New Praesepe white dwarfs and the initial mass-final mass relation

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ABSTRACT

We report the spectroscopic confirmation of four further white dwarf members of Praesepe. This brings the total number of confirmed white dwarf members to eleven making this the second largest collection of these objects in an open cluster identified to date. This number is consistent with the high mass end of the initial mass function of Praesepe being Salpeter in form. Furthermore, it suggests that the bulk of Praesepe white dwarfs did not gain a substantial recoil kick velocity from possible asymmetries in their loss of mass during the asymptotic giant branch phase of evolution. By comparing our estimates of the effective temperatures and the surface gravities of WD0833+194, WD0840+190, WD0840+205 and WD0843+184 to modern theoretical evolutionary tracks we have derived their masses to be in the range $0.72-0.76M_\odot$ and their cooling ages $\sim$300Myrs. For an assumed cluster age of 625 ± 50Myrs the infered progenitor masses are between $3.3-3.5M_\odot$. Examining these new data in the context of the initial mass-final mass relation we find that it can be adequately represented by a linear function (a_0=0.289$\pm$0.051, a_1=0.133$\pm$0.015) over the initial mass range $2.7M_\odot$ to $6M_\odot$. Assuming an extrapolation of this relation to larger initial masses is valid and adopting a maximum white dwarf mass of $1.3M_\odot$, our results support a minimum mass for core-collapse supernovae progenitors in the range $\sim$6.8-8.6$M_\odot$.

Key words:
stars: white dwarfs; supernovae; galaxy: open clusters and associations: Praesepe

1 INTRODUCTION

The initial mass-final mass relation (IFMR) characterises the amount of material stars with primordial masses $M\lesssim10M_\odot$ cast out into interstellar space during post main sequence evolution, en route to becoming white dwarfs. Accordingly, the form of this relation is of considerable importance to investigations relating to the chemical evolution of the Milky Way and galaxies in general. The details of the upper end of the IFMR also have relevance to supernovae studies since theoretical predictions of the rate of these explosions are rather sensitive to the assumed minimum mass of a core-collapse progenitor. Furthermore, the form of the IFMR conveys information on the mass loss processes which occur during the final stages of stellar evolution, which are difficult to model in a physical context.

Arguably the most robust method with which to place (semi-) empirical constraints on the form of the IFMR is via the study of white dwarfs in open clusters (e.g. Weidemann 1977, Romanischin & Angel 1980, Weidemann 2000). Since the constituents of an open cluster have a common age, determinable from the main sequence turn-off mass (e.g. King & Schuler 2005), the lifetime of a progenitor star can be estimated from the difference between this age and the cooling time of the resulting white dwarf. Subsequently, the progenitor masses can be determined by comparing their estimated lifetimes to the predictions of stellar evolutionary models.

Unfortunately, until quite recently, the small numbers of WDs recovered in each open cluster ($\sim$30 WDs in 14 clusters), their intrinsic faintness and the significant distances involved has meant that the uncertainties in clusters ages and in white dwarf mass determinations (and hence cooling time estimates), have conspired to produce significant scatter in the semi-empirical IFMR (e.g. Claver et al. 2001). Encouragingly, with time on 8/10m class telescopes now readily available, this situation is beginning to improve. For example, Kalirai et al. (2005) and Williams et al. (2005) have spectroscopically identified 16 and 6 likely white dwarf members of the rich but relatively distant open clusters M37 and M35 respectively.

