Further investigation of white dwarfs in the open clusters NGC 2287 and NGC 3532

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ABSTRACT

We report the results of a CCD imaging survey, complemented by astrometric and spectroscopic follow-up studies, that aims to probe the fate of heavy-weight intermediate-mass stars by unearthing new, faint, white dwarf members of the rich, nearby, intermediate-age open clusters NGC 3532 and NGC 2287. We identify a total of four white dwarfs with distances, proper motions and cooling times which can be reconciled with membership of these populations. We find that WD J0643–203 in NGC 2287, with an estimated mass of $M = 1.02-1.16 \,\mathrm{M_{\odot}}$, is potentially the most massive white dwarf so far identified within an open cluster. Guided by the predictions of modern theoretical models of the late-stage evolution of heavy-weight intermediate-mass stars, we conclude that there is a distinct possibility that it has a core composed of O and Ne. We also determine that despite the cooling times of the three new white dwarfs in NGC 3532 and the previously known degenerate member NGC 3532-10 spanning ~90 Myr, they all have remarkably similar masses ($M \sim 0.9-1 \,\mathrm{M_{\odot}}$). This is fully consistent with the results from our previous work on a heterogeneous sample of ~ 50 white dwarfs from 12 stellar populations, on the basis of which we argued that the stellar initial-final mass relation is less steep at $M_{\text{init}} > 4 \,\mathrm{M}_{\odot}$ than in the adjacent lower initial mass regime. This change in the gradient of the relation could account for the secondary peak observed in the mass distribution of the field white dwarf population and mitigate the need to invoke close binary evolution to explain its existence. Spectroscopic investigation of numerous additional candidate white dwarf members of NGC 3532 unearthed by a recent independent study would be useful to confirm (or otherwise) these conclusions.

Key words: white dwarfs – open clusters and associations: individual: NGC 2287 – open clusters and associations: individual: NGC 2516 – open clusters and associations: individual: NGC 3532.

1 INTRODUCTION

Only H, He and Li are believed to have been created in significant quantities during the earliest stages in the evolution of the Universe (e.g. Wagoner, Fowler & Hoyle 1967). Heavier elements, including the two main constituents of the Earth's atmosphere, O and N, are manufactured by stars (Burbidge et al. 1957). These species are

fed into the interstellar medium (ISM) of our Galaxy and others primarily during the latter phases in the stellar life cycle when stars, depending on their mass, evolve either towards a supernova explosion or up the asymptotic giant branch (AGB) and through the planetary nebula phase. Subsequently, they are mixed into the ambient gas (Scalo & Elmegreen 2004) from which they will be incorporated into future generations of stars and planets.

A detailed understanding of how stellar populations build up and modify the metallicity of the ISM over time is essential to fully comprehend the formation and the evolution of galaxies. An important

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aspect of this is the knowledge of the amount and the composition of the gas a star of a particular initial mass (and metallicity) will return to the ISM during its lifetime. This is intimately linked to its final evolutionary state. Most low- and intermediate-mass stars $(M_{\rm init} \lesssim 5-6\,{
m M}_{\odot})$ are anticipated to end their lives as either He or CO white dwarfs, while massive objects ($M_{\text{init}} \gtrsim 10 \,\mathrm{M_{\odot}}$) are expected to perish in Fe core-collapse Type II supernovae explosions. The fate of the heaviest intermediate mass stars (IMS) which lie in the intervening mass range, however, remains very uncertain (e.g. Siess 2006), despite these being comparable in number to the massive objects. Stellar evolutionary models suggest that the C in a partially degenerate core of an aged heavy-weight IMS ignites when it achieves $M \gtrsim 1.05 \,\mathrm{M}_{\odot}$ and burns to O and Ne (Nomoto 1984, 1987), before the star enters a phase of super-asymptotic giant branch (super-AGB) evolution. The very high temperature environment at the bottom of the convective envelopes of super-AGB stars favours the production of isotopes such as ⁷Li, ¹⁴N, ¹³C and ²⁶Al (Siess 2010). If this chemically enriched envelope gas is removed before the core attains $M \sim 1.37 \,\mathrm{M_{\odot}}$, the star likely ends its life as an ultramassive ($M \sim 1.1-1.35 \,\mathrm{M}_{\odot}$) ONe white dwarf (e.g. Ritossa, Garcia-Berro & Iben 1996; Garcia-Berro, Ritossa & Iben 1997). However, if the degenerate interior reaches $M \sim 1.37 \,\mathrm{M_{\odot}}$, then electron captures on to ²⁴Mg and ²⁰Ne will lead to a core collapse and a weak Type II electron capture supernova explosion (ECSNe; Nomoto 1984). The temperatures and particle densities inherent to ECSNe are anticipated to generate a somewhat more exotic cocktail of elements that also includes ⁶⁴Zn, ⁷⁰Ge, ⁹⁰Zr and possibly heavy *r*-process elements (A > 130; Qian 2008), but which is relatively poor in α -process elements and Fe (Wanajo et al. 2009).

Unfortunately, the treatment of key physical processes within these calculations remains rather rudimentary. This limits the capacity of stellar evolutionary theory to make firm predictions regarding the fate of stars in this mass range. For example, the details of how convective mixing is implemented in the models, especially during the He core burning phase, can systematically shift the initial mass range of super-AGB stars by $\sim 2 M_{\odot}$ (e.g. Gil-Pons, Gutiérrez & García-Berro 2007). It remains an open question as to whether during the super-AGB phase the atmospheres are cool enough to form dust (Poelarends et al. 2008). Dust appears to be essential for the efficient transfer of net outward momentum from the radiation field to the envelope gas, at least in thermally pulsing AGB stars (e.g. Wachter et al. 2002), so it is still uncertain if single stars in this mass range can evolve into ultramassive white dwarfs (UMWDs) at all.

Investigations of field UMWDs have been unable to provide unambiguous evidence in support of an evolutionary link with heavyweight IMSs, perhaps because this sizeable population is heterogeneous in origin. For example, Liebert, Bergeron & Holberg (2005a) found that the spatial distribution of the highest mass white dwarfs detected in the extreme ultraviolet (EUV) sky surveys, including 10 with $M \gtrsim 1.1 \,\mathrm{M}_{\odot}$, is remarkably similar to that of the young stellar populations in the vicinity of Gould's Belt. It has been argued that, given their space motions and cooling times, the UMWDs GD 50 and PG0136+251 could be associated with the young Pleiades open cluster (Dobbie et al. 2006a). In contrast, however, the empirical white dwarf mass distribution, when compared to the output of traditional population synthesis calculations, suggests that the majority of UMWDs may be produced through the merging of the lower mass components of primordial close binary systems, at least at the higher galactic latitudes (Yuan 1992; Liebert et al. 2005a).

The study of white dwarfs that are demonstrably bound members of young open clusters can provide better insight into the fate of heavy-weight IMSs. This is because these populations are coeval and have comparatively well-determined ages, making it possible to place tighter constraints on the prior evolution of their degenerate members. With ready access to large telescopes, the number of high-mass white dwarfs known to be members of open clusters has increased substantially during the last few years (\sim 30 degenerates with $M > 0.8 \,\mathrm{M_{\odot}}$ in ~10 populations, e.g. Dobbie et al. 2004; Williams, Bolte & Koester 2004, 2009; Kalirai et al. 2005). However, there remain very few, if any, known cluster white dwarfs with $M \gtrsim 1.05 \,\mathrm{M_{\odot}}$. Amongst the most promising candidates are LB 1497 (Pleiades; Bergeron, Saffer & Liebert 1992), KRR 24 (NGC 2099; Kalirai et al. 2005) and four objects in NGC 2168 (Williams et al. 2009), but their estimated masses are either borderline or have large uncertainties due to the rather modest quality of the spectroscopy used to determine their fundamental parameters. It is unclear if this lack of compelling candidate cluster UMWDs is a manifestation of a real deficit or merely down to counting statistics. At present, NGC 2168 is by far the richest young population in which the white dwarf cooling sequence has been spectroscopically studied down to its termination. Extrapolation of the cluster mass function beyond the main-sequence turn-off mass suggests that the central regions of NGC 2168 should contain ~18 white dwarf members (Kalirai et al. 2003). Williams et al. (2009) identified 12-14 possible degenerate members from their UBV imaging of the cluster core which is marginally consistent with this prediction ($P \sim 0.09$ for 12 objects), especially considering that a non-zero proportion of the cluster white dwarfs will be hidden from view by binary companions in earlier evolutionary phases (e.g. Williams 2004).

