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Letter to the Editor

First VLT spectra of white dwarfs in a globular cluster

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Abstract. We present the first spectra obtained with the *Very Large Telescope* for white dwarfs in a globular cluster. Estimates of atmospheric parameters are obtained and compared to evolutionary tracks. We discuss possible implications for the distance scale of globular clusters and white dwarf evolution and demonstrate how white dwarfs might be used to establish an independent distance scale to globular clusters.

Key words: Stars: fundamental parameters – Stars: Population II – Stars: white dwarfs – globular clusters: individual: NGC 6397

1. Introduction

White dwarfs are the final stage of all low-mass stars and therefore all single stars in a globular cluster that currently finish their nuclear-burning lifetimes are expected to evolve into white dwarfs. As this has been the situation for many billions of years globular clusters should contain many white dwarfs. However, these stars managed to evade detection until photometric white dwarf sequences in globular clusters were discovered recently by observations with the *Hubble Space Telescope* (HST) (Paresce et al. 1995, Richer et al. 1995, 1997, Cool et al. 1996, Renzini et al. 1996). Photometric observations contain only a limited amount of information: The two chemically distinct white dwarfs sequences (hydrogen-rich DA's and helium-rich DB's) in principle can be distinguished by their photometric properties alone in the temperature range $10,000\,K \leq T_{\mathrm{eff}} \leq 15,000\,K$ (see Bergeron et al. 1995a). Renzini et al. (1996) classified two white dwarfs in NGC 6752 as DB's by this method. However, without a spectral classification, both stars can also be explained as high mass DA white dwarfs, possibly a product of merging. Richer et al. (1997) speculate that the brightest white dwarf in M 4 (V=22.08) might be a hot (27,000K) DB star.

The location of the white dwarf cooling sequence (and thus the brightness of the white dwarfs) is also sensitive to the white dwarf mass. Renzini et al. (1996) argued that the white dwarf masses in globular clusters are constrained to the narrow range $0.51\mathrm{M}_\odot \leq \mathrm{M_{WD}} \leq 0.55\mathrm{M}_\odot$, but some systematic differences between clusters are obvious: At a given metallicity some globular clusters (e.g. NGC 6752) possess very blue horizontal branches (HB's) with HB star masses as low as $0.50\mathrm{M}_\odot$. Such extreme HB stars evolve directly to low-mass C/O white dwarfs (bypassing the AGB), shifting the mean white dwarf mass closer to $0.51\mathrm{M}_\odot$. Other clusters show only red HB stars, which will evolve to the AGB and form preferably white dwarfs with masses of $\approx 0.55\mathrm{M}_\odot$.

Low-mass white dwarfs ($M<0.45\mathrm{M}_\odot$) with a degenerate He core are produced if the red giant branch evolution is terminated by binary interaction before the helium core exceeds the minimum mass for helium burning. Recently, Cool et al. (1998) found 3 faint UV-bright stars in NGC 6397 which they suggest could be He white dwarfs (supported by Edmonds et al. 1999). Massive white dwarfs may be produced from blue stragglers or by collisions of white dwarf-binaries with subsequent merging (e.g. Marsh et al. 1995).

Only a detailed spectroscopic investigation can provide masses and absolute luminosities of the individual globular cluster white dwarfs. This is also very important for the use of white dwarfs as standard candles to derive distances to globular clusters (Renzini et al. 1996): The basic idea is to fit the white dwarf cooling sequence of a globular cluster to an appropriate empirical cooling sequence of local white dwarfs with well determined trigonometric parallaxes. The procedure is analogous to the classical main sequence fitting but avoids the complications with metallicity – white dwarfs have virtually metal free atmospheres. In addition they are locally much more abundant than metal-poor subdwarfs. The arrival of the HIPPARCOS results as well as new metallicity determinations have rekindled the debate on globular cluster distances (see the review by Reid 1999 and references therein). A further check on the distance is therefore urgently needed.
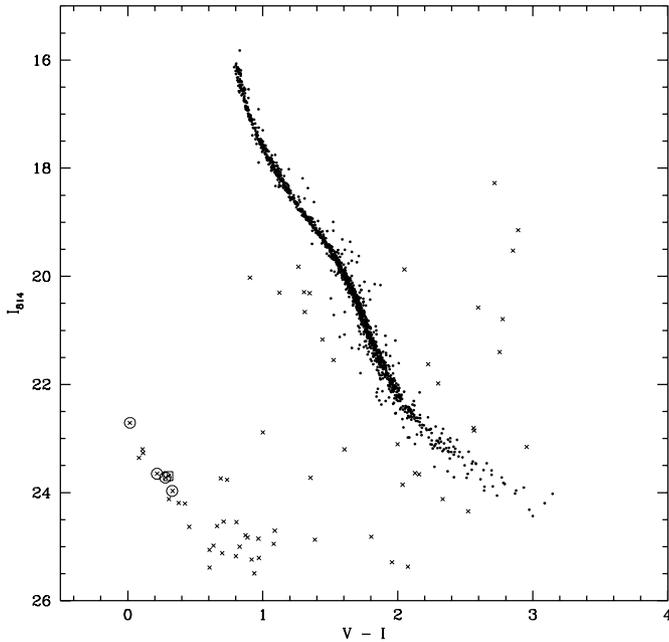

