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A new detailed examination of white dwarfs in NGC 3532 and NGC 2287⋆

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ABSTRACT

We present the results of a photometric and spectroscopic study of the white dwarf candidate members of the intermediate age open clusters NGC 3532 and NGC 2287. Of the nine objects investigated, it is determined that six are probable members of the clusters, four in NGC 3532 and two in NGC 2287. For these six white dwarfs, we use our estimates of their cooling times together with the cluster ages to constrain the lifetimes and masses of their progenitor stars. We examine the location of these objects in initial mass–final mass space and find that they now provide no evidence for substantial scatter in initial mass–final mass relation (IFMR) as suggested by previous investigations. Instead, we demonstrate that, when combined with current data from other solar metallicity open clusters and the Sirius binary system, they hint at an IFMR that is steeper in the initial mass range 3 $M_{\odot} \lesssim M_{\rm init} \lesssim 4\ M_{\odot}$ than at progenitor masses immediately lower and higher than this. This form is generally consistent with the predictions of stellar evolutionary models and can aid population synthesis models in reproducing the relatively sharp drop observed at the high mass end of the main peak in the mass distribution of white dwarfs.

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

1 INTRODUCTION

Standard stellar evolutionary theory predicts the existence of a positive correlation between the main-sequence mass of a star ($M \lesssim 10\ M_{\odot}$) and the mass of the white dwarf remnant left behind after it has expired. This is frequently referred to as the initial mass–final mass relation (IFMR). A secure and detailed knowledge of the form of the IFMR is important to a number of very active areas of astrophysical research. For example, the relation is a key ingredient of models of the chemical evolution of the Galaxy as it provides an estimate of the amount of gas, enriched with C, N and other metals, a low or intermediate mass star returns to the interstellar medium (e.g. Carigi, Colin & Peimbert 1999). Moreover, understanding the form of the IFMR is crucial to deciphering information locked up in the white dwarf luminosity functions of stellar populations (e.g. Oswalt et al. 1996; Jeffery et al. 2007). The shape of the upper end of the IFMR is of special interest as it places limits on the minimum mass of a star that will experience a Type II supernova explosion. With robust constraints on this mass, for example, the observed diffuse supernovae neutrino background can serve as an empirical normalization check on estimates of the star formation history of the Universe (e.g. Hopkins & Beacom 2006).

Unfortunately, due to the complexity of the physical processes occurring within stars, especially during the final stages of the stellar lifecycle, the form of the IFMR is rather difficult to ascertain from first principles. For example, the mass of the stellar core which ultimately becomes the white dwarf is probably modified with each thermal pulse cycle on the asymptotic giant branch (AGB). The final remnant mass predicted by evolutionary models is therefore dependent on the length of time a star is assumed to spend on the AGB. However, evolution on the AGB is terminated by the removal of the stellar envelope so the predicted duration of this phase is susceptible to the assumptions made about the rate at which envelope mass is lost (e.g. Iben & Renzini 1983). While significant inroads are being made in the theoretical understanding of mass loss on the AGB (e.g. Bowen 1988; Wachter et al. 2002), a comprehensive and robust physical treatment remains elusive.

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Therefore, empirical data currently play a crucial role in improving our understanding of the form of the IFMR. Arguably the best way at present to obtain observational-based constraints on the IFMR is through the study of the white dwarf members of open star clusters. The ages of these coeval populations can be determined from the location of the main-sequence turn-off or the lithium depletion boundary in the sequence of the lowest mass members (e.g. Pleiades; Stauffer, Schultz & Kirkpatrick 1998). The progenitor star lifetimes and ultimately their masses can then be estimated by calculating the difference between the age of the parent population and the cooling times of white dwarf members. It is worth pointing out, however, that as theoretical input is required at this latter stage, in the form of stellar evolutionary models, constraints acquired in this way are more appropriately termed semi-empirical (e.g. Weidemann & Koester 1983).

With greater access to 8-m class telescopes and the availability of improved instrumentation, the last few years has seen a flurry of new studies of the white dwarf candidate members of open star clusters aimed at constraining the form of the IFMR. For example, Claver et al. (2001) have presented the results of a detailed photometric and spectroscopic study of five white dwarf members of Praesepe. Williams, Bolte & Koester (2004) have undertaken a spectroscopic study of the degenerate candidate members of NGC 2168. Kalirai et al. (2005) have obtained multi-object spectroscopy of well over a dozen white dwarf candidate members of NGC 2099. Dobbie et al. (2004, 2006a) and Casewell et al. (2009) have identified and spectroscopically analysed a number of new white dwarfs in Praesepe. Williams & Bolte (2007) have investigated degenerate candidate members of both NGC 6633 and NGC 7063, while Kalirai et al. (2008) present spectroscopy of white dwarf candidate members of two older open clusters, NGC 7789 and NGC 6819. Most recently, Rubin et al. (2008) have unearthed six white dwarf candidate members of the intermediate aged cluster NGC 1039. Combined, these studies have increased the number of data points on the semi-empirical IFMR by over a factor of 2. However, only the work of Williams, Bolte & Koester (2004, 2009) and Rubin et al. (2008) has provided a substantial number of new points in the $M_{\rm init} \gtrsim 4\ \mathrm{M}_{\odot}$ regime. The upper portion of the IFMR remains rather poorly constrained, with large scatter amongst the data, the bulk of which currently comes from only three clusters, NGC 1039, NGC 2516 and NGC 2168. Indeed, to further complicate the situation, the metallicity of NGC 2168 is subsolar by approximately a factor of 2, and thus the data points from this cluster might not be expected to occupy the same region of initial mass–final mass space as those from solar metallicity clusters such as the Pleiades, NGC 2516 and NGC 1039 (e.g. Marigo 2001).

In a bid to improve the current state of affairs, we have recently focused our efforts on open clusters with $\tau \lesssim 300$ Myr, corresponding to the lifetime of a $M \approx 4\ \mathrm{M}_{\odot}$ star, and with metallicities close to solar so that the influence of this parameter on the data from cluster to cluster is minimal or even negligible. Here, we present the results of a new investigation of the nine white dwarf candidate members of NGC 2287 (M41) and NGC 3532. In the next section, we review the parameters of these two clusters and the work previously undertaken on their white dwarf populations. Next, we describe the acquisition and analysis of new photometry and spectroscopy for these objects and then use these to re-assess cluster membership status. Finally, we examine those white dwarfs with parameters consistent with being members of the two clusters in the context of the IFMR.