In the light of this, we have undertaken a new survey of two open clusters. NGC 3532 and NGC 2287, that aims to identify and characterize the white dwarf remnants of their recently deceased heavy-weight IMS members. Both targets are rich, nearby, young/intermediate age populations ($\tau = 300 \pm 25$ and 243 \pm 40 Myr, respectively; Harris et al. 1993; Koester & Reimers 1993; Meynet, Mermilliod & Maeder 1993; Kharchenko et al. 2005; Sharma et al. 2006) which, as outlined in Dobbie et al. (2009a), have been previously searched photographically for white dwarfs (e.g. Romanishin & Angel 1980; Reimers & Koester 1989). However, none of the six photometric candidates subsequently confirmed through spectroscopy as white dwarf members of these two populations (Koester & Reimers 1981, 1993; Dobbie et al. 2009a) appears to have formed from progenitors with $M \gtrsim 5 \,\mathrm{M}_{\odot}$, despite both clusters being relatively rich. It is possible the remnants of these stars have remained undetected until now because they lie beyond the detection limits of the photographic plates (e.g. Clem et al. 2011). Indeed, the total mass of NGC 3532 is estimated to be $M_{\text{tot}} > 2000 \,\text{M}_{\odot}$ (Fernandez & Salgado 1980). This is approximately twice that of the 150 Myr old cluster, NGC 2516 (Jeffries, Thurston & Hambly 2001), the central regions of which harbour four massive white dwarfs descended from stars with $M \gtrsim 5 \,\mathrm{M}_{\odot}$ (Koester & Reimers 1996). On the assumption that the initial mass functions of these populations were of a similar power-law form (e.g. Salpeter 1955), it could be expected that 4 ± 2 degenerate remnants from stars with $M \gtrsim 5.5\,{
m M}_{\odot}$ reside within NGC 3532 and approximately half this number within NGC 2287.

In subsequent sections, we outline our new, more sensitive CCDbased survey of these clusters and detail our initial selection of candidate white dwarf members. We describe our spectroscopic follow-up observations of these sources, the analysis of the spectral data sets and the determination of the fundamental parameters of the new white dwarfs uncovered. In Section 4, we estimate the distances and proper motions of the degenerates and compare these to the properties of their proposed host clusters. For those white dwarfs we find to be probable members of NGC 3532 and NGC 2287, we derive progenitor masses and conclude by discussing them in the context of stellar evolution and the stellar initial–final mass relation (IFMR). First, however, we briefly revisit the four high-mass white dwarf members of NGC 2516, which have traditionally been used to define the upper end of the IFMR. We use our new and improved spectroscopy to place tighter limits on their fundamental parameters and inferred progenitor masses.

2 THE NGC 2516 WHITE DWARFS REVISITED

The open cluster NGC 2516 was recognized several decades ago as an attractive target for investigating the form of the upper end of the IFMR (e.g. Reimers & Koester 1982). It is young (e.g. 140 Myr, Meynet et al. 1993; 158 Myr, Sung et al. 2002; 120 Myr, Kharchenko et al. 2005), comparatively nearby, (e.g. 430^{+80}_{-70} pc, Dachs & Kabus 1989; 407_{-20}^{+22} pc, Terndrup et al. 2002; 404_{-8}^{+7} pc, An, Terndrup & Pinsonneault 2007) and has a metallicity close to solar (e.g. $[Fe/H] = -0.10 \pm 0.04$, Sung et al. 2002; $[Fe/H] = +0.01 \pm$ 0.07, Terndrup et al. 2002). Moreover, with a mass that is approximately twice that of the Pleiades, it is relatively rich ($M_{tot} = 1240$ -1560 M_☉; Jeffries et al. 2001). A deep UV and red photographic survey of 25 deg² of sky centred on the cluster was performed by Reimers & Koester (1982) and led to the identification of nine blue candidate white dwarf members. Ultimately, four of these were confirmed through spectroscopy to be DA cluster members and found to have masses significantly greater than the objects populating the peak of the field white dwarf mass distribution (NGC 2516-1, -2, -3 and -5; Reimers & Koester 1982; Koester & Reimers 1996). Although early optical spectra, obtained with the European Southern Observatory's (ESO's) 3.6-m telescope, were of sufficient quality to allow confirmation of the trend that higher mass stars evolve to become more massive degenerates and to argue that the maximum mass of a white dwarf progenitor is $M_{\text{init}} \gtrsim 6 \,\mathrm{M}_{\odot}$ (e.g. Koester & Reimers 1996), their rather modest signal-to-noise ratio (S/N) at $\lambda \lesssim 4000$ Å suggests significant further reduction of the statistical uncertainties on the mass and cooling time estimates for these objects could be achieved with modern data.

Therefore, we re-observed the white dwarf members of NGC 2516 with ESO's 8-m Very Large Telescope (VLT) Unit Telescope 2 (UT2) and the FOcal Reducer and low dispersion Spectrograph (FORS1). A detailed description of the FORS instruments may be found on the ESO web pages.1 The data were acquired in service mode within the periods 2007 April 24-27 and 2007 October 06 to November 21. Since these targets are comparatively bright, we specified fairly relaxed constraints on the sky conditions and thus these observations were generally undertaken in poorer seeing and/or with some clouds present. All the FORS1 data were acquired using the 2 \times 2 binning mode of the E2V CCD, the 600B+12 grism and a 1.6-arcsec slit which gives a notional resolution of $\lambda/\Delta\lambda \sim$ 500. Flat and arc exposures were obtained within a few hours of the acquisition of each of the science frames. The spectra were reduced and extracted following the procedure outlined in Section 3.3. A spectrum of the featureless DC white dwarf WD 0000+345 was obtained with an identical set-up during this period and was used to remove the remaining instrumental response. We have used a grid of synthetic spectra and followed the procedures described in Sections 4.1 and 4.2 to redetermine the effective temperatures and



Figure 1. The results of our fitting of synthetic profiles (thin black lines) to the observed Balmer lines, H β to H-8, of the four white dwarf candidate members of NGC 2516 (thick grey lines). The flux_{λ} units are arbitrary.

surface gravities of these four stars (Fig. 1 and Table 1). To serve as a check on the repeatability of the output from our spectral analysis procedure, NGC 2516-1 was re-observed by us with the VLT UT1 and FORS2 on 2010 February 06 (see Section 3.3). The excellent agreement between the parameter estimates for NGC 2516-1, we derive from the two distinct sets of observations, lends confidence to our reduction and analysis process. Subsequently, for internal and external consistency, we have used the CO core, thick H-layer evolutionary models of Fontaine, Brassard & Bergeron (2001) to determine their masses and their cooling times (Table 1).

From the earlier ESO observations, Koester & Reimers (1996) determined that NGC 2516-2 and NGC 2516-5 most likely have $M > 1.0 \,\mathrm{M_{\odot}}$, with a best estimate for the former of $M = 1.05 \,\mathrm{M_{\odot}}$. Claver et al. (2001) used these results and the stellar evolutionary models of Girardi et al. (2000) to infer the masses of their progenitor stars to be $M_{\text{init}} \sim 6 \,\mathrm{M}_{\odot}$. Since these latter estimates are consistent with the initial masses at and above which stars of solar metallicity are predicted by that generation of the Padova group calculations to reach sufficiently high central temperatures to ignite C and, also, the former values are larger than the H-depleted core masses in these models ($M = 0.97 \,\mathrm{M}_{\odot}$), it has been suggested that the NGC 2516 white dwarfs may be composed of O and Ne (e.g. Weidemann 2005). However, based on our new improved spectroscopy, we find that it is most likely that all four (known) white dwarf members of the cluster have $M < 1.0 \,\mathrm{M_{\odot}}$. This places them below more recent theoretical predictions for the minimum mass of ONe core white dwarfs (e.g. $M \sim 1.05 - 1.1 \,\mathrm{M_{\odot}}$; Gil-Pons et al. 2003; Siess 2007). All four of these objects also now appear to lie within a fairly narrow (final) mass range (Table 1) despite extending over \sim 30 Myr in the cooling age domain (corresponding to $\sim 0.5 M_{\odot}$ variation in initial mass, e.g. Table 2). Some stellar evolutionary models predict that

¹ http://www.eso.org/instruments/fors2/

Table 1. Details of the four white dwarf members of NGC 2516 derived from FORS1 (top) and FORS2 (bottom) observations. The tabulated spectroscopic S/N estimates correspond to per resolution element over the range $\lambda = 4150-4300$ Å. Masses and cooling times for each star have been estimated using the mixed CO core composition 'thick H-layer' evolutionary calculations of the Montreal Group (e.g. Fontaine, Brassard & Bergeron 2001). The quoted limits on the near-IR magnitudes of the white dwarfs correspond to 3σ detections in the images.