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Fig. 1. Colour-magnitude diagram of NGC 6397 (King et al. 1998, their Fig. 2). Open circles mark the four white dwarfs for which spectra could be obtained, the open square marks WF4-205 (see text).
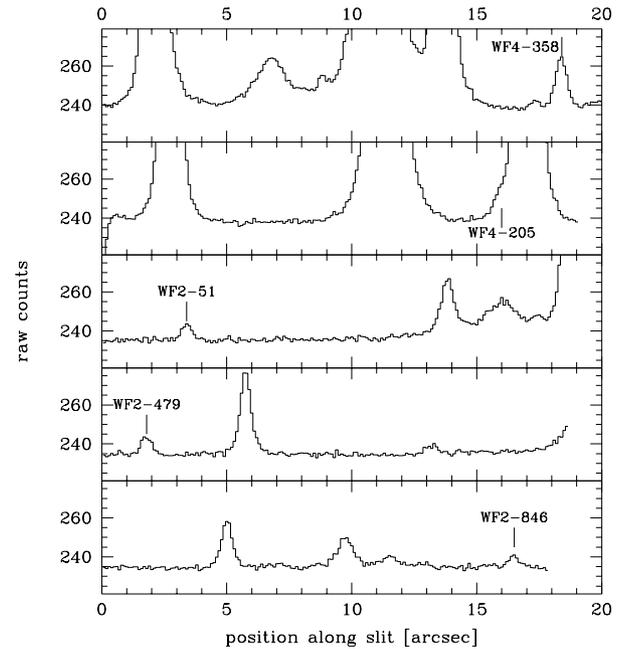

Fig. 2. Traces through the slits along the spatial axis. The lines mark the white dwarf spectra (WF4-205 unfortunately lies on the wing of a much brighter star).

Table 1. Target coordinates and photometric data (Cool priv. comm.).

Star	α_{2000}	δ_{2000}	V	$V - I$
WF4-358	$17^h 40^m 58\overset{s}{.}52$	$-53°42'25.3''$	$22\overset{m}{.}73$	$+0\overset{m}{.}02$
WF2-479	$17^h 41^m 07\overset{s}{.}06$	$-53°44'45.1''$	$23\overset{m}{.}87$	$+0\overset{m}{.}22$
WF4-205	$17^h 41^m 01\overset{s}{.}58$	$-53°43'15.3''$	$23\overset{m}{.}99$	$+0\overset{m}{.}30$
WF2-51	$17^h 41^m 04\overset{s}{.}52$	$-53°43'55.8''$	$24\overset{m}{.}00$	$+0\overset{m}{.}28$
WF2-846	$17^h 41^m 01\overset{s}{.}78$	$-53°44'47.2''$	$24\overset{m}{.}30$	$+0\overset{m}{.}33$

We started an observing programme at the ESO *Very Large Telescope (VLT)* to obtain spectra of white dwarfs in globular clusters. The programme consists of two parts: First, low S/N (≈ 10) spectra of the white dwarf candidates are obtained to verify their spectral type and estimate their effective temperatures. In a second run we plan to observe higher S/N (≈ 30) spectra that will allow to derive $\log g$ with an internal error of ≤ 0.1dex. Here we report on the very first results for NGC 6397.