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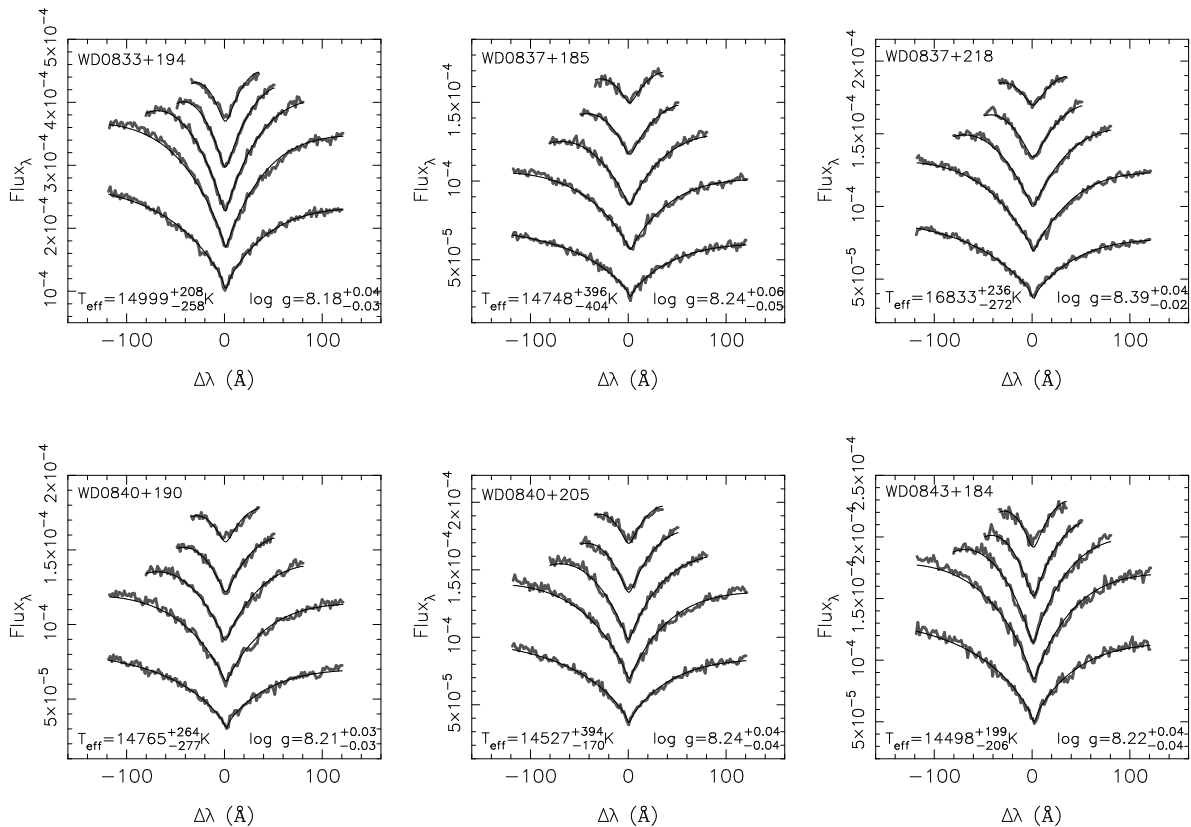
Figure 1. The results of our fitting of synthetic profiles (thin black lines) to the observed Balmer lines, H-β to H-8, (thick grey lines). The flux$_\lambda$ units are arbitrary.

These two populations of white dwarfs are found to be consistent with a monotonically increasing IFMR for progenitor mass ranges M$\sim$2.8-3.4M$_\odot$ and M$\sim$4.5-5.5M$_\odot$, respectively.

Nevertheless, while significant additional pieces of the jigsaw puzzle have recently been put in place, much work remains to be done before we are able to claim a thorough understanding of the IFMR. Accordingly, we recently embarked on a search for white dwarfs members of the modestly rich and relatively nearby Praesepe open cluster (M44, NGC2632). Using proper motions measurements and photographic photometry drawn from the USNO-B1.0 catalogue and SuperCosmos archive we identified 6 new candidates in a $5° \times 5°$ region centered on the cluster, to add to the five previously known Praesepe white dwarfs. Futhermore, two of these new candidates were confirmed spectroscopically. Full details of these objects are given in Table 1 of Dobbie et al. (2004).

In this work we present new low resolution optical spectroscopy which confirms that the four remaining candidates are also white dwarfs. Additionally, we use new data to provide refined estimates of the effective temperatures and surface gravities of LB5959 and WD0837+218. We re-examine the membership status of each of these objects and present a new astrometric measurement of the high mass "Praesepe" white dwarf LB5893 which establishes that it has a proper motion which is consistent with cluster membership. We discuss the implications of our findings in relation to the initial mass function of Praesepe and kinematic effects of mass loss in the final stages of the evolution of the white dwarf progenitors. Adopting an age of 625±50Myrs for the cluster, we estimate the masses of these progenitor stars and examine our results in the context of previous work on the initial mass-final mass relation.