ID	S/N	$T_{\rm eff}({\rm K})^a$	$\log g^a$	V^b	J	K _S	M_V	$M({ m M}_{\bigodot})$	$\tau_{\rm c}$ (Myr)
NGC 2516-1	65	29354^{+329}_{-341}	$8.48\substack{+0.05 \\ -0.04}$	19.18 ± 0.10	>19.6	>18.0	$10.80\substack{+0.13 \\ -0.13}$	0.93 ± 0.04	49^{+11}_{-11}
NGC 2516-2	75	34913^{+533}_{-400}	$8.53\substack{+0.06 \\ -0.06}$	19.27 ± 0.07	19.08 ± 0.19	>18.0	$10.56\substack{+0.13 \\ -0.13}$	0.97 ± 0.04	23^{+8}_{-7}
NGC 2516-3	130	28708^{+166}_{-176}	$8.49\substack{+0.03 \\ -0.03}$	19.46 ± 0.13	>19.6	>18.0	$10.87\substack{+0.13 \\ -0.13}$	0.94 ± 0.04	55^{+12}_{-11}
NGC 2516-5	150	31844^{+173}_{-174}	$8.54\substack{+0.03 \\ -0.03}$	19.24 ± 0.14	>19.6	>18.0	$10.74_{-0.14}^{+0.14}$	0.97 ± 0.04	40^{+10}_{-9}
NGC 2516-1	75	29191^{+312}_{-321}	$8.50\substack{+0.04 \\ -0.04}$	-	-	_	$10.85\substack{+0.13 \\ -0.13}$	0.94 ± 0.04	53^{+12}_{-11}

^aFormal fitting uncertainties.

^b As reported in Koester & Reimers (1996).

Table 2. Inferred progenitor masses of all the known white dwarf members of NGC 2516 for the most likely cluster age (column 2) and plausible limiting ages (columns 3 and 4). The white dwarf cooling times were derived using CO core tracks and the stellar lifetimes have been transformed to masses using the solar metallicity evolutionary models of Girardi et al. (2000).

ID		$M_{\rm init}({\rm M}_{\bigodot})$	
Adopted cluster age	150 Myr	120 Myr	180 Myr
NGC 2516-1	$5.35\substack{+0.31 \\ -0.22}$	$6.26\substack{+0.58 \\ -0.43}$	$4.84_{-0.16}^{+0.20}$
NGC 2516-2	$4.91\substack{+0.14 \\ -0.11}$	$5.45\substack{+0.24 \\ -0.16}$	$4.51_{-0.09}^{+0.11}$
NGC 2516-3	$5.50\substack{+0.39 \\ -0.26}$	$6.56\substack{+0.67 \\ -0.52}$	$4.94_{-0.18}^{+0.22}$
NGC 2516-5	$5.19\substack{+0.23 \\ -0.17}$	$5.94\substack{+0.46 \\ -0.32}$	$4.73_{-0.14}^{+0.16}$

the masses of ONe remnants are a strong function of initial mass (e.g. Iben & Tutukov 1985). Moreover, at the most probable age for this cluster, the inferred progenitor masses are now all some way below $6 M_{\odot}$. So, in the light of these new observational results and more recent theoretical predictions, we propose that the cores of the NGC 2516 white dwarfs are composed of C and O rather than O and Ne. If there are ONe core UMWDs within this cluster, they remain to be found.

As the presence of a close companion can substantially impact the evolution of a star, it is also worth briefly discussing here the new near-IR imaging $(J \text{ and } K_S)$ of these objects recently obtained as part of the ESO Visible and Infrared Survey Telescope for Astronomy (VISTA; Dalton et al. 2006; Emerson, McPherson & Sutherland 2006) Hemisphere Survey. This reveals no evidence of unresolved cool companions with $M > 0.04 \,\mathrm{M_{\odot}}$ to NGC 2516-1, -3 or -5. However, these data hint at a possible near-IR excess to NGC 2516-2 (see Fig. 2 and Table 1). These observations were obtained during 2009 December in modest seeing ($\sim 1 \operatorname{arcsec}$). Assuming the source detected at 07h57m50.79s -60°49'55.1" (J2000.0) in the J-band imaging is associated with NGC 2516-2 (there is no detection in the shallower $K_{\rm S}$ imaging, see Table 1), then we appear to be observing about a factor of 2 too much flux in this waveband (we estimate a < 10 per cent likelihood of a chance alignment based on the density of sources of similar or greater brightness in the image). According to the grids of synthetic photometry of Holberg & Bergeron (2006), a $T_{\rm eff} = 35\,000$ K, log g = 8.5 white dwarf could be expected to have V - J = -0.71 ($M_J = 11.2$), but from the VISTA photometry we



Figure 2. A $1 \times 1 \operatorname{arcmin}^2 J$ -band image centred on NGC 2516-2 (north is up and east is to the left). A weak source is seen within $\sim 1 \operatorname{arcsec}$ of the position of this white dwarf as measured from photographic plates (Reimers & Koester 1982).

estimate that NGC 2516-2 has $V - J = 0.19 \pm 0.20$. Although we have not applied any transformations to either the synthetic or the observed photometry to account for the slight differences in the filter systems, any discrepancies are expected to be very small. Moreover, foreground reddening towards the cluster is relatively low, $E(V - J) \approx 0.16$, based on E(B - V) = 0.07 (Kharchenko et al. 2005) and the interstellar extinction curve of Fitzpatrick (1999). We note that according to the NEXTGEN models of Baraffe et al. (1998), an object with $M_J \sim 11$ ($M_{K_S} \sim 10$) has a mass of only ~50 $M_{Jupiter}$ at the age of NGC 2516. Deeper J and K data for NGC 2516-2 should be obtained, in good seeing, to confirm or otherwise the presence of a substellar companion.

3 OBSERVATIONS AND SELECTION OF TARGETS

3.1 The optical imaging surveys

We retrieved *B*- and *V*-band imaging covering $\sim 0.3 \text{ deg}^2$ of sky towards each of NGC 2287 and NGC 3532 from the ESO data archive²

² http://archive.eso.org/cms/



Figure3. Schematic plots of the open clusters NGC 3532 (left) and NGC 2287 (right) with the regions in each which have been surveyed with the ESO 2.2 m + WFI highlighted (large open rectangles). Candidate white dwarf members of the clusters identified from their location in B - V, V colour–magnitude diagrams (five-point stars, both solid and open) and objects which have been followed up spectroscopically with the VLT + FORS (open circles) are overplotted. The locations of previously known white dwarf members of the two clusters are also shown (squares).

(see Fig. 3). These observations, which consist of a short (20- or 30-s) and two 240-s integrations per filter, were undertaken as part of the ESO Imaging Survey on the nights of 1999 December 03 (dark) and 2000 February 24 (bright) respectively, with the Wide Field Imager (WFI; Baade et al. 1999) and the 2.2-m telescope located at La Silla, Chile. The ESO WFI consists of a mosaic of eight *EEV*4096 \times 2048 pixel CCDs and covers an area of 34 \times 33 arcmin² per pointing. The data were reduced using the Cambridge Astronomical Survey Unit CCD reduction toolkit (Irwin & Lewis 2001). We followed standard procedures, namely subtraction of the bias, flat-fielding, astrometric calibration and co-addition. Subsequently, we performed aperture photometry on the reduced images using a circular window with a diameter of 1.5 times the full width at half-maximum of the mean point spread function (\sim 1.0-1.3 arcsec). Finally, we morphologically classified all sources detected in the combined frames and constructed merged catalogues of photometry.