2 TWO OPEN CLUSTERS RIPE FOR A NEW 8-M STUDY

2.1 White dwarf candidate members of NGC 3532

NGC 3532 ($11^{\rm h}05^{\rm m} - 58^{\circ}45'$, J2000.0) is a comparatively rich and nearby open cluster yet has been relatively little studied, particularly in the last two decades. This is probably because it appears in projection against the Galactic plane ($b \sim 1\overset{\circ}{.}3$). Despite this low Galactic latitude, extinction along the line-of-sight to the cluster is low. For example, Fernandez & Salgado (1980) and Meynet, Mermilliod & Maeder (1993) use *UBV* photometry to determine $E(B-V) \approx 0.04$, from Strömgren data Eggen (1981) estimate $E(b-y) = 0.023$ (which equates to $E(B-V) \approx 0.03$) and Nicolet (1981) find $E(B-V) = 0.052 \pm 0.010$ using Geneva photometry. Moreover, NGC 3532 appears to have a metallicity close to the solar value. From a photometric investigation of the giant members, Claria & Lapasset (1988) found no evidence for a significant ultraviolet (UV) excess or cyanogen anomaly while Twarog, Ashman & Anthony-Twarog (1997) concluded from an independent David Dunlop Observatory based study that [Fe/H] = −0.02.

While it is unfortunate that there are less than a handful of age estimates for NGC 3532 in the recent literature, at least the few that are available appear to be consistent. For example, Meynet et al. (1993) compared isochrones generated from the stellar models of Schaller et al. (1992), which include a moderate level of convective core overshooting, and *UBV* photometry to obtain $\tau = 316$ Myr. Koester & Reimers (1993), using moderate core overshoot models, determined an age of $\tau = 302 \pm 154$ Myr for a turn-off absolute magnitude of $M_V = -0.75 \pm 0.25$. Kharchenko et al. (2005) estimate an age of $\tau = 282$ Myr based on photometry from the 2MASS Point Source Catalogue (PSC; Skrutskie et al. 2006) and the stellar modelling of the Padova group (e.g. Girardi et al. 2000). Therefore, it appears reasonable to conclude that the age of NGC 3532 lies within the range $\tau = 300 \pm 25$ Myr.

Robichon et al. (1999) used *Hipparcos* data to determine the cluster distance modulus to be $m - M = 8.04^{+0.37}_{-0.32}$. This is notably less than the recent estimate of $m - M = 8.61$ obtained from 2MASS PSC data (Kharchenko et al. 2005). Nevertheless, these two determinations bracket the results from most other studies. Fernandez & Salgado (1980) estimate $m - M = 8.45 \pm 0.27$, Eggen (1981) find $m - M = 8.5 \pm 0.25$ while Meynet et al. (1993) conclude that $m - M = 8.35$. Reimers & Koester (1989) exploited this relative proximity and the low levels of foreground reddening, using deep UV and red Schmidt plates to identify seven blue candidate white dwarf cluster members. Low-resolution spectroscopy obtained with the 3.6-m European Southern Observatory (ESO) telescope and the Faint Object Spectrograph and Camera (EFOSC) confirmed the degenerate nature of three of these stars. A subsequent extended photometric and spectroscopic survey of NGC 3532 unearthed a further three white dwarf candidate members (Koester & Reimers 1993).

While analysis of the EFOSC spectroscopy confirmed that these white dwarfs are young ($T_{\rm eff} \approx 20\,000$–$30\,000$ K), as would be expected if they are members of NGC 3532, due to the low signal-to-noise ratio of these data blueward of 4000 Å, the uncertainties in determinations of their surface gravities and hence in estimates of their masses and cooling times remain large (e.g. see Koester & Reimers 1993). The location of these white dwarfs in initial mass–final mass space as revealed by a number of recent studies, e.g. Ferrario et al. (2005) and Catalan et al. (2008), is suggestive of significant dispersion in the IFMR. A large intrinsic scatter in the relation would have important implications for our understanding of stellar evolution and pose a huge complication for investigations which rely on the IFMR being close to monotonic (e.g. Jeffery et al. 2007). However, before firm conclusions are drawn on this matter, better photometric and spectroscopic data should be acquired for these stars so that the cluster membership status of each can be soundly examined and more stringent limits placed on their masses and cooling times.

2.2 White dwarfs candidate members of NGC 2287 (M41)

An early detailed investigation of the moderately populated NGC 2287 ($06^{h}46^{m} - 20°45'$, J2000.0) determined the distance to the cluster to be $D = 725$ pc and levels of extinction along this line-of-sight to be very low, $E(B - V) = 0.01$ (Cox 1954). These estimates are corroborated by the results of more recent studies where state-of-the-art theoretical isochrones have been fit to the observed cluster sequence. For example, based on an analysis of *UBV* photometry of cluster members, Meynet et al. (1993) derive a distance modulus of $m - M = 9.15$ and estimate $E(B - V) = 0.01$. Kharchenko et al. (2005) determine $m - M = 9.30$ and $E(B - V) = 0.03$ based on a study of near-IR data from the 2MASS PSC (Skrutskie et al. 2006). Sharma et al. (2006) estimate $m - M = 9.26$ and $E(B - V) = 0.01$ from *BVI* imaging obtained with the Kiso Schmidt telescope.