2   OPTICAL SPECTROSCOPY OF THE REMAINING FOUR CANDIDATE WHITE DWARF MEMBERS

We have acquired optical spectra (3200-6000Å) of the four remaining candidate white dwarf members of Praesepe from Dobbie et al. (2004), using the William Herschel Telescope and the ISIS spectrograph. The observations were conducted during the service time nights of 2005/01/10 and 2005/11/07 and the visitor night of 2006/02/02. Sky conditions were good on the first and third nights with clear skies and seeing $\sim$0.7-0.9". On the second night there was some thin and patchy cirrus and seeing was slightly poorer, $\sim$1.0-1.2". All data were obtained on the blue arm of ISIS, using the EEV12 detector, the R300B grating and a slit width of 1" to provide a spectral resolution of $\approx$ 3.5Å. The total exposure time for each object was 45 minutes made up from a series of 15 minute integrations. The CCD frames 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 CuAr+CuNe arc spectra. To facilitate the removal of the instrument signature from the science spectra we obtained observations of the spectral standard stars PG0843+546 (Massey et al. 1988) and G191-B2B (Oke 1990).

Table 1. Details of the four new confirmed white dwarf candidate cluster members (top) and the two white dwarfs members identified by Dobbie et al. (2004; bottom) for which we have obtained improved spectroscopic data. 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).

WD	ID in D04	$T_{eff}(K)$	log g	$M(M_\odot)$	$\tau_c(Myrs)$
0833+194	candidate 1	14999^{+208}_{-258}	$8.18^{+0.04}_{-0.03}$	0.72 ± 0.02	262^{+15}_{-14}
0840+190	candidate 4	14765^{+264}_{-277}	$8.21^{+0.03}_{-0.03}$	0.74 ± 0.02	288^{+14}_{-13}
0840+205	candidate 5	14527^{+394}_{-170}	$8.24^{+0.04}_{-0.04}$	0.76 ± 0.03	316^{+21}_{-19}
0843+184	candidate 6	14498^{+199}_{-206}	$8.22^{+0.04}_{-0.04}$	0.75 ± 0.03	308^{+20}_{-19}
0837+185	candidate 2	14748^{+396}_{-404}	$8.24^{+0.06}_{-0.05}$	0.76 ± 0.04	303^{+28}_{-25}
0837+218	candidate 3	16833^{+236}_{-272}	$8.39^{+0.04}_{-0.02}$	0.86 ± 0.02	267^{+14}_{-13}

D04: Dobbie et al. (2004)

3 ANALYSIS OF THE DATA

3.1 Model white dwarf spectra

The broad hydrogen Balmer lines evident in the data presented in Figure 1 are consistent with all four objects without prior spectroscopic data being DA white dwarfs. We have used the latest 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 new grid of pure-H synthetic spectra covering the T_{eff} and surface gravity ranges 10000-34000K and log g=7.0-9.0 respectively. We have employed a model H atom incorporating the 8 lowest energy levels and one superlevel extending from n=9 to n=80, where the dissolution of the high lying levels was treated by means of the occupation probability formalism of Hummer & Mihalas (1988), generalised to the non-LTE situation by Hubeny, Hummer & Lanz (1994). All calculations included the bound-free and free-free opacities of the H^- ion and incorporated a full treatment for the blanketing effects of HI lines and the Lyman $-\alpha$, $-\beta$ and $-\gamma$ satellite opacities as computed by N. Allard (e.g. Allard et al. 2004). In contrast to the grid of models used in our previous work where radiative equilibrium was assumed (Dobbie et al. 2004), these latest calculations include, where appropriate, a treatment for convective energy transport according to the ML2 prescription of Bergeron et al. (1992), adopting a mixing length paramater, α=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 was treated using Allard's data (including the quasi-molecular opacity) and an approximate Stark profile (Hubeny, Hummer & Lanz 1994) respectively. In the spectral synthesis step detailed profiles for the Balmer lines were calculated from the Stark broadening tables of Lemke (1997).