As these archival data sets are more than a decade old, detailed sky transparency information [e.g. Line Of Sight Sky Absorption Monitor (LOSSAM)] for the time at which these observations were conducted is not available to us. Accordingly, to gauge the sky conditions we have examined the instrumental magnitudes of a series of bright (but not saturated) stars in the three sequential sub-integrations per filter. These were found to exhibit only small systematic differences of the order of a few per cent from frame to frame. We have taken this to indicate that the sky was largely clear at the time of these observations. Subsequently, to convert the *B* and *V* instrumental magnitudes on to the standard Johnson system, we adopted zero-points, colour terms and airmass coefficients of $k_0 = 24.53$ and 24.12, ${}^{3} k_1 = 0.31$ and -0.09 and $k_2 = 0.20$ and 0.11, 4

³ www.eso.org/sci/facilities/lasilla/instruments/wfi/inst/zeropoints/ ColorEquations/

⁴ www.eso.org/sci/facilities/lasilla/telescopes/d1p5/misc/Extinction.html

respectively. While we have not performed a rigorous photometric calibration of these data, we believe the accuracy of our magnitudes, where sufficient photons have been detected, is good to ~ 10 per cent. This is sufficient for the purpose of our initial surveys. We estimate from the number of point-like sources detected in the combined frames that these data sets are $\gtrsim 50$ per cent complete at *B*, *V* ≈ 21.5 and *B*, *V* ≈ 22 for NGC 3532 and NGC 2287, respectively.

3.2 Selection of candidate white dwarf members of NGC 3532 and NGC 2287

We have used our catalogues of photometry to construct B - V, V colour-magnitude diagrams for all point-like sources in the optical data (Fig. 4). As a guide to the location of the white dwarf cooling sequence of each cluster, we have highlighted the previously known degenerate members within the surveyed areas (filled squares). Additionally, we have overplotted evolutionary tracks for $M = 0.7, 1.1 \text{ M}_{\odot}$ (CO core, thick H-layer; Fontaine et al. 2001) and $M = 1.16 \text{ M}_{\odot}$ (ONe core, thick H-layer; Althaus et al. 2007) white dwarfs. These have been modified to account for the distance to and foreground reddening towards each cluster i.e. $V - M_V = 8.35$, E(B - V) = 0.05 for NGC 3532 and $V - M_V = 9.30$, E(B - V) = 0.01 for NGC 2287 (see Table 3). Reassuringly, a glance at Fig. 4 reveals that the previously known white dwarf cluster members recovered here lie close to these theoretical tracks.

Since we are primarily interested in identifying the oldest, most massive cluster white dwarfs, for each population we have used the *V* magnitude of the faintest previously known degenerate member ($V \approx 19.8$ for NGC 3532 and $V \approx 20.5$ for NGC 2287) as a guide as to where to set the bright limits of our candidate selection boxes (dashed lines). Moreover, as the lower end of the theoretical tracks plotted in Fig. 4 correspond to the expected locations of white dwarfs which have cooled for a time approximately equal to the maximum likely age of each cluster ($\tau \approx 330$ Myr for NGC 3532



Figure 4. B - V, V colour-magnitude diagrams for all objects classified as stellar (dots) in the ESO WFI imaging of NGC 3532 (left) and NGC 2287 (right). As a guide to the likely location of the cluster white dwarfs, we have highlighted the previously known cluster white dwarfs recovered here (squares) and also overplotted evolutionary tracks for 0.7, 1.1 M_☉ (both CO core, thick H-layer; Fontaine et al. 2001) and 1.16 M_☉ (ONe core, thick H-layer; Althaus et al. 2007) white dwarfs. These tracks have been shifted to distances of $V - M_V = 8.35$ and $V - M_V = 9.30$ and adjusted to allow for a foreground reddenings of E(B - V) = 0.05 and E(B - V) = 0.01 for NGC 3532 and NGC 2287, respectively. The remaining symbols are as defined in the caption of Fig. 3.

Table 3. A summary of the distances and reddenings we adopted in our photometric search for candidate white dwarf members of NGC 2287 and NGC 3532 and the cluster ages and metallicities we assumed in estimating progenitor masses.

Cluster	$V - M_V$	E(B - V)	τ (Myr)	[Fe/H]
NGC 2287	9.30	0.01	243 ± 40	0.00
NGC 3532	8.35	0.05	300 ± 25	0.00

and $\tau \approx 280$ Myr for NGC 2287), we have used these to define the faint limits of our selection boxes. In determining our selection criteria with respect to colour, we have adopted as the red limit the coolest point of the three evolutionary tracks plotted in Fig. 4. This represents a $M = 0.7 \,\mathrm{M_{\odot}}$ white dwarf at the maximum probable age of each cluster. The blue limit is defined by the colour of the $M = 1.16 \,\mathrm{M_{\odot}}$ track and includes an allowance for the estimated uncertainty in the B - V colours (~0.15 mag). The application of these selection criteria leads to the identification of seven and four candidate white dwarf members of NGC 3532 and NGC 2287, respectively. Summary details for these objects, including their coordinates and provisional magnitudes, are given inTable 4. We note that NGC 2287-WDC J0646–2032 has been previously identified as a potential white dwarf member of NGC 2287 (Romanishin & Angel 1980).

3.3 Follow-up spectroscopy with the VLT and FORS

We have obtained follow-up low-resolution optical spectroscopy spanning $\lambda \approx 3750-5200$ Å for six of the candidates listed in Table 4

using the ESO VLT (UT1) and FORS2. These data were acquired in visitor mode on the nights of 2010 February 06 and 07. While seeing was generally good throughout this period, sky transparency on the first night was less than optimal with long spells of moderately thick cirrus. Fortunately, during the second night the sky was largely clear. The data were captured using the 2×2 binning mode of the blue optimized *E2V* CCD, the 600B+24 grism and a 1.3-arcsec slit, which provides a notional spectral resolution of $\lambda/\Delta\lambda \sim 600$. Flat and arc exposures were obtained within a few hours of the acquisition of the science frames.

The CCD data were debiased and flat-fielded using the IRAF procedure CCDPROC. Cosmic ray hits were removed using the routine LACOS SPEC (van Dokkum 2001). Subsequently, the data sets were extracted using the APEXTRACT package and wavelength calibrated by comparison with He+HgCd arc spectra. Remaining instrumental signature was removed using a spectrum of the featureless DC white dwarf LHS 2333 which was obtained using an identical set-up towards the beginning of our programme. The approximate S/N of the co-added data sets is listed in Table 5.

In error, we also spectroscopically observed a source in the direction of NGC 2287 which our photometry indicates is not associated with this cluster (concentric open circles in right-hand panels of Figs 3 and 4). We include this object in the remainder of our investigation as a test of our other membership selection criteria.

4 FUNDAMENTAL PARAMETERS OF THE WHITE DWARF CANDIDATE MEMBERS OF NGC 3532 AND NGC 2287

The energy distributions of all spectroscopically confirmed white dwarfs display the strongly pressure-broadened H-Balmer lines

Table 4. A summary of the astrometric and photometric properties of the 11 candidate white dwarf members of NGC 3532 and NGC 2287 unearthed by our *B*, *V* survey imaging of 0.3 deg^2 of sky towards each cluster. In column 2 we include the ID numbers of candidates towards NGC 3532 as listed in table 2 of Clem et al. (2011).

Survey	Other	RA	Dec.	V	B - V	VLT+FORS
designation	IDs	J20			?	
		(^{h m s})	(°′′′′)			
NGC 3532-WDC J1105-5857	WDJ1105-585, 198279	11 05 23.86	-58 57 23.00	20.6	0.01	Y
NGC 3532-WDC J1106-5856	161574	11 06 16.87	$-58\ 56\ 04.90$	20.0	0.15	Ν
NGC 3532-WDC J1106-5905	WD J1106-590, 160608	11 06 18.35	-59 05 17.33	20.1	0.07	Y
NGC 3532-WDC J1106-5843	WD J1106-584, 134356	11 06 51.65	-58 43 49.03	20.2	0.11	Y
NGC 3532-WDC J1106-5847	128702	11 06 59.07	-58 47 33.85	20.8	-0.03	Ν
NGC 3532-WDC J1107-5842	WD J1107-584, 109695	11 07 21.97	-58 42 12.54	20.5	-0.36	Y
NGC 3532-WDC J1107-5848	104388	11 07 28.74	$-58\ 48\ 24.25$	20.8	0.07	Ν
NGC 2287-WDC J0644-2033	_	06 44 39.84	-20 33 34.08	21.0	-0.25	Ν
NGC 2287-WDC J0645-2025	WD J0645-202	06 45 22.07	$-20\ 25\ 09.67$	21.0	-0.12	Y
NGC 2287-WDC J0645-2050	_	06 45 29.93	$-20\ 50\ 18.45$	21.0	-0.32	Ν
NGC 2287-WDC J0646-2032	WD J0646-203, NGC 2287-4	06 46 01.08	-20 32 03.42	20.9	-0.27	Y

Table 5. Details of the new white dwarf candidate members of NGC 3532 (upper) and NGC 2287 (lower) and the 'test' object in the direction of the latter cluster (bottom) observed with the VLT. The tabulated spectroscopic S/N estimates correspond to per resolution element over the range $\lambda = 4150-4300$ Å. Masses and cooling times for each star have been estimated using the mixed CO core composition 'thick H-layer' evolutionary calculations of the Montreal Group (Fontaine et al. 2001). The errors in absolute magnitudes, masses and cooling times shown here are derived by propagating more realistic uncertainties in effective temperature and surface gravity of 2.3 per cent and 0.07 dex, respectively.