Recent age determinations for the cluster, which employ stellar models including a moderate level of convective core overshoot, are at a reasonable level of agreement with one and other. For example, Meynet et al. (1993) conclude that the cluster is $\tau = 240$ Myr, while Harris et al. (1993) determine an age of $\tau = 200$ Myr. Kharchenko et al. (2005) estimate the age of NGC 2287 to be $\tau = 280$ Myr, while Sharma et al. (2006) favour $\tau = 250$ Myr. Thus, the weight of evidence favours the age of NGC 2287 to lie within the range $\tau = 243 \pm 40$ Myr. However, metallicity estimates for NGC 2287 are somewhat scattered. In their catalogue of spectroscopic stellar abundance determinations, Cayrel de Strobel et al. (1992) quote values of [Fe/H] = 0.00 and [Fe/H] = −0.25 for the cluster members HD 49091 and HD 49068, respectively. Cameron (1985) used *UBV* photometry of 14 members to derive [Fe/H] = +0.065 while from Strömgren photometry of F star members, Nissen (1988) determined [Fe/H] = −0.10. Collectively, these results point towards the metallicity of NGC 2287 being close to the solar value, perhaps marginally less.

The youthful age, the relative proximity and the low line-of-sight reddening of NGC 2287 make it a particularly suitable target for the study of the IFMR, as was recognized several decades ago. Indeed, Romanishin & Angel (1980) undertook a search of the cluster using photographic plates and this led to the identification of five candidate white dwarf members. Follow-up spectroscopic observations obtained with the 3.6-m ESO telescope and the Image Dissector Scanner confirmed at least three of these objects to be white dwarfs, two with $T_{\rm eff} \approx 25\,000$ K and one with $T_{\rm eff} \approx 13\,000$ K (Koester & Reimers 1981). It was concluded by these authors that the two hotter stars were likely to be cluster members while the cooler white dwarf was probably a foreground object. However, as the quality of the existing spectral data is rather poor, no detailed analyses of the Balmer line profiles in the spectral energy distributions of these stars have ever been undertaken. Thus, robust estimates of the effective temperatures and surface gravities are unavailable to confirm or otherwise these conclusions and to allow these objects to be fully exploited in the context of the IFMR.

3 OBSERVATIONS AND DATA ANALYSIS

3.1 FORS1 spectroscopy of white dwarf candidate members of NGC 3532 and NGC 2287

Low-resolution, high signal-to-noise ratio optical spectroscopy of the nine white dwarf candidate members of the clusters NGC 3532 and NGC 2287 was obtained in service mode with the ESO Very Large Telescope (VLT) and the Focal Reducer and low dispersion Spectrograph (FORS1) within the periods 2007 April 24–27 and 2007 October 06–November 21. A full description of the FORS1 instrument may be found on the ESO webpages.[1] As these targets are comparatively bright, we specified fairly relaxed constraints on the sky conditions and thus the observations were generally undertaken in poorer seeing and/or with some cloud present. All data were acquired using the 2 × 2 binning mode of the E2V CCD, the 600B+12 grism and a 1.6-arcsec slit which gives a nominal 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 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 spectra were extracted using the APEXTRACT package and wavelength calibrated by comparison with the He+HgCd arc spectra. Remaining instrument signature was removed using a spectrum of the featureless DC white dwarf WD0000+345 obtained with an identical set-up during this programme.

3.2 The model atmosphere calculations

We have used 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 (v48; Hubeny, I. and Lanz, T. 2001, http://nova.astro.umd.edu/) to generate a grid of pure-H synthetic spectra covering the $T_{\rm eff}$ and surface gravity ranges 14 000–35 000 K and log $g = 7.25$–8.75, respectively. We have employed a model H atom incorporating the eight lowest energy levels and one superlevel extending from $n = 9$ to 80, where the dissolution of the high-lying levels was 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 assumed radiative equilibrium and included the bound-free and free–free opacities of the H^- ion and incorporated a full treatment for the blanketing effects of H I lines and the Lyman $-\alpha$, $-\beta$ and $-\gamma$ satellite opacities as computed by N. Allard (e.g. Allard et al. 2004). 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 was 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).

3.3 Determination of the effective temperatures and surface gravities

As is our previous work (e.g. Dobbie et al. 2006a), comparison between the models and the data is undertaken using the spectral