3.2 Determination of effective temperatures and surface gravities

As discussed in Dobbie et al. (2004), comparison between the models and the data is undertaken using the spectral fitting program XSPEC (Shafer et al. 1991). 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 fit 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 minimised. Errors in the T_{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 et al. 1976).

Given the probable age of the Praesepe cluster ($\sim$600-700Myrs), a number of the white dwarf members may have effective temperatures approaching that at which the H-Balmer lines reach their maximum equivalent width ($T_{eff}\sim$12500-13500K). Previous spectroscopic studies of DA white dwarfs in this temperature regime indicate that the sensitivity to surface gravity of the equivalent widths of the lower order Balmer lines (e.g. H-β, H-γ) is reduced here (e.g. Daou et al. 1990). Therefore, in the present analysis all lines from H-β to H-8 are included in the fitting process. Furthermore, given that we assign each line an independent normalisation parameter, there is the potential for obtaining two solutions for T_{eff} in this regime (e.g. Gianninas et al. 2005). Hence minimum χ^2 has been approached from both the high and low temperature ends of the model grid.

No convincing fit with $T_{eff}\leqslant$13500K is found to any of the datasets; the overall spectral shape of the data (ie. lines and continuum) are well matched by models at the temperature and surface gravity solutions determined here. The results of our fitting procedure are given in Table 1 and shown overplotted on the data in Figure 1. As a check for potential systematic errors (e.g. Napiwotzki et al. 1999) we have validated the results with an independent analysis technique (FITSB2; Napiwotzki et al. 2004) and a different set of model atmospheres (the LTE atmospheres used by Koester et al. 2001). Differences between individual results were found to
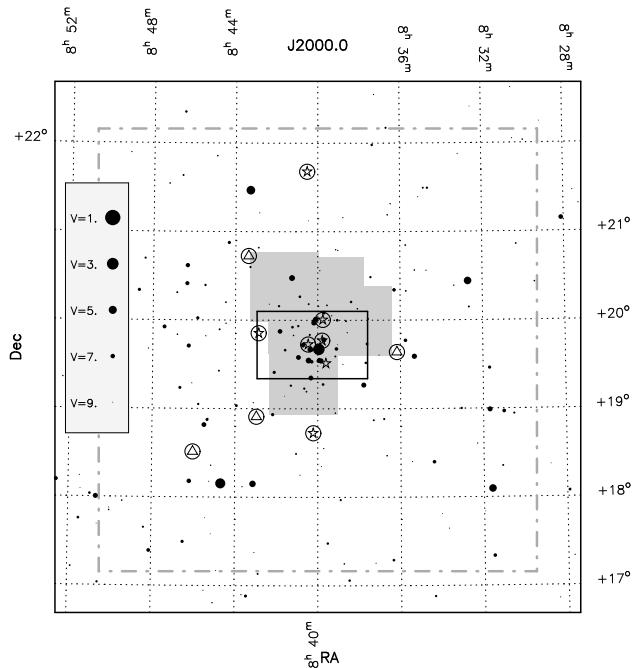
Figure 2. A schematic plot of the Praesepe cluster showing stars down to V ≈ 9 and the areas surveyed by Anthony-Twarog (1982, 1984; solid outline) and Claver et al. (2001; grey shading). The region included our investigation is outlined (dashed grey line). All objects listed in Table 1 of Dobbie et al. (2004; open circles) and the five 'original' white dwarf cluster members (open stars) are also overplotted. The locations of the four new spectroscopically confirmed white dwarf candidate members are highlighted (open triangles).

be well within the error limits quoted in Table 1 and no significant systematic discrepancies were apparent. Nevertheless, it should be noted that the parameter errors quoted here are formal 1σ fit errors and may underestimate the true uncertainties.