WD	S/N	T _{eff} ^a (K)	$\log g^a$	V	M_V	M (M _☉)	τ _c (Myr)	$\mu_{\alpha}\cos\delta$ (mas yr ⁻¹)	μ_{δ} (mas yr ⁻¹)	Mem?
J1105-585	120	13329^{+647}_{-442}	$8.19^{+0.06^a}_{-0.11}$	20.33 ± 0.04	$11.75_{-0.11}^{+0.11}$	0.72 ± 0.04	370^{+50}_{-43}	$+4.5 \pm 4.1$	-6.9 ± 4.1	×
J1106-590	115	19690^{+333}_{-339}	$8.45\substack{+0.03 \\ -0.03}$	20.04 ± 0.03	$11.51\substack{+0.13 \\ -0.13}$	0.90 ± 0.04	188^{+29}_{-26}	-7.9 ± 3.4	$+0.5\pm3.4$	\checkmark
J1106-584	100	18833^{+338}_{-335}	$8.52\substack{+0.03 \\ -0.03}$	20.16 ± 0.04	$11.71\substack{+0.13 \\ -0.13}$	0.94 ± 0.04	243^{+37}_{-32}	-5.7 ± 3.8	-1.0 ± 3.6	\checkmark
J1107-584	80	20923^{+505}_{-497}	$8.61\substack{+0.07 \\ -0.07}$	20.19 ± 0.04	$11.69_{-0.13}^{+0.14}$	1.00 ± 0.04	210^{+33}_{-29}	-3.9 ± 3.9	$+4.6\pm4.3$	\checkmark
J0645-202	60	$14716\substack{+378\\-452}$	$7.97\substack{+0.04 \\ -0.04}$	20.97 ± 0.04	$11.26\substack{+0.11 \\ -0.11}$	0.59 ± 0.04	200^{+30}_{-26}	$+3.1\pm4.3$	$+9.9\pm6.4$	×
J0646-203	115	25520^{+380}_{-351}	$8.82\substack{+0.06\\-0.06}$	20.91 ± 0.03	$11.73\substack{+0.15 \\ -0.15}$	1.12 ± 0.04	175^{+27}_{-25}	-4.2 ± 3.4	-0.3 ± 2.6	\checkmark
J0644-205	90	$12376\substack{+230 \\ -233}$	$7.98\substack{+0.06 \\ -0.05}$	20.52 ± 0.03	$11.57\substack{+0.10 \\ -0.10}$	0.59 ± 0.04	334^{+41}_{-35}	$+6.9\pm3.3$	-3.4 ± 3.3	×

^aFormal fit errors - see text for further details.

characteristic of the spectral type DA. To obtain estimates of the fundamental parameters of our six candidates (and our test object) so that we can further scrutinize their cluster membership status, we have compared the Balmer lines in each spectrum to synthetic line profiles obtained from model atmosphere calculations.

4.1 The model atmosphere calculations

The grid of synthetic pure H spectra we use here is virtually identical to the one used in our previous work on these open clusters (i.e. Dobbie et al. 2009a) with the exception that it has been extended to slightly lower effective temperatures ($T_{\rm eff} = 12500-35000$ K). To reiterate, our models have been generated using relatively recent versions of the plane-parallel, hydrostatic, non-local thermodynamic equilibrium (non-LTE) atmosphere and spectral synthesis codes TLUSTY (v200; Hubeny 1988; Hubeny & Lanz 1995) and SYNSPEC (v49; Hubeny & Lanz 2001, http://nova.astro.umd.edu/). The model H atom employed in the calculations incorporates the eight lowest energy levels and one superlevel extending from n = 9 to 80. Dissolution of the high lying levels has been treated by means of the occupation probability formalism of Hummer & Mihalas

(1988), generalized to the non-LTE situation by Hubeny, Hummer & Lanz (1994). The calculations included the bound-free and freefree opacities of the H⁻ ion and incorporated a full treatment for the blanketing effects of H_I lines and the Lyman α , Lyman β and Lyman γ satellite opacities as computed by N. Allard (e.g. Allard et al. 2004). For models with $T_{\rm eff} > 16\,000\,\rm K$ we assumed radiative equilibrium while at $T_{\rm eff} \leq 16\,000\,\rm K$ we included a treatment for convective energy transport according to the ML2 prescription of Bergeron et al. (1992), with a mixing length parameter of $\alpha =$ 0.6. During the calculation of the model structure the hydrogen line broadening was addressed in the following manner: the broadening by heavy perturbers (protons and hydrogen atoms) and electrons were treated using Allard's data (including the quasi-molecular opacity) and an approximate Stark profile (Hubeny et al. 1994), respectively. In the spectral synthesis step detailed profiles for the Balmer lines were calculated from the Stark broadening tables of Lemke (1997).

4.2 Effective temperatures and surface gravities

As in our previous work (e.g. Dobbie et al. 2009b, 2012), the comparison between the models and the data is undertaken using the spectral fitting program XSPEC (Shafer, Arnaud & Tennant 1991). In the present analysis, all lines from H β to H-8 are included in the fitting process. XSPEC works by folding a model through the instrument response before comparing the result to the data by means of a χ^2 -statistic. The best-fitting model representation of the data is found by incrementing free grid parameters in small steps, linearly interpolating between points in the grid, until the value of χ^2 is minimized. Formal errors in the T_{eff} values and log g values are calculated by stepping the parameter in question away from its optimum value and redetermining minimum χ^2 until the difference between this and the true minimum χ^2 corresponds to 1σ for a given number of free model parameters (e.g. Lampton, Margon & Bowyer 1976). The results of our fitting procedure are given in Table 5 and are shown overplotted on the data in Fig. 5.

It should be noted that the formal 1σ parameter errors quoted here undoubtedly underestimate the true uncertainties. In our subsequent analysis, we have adopted what are considered more realistic levels of uncertainty of 2.3 per cent and 0.07 dex in effective temperature and surface gravity, respectively (e.g. Napiwotzki, Green & Saffer 1999).

4.3 Distances

To place stringent constraints on the distances and to measure the proper motions of the seven new spectroscopically confirmed DA white dwarfs, we have obtained additional observations with the Inamori Magellan Areal Camera and Spectrograph (IMACS) and



Figure 5. The results of our fitting of synthetic profiles (thin black lines) to the observed Balmer lines, $H\beta$ to H-8, of the six white dwarf candidate members of NGC 3532 and NGC 2287 (thick grey lines). The flux_{λ} units are arbitrary.

the 6.5-m Magellan Baade telescope. IMACS is a wide-field imaging system (or multi-object spectrograph) in which light from the Gregorian secondary of the telescope is fed to one of two cameras, either short (f/2.5) or long (f/4.3). The former camera, which was used for these observations, contains a mosaic of eight 2048 × 4096 pixel *E2V* CCDs. It covers a 27.5 × 27.5 arcmin² (0.20 arcsec pixels) area of sky per pointing but suffers from strong vignetting at distances >15 arcmin from the field centre.