2. Observations and data reduction

Cool et al. (1996) discovered the white dwarfs using the *Wide Field and Planetary Camera 2* (WFPC2) onboard the HST to observe the globular cluster NGC 6397. From the improved colour-magnitude diagram of King et al. (1998) targets brighter than $V \approx 25^m$ were selected (see Fig. 1). The WFPC2 images were convolved to a seeing of $0\overset{''}{.}5$ to select targets that are sufficiently uncrowded to be observable from the ground (see Table 1 and Fig. 2). The stars were observed with the *FOcal Reducer/low dispersion Spectrograph* (FORS) at Unit Telescope 1 of the VLT using the high resolution collimator ($0\overset{''}{.}1$/pixel) to allow better extraction of the spectra and get a better handle on cosmic rays. We used the *multi-object spectroscopy* (MOS) mode with the grism 300V and a slit width of $0\overset{''}{.}8$. The slit width was chosen to be larger than the required seeing to avoid slit losses due to imperfect pointing of the telescope. The data were obtained in service mode under excellent conditions (seeing below $0\overset{''}{.}55$, no moon) with a total exposure time of 90 minutes. The final resolution as judged from a wavelength calibration spectrum obtained with a $0\overset{''}{.}5$ slit is ≈ 11.5 Å. A trace along the spatial axis of the slitlets at about 4550 Å is plotted in

Fig. 2. Unfortunately WF4-205 lies so close to a bright star that even at this excellent seeing its spectrum could not be extracted.

Due to the use of slit blades instead of fibers or masks the MOS slitlets are very well defined and can be treated like long slits. The spectra were therefore corrected for bias, flat-fielded, wavelength calibrated, and extracted as described by Moehler et al. (1997). We find only a diffuse and rather low sky background without any strong sky lines below 5150 Å. The spectra were relatively flux calibrated using LTT 7987 (Hamuy et al. 1992) and are plotted in Fig. 3. All four stars display only strong broad Balmer lines, which is characteristic for hydrogen-rich white dwarfs (DA stars).

3. Atmospheric parameters

Although the white dwarf spectra have low signal-to-noise, they are sufficient for rough parameter estimates. The atmospheric parameters are obtained by simultaneously fitting profiles of the observed Balmer lines with model spectra using the least-square algorithm of Bergeron et al. (1992; see Napiwotzki et al. 1999 for minor modifications). Analyses were performed with
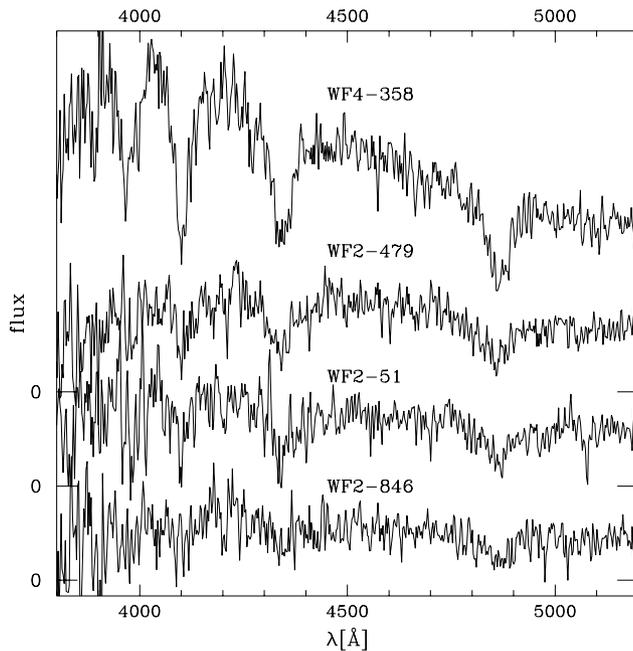
Fig. 3. The (relatively flux-calibrated) spectra of the white dwarfs in NGC 6397. The spectra of the three faintest stars are offset from each other as they would otherwise overlap. WF4-358 has no additional offset relative to WF2-479.

Fig. 4. Sample fits to the spectra of WF4-358 ($T_{\rm eff}$ = 18,200 K, $\log g$ = 7.3) and WF2-479 ($T_{\rm eff}$ = 11,000 K, $\log g \doteq$ 7.7).

Koester's LTE models as described in Finley et al. (1997). As a check we repeated the analysis of the hottest star in our sample (WF4-358) with the non-LTE grid described in Napiwotzki et al. (1999). Since the non-LTE code does not treat convection and ignores molecular opacities reliable atmospheric models cannot be calculated for the three cooler white dwarfs.