[1] http://www.eso.org/instruments/fors1/

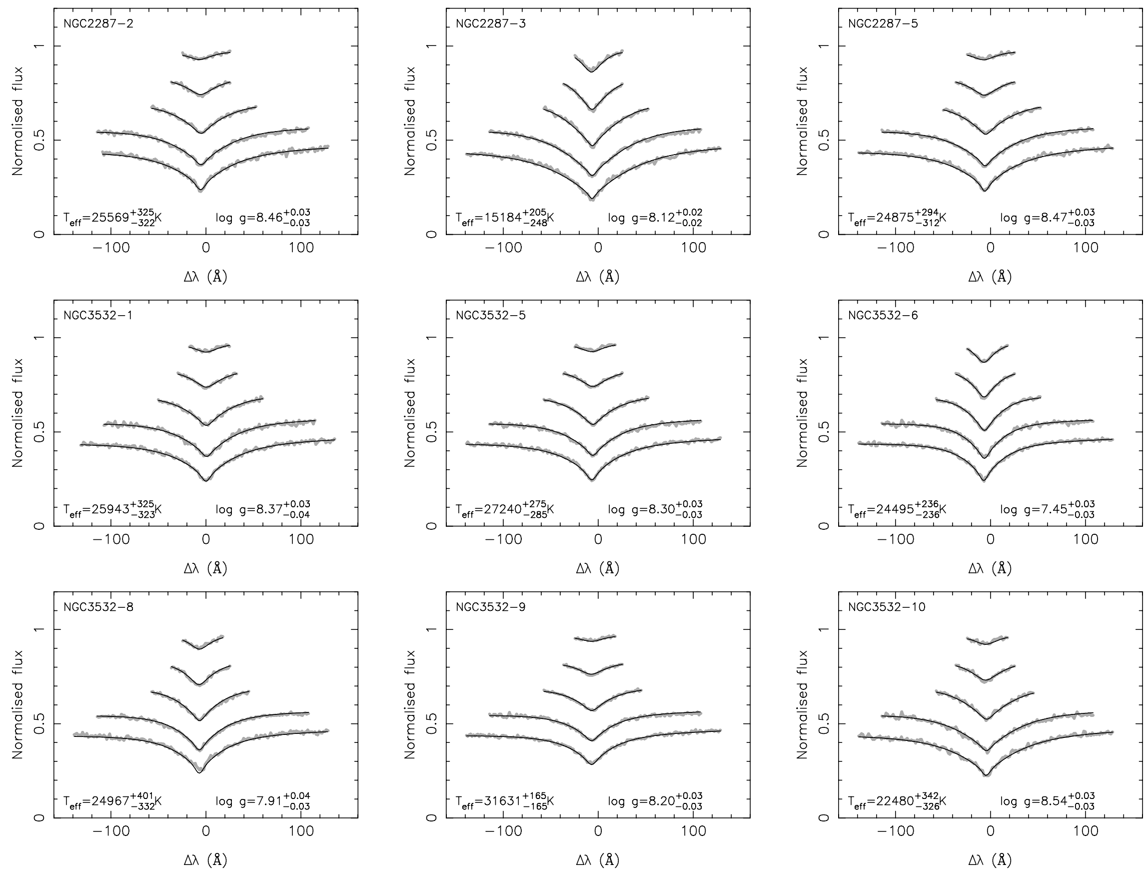

Figure 1. The results of our fitting of synthetic profiles (thin black lines) to the observed Balmer lines, H-β to H-8, of the nine white dwarf candidate members of NGC 3532 and NGC 2287 (thick grey lines). The flux$_\lambda$ units are arbitrary.

Table 1. Details of the nine white dwarf candidate members of NGC 3532 and NGC 2287. 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 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.

ID in lit.	$T_{\rm eff}$(K)*	log g*	m$_V$	M_V	M(M$_\odot$)	τ_c (Myr)	$M_{\rm init}$(M$_\odot$)
NGC 2287-2	25569^{+325}_{-322}	$8.46^{+0.03}_{-0.02}$	20.32 ± 0.05	$11.06^{+0.12}_{-0.12}$	0.91 ± 0.04	81^{+15}_{-13}	$4.45^{+0.58}_{-0.38}$
NGC 2287-3	15184^{+205}_{-248}	$8.12^{+0.02}_{-0.02}$	19.82 ± 0.03	$11.31^{+0.10}_{-0.10}$	0.68 ± 0.04	229^{+27}_{-24}	–
NGC 2287-5	24875^{+294}_{-312}	$8.47^{+0.03}_{-0.03}$	20.54 ± 0.03	$11.13^{+0.12}_{-0.12}$	0.91 ± 0.04	92^{+16}_{-14}	$4.57^{+0.64}_{-0.43}$
NGC 3532-1	25943^{+325}_{-323}	$8.37^{+0.03}_{-0.04}$	19.16 ± 0.02	$10.87^{+0.12}_{-0.11}$	0.86 ± 0.04	60^{+13}_{-12}	$3.83^{+0.18}_{-0.15}$
NGC 3532-5	27240^{+275}_{-285}	$8.30^{+0.03}_{-0.03}$	19.01 ± 0.02	$10.66^{+0.11}_{-0.12}$	0.82 ± 0.04	38^{+10}_{-9}	$3.71^{+0.15}_{-0.13}$
NGC 3532-6	24495^{+236}_{-236}	$7.45^{+0.03}_{-0.03}$	19.28 ± 0.02	$9.56^{+0.11}_{-0.11}$	0.40 ± 0.04	17^{+1}_{-1}	–
NGC 3532-8	24967^{+401}_{-332}	$7.91^{+0.04}_{-0.03}$	19.17 ± 0.02	$10.23^{+0.11}_{-0.11}$	0.59 ± 0.04	19^{+3}_{-1}	–
NGC 3532-9	31631^{+138}_{-165}	$8.20^{+0.03}_{-0.03}$	18.47 ± 0.02	$10.18^{+0.11}_{-0.12}$	0.76 ± 0.04	10^{+3}_{-1}	$3.57^{+0.12}_{-0.11}$
NGC 3532-10	22480^{+342}_{-326}	$8.54^{+0.03}_{-0.03}$	19.82 ± 0.02	$11.44^{+0.12}_{-0.12}$	0.96 ± 0.04	149^{+22}_{-19}	$4.58^{+0.47}_{-0.33}$

*Formal fit errors – see text for further details.

fitting program XSPEC (Shafer et al. 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. Errors in the $T_{\rm eff}$s and log g s 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

Table 2. Coefficients determined for equation (1), the transformation between instrumental magnitudes and Johnson *V*.

K_0	K_1	K_2	K_3
22.326 ± 0.012	-0.104 ± 0.009	0.213 ± 0.014	-0.138 ± 0.011

procedure are given in Table 1 and shown overplotted on the data in Fig. 1. It should be noted that the parameter errors quoted here are formal 1σ fit errors and undoubtedly underestimate the true uncertainties. In our subsequent analysis, we assume 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).

3.4 *V*-band CCD photometry of the white dwarfs

V-band CCD imaging of the nine white dwarfs candidate members of NGC 2287 and NGC 3532 was obtained on the nights of 2008 March 6 and 7 with the Australia National University's 40-arcsec telescope and the Wide Field Imager (WFI) located at Siding Spring Observatory. Conditions on both nights were comparatively good with photometric skies and seeing as measured from the images of $\sim$1.5 arcsec. The WFI consists of a mosaic of eight MIT Lincoln Labs 4096 × 2048 pixel CCDs which covers an area of 52 × 52 arcmin^2 in each pointing. Throughout our run, however, CCD6 was non-functional. All data were reduced using the Cambridge Astronomical Survey Unit CCD reduction toolkit (Irwin & Lewis 2001) to follow standard procedures, namely subtraction of the bias, flat-fielding, astrometric calibration and stacking. Aperture photometry was performed on the stacked images using a circular window with a diameter of 1.5× the full width at half-maximum of the mean point spread function. The Landolt fields SA98 and SA104 (Landolt 1992) were observed a number of times during the latter night so that instrumental magnitudes could be transformed on to the standard *V* Johnson system,

$$m_V = -2.5\log(ADU/t_{\rm exp}) + K_0 + K_1 X + K_2(B-V) + K_3 X(B-V), \quad (1)$$

where *ADU* is a measure of the total counts from the source, $t_{\rm exp}$ the exposure time and *X* the airmass. The coefficients and their respective errors were determined to have the values shown in Table 2. The $B-V$ colour of each white dwarfs was estimated from the known effective temperature and surface gravity using the synthetic photometry of Bergeron, Wesemael & Beauchamp (1995) as updated by Holberg & Bergeron (2006). Our estimates of the *V* magnitudes of the nine white dwarfs are listed in the final column of Table 1.

