses a good agreement for the bright portion (22 ≤ B ≤ 23). However, the theoretical sequences toward fainter magnitudes appear to fit the blue (hot) edge of the observed WDs. It is noteworthy that a WD with a stellar mass $M = 0.5 M_\odot$ is a lower limit for WDs with CO core; actual WDs are expected to be slightly more massive ($\sim 0.53 M_\odot$; Renzini et al. 1996). Current uncertainties on reddening (0.02 across the cluster; Schlegel et al. 1998) and on cluster distance cannot account for the observed systematic drift in color. This evidence suggests that the observed WD cooling sequence is redder than expected.

In principle one can find several plausible reasons for such an occurrence. In particular, we note that for 22 ≤ B we are already below the so-called DB gap (Hansen & Liebert 2003), i.e., WDs with He atmospheres could be present. Data plotted in Figure 3b show that by adopting WD cooling sequences for CO core, and He envelopes by Benvenuto & Althaus (1997) together with He atmosphere models by Bergeron et al. (1995), the cooling sequence is indeed moving toward redder colors. Note that the cutoff of the cooling sequences in the bright region is due to the fact that He atmosphere models do not cover this temperature region. The comparison between theory and observations indicates that the bulk of the observed WDs might be of the DB type. This evidence, as suggested by the referee, is in contrast with current spectroscopic findings by Moehler et al. (2004) concerning cluster WDs. They identified H Balmer lines in four and seven WDs in NGC 6397 and in NGC 6752, thus suggesting that these objects are of the DA type. The same outcome applies to field WDs for which DA WDs are $\approx 80\%$ of the entire sample (Koester & Chanmugam 1990). An explanation of this discrepancy should wait for new spectroscopic measurements.

As shown in the bottom panel of Figure 3, a different possibility is given by the occurrence of He core WDs. Interestingly enough, predicted WD cooling sequences for He core structures by Serenelli et al. (2002), transformed into the observational plane by adopting He atmosphere models, also account for the observed distribution. This working hypothesis, once confirmed, indicates that a substantial fraction of WDs in ω Cen might be the evolutionary aftermath of binary systems. According to curr-
rent knowledge, candidate cluster He core WDs have been identified only in systems with high central densities and short two-body relaxation times (NGC 6397, log $\rho_0 = 5.68 \ L_{\odot} \ pc^{-3}$, Taylor et al. 2001; 47 Tuc, log $\rho_0 = 4.77 \ L_{\odot} \ pc^{-3}$, Edmonds et al. 2001). However, $\omega$ Cen presents a relatively low central density (log $\rho_0 = 3.12 \ L_{\odot} \ pc^{-3}$) and therefore fills an empty region of the parameter space predicted by Hansen et al. (2003, see their Fig. 8). Current findings are marginally affected by the adopted theoretical predictions. Different sets of WD cooling sequences (Fontaine et al. 2001; Prada Moroni & Straniero 2002), transformed into the $(B - R, B)$-plane by adopting the same atmosphere models, agree quite well with each other.

Finally, it is worth noting that current $H\alpha - R, R$ data (see Fig. 4) show that a good fraction of detected WDs ($\sim 1600$) are $H\alpha$-bright, and indeed they attain $H\alpha - R$ colors systematically bluer than predicted.

It would be worth to mention that blending and/or binarity could also affect observed colors. Therefore, no firm conclusion can be reached on the basis of current data. More detailed photometric and spectroscopic investigations of this large sample of cluster WDs will provide fundamental hints concerning their cooling and progenitors.

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