Fitting the lines H_β to H_ϵ for WF4-358 (see Fig. 4) gives 18,200±1300 K and 7.30±0.36 for $T_{\rm eff}$ and $\log g$, respectively (χ^2 = 0.93). The errors given here are 1σ errors obtained from the χ^2 fit. Omitting H_ϵ from the fit results in 17,800 K and 7.19 (χ^2 = 1.02) with more or less unchanged errors. The results of the non-LTE analysis are essentially identical to those obtained with Koester's models, differing only by small fractions of the formal errors ($\Delta T_{\rm eff} \approx 500$ K, $\Delta \log g \approx$ 0.07 dex). The surface gravity is surprisingly low and suggests that WF4-358 could be a bright (M_V=9$^{\rm m}$7) helium white dwarf of (0.36±0.12)M$_\odot$. Within the error bars, however, the derived parameters are also consistent with a low-mass C/O white dwarf. For the remaining three stars the S/N is too low to determine $T_{\rm eff}$ and $\log g$ simultaneously. We thus fitted H_δ, H_γ, H_β (H_ϵ being too noisy) for WF2-51, WF2-479, and WF2-846 for three fixed values of $\log g$ (8.0, 7.7, 7.5, see Fig. 4 for an example). These $\log g$ values correspond to C/O white dwarfs of ≈ 0.6M$_\odot$, low-mass C/O white dwarfs of ≈ 0.5M$_\odot$, and He white dwarfs of ≈ 0.4M$_\odot$, respectively (see below). The formal errors are ≈ 550 K (WF2-479), ≈ 650 K (WF2-846, WF4-358), and ≈ 790 K (WF2-51). The errors for the cooler stars are relatively small despite their low S/N because – at fixed $\log g$ – the line profiles are much more sensitive to temperature variations at $T_{\rm eff} \approx 11,000$ K than at $T_{\rm eff} \approx 18,000$ K.

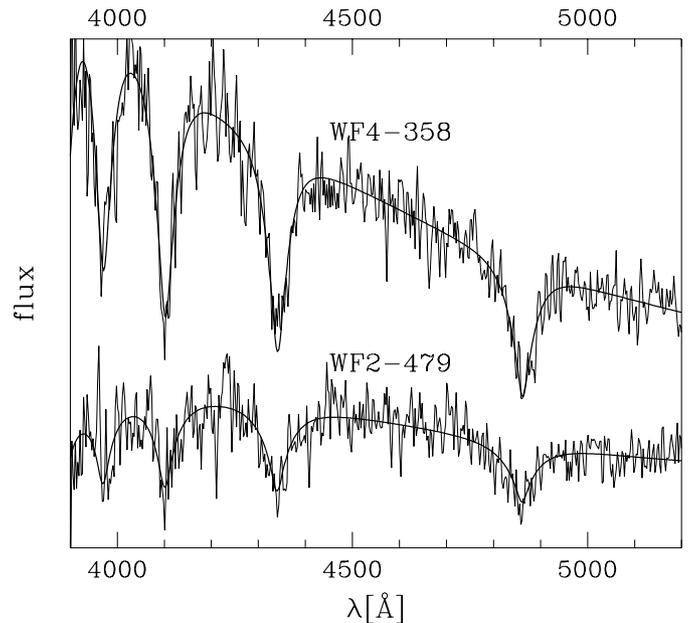The relatively large χ^2 value for WF2-51 suggests that either the noise in this spectrum has been underestimated or that the spectrum contains additional features that are not well described by the model spectra. The temperatures derived from the Balmer lines agree quite well with those obtained from $(V - I)_0$ using the theoretical colours of Bergeron et al. (1995a, $\log g$ = 8.0).

The masses given in Table 2 were derived by interpolation between the evolutionary tracks of C/O white dwarfs calculated by Blöcker (1995) and the He white dwarf tracks of Driebe et al. (1998). Finally, absolute magnitudes M_V were calculated for each parameter set with the photometric calibration of Bergeron et al. (1995a).