4 DISCUSSION

4.1 Membership status of the nine white dwarfs

We have used the estimates of the effective temperatures and surface gravities of the white dwarfs shown in Table 1 and the model grids of Bergeron et al. (1995), as revised by Holberg & Bergeron (2006), to derive absolute magnitudes (M_V; see Table 1). Subsequently, we have determined the distance modulii of the nine white dwarfs, neglecting extinction which is believed to be low $A_V \lesssim 0.12$ 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 (dash–dotted lines) in

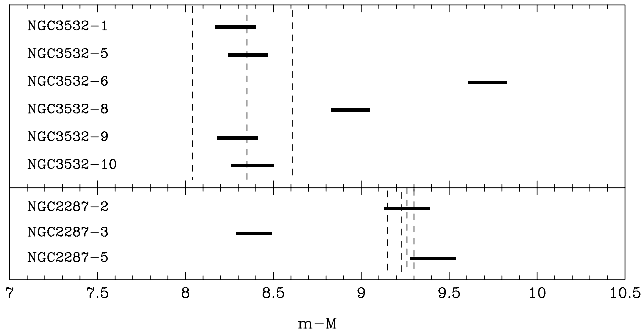

Figure 2. The derived distance modulii of the nine white dwarfs included in this study. The distance modulus of NGC 3532 as estimated by Meynet et al. (1993; $m-M=8.35$), Robichon et al. (1999; $m-M=8.04$) and Kharchenko et al. (2005; $m-M=8.61$) and the distance modulus of NGC 2287 as estimated by Harris (1993; $m-M=9.23$), Meynet et al. (1993; $m-M=9.15$), Kharchenko et al. (2005; $m-M=9.30$) and Sharma et al. (2006; $m-M=9.26$) are overplotted. The white dwarfs which are non-members are clearly distinguished.

Fig. 2. It is clear from Fig. 2 that NGC 3532-6 and NGC 3532-8 lie beyond NGC 3532 and thus are most probably field objects. Moreover, −3 appears to lie to the foreground of NGC 2287 as concluded by Koester & Reimers (1981) and is also probably a field white dwarf. The remaining six objects have distance modulii which argue strongly that they are members of NGC 3532 or NGC 2287. These stars are suitable for placing constraints on the form of the IFMR.

4.2 The IFMR

4.2.1 Cluster parameters, initial masses and excluded objects

The masses and cooling times of the six cluster white dwarfs have been determined using modern evolutionary tracks supplied by the Montreal group (e.g. Fontaine, Brassard & Bergeron 2001). So that this work is generally consistent with other recent studies in this area (e.g. Dobbie et al. 2006a; Williams & Bolte 2007) we have adopted the calculations which include a mixed CO core and thick H surface layer structure. The masses and cooling times shown in Table 1 have been derived using cubic splines to interpolate between points in this grid. We note that these mass determinations are relatively insensitive to our choice of core composition and if instead we had adopted thin H-layer models these estimates would be systematically lower by only 0.02 $M_\odot$, which is within our present level of precision.

The lifetime of the progenitor star of each of these six objects has been derived by subtracting the estimated cooling time, shown in Table 1, from the adopted cluster age, where, for the reasons outlined in Section 2, it has been assumed that $\tau = 243 \pm 40$ Myr for NGC 2287 and $\tau = 300 \pm 25$ Myr for NGC 3532. In this calculation, we have taken the errors in the cooling times to have magnitudes as shown within the brackets of the relevant column of Table 1. These are based on more likely levels of uncertainty in our effective temperature and surface gravity determinations of 2.3 per cent and 0.07 dex, respectively (e.g. Napiwotzki et al. 1999). Subsequently, we have used cubic splines to interpolate between the lifetimes calculated for stars of solar composition[2] by Girardi et al. (2000) and have constrained the masses of these six progenitors to

[2] Based on the Anders & Grevasse (1989) definition.

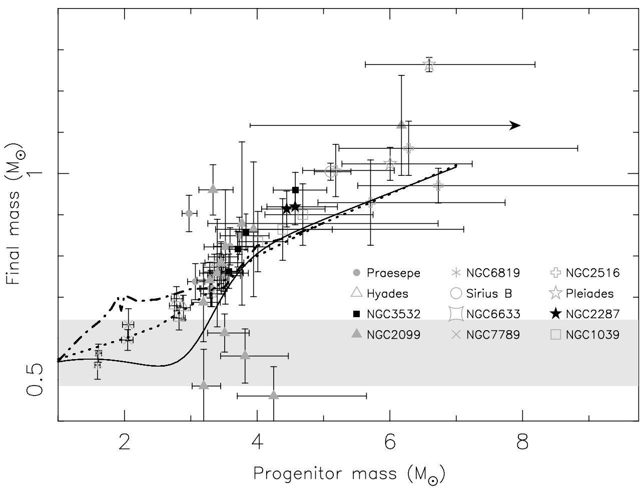

Figure 3. The locations of the white dwarf members of NGC 3532 and NGC 2287 in initial mass–final mass space. Data points from a number of other populations with metallicities close to the solar value are also shown (see text for details). The theoretical IFMR of Marigo et al. (2007; dot–dashed heavy line), the semi-empirical IFMR of Weidemann (2000; heavy dotted line) and the initial mass–core mass at first thermal pulse relation from Karakas, Lattanzio & Pols (2002; medium solid line) are overplotted. The peak in the field white dwarf mass distribution ($\pm 1\sigma$) is represented by the band of grey shading.

the values shown in the final column of Table 1. We note in this context and in the framework of main-sequence turn-of-based cluster age estimates that current eclipsing binary data are consistent with $\alpha_{\rm OV} = 0.2$ (i.e. a moderate level of) convective core overshooting across the broad mass range $M \sim$ 2–30 $M_\odot$ (Claret 2007). However, we caution that the errors we quote here in progenitor mass are merely approximations since they have not been determined through a detailed statistical analysis (e.g. Salaris et al. 2009). Nevertheless, their magnitudes should provide a guide to the impact of the uncertainties in both the white dwarf parameters and the cluster ages which are main sources of error on the final and initial masses, respectively (Salaris et al. 2009).