4 DISCUSSION

4.1 White dwarf membership status, the initial mass function of Praesepe and recoil kicks

We have used modern evolutionary tracks supplied by the Montreal group (e.g. Fontaine, Brassard & Bergeron 2001) to determine the masses and cooling times of our four new white dwarfs. We have adopted the calculations which include a mixed CO core and thick H surface layer structure, which make this work consistent with other recent studies in this area (e.g. Liebert et al. 2005a). The masses and cooling times shown in Table 1 have been derived using cubic splines to interpolate between points in this grid. At the present level of precision these mass determinations are not sensitive to our choice of core composition. However, if instead we had adopted thin H-layer models these estimates would be systematically lower by $0.02M_\odot$. Nevertheless, we can conclude that all four white dwarfs have masses which are significantly larger than those typical of field white dwarfs, the distribution of which is found to be strongly peaked at $0.565M_\odot$ (e.g. Liebert et al. 2005b, Bergeron, Liebert & Fulbright 1995, Marsh et al. 1997). These comparatively high masses and the projected spatial distribution of the white dwarfs (Figure 2) argue that our objects are associated with the Praesepe open cluster.

Table 2. Progenitor lifetimes and corresponding masses based on the white dwarf cooling times shown in Table 1, the Z=0.019 stellar evolutionary models of Girardi et al. (2000) and an assumed cluster age of 625±50Myrs.

Progenitor of WD	τ_{prog} (Myrs)	M_{prog} ($M_\odot$)
0833+194	363^{+52}_{-52}	$3.30^{+0.24}_{-0.18}$
0840+190	337^{+52}_{-52}	$3.38^{+0.27}_{-0.20}$
0840+205	309^{+53}_{-54}	$3.49^{+0.35}_{-0.24}$
0843+184	317^{+53}_{-54}	$3.46^{+0.33}_{-0.23}$
0837+185	322^{+56}_{-57}	$3.44^{+0.36}_{-0.25}$
0837+218	358^{+52}_{-52}	$3.31^{+0.24}_{-0.18}$

In an effort to quantify the level of contamination by field white dwarfs in our assembly of probable Praesepe members, we have repeated our original survey procedure on four $5°\times5°$ fields flanking the cluster to the NE, NW, SE and SW. Only 2 objects in total have been flagged as candidate white dwarf members of Praesepe according to the selection criteria we applied in Dobbie et al. (2004). There is no guarantee that spectroscopic data would confirm either of these two objects to be a white dwarf. Thus we conclude that contamination by field white dwarfs is at a very low level.

Nevertheless, it is worth recalling here that LB5893, one of the five "original" white dwarf members of Praesepe, was not recovered by our survey. Since Luyten (1966) measured a proper motion of $\mu_\alpha\cos\delta$=-34 mas yr^{-1}, μ_δ=-14 mas yr^{-1}, albeit with large uncertainties, in Dobbie et al. (2004) we concluded that the USNO-B1.0 astrometry of $\mu_\alpha\cos\delta=-56$ mas yr^{-1}, $\mu_\delta=-14$ mas yr^{-1}, may have been adversely affected by the proximity of the star KW195. Claver et al. (2001) previously reached a similar conclusion on finding that their proper motion measurement of this object, which relied on POSS-I plates for epoch 1, also failed to confirm cluster membership. Given the lingering uncertainties in the proper motion of LB5893 and the rather peculiar location of this object in the semi-empirical IFMR (see Figure 11 of Claver et al. 2001), we have used the POSS-II F band image (1989/11/08) and a V band image (2001/02/04) obtained from the Canada-France-Hawaii Telescope archive at the Canadian Astrophysical Data Center to obtain a refined astrometric measurement for LB5893. Our estimate of $\mu_\alpha\cos\delta=-34\pm9$ mas yr^{-1}, $\mu_\delta=-18\pm12$ mas yr^{-1} supports the original proper motion determination of Luyten (1966) and argues strongly that LB5893 is a member of Praesepe. Therefore in the subsequent discussion we accept that the number of Praesepe white dwarfs is at least eleven.