We acquired 30-s integrations on each object through the V_{Bessell} filter during the photometric night of 2010 April 09 (JD = 2455296.25) when the seeing was ~0.7 arcsec. All targets were centred on CCD 2 to negate the effects of chip-to-chip colour sensitivity variations. The frames were reduced, as per the ESO WFI data, using the Cambridge Astronomical Survey Unit CCD reduction toolkit (Irwin & Lewis 2001) to follow the steps listed in Section 3.1. As before, we performed aperture photometry on the reduced images using a circular window with a diameter of 1.5 times the full width at half-maximum of the mean point spread function (~0.7 arcsec). Several different standard star fields were also observed on CCD 2 through both the V_{Bessell} and the I_{CTIO} filters during the course of this run to allow us to transform our instrumental magnitudes on to the Johnson system,

$$m = -2.5 \gtrsim g \,(\text{ADU}/t_{\text{exp}}) + K_0 + K_1 X + K_2 (V - I),$$
 (1)

where ADU is a measure of the total counts from the source, t_{exp} the exposure time and X the airmass. The coefficients and their respective errors were determined to have the values shown in Table 6 and our revised V magnitude estimates for the white dwarfs are given in Table 5. For the objects in the field of NGC 2287, this more precise photometry is consistent with that based on the ESO WFI data. For the NGC 3532 white dwarfs, our refined magnitudes are in excellent agreement with the values determined by Clem et al. (2011), but typically brighter than our preliminary WFI measurements by 0.1–0.3 mag. This suggests that our survey of this cluster is shallower by 0.1–0.3 mag at V than was initially concluded.

We have used our measurements of the effective temperatures and surface gravities of the white dwarfs shown in Table 5 and the model grids of Bergeron, Wesemael & Beauchamp (1995), as revised by Holberg & Bergeron (2006), to derive absolute magnitudes (M_V ; see Table 5). Subsequently, we have determined the distance moduli of all seven white dwarfs observed with the VLT and FORS, neglecting foreground extinction which is low ($A_V \leq 0.15$) along the lines of sight to NGC 3532 and NGC 2287. These are plotted (solid bars) along with a number of distance estimates available in the literature for each of these clusters (dashed vertical lines) in Fig. 6. Based on examination of this figure, we consider that five out of the six white dwarf candidate cluster members have estimated distances which are consistent with those of their putative parent populations (i.e. within 2σ of the mean). However, we find WD J0645–202 to lie substantially behind NGC 2287 and on this basis conclude that it is probably a field object. Not unexpectedly, the cooler, redder, 'test' white dwarf, WD J0644-205, appears to reside in front of this cluster, albeit marginally.

Table 6. The coefficients (zero-point, airmass and colour term) determined for equation (1), the transformation between instrumental magnitudes and Johnson *V*.

K ₀	K_1	<i>K</i> ₂
27.447 ± 0.020	-0.142 ± 0.016	0.0004 ± 0.0062



Figure 6. The derived distance moduli of the white dwarf candidate members of NGC 3532 (upper panel) and NGC 2287 (lower panel) observed with the VLT and FORS. The estimated distance modulus of a control object lying in the field of NGC 2287 is also shown (grey typeface). The distance modulus of NGC 3532 as estimated by Meynet, Mermilliod & Maeder (1993; $V - M_V = 8.35$), Robichon et al. (1999; m - M = 8.04) and Kharchenko et al. (2005; $V - M_V = 8.61$) and the distance modulus of NGC 2287 as estimated by Harris et al. (1993; $V - M_V = 9.41$), Meynet, Mermilliod & Maeder (1993; $V - M_V = 9.15$), Kharchenko et al. (2005; $V - M_V = 9.30$) and Sharma et al. (2006; $V - M_V = 9.30$) are overplotted. All new white dwarf candidate members have distances consistent with their proposed host clusters, except WD J0645–202 which appears to lie someway behind NGC 2287.

4.4 Proper motions

To further explore the cluster membership credentials of these white dwarfs, we have exploited the epoch difference of approximately a decade between the archival ESO WFI V-band data sets and our new IMACS V-band images to measure their relative proper motions. Astrometry is a potentially powerful method of discriminating members of a cluster from the general field population (e.g. Hambly, Hawkins & Jameson 1993). We have re-examined the images using the Cambridge Astronomical Survey Unit (CASU) reduction toolkit to determine the positions, in pixels, of bright (but not saturated), unblended, stellar-like objects lying within ~ 2 arcmin and on the same CCD chip as each candidate. We cross-matched these lists of reference star positions using the STARLINK TOPCAT software. Subsequently, we employed routines in the STARLINK SLALIB library to construct six coefficient linear transforms between the two images of each candidate, where $>3\sigma$ outliers were iteratively clipped from the fits. The proper motions, in pixels, were determined by taking the differences between the observed and predicted locations of candidates in the second epoch imaging. These were then converted into mas yr⁻¹ in right ascension and declination using the world coordinate systems of the data sets and dividing by the time baseline between the two observations (~10.12 yr for NGC 3532 and 10.35 yr for NGC 2287). The uncertainties on these measurements were estimated from the dispersion observed in the (assumed zero) proper motions of stars with similar brightness ($|\Delta V| \leq 0.5$ mag) surrounding each white dwarf. The relative proper motion vector point diagrams for the objects towards each cluster are shown in Fig. 7 (five-point stars) and the measurements are listed in Table 5. The absolute proper motions of each cluster, on the Hipparcos system (Kharchenko et al. 2005; van Leeuwen 2009), have been overplotted (grey open circles) after shifting them by $\mu_{\alpha} \cos \delta$, $\mu_{\delta} = +2.8, -1.7$ and -1.2, -1.8 mas yr⁻¹ for NGC 3532 and NGC 2287, respectively, to account for the difference between the relative and the absolute frames of reference. These offsets were estimated by taking the median of the absolute proper motions of stars at the faint end of the United States Naval Observatory CCD Astrograph Catalog 3 (UCAC3) catalogue which reside within the survey areas. We note that there is a substantial overlap with our reference stars.



Figure 7. A vector point diagram of the relative proper motions of the seven spectroscopically observed white dwarfs towards NGC 3532 (left) and NGC 2287 (right). The proper motions expected to be displayed by members of the two clusters are overplotted (grey open circles). These have been shifted to account for the difference between the relative and absolute frames of reference. Objects with proper motions deemed consistent with the cluster populations are highlighted (solid symbols). The proper motion of an additional photometric candidate white dwarf member of NGC 3532 is also shown (open triangle, see text for further details).

Of the three white dwarfs in the direction of NGC 2287 that were observed with the VLT and FORS2, we find only WD J0646-203 (solid star in right-hand panel) has a proper motion which we deem to be consistent with this cluster (i.e. within 2σ). While three objects (solid stars in left-hand panel) towards NGC 3532 have proper motions within 1σ of the cluster mean value, WD J1105-585 (leftmost open star) lies more than 3σ away and on these grounds seems unlikely to be associated with NGC 3532. The proper motion of NGC 3532-WDC J1105-5842 (open triangle), an additional object which we were able to include in our astrometric study due to its spatial proximity to WD J1105-585, is found to be discrepant from that of the cluster at >4 σ ($\mu_{\alpha} \cos \delta$, $\mu_{\delta} = -20.9 \pm 3.0, \pm 2.8 \pm$ 5.4 mas yr^{-1}). This object has similar colours to WD J1106-590 and WD J1106-584, $B - V \approx 0.1$ and despite lying close enough to the theoretical tracks in the B - V, V colour-magnitude diagram to be considered a photometric cluster member, was too bright ($V \approx$ 19.7) to have featured in our spectroscopic follow-up programme.

5 NEW SOUTHERN OPEN CLUSTER WHITE DWARFS

The four objects identified in Section 4 as having properties consistent with cluster membership represent the faintest white dwarfs in NGC 3532 and NGC 2287 unearthed to date. Once again, we have used the evolutionary models of Fontaine et al. (2001) to determine their masses and cooling times. For completeness, we have also derived the masses and cooling times for the three white dwarfs in our spectroscopic sample which we have already rejected as probable field objects. So that this work is consistent with our previous efforts and those of several other recent studies in this area (e.g. Kalirai et al. 2008; Casewell et al. 2009; Dobbie et al. 2009a; Williams et al. 2009), we have (initially) adopted the calculations which include a mixed CO core and thick H surface layer structure.