The locations of the six white dwarf members of NGC 3532 and NGC 2287 in initial mass–final mass space are shown plotted in Fig. 3, with data from the extensively studied Sirius system (e.g. Barstow et al. 2005) and a number of other clusters which have metallicities that are found to be reasonably close to the solar value (within 30–40 per cent). While Sirius B is not associated with a particular star cluster, we include it here since there are relatively few objects in the $M_{\rm init} \gtrsim 5\ M_\odot$ regime and the uncertainties on individual points here are particularly large. To determine the initial and final masses of the white dwarf members of these additional populations we have used the same model grids and methodology as applied to NGC 3532 and NGC 2287. For the Pleiades we have assumed an age of $\tau = 125 \pm 25$ Myr (e.g. Ferrario et al. 2005) and have utilized the white dwarf parameters determined by Dobbie et al. (2006a,b). In the cases of NGC 6819 (Kalirai et al. 2008), NGC 7789 (Kalirai et al. 2008), the Hyades (Claver et al. 2001), Praesepe (Claver et al. 2001; Casewell et al. 2009), NGC 6633 (Williams & Bolte 2007), NGC 1039 (Rubin et al. 2008) and Sirius (Liebert et al. 2005a), we have adopted for the cluster age and the effective temperatures and surface gravities of the white dwarf members, the values listed in the relevant referenced work.

Although Kalirai et al. (2005) adopted an age of $\tau = 650$ Myr and a substantially subsolar composition for NGC 2099, the results from two recent spectroscopic studies suggest that the cluster has near solar metallicity. Marshall et al. (2005) measure [Fe/H] = +0.05 ± 0.05 from moderate resolution spectroscopy of eight giant members while Hartman et al. (2008) determine [M/H] = +0.02 ± 0.04 from high-resolution spectroscopy of candidate members with $T_{\rm eff} >$ 4500 K. Moreover, during the last 15 years the bulk of age estimates for NGC 2099 obtained using theoretical isochrones generated from solar metallicity stellar models which include moderate levels of convective core overshooting, have found values within the range τ = 450–550 Myr, e.g. $\tau = 450$ Myr, Mermilliod et al. (1996); $\tau =$ 520 Myr, Kalirai et al. (2001); $\tau = 450$ Myr, Kiss et al. (2001) and $\tau = 550$ Myr, Hartman et al. (2008). Here, we have assumed the cluster has solar metallicity and have adopted the mean of the above age determinations, $\tau \sim 490 \pm 70$ Myr, where the error bound has been tuned to envelope the bulk of these estimates.

Both Ferrario et al. (2005) and Dobbie et al. (2006a) adopted $\tau = 158$ Myr for NGC 2516, a key cluster for constraining the form of the top end of the IFMR. This age was drawn from the work of Sung et al. (2002) and is marginally larger than that adopted by Koester & Reimers (1996), $\tau = 140$ Myr which is from the work of Meynet et al. (1993). Kharchenko et al. (2005) recently derived $\tau = 120$ Myr using 2MASS PSC data, but this is based on only three cluster stars. Since the work of Ferrario et al. (2005) and Dobbie et al. (2006a), a new detailed photometric study of the cluster (Lyra et al. 2006), which used the isochrones of Girardi et al. (2000), has concluded that $\tau = 140$ Myr. Looking at all these estimates collectively, we conclude that the age of NGC 2516 most probably lies within the range 145 ± 30 Myr.

We have excluded a number of white dwarf candidate members of these clusters from our subsequent analysis for the following reasons: WD0837+218 is more likely to be a field star than a member of Praesepe (Casewell et al. 2009), WD0836+201 is strongly magnetic and may have a substantially different evolutionary history to that of a typical non-magnetic star (e.g. Wickramasinghe & Ferrario 2000; Tout et al. 2008), WD0836+185, NGC 6633 LAWDS 4 and 7 may be double-degenerate systems as suggested by photometric or radial velocity data, in which case close binary interaction could have significantly impacted their evolution, NGC 6633 LAWDS 16 is a DB white dwarf for which determinations of effective temperature and surface gravity are considerably less certain (e.g. Kepler et al. 2007), NGC 2099 WD 6 and 21 do not have spectroscopic surface gravity determinations, NGC 2099 WD 15,16 and 17 are found to be too old at the revised age of their putative parent cluster, NGC 1039 LAWDS 20, S1 and 9 have proper motions, as listed in the SuperCOSMOS Sky Survey data base (Hambly et al. 2001), which are $\sim 3.3\sigma$, $\sim 4.1\sigma$ $\sim 2.3\sigma$ from the mean of their putative parent cluster and are thus likely to be field stars (see Fig. 4) and NGC 7063 LAWDS 1,[3] with $M \lesssim 0.4\ M_\odot$ (Williams & Bolte 2007), has a proper motion as listed in the USNO-B1.0 catalogue of $\mu_\alpha \cos\delta = -2 \pm 4$ mas yr^{-1} and $\mu_\delta = -22 \pm 8$ mas yr^{-1} and as measured by us from blue Palomar Sky Survey plates (O269, 1951 July 5 and SJ04686, 1992 July 26) of $\mu_\alpha \cos\delta = 2.1 \pm 5.9$ mas yr^{-1} and $\mu_\delta = -19.0 \pm 5.6$ mas yr^{-1}, which argues it is more likely to be a field star than a cluster member ($\mu_\alpha \cos\delta = 1.24 \pm 0.41$ mas yr^{-1} and $\mu_\delta = -2.83$ mas yr^{-1}; Kharchenko et al. 2005).

[3] The proper motion is listed in the SuperCOSMOS Sky Survey data base as $\mu_\alpha \cos\delta \approx -80 \pm 307$ mas yr^{-1} and $\mu_\delta \approx -60 \pm 302$ mas yr^{-1}. These huge uncertainties may indicate that there was a problem with the measurement.