As a consequence of the optical (O-E⩽0) and near-infrared selection criteria (no 2MASS detection or blue) our survey is biased against the detection of white dwarfs in unresolved binary systems with stars with masses M≳$0.1M_\odot$ (spectral types earlier than M6-7). Thus in the context of the cluster simulations of Williams et al. (2004), in reflection, it seems more appropriate to compare our results to the predicted observable number of single white dwarfs (ie. the predicted total observed number - the predicted number observed in binaries). We find that the observed number is inconsis-
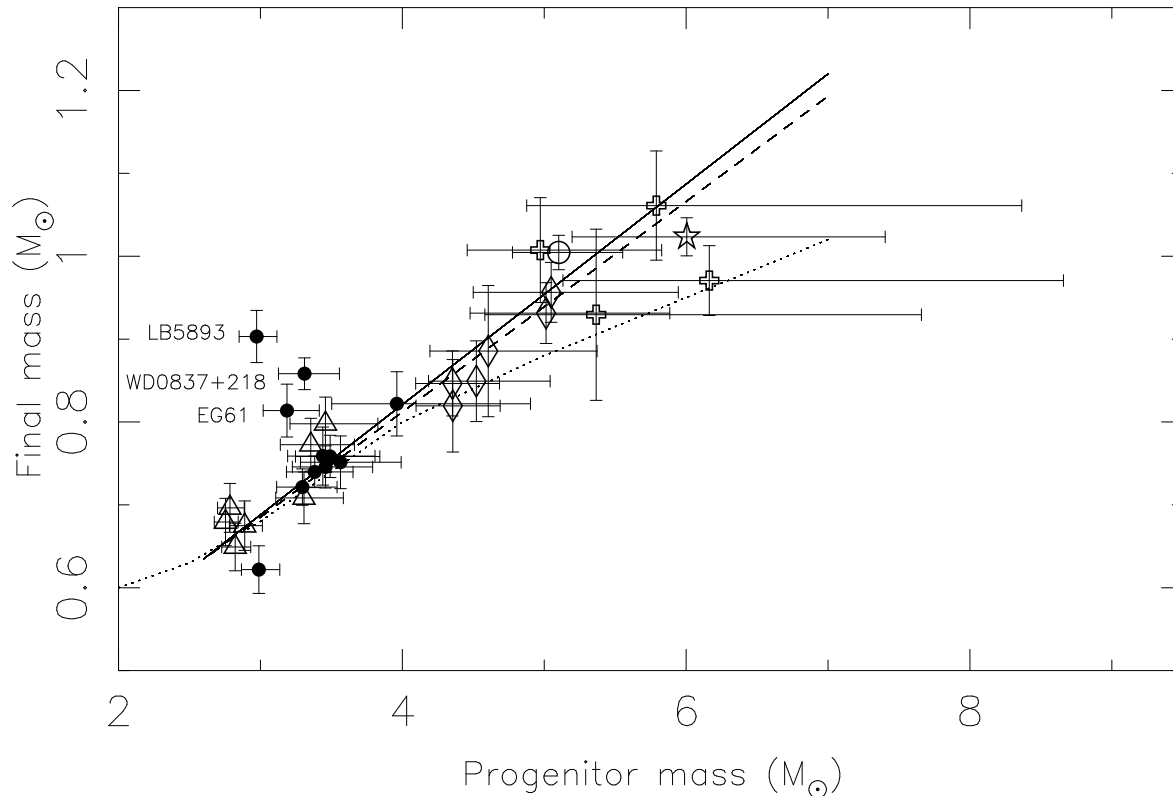
Figure 3. Initial mass-final mass for the white dwarf members of the Hyades (open triangles), Praesepe (black circles), M35 (open diamonds), NGC2516 (open '+'s) and the Pleiades (open star). Sirius B is also shown (open circle). A linear fit to the data based on CO (solid line)/C(dashed line) cores and the relation of Weidemann (2000; dotted line) are overplotted.

tent with these predictions, for any reasonable value of the maximum mass of a white dwarf progenitor (M_{crit}), if a steep power-law (Γ=2) shape is assumed to describe the initial mass function (IMF) of Praesepe. In constrast, we find that the observed number is consistent with the results of the simulations if instead the IMF is assumed to have been Salpeter in form for any reasonable value for M_{crit} (P$\approx$0.19 for M_{crit}=10$M_{\odot}$). Accordingly, we adjudge that there is not a deficit of white dwarfs, at least single objects, in this open cluster. If our conclusion is correct then these results suggest that the bulk of Praesepe white dwarfs did not gain a significant recoil kick velocity from possible asymmetries in their loss of mass during the asymptotic giant branch phase of evolution. Fellhauer et al. (2003) find that if the mean kick velocity extended to a white dwarf during this phase is greater than twice the cluster velocity dispersion (the one-dimensional velocity dispersion of Praesepe is 0.67$\pm$0.23kms^{-1}; Madsen et al. 2002) then a significant fraction of these objects evaporate from the cluster ($\gtrsim$60% at 600-700Myrs).