4. The distance to NGC 6397

The old distance modulus to NGC 6397 was $(m-M)_0 = 11^{\rm m}71$ with a reddening of E_{B-V} of $0^{\rm m}18$ (Djorgovski 1993). Using local metal-poor subdwarfs to fit the main sequence of NGC 6397 Reid & Gizis (1998) obtained a mean distance modulus of $(m - M)_0 = 12^{\rm m}20 \pm 0^{\rm m}15$ for $E_{B-V} = 0^{\rm m}19$. Thus NGC 6397 is a good example for the large differences between old and new distances to globular clusters. The absolute magnitudes given in Table 2 for $\log g$ = 7.5, 7.7, 8.0 (M$_{\rm WD}$ = 0.4M$_\odot$, 0.5M$_\odot$, 0.6M$_\odot$) yield mean true distance moduli (for E_{B-V} = $0^{\rm m}18$) $(m - M)_0$ of $12^{\rm m}3$, $12^{\rm m}0$, and $11^{\rm m}6$, respectively, with an r.m.s. error of $0^{\rm m}17$. Considering the error bars of the various distance determinations the long distance scale would be more consistent with white dwarf masses ≤ 0.5M$_\odot$ and the short distance scale with masses > 0.5M$_\odot$. The longer distance moduli obtained for low-mass white dwarfs also result in masses for blue HB stars (Heber et al. 1997) and a hot post-AGB star (ROB 162, Heber & Kudritzki 1986) that agree with canonical evolutionary theory.

Table 2. Effective temperatures and χ^2 values for the white dwarfs from the fit of H_δ, H_γ, H_β at fixed $\log g$ (see text for details). Also given are masses derived from theoretical tracks of Blöcker (1995) and Driebe et al. (1998) and absolute magnitudes (Bergeron et al. 1995a). Using Bergeron et al.'s (1995a) Table 3 we derived $T_{\mathrm{eff},(V-I)_0}$ from $(V-I)_0$, which was calculated from $V-I$ assuming $E_{V-I} = 0\overset{\mathrm{m}}{.}225$.

star	χ^2	T_{eff} [K]	$T_{\mathrm{eff},(V-I)_0}$ [K]	$\mathbf{M}$ [$M_\odot$]	M_V
		$\log g = 7.5$			
WF4-358	1.04	18900		0.42	$10\overset{\mathrm{m}}{.}0$
WF2-479	1.15	10800		0.39	$11\overset{\mathrm{m}}{.}1$
WF2-51	1.46	10900		0.39	$11\overset{\mathrm{m}}{.}1$
WF2-846	0.71	10500		0.38	$11\overset{\mathrm{m}}{.}2$
		$\log g = 7.7$			
WF4-358	1.07	19500		0.48	$10\overset{\mathrm{m}}{.}3$
WF2-479	1.14	11000		0.46	$11\overset{\mathrm{m}}{.}4$
WF2-51	1.46	11100		0.46	$11\overset{\mathrm{m}}{.}4$
WF2-846	0.71	10600		0.46	$11\overset{\mathrm{m}}{.}5$
		$\log g = 8.0$			
WF4-358	1.13	20300	19400	0.62	$10\overset{\mathrm{m}}{.}7$
WF2-479	1.14	11200	11500	0.59	$11\overset{\mathrm{m}}{.}8$
WF2-51	1.47	11300	10800	0.59	$11\overset{\mathrm{m}}{.}8$
WF2-846	0.71	10800	10300	0.59	$11\overset{\mathrm{m}}{.}9$

The distance moduli derived for a given $\log g$ from Tables 1 and 2 show a systematic variation with the brightest star (WF4-358) yielding the smallest distance and the faintest star (WF2-846) giving the largest distance. This variation could reflect the fact that the stars may not all have the same surface gravity: From their different apparent magnitudes (i.e. different absolute magnitudes) it is plausible that WF4-358 has the smallest $\log g$ and WF2-846 the largest. The quality of the current data, however, does not allow to verify this idea.

5. Conclusions

Using VLT-FORS1 multi object spectroscopy we have confirmed four white dwarf candidates to be hydrogen-rich DA white dwarfs. The gravity determined for the brightest star, WF4-358, suggests that it could be a He white dwarf with a mass of $(0.36\pm0.12)M_\odot$, although the error bars are large enough to also accommodate a C/O white dwarf. Temperatures derived for the three cooler and fainter stars for fixed $\log g$ would put them near the red edge of the ZZ Ceti instability strip, for which Bergeron et al. (1995b) determine a temperature range of 11,160 K

to 12,460 K using their preferred ML2/α=0.6 prescription for the treatment of convection. Therefore, a search for photometric variability of WF2-479 and WF2-51 – if successful – could place important additional constraints on these stars. The systematic variation of the distance moduli derived for a given $\log g$ shows that the assumption of a constant mass for all white dwarfs in a globular cluster may bias a distance determination. However, due to the low S/N of the current data, these results are preliminary. Once higher quality spectra are available, which will allow more accurate parameter (and thus mass) determinations, analyses of white dwarfs in globular clusters will become a powerful tool for independent distance estimates.

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