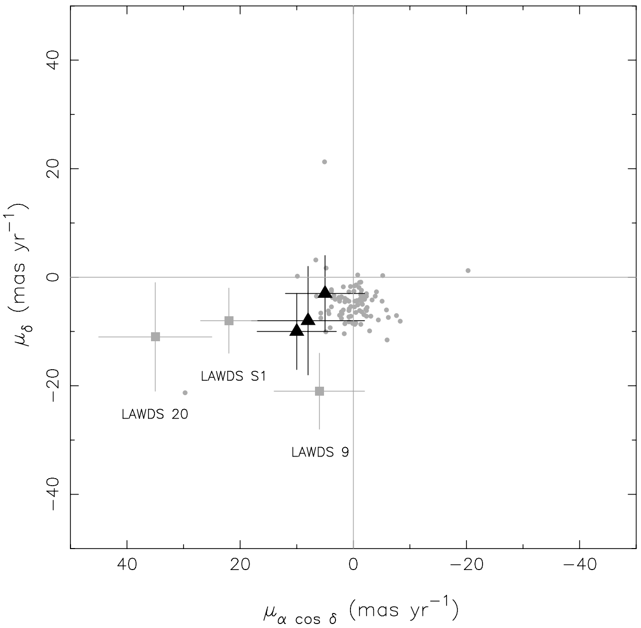

Figure 4. SuperCOSMOS proper motion measurements for white dwarf candidate members of NGC 1039 recently identified by Rubin et al. (2008). The motions of the three massive white dwarfs (filled triangles) are consistent with those of the cluster members colour selected by Irwin et al. (2006; small filled circles). The white dwarfs with masses close to 0.6 M$_{\odot}$ are also shown (filled squares). The proper motions of LAWDS 20 and LAWDS S1 are inconsistent with membership of NGC 1039, while the proper motion of LAWDS 9 indicates it too is more likely to be a field star.

4.2.2 A new look at the form of the IFMR

What is immediately apparent from Fig. 3 is that the white dwarfs of NGC 3532 cannot now substantiate any claim that there is significant scatter in the IFMR as could their location in the plots of some other recent studies of the IFMR (e.g. Ferrario et al. 2005; Catalan et al. 2008). The NGC 3532 data points in these investigations are based on the older spectroscopy of Reimers & Koester (1989) and Koester & Reimers (1993) which is of lower quality than the data presented here. At the revised cluster age and metallicity, the locations of the majority of the NGC 2099 white dwarfs now appear to be entirely consistent with those of the Hyades, Praesepe, NGC 3532 and NGC 6633 clusters. There are only six substantially deviant data points amongst the 49 shown in Fig. 3. It is noteworthy that it is the white dwarf population of the most distant cluster in this sample, NGC 2099, where proper motions are lacking and distance determinations are most unreliable, which presents the highest proportion of outliers, 36 per cent or five out of these six. Kalirai et al. (2005) estimate a contamination level of $\sim$25 per cent, equating to $\sim$6 interlopers in their total spectroscopically observed sample of 24 objects, so it seems feasible that at least some proportion of these deviant points are simply field stars. Indeed, the masses of four of these objects reside within the peak in the field white dwarf mass distribution, ($M = 0.565$ M$_{\odot}$, $\sigma = 0.08$ M$_{\odot}$, Liebert, Bergeron & Holberg 2005b), shown by the grey shaded region. Proper motion measurements for white dwarf candidate members of NGC 1039 (Rubin et al. 2008) which appeared to occupy this part of initial mass–final mass space (Rubin et al. 2008) confirm that two stars (NGC 1039 LAWDS 20 and S1) and argue strongly that a third (NGC 1039 LAWDS 9), are simply field objects (see Fig. 4). Moreover, with our improved photometry and spectroscopy of the NGC 3532 white dwarfs we have also demonstrated here that the two candidate members which would otherwise reside in this region of initial mass–final mass space are field stars.

Another possibility that cannot be discounted is that some of these low-lying stars have formed through a close binary evolutionary channel, most probably where the post-main-sequence phases have been terminated prematurely by the loss of envelope mass through the formation of a common envelope (Willems & Kolb 2004). The modelling of Iben & Tutukov (1985) demonstrates that a $M = 4$ M$_{\odot}$ star which experiences Roche Lobe overflow while ascending the Red Giant Branch can result in the production of a $M_{\rm final} = 0.523$ M$_{\odot}$ white dwarf. It would be informative, although difficult in practice, to obtain near-IR photometry to search for evidence of the presence of cool low mass companions to these NGC 2099 white dwarfs once they had been shown to have proper motion consistent with the cluster. It has also been suggested a number of times that binarity could have played a role in the distinctive location of LB5893 above the bulk of stars in initial mass–final mass space (e.g. Claver et al. 2001; Casewell et al. 2009). Praesepe is known to harbour a number of blue straggler stars (e.g. 40 Cancri and Epsilon Cancri; Ahumada & Lapasset 2007). A proportion of these likely form as a consequence of mass-transfer between and the eventual coalescense of the components of primordial binaries (e.g. Lombardi et al. 2002). In terms of evolution, these stars appear to be retarded with respect to their parent population. Thus, it seems plausible that the progenitor of LB5893 was a blue straggler and thus the whole evolution of this star has been somewhat delayed with respect to the general Praesepe population. NGC 2099 WD11, which also sits above the bulk of stars in initial mass–final mass space, might have a similar evolutionary history.