4.2 The masses of the progenitor stars of the Praesepe white dwarfs

The metalicities of the Praesepe and the Hyades open clusters are found, within uncertainties, to be very similar. For example, Cayrel de Strobel (1990) and Boesgaard & Budge (1988) determine [Fe/H]=0.10$\pm$0.06 and [Fe/H]=0.13$\pm$0.07 respectively for the former, while Cayrel, Cayrel de Strobel & Campbell (1985) and Perryman et al. (1998) find [Fe/H]=0.12$\pm$0.03 and [Fe/H]=0.14$\pm$0.05 respectively, for the latter. Furthermore, it has been recognised for

decades that the space motions of the two clusters are comparable (e.g. Schwarzchild & Hertzsprung 1913, Eggen 1992, Madsen et al. 2002), leading to the suggestion that Praesepe is a member of a Hyades supercluster. If this is the case it is likely that the ages of the two clusters are similar.

The bulk of determinations place the age of the Hyades cluster in the range 500-900Myrs (e.g. Barry et al. 1981, Kroupa 1995). Perryman et al. (1998) have estimated an age of 625$\pm$50Myrs by fitting theoretical isochrones, which included a treatment for convective overshoot, to the Hipparcos-based cluster Hertzsprung-Russell diagram. Claver et al. (2001) have compared modern theoretical isochrones for ages 500, 700 and 1000Myrs to the Praesepe sequence as observed in their V,V-I colour-magnitude diagram. They conclude that the upper main sequence is poorly reproduced by the 1000Myr isochrone but can be considered consistent with either of the two younger models. In addition, recent work on the X-ray properties of solar type Praesepe members reveals that these are similar to those of the F and G stars of the Hyades (Franciosini et al. 2003). Furthermore, we note that the most detailed study to date of the spatial distribution and dynamics of the cluster (Adams et al. 2002) finds no evidence for the existence of a subcluster as suggested by Holland et al. (2001). Therefore, we follow Claver et al. (and more recently Ferrario et al. 2005) and in our subsequent discussion assume the age of Praesepe is 625$\pm$50Myrs.

We have derived the lifetime of the progenitor star of each of the four new white dwarf members by subtracting the estimated cooling time, shown in Table 1, from the adopted cluster age. The results of this process are shown in Table 2. For consistency, we obtained new spectroscopy of comparable quality for WD0837+218

and WD0837+185 (Figure 1) and analysed it using our new grid of model atmospheres. Thus we also provide in Tables 1 and 2, revised effective temperatures, surface gravities, masses, cooling times and progenitor lifetimes for these two objects. We note that the bulk of the discrepancy between the new and old parameter estimates for these two objects stems from the different datasets used in the two analyses. The spectral datasets in Dobbie et al. (2004) were of comparatively low quality and the true level of uncertainty in the associated effective temperature and surface gravity estimates appears to have been slightly underestimated by our formal error analysis.

Subsequently, we have used cubic splines to interpolate between the lifetimes calculated for stars of solar composition by Girardi et al. (2000) and have constrained the masses of these six progenitors to the values shown in Table 2. The quoted errors take into account the uncertainty in the cluster age. The locations in initial mass-final mass space of all six of these objects and the five original Praesepe white dwarfs, where their masses, cooling times and progenitor lifetimes and progenitor masses have been derived on the basis of the effective temperature and surface gravity measurements of Claver et al. (2001), are shown in Figure 3 (filled circles). We point out that five of the Praesepe white dwarfs virtually sit on top of each other in this plot.

4.3   The initial mass-final mass relation

Since the Hyades has a comparatively robust age determination we have added to Figure 3 the seven single white dwarf members of this cluster (open triangles). Their initial and final masses are derived from the effective temperature and surface gravity measurements listed in Claver et al. (2001). As there still appears to be considerable uncertainty as to the age of M37 (e.g. Kharchenko et al. 2005, Kalirai et al. 2005, Twarog et al. 1997), we do not include in Figure 3 recent data from this cluster. However, the eighteen white dwarfs from Praesepe and the Hyades only define the initial mass-final mass relation for $2.7M_\odot \lesssim M_{prog} \lesssim 4M_\odot$. Therefore, we have also added to this plot Sirius B (open circle; Liebert et al. 2005a) and the white dwarf members of three other relatively well characterised but much younger open clusters ($\tau \lesssim 200$Myrs), the Pleiades (open star), M35 (open diamonds; Williams et al. 2005) and NGC2516 (open '+'s; Koester & Reimers 1996).