5.1 Is WD J0646-203 in NGC 2287 an ONe core white dwarf?

Based on our measurements of effective temperature and surface gravity, we have determined the mass of WD J0646–203 to be M = $1.12 \pm 0.04 \,\mathrm{M_{\odot}}$ (Table 5). While the astrometric characteristics, the distance modulus and the projected location of this white dwarf only ~ 0.37 from the cluster centre (i.e. within the projected tidal radius, e.g. Cox 1954; Piskunov et al. 2008) are firmly suggestive of an association with NGC 2287, we have none the less explored the likelihood that it is merely a field star. At $T_{\rm eff} > 25\,000\,{\rm K}$, WD J0646-203 is hot enough to radiate significantly in the EUV and, had it been located within the Local Bubble, would likely have been detected in the EUV all-sky surveys (Pye et al. 1995; Bowyer et al. 1996). Vennes et al. (1997) have computed the space density of EUV-detected white dwarfs to be $n \approx 1.6-2.2 \times 10^{-5} \text{ pc}^{-3}$. Liebert et al. (2005a) have estimated that only \sim 1/5th of white dwarfs in the Palomar–Green Survey have $M > 0.8 M_{\odot}$, while Vennes et al. (1997) find that 10 out of their sample of 90 have $M \gtrsim 1.1 \,\mathrm{M_{\odot}}$. We estimate that as a result of flagging as potential members those objects with distance moduli consistent with the cluster mean at the 2σ level, our survey has probed a volume of ~9500 pc³. Thus, with the above space densities we should have expected to unearth ~ 0.04 hot, massive field white dwarfs in our study of NGC 2287. Assuming a Poisson distribution, we determine that the probability of us detecting one field object with the characteristics of WD J0646-203 is rather low, $P \lesssim 0.04$, and we are led to conclude that this white dwarf is a bona fide member of NGC 2287.

Some theoretical studies suggest that the surface H-layers of the most massive white dwarfs may be of significantly lower mass than the $10^{-4} \,\mathrm{M_{\odot}}$ adopted in the 'standard' evolutionary models (e.g. Garcia-Berro et al. 1997). Consequently, we have re-evaluated the parameters of WD J0646-203 using the thin H-layer models of the Montreal group which allow for a surface H mass of only 10^{-10} M_{\odot}. In this case, we obtain a slightly lower mass and marginally shorter cooling time but the differences between the two determinations are less than $0.02 \,M_{\odot}$ and 3 Myr, respectively. Since we know the effective temperature of WD J0646-203 from our spectroscopy, to perform something of a sanity check on these mass determinations, we have also estimated it by assuming, a priori, that this white dwarf lies at the distance of the cluster, calculating its radius and applying a theoretical mass-radius relation. If the assumption of cluster membership is safe, the systematic uncertainty in the mass estimate, which relates to our spectroscopic analysis method and our choice of atmosphere code for generating the synthetic H line profiles (e.g. Liebert et al. 2005a), should be reduced here. Using the effective temperature shown in Table 5, the arithmetic mean of the four distance moduli listed in the caption of Fig. 6 $(m_V - M_V)$ 9.29 ± 0.09) and the mass-radius relation from the thick and thin Hlayer CO core evolutionary models, we determine WD J0646-203 to have $M = 1.09 \pm 0.03$ and 1.07 ± 0.03 M_{\odot}, respectively.

These values argue that WD J0646-203 is potentially the most massive white dwarf yet identified within an open cluster. For example, LB1497, the sole white dwarf located within the projected tidal radius of the Pleiades cluster, has $M = 1.05 \pm 0.02 \,\mathrm{M_{\odot}}$, based on a weighted mean of the estimates in Bergeron et al. (1995), Dobbie et al. (2006b) and Vennes & Kawka (2008), which were derived using thick H-laver CO core evolutionary models. The masses of the four most massive white dwarfs recently unearthed in the slightly metal-poor cluster NGC 2168, which were also derived using thick H-layer CO core tracks, appear to be clumped around M = 1.01– 1.02 M_☉ (Williams et al. 2009). Indeed, our CO core based mass determinations for WD J0646-203 sit on or above recent theoretical predictions for the minimum mass of ONe core white dwarfs (e.g. $M \sim 1.05-1.1 \,\mathrm{M_{\odot}}$; Gil-Pons et al. 2003; Siess 2007). The most likely progenitor mass we infer of $M_{\rm init} \sim 6.3-6.4 \,\mathrm{M_{\odot}}$ (thin or thick H-layer white dwarf models) is also consistent with the initial mass range where some solar metallicity stellar evolutionary calculations, which include overshooting from the convective regions of the star, predict central C ignition $(M_{\text{init}} > 6 \text{ M}_{\odot})$, e.g. Eldridge & Tout 2004; Bertelli et al. 2009). While the ignition of C in the core is anticipated to occur only at larger initial masses (by $\sim 1-2 M_{\odot}$) in stellar models that neglect to treat this phenomenon, a number of distinct observational-based results provide compelling arguments in favour of significant convective overshooting (e.g. Woo et al. 2003; Claret 2007; Salaris et al. 2009). Moreover, despite our inferred progenitor mass $(M_{\rm init} \sim 5.2 \,\mathrm{M_{\odot}})$ for a cluster age towards the upper end of the plausible range for NGC 2287 (see Table 7), probably being too low for a star of this composition to have experienced central C burning, in this eventuality, WD J0646-203 would appear as something of an outlier in a semi-empirical IFMR, sitting $\gtrsim 0.1 \, \text{M}_{\odot}$ above all other white dwarfs from solar metallicity populations located in this part of the initial mass domain, e.g. the well-studied Sirius B (Barstow et al. 2005; Liebert et al. 2005b) and the NGC 3532 and NGC 2516 objects studied by us here using a similar spectroscopic set-up and the same models and analysis techniques cluster around $M \sim 0.95 - 1.0 \,\mathrm{M_{\odot}}$. Of course, this variation could be statistical in nature but earlier we noted that our estimates of mass obtained using two different approaches are in good agreement.

Table 7. Inferred progenitor masses of all the known white dwarf members of NGC 2287 for the most likely cluster age (column 2) and plausible limiting ages (columns 3 and 4). The cooling times of all white dwarfs were initially derived using CO core tracks. The cooling time of WD J0646–203 was also evaluated using ONe models (bottom row). The estimated stellar lifetimes have been transformed to masses using the solar metallicity evolutionary models of Girardi et al. (2000) *Upper limit of model grid (20 M_{\odot}).

ID Adopted cluster age	243 Myr	$M_{\rm init}({ m M}_{\odot})$ 203 Myr	283 Myr
NGC 2287-2	$4.45_{-0.15}^{+0.20}$	$4.99_{-0.22}^{+0.28}$	$4.08\substack{+0.14 \\ -0.10}$
NGC 2287-5	$4.57\substack{+0.24 \\ -0.18}$	$5.16\substack{+0.37 \\ -0.25}$	$4.17\substack{+0.16 \\ -0.12}$
WD J0646-203	$6.41^{+1.54}_{-0.87}$	$9.73^{*}_{-2.58}$	$5.22^{+0.68}_{-0.39}$
WD J0646-203	$5.94\substack{+1.19 \\ -0.60}$	$8.06\substack{+7.14 \\ -1.34}$	$5.02^{+0.51}_{-0.32}$

Bearing in mind that objects of ONe composition are expected to adhere to a slightly different mass-radius relation, we have reevaluated the parameters of WD J0646-203 once again, this time using the ONe core evolutionary tracks of Althaus et al. (2007). Based on our spectroscopic effective temperature and surface gravity measurements, we estimate a mass and a cooling time of M = $1.09 \pm 0.04 \,\mathrm{M_{\odot}}$ and $\tau_{\rm cool} = 164^{+26}_{-22}$ Myr, respectively. Following our other approach, where we assume WD J0646-203 lies at the distance of NGC 2287, we determine $M = 1.05 \pm 0.03 \,\mathrm{M_{\odot}}$. These revised parameters for our object remain in accord with modern theoretical estimates of the minimum mass of an ONe core UMWD at approximately solar metallicity (Siess 2007) and, for the most likely cluster age, lead to an inferred progenitor mass consistent with the initial mass range where central C ignition is anticipated (see Table 7). Clearly it not possible for us to definitively determine the composition of the core of WD J0646-203, but on the basis of our new observations and guided by modern theoretical calculations, we conclude that there is a distinct possibility that it consists of O and Ne, having evolved from a single, heavy-weight, intermediate-mass progenitor star.

5.2 The NGC 3532 white dwarfs

In our previous work on NGC 3532, we revisited six white dwarfs in the direction of the cluster and confirmed four as members (Dobbie et al. 2009a). Two objects, NGC 3532-6 and NGC 3532-8, were rejected by us on the basis that our revised estimates of their distances are incompatible with that of the cluster. We have now found three further white dwarfs members of NGC 3532, taking the total number to seven and making this one of the richest hauls of cluster degenerates where good quality optical spectroscopy has been secured. This population is important since NGC 3532 has a turn-off mass of $M_{init} \approx 3.5 \, M_{\odot}$ and spans the age gap between the younger NGC 2168 and more mature Praesepe and Hyades clusters.