We find that the current crop of solar metallicity open cluster white dwarfs appears to offer no decisive evidence that non-magnetic stars which have effectively evolved in isolation, experience strong differential mass loss, at least within the initial mass range explored here. A number of recent studies have shown that a simple linear function, $M_{\rm final} = M_{\rm init}\, m + c$, is a reasonable approximation to the semi-empirical IFMR. For example, based on the data from the Sirius binary system and seven open clusters, including the metal poor NGC 2168, Ferrario et al. (2005), determined best-fitting parameters of $m = 0.10038 \pm 0.00518$ and $c = 0.43443 \pm 0.01467$ over the range 2.5 M$_{\odot}$ $\lesssim M_{\rm init} \lesssim$ 6.5 M$_{\odot}$. With the addition of data from three more open clusters, Kalirai et al. (2008) obtained parameters of $m = 0.109 \pm 0.007$ and $c = 0.394 \pm 0.025$ over the range 1.16 M$_{\odot}$ $\lesssim M_{\rm init} \lesssim$ 6.5 M$_{\odot}$. However, there is some evidence within the data shown in Fig. 3 that the IFMR is somewhat steeper in the range 3 M$_{\odot}$ $\lesssim M_{\rm init} \lesssim$ 4 M$_{\odot}$ than for initial masses immediately lower and higher than this. For example, taking the four lowest mass Hyades stars and the white dwarfs of NGC 7789 and NGC 6819, spanning the range 1.6 M$_{\odot}$ $\lesssim M_{\rm init} \lesssim$ 3.0 M$_{\odot}$, we estimate $\Delta M_{\rm final}/\Delta M_{\rm init} = 0.0981 \pm 0.0301$. For the white dwarfs lying within the range 3 M$_{\odot}$ $\lesssim M_{\rm init} \lesssim$ 4 M$_{\odot}$, excluding the outliers we determine $\Delta M_{\rm final}/\Delta M_{\rm init} = 0.2279^{+0.1151}_{-0.0707}$. Over the initial mass regime 3.8 M$_{\odot}$ $\lesssim M_{\rm init} \lesssim$ 5 M$_{\odot}$ we estimate $\Delta M_{\rm final}/\Delta M_{\rm init} = 0.1231^{+0.0548}_{-0.0624}$, where for the NGC 1039 white dwarfs alone we find $\Delta M_{\rm final}/\Delta M_{\rm init} \leq 0.1269$. We note that Ferrario et al. (2005) have demonstrated that population synthesis models which adopt an IFMR which has a feature of this nature can reproduce the relatively sharp drop observed at the high mass end of the main peak in the mass distribution of white dwarfs (e.g. Liebert et al. 2005b; Kepler et al. 2007; Marsh et al. 1997).

The trends outlined by the bulk of the data in Fig. 3 bear some resemblance to those of the initial mass–core mass at first thermal pulse relation (thin solid line). This theoretical track is likewise relatively flatter at $M_{\rm init} \lesssim 3$ M$_{\odot}$ since stars with $M_{\rm init} \lesssim 2.3$ M$_{\odot}$ develop comparable degenerate He cores after core-H exhaustion (e.g. Wagenhuber & Groenewegen 1998). It also becomes notably steeper for 3 M$_{\odot} \lesssim M_{\rm init} \lesssim 4$ M$_{\odot}$, as a result of the sensitivity of the mass of the H-exhausted core to the initial mass (e.g. Becker & Iben 1979). The slope of this relation then decreases at $M_{\rm init} \gtrsim$ 4 M$_{\odot}$, since here the He-burning shell in the early-AGB phase is predicted to be sufficiently potent to power a (second) dredge-up event which reduces the mass of the H-depleted core (Becker & Iben 1979). The reasons that the IFMR should follow rather closely the initial mass–core mass at first thermal pulse relation, more especially for $M_{\rm init} \gtrsim 3$ M$_{\odot}$, have been discussed in depth by Weidemann (2000). His estimate of the IFMR is overplotted on the data in Fig. 3 (heavy dotted line). In brief, during the interpulse period when the He burning shell is inactive, the H-exhausted core increases in mass. However, the re-ignition of the He-shell in a flash, drives intershell convection which for a short period extends into the CO core, mixing C-rich material up into this zone. Subsequently, the H-rich convective envelope extends down into the intershell region, dredging processed elements up to the stellar surface and effectively reducing the mass of the H-deficient core. If dredge-up is particularly efficient, that is, the mass of material mixed into the predominantly H-envelope is comparable to the increase in the mass of the core, $\lambda \approx 1$, then the core does not grow appreciably while the star evolves on the thermally pulsing AGB. Detailed modelling of AGB evolution indicates that the maximum λ value attained during the TP-AGB is a strong function of initial mass, with $M_{\rm init} \gtrsim$ 3 M$_{\odot}$ reaching large λ after only a few thermal pulses (e.g. Herwig 2000; Karakas, Lattanzio & Pols 2002). Indeed, a recent theoretical IFMR for solar metallicity (Marigo & Girardi 2007; dot–dashed heavy line) reproduces the steepening in the range 3 $\lesssim M_{\rm init} \lesssim$ 4 M$_{\odot}$ and the decrease of the slope at $M_{\rm init} \gtrsim 4$ M$_{\odot}$. However, the data in $M_{\rm init} \gtrsim 3.3$ M$_{\odot}$ regime appear to sit slightly above (a few hundredths of a solar mass) both this and the initial mass–core mass at first thermal pulse relation which may indicate that third dredge-up may not be quite as efficient here as assumed in the Padova models. Nevertheless, the similarities between the forms of the theoretical relations and the trends delineated by the bulk of white dwarfs from solar metallicity open clusters lend some assurance to the results of modern stellar evolutionary calculations.

5 SUMMARY

We have obtained high signal-to-noise ratio low-resolution optical spectroscopy of the nine candidate white dwarfs members of NGC 3532 and NGC 2287 with FORS1 and the VLT. The analysis of these data and of new *V*-band photometry indicates that only six of these objects are probably members of the clusters. These six objects, in particular the four members of NGC 3532, do not substantiate any claim that there is substantial scatter in the IFMR. While a simple linear fit to these data could still be deemed acceptable, there are now clear hints that the IFMR is steeper in the initial mass range 3 M$_{\odot} \lesssim M_{\rm init} \lesssim 4$ M$_{\odot}$ than at progenitor masses immediately lower and higher than this. This result is consistent with the predictions of stellar evolutionary models. Moreover, it can help explain the relatively sharp drop in the number density of white dwarfs on the high mass side of the main peak in the white dwarf mass distribution. Unfortunately, the IFMR remains rather poorly constrained at $M_{\rm init} \gtrsim 5$ M$_{\odot}$, where there is particular interest in its form. Additional white dwarfs and improved spectroscopy on existing data points are urgently required in this progenitor mass range.

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