Despite our new study probing fainter magnitudes than the previous photographic survey of the cluster, we have not identified any compelling candidate ultramassive ONe core white dwarf members of NGC 3532 (i.e. $M \gtrsim 1.05 \,\mathrm{M_{\odot}}$ and $M_{\rm init} \gtrsim 6 \,\mathrm{M_{\odot}}$). Instead, the three new fainter degenerate members have masses that are similar to that of the previously known faintest white dwarf in the cluster, NGC 3532-10. Intriguingly, despite their comparable masses, we find that the cooling times of these four most massive white dwarf members span a range of ~90–100 Myr, irrespective of our choice of thick or thin H-layer evolutionary models. For example, for WD J1106–584 we estimate $\tau_{\rm cool} \sim 240$ Myr while for NGC 3532-10 we determined $\tau_{\rm cool} \sim 150$ Myr. We suggested in our previous study, where we analysed an ensemble of ~50 white dwarfs from ~10 mainly cluster populations, that the IFMR is less steep at $M_{\rm init} \approx 4 \,\mathrm{M_{\odot}}$ than immediately below this initial mass regime. We noted that the distribution of these white dwarfs mirrored the form of the theoretical relationship between the initial mass of a star and the mass of the CO core at the time of the first thermal pulse (1TPR) as it evolves on to the AGB (e.g. Becker & Iben 1979). Salaris et al. (2009) independently reached a similar conclusion regarding the slope of the (semi-) empirical relation by comparing the heterogeneous open cluster data to an IFMR predicted by the BaSTI stellar evolutionary models of Pietrinferni et al. (2004).

Nevertheless, given the rather heterogeneous nature of that ensemble of white dwarfs, it is conceivable that cluster to cluster age uncertainties could have conspired in such a way to mislead us. For example, if the ages of the youngest populations which dominate the upper end of the relation are systematically underestimated with respect to the more mature populations which dominate the lower end, then the semi-empirical IFMR would appear less steep at higher initial masses. However, independent of both the age we adopt for NGC 3532, within plausible limits, and our choice of white dwarf evolutionary model grid (thick or thin surface H-layers), the location in initial-final mass space of these seven degenerates (Fig. 8 and see also Table 8), which span a broad range in initial mass yet are vulnerable to only a single cluster age uncertainty, is also consistent with the trend outlined by the 1TPR (e.g. Wagenhuber & Groenewegen 1998) and the theoretical IFMR (e.g. Marigo & Girardi 2007). This lends some further support to both our earlier conclusion and that of Salaris et al. (2009) regarding the form of the IFMR.

Population synthesis calculations which adopt an IFMR with a lower gradient above $M_{\text{init}} \approx 4 \,\mathrm{M}_{\odot}$ than in the immediately lower initial mass regime better reproduce the shape of the field white dwarf mass distribution, in particular the secondary peak at $M \sim$ $0.8-1.0 \,\mathrm{M}_{\odot}$, than those which employ a relation with a simple linear form (Ferrario et al. 2005). It has been proposed previously that $\gtrsim 80$ per cent of white dwarfs with $M > 0.8 \,\mathrm{M_{\odot}}$ might originate from binary mergers (e.g. Liebert et al. 2005a), but such a change in the gradient of the IFMR mitigates the need to invoke such an evolutionary channel to explain their existence. That stellar evolution might be able to readily produce large CO cores without the need for mergers is potentially important in the context of Type Ia supernovae which are believed to result from the complete thermonuclear disruption of massive CO white dwarfs (e.g. Yungelson & Livio 2000). For example, in a leading, current, theoretical formation channel, the sub-Chandrasekhar double-detonation model, the more massive a CO core progenitor, the less material is required to be accreted to trigger the explosion. We note that the lifetimes of those stars to which the less steep section of the IFMR is applicable (i.e. $M_{\text{init}} \gtrsim 4 \,\mathrm{M}_{\odot}$) are comparable to the time-scales of the prompt component of the Type Ia delay time distribution (e.g. see Ruiter et al. 2011).

6 SUMMARY

We have performed a CCD photometric survey, complemented by optical spectroscopic and astrometric follow-up studies, of $\sim 0.3 \text{ deg}^2$ of sky towards each of the young/intermediate age open clusters NGC 3532 and NGC 2287, in a bid to unearth intrinsically faint white dwarf members. This work has led to the



Figure 8. The location of the seven known NGC 3532 white dwarfs in initial-final mass space for the most likely cluster age (300 Myr, black triangles) and appropriate limiting ages (275 Myr, grey circles and 325 Myr, grey squares). A theoretical IFMR from Marigo & Girardi (2007) (dark-grey dashed line) and a 1TPR from Wagenhuber & Groenewegen (1998) (light-grey dot-dashed line) are overplotted.

Table 8. Inferred progenitor masses of all the known white dwarf members of NGC 3532 for the most likely cluster age (column 2) and plausible limiting ages (columns 3 and 4). The white dwarf cooling times were derived using CO core tracks and the stellar lifetimes have been transformed to masses using the solar metallicity evolutionary models of Girardi et al. (2000).

ID		$M_{\rm init}({\rm M}_{\bigodot})$	
Adopted cluster age	300 Myr	275 Myr	325 Myr
NGC 3532-1	$3.83^{+0.09}_{-0.07}$	$3.99^{+0.10}_{-0.09}$	$3.69^{+0.08}_{-0.06}$
NGC 3532-5	$3.71\substack{+0.06 \\ -0.05}$	$3.85\substack{+0.07 \\ -0.06}$	$3.59\substack{+0.06\\-0.04}$
NGC 3532-9	$3.57\substack{+0.02 \\ -0.01}$	$3.69\substack{+0.02 \\ -0.01}$	$3.47\substack{+0.01\\-0.01}$
NGC 3532-10	$4.58\substack{+0.35 \\ -0.24}$	$4.92\substack{+0.43 \\ -0.31}$	$4.30\substack{+0.28 \\ -0.19}$
WDJ1106-590	$5.14\substack{+0.69 \\ -0.39}$	$5.70^{+1.19}_{-0.57}$	$4.76\substack{+0.47 \\ -0.32}$
WDJ1106-584	$6.92^{+4.92}_{-1.28}$	$9.01\substack{+9.14 \\ -2.42}$	$5.86^{+1.75}_{-0.75}$
WDJ1107-584	$5.64^{+1.33}_{-0.59}$	$6.58\substack{+2.60 \\ -1.05}$	$5.11\substack{+0.79 \\ -0.42}$

identification of four new white dwarfs which are probably cluster members, three in NGC 3532 and one in NGC 2287. Spectroscopic analysis of these objects has revealed WD J0646–203 to be potentially the most massive white dwarf member of an open cluster unearthed so far, with there being a distinct possibility of it having a core composed of O and Ne ($M = 1.02-1.16 \,\mathrm{M_{\odot}}$). Our study has also shown that, despite a range of ~90 Myr in age, the four most massive degenerates in NGC 3532 are rather similar in mass, consistent with our earlier suggestions that the IFMR could be less steep at $M_{\rm init} \gtrsim 4 \,\mathrm{M_{\odot}}$ than at initial masses immediately below this (Fig. 8). The results of our analysis of new and improved spectroscopy of the four known NGC 2516 white dwarfs are also in agreement with our prior conclusion.

However, further studies of young/intermediate age, rich, open clusters remain necessary to better determine the relative frequencies of massive and ultramassive degenerates and to pin down the maximum mass of a white dwarf that can form via canonical stellar evolution. It appears probable that additional constraints on the form of the IFMR will come from NGC 3532, since a more extensive CCD survey of the cluster has recently unearthed many more faint candidate white dwarf members (Clem et al. 2011). Low-resolution optical spectroscopy with good S/N is now required to characterize these objects. Substantial amounts of time on the current generation of large telescopes would be required to obtain spectroscopy of the faintest white dwarf members of attractive, even richer but more distant clusters. Alternatively, it might be possible to address this type of investigation photometrically since simulations suggest that in the U, U - V colour-magnitude diagram of a very rich cluster with $\tau \sim 200-300$ Myr (e.g. NGC 6705), a putative UMWD population would define a rather prominent blue hook at the bottom end of the cooling sequence and give rise to a secondary peak in the U-band luminosity function. Detection of this feature would need photometry of good quality down to $V \approx 25$, so even this approach could prove rather challenging given the likely levels of scattered light from the large number of intrinsically bright stars in rich clusters of this age.

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