Using a new high S/N spectrum obtained with the WHT and our grid of TLUSTY models we have redetermined the effective temperature and surface gravity of the only known Pleiades white dwarf WD0349+247 (LB1497) to be $T_{eff}=32841^{+175}_{-169}$ and log $g=8.63^{+175}_{-169}$ respectively (Figure 4). This corresponds to a mass of $1.02\pm0.02M_\odot$, in excellent agreement with the gravitational redshift determination ($1.02\pm^{+0.04}_{-0.05}M_\odot$; Wegner et al. 1991). For the white dwarf members of M35 and NGC2516 we adopt the effective temperatures and surface gravities listed in Table 1 of Ferrario et al. (2005). Excepting M35, where, given the result of Kalirai et al. (2003), we prefer an age of 160 ± 25Myrs, the progenitor mass for each of these white dwarfs is derived assuming the system/cluster age and metallicity adopted by Ferrario et al. (2005). The upper limits to the progenitor masses of the white dwarf members of NGC2516 and the Pleiades displayed in Figure 3 have been determined by supplementing the model grid of Girardi with an evolutionary calculation for a 9M$_\odot$ star drawn from a grid of a previous generation of the Padova models (Bressan et al. 1993).

An examination of the thirty stars in Figure 4 indicates that the majority appear to follow rather closely a monotonic relation between their initial and final masses. Indeed, the white dwarf mem-
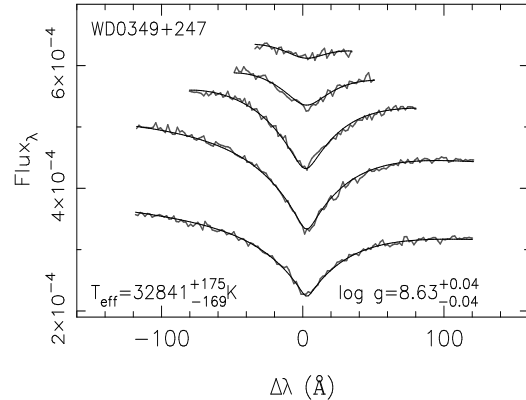
Figure 4. The results of our fitting of synthetic profiles (thin black lines) to the observed Balmer lines of WD0349+247, H-β to H-8, (thick grey lines). The flux$_\lambda$ units are arbitrary.

bers of the subsolar metalicity cluster M35 ([Fe/H]$\approx$-0.3; Sung & Bessell 1999) seem to form a natural extension of the relation defined by the Hyades and Praesepe white dwarfs (see Figure 3). This suggests that any effect metallicity may have on the form of the IFMR is probably not detectable at our current level of precision. Nevertheless, two stars, both attributable to Praesepe, appear to deviate more significantly ($\gtrsim 3\sigma$) from the general relation (LB5893 and WD0837+218). As briefly discussed by Claver et al. (2001) and Dobbie et al. (2004) these white dwarfs appear to be too hot for their relatively high masses. We note here that their masses are coincident with the secondary peak in the mass distribution of white dwarfs ($>0.8M_\odot$; see Figure 13 of Liebert et al. 2005b). As discussed by Liebert et al. it has been suggested that a significant proportion of the white dwarfs in this secondary peak may be the progeny of close binary systems.

The initial mass-final mass data shown in Figure 3 can be reasonably approximated by a linear function. In deriving the coefficients for this we exclude the two objects which appear to deviate most strongly from the general relation as these most likely result from close binary evolution. Additionally, we choose to reject from the our fit the magnetic white dwarf EG61 as the true uncertainties in the effective temperature and surface gravity determinations for this star, obtained from the Zeeman split profiles of the Balmer lines, could be significantly larger than the formal errors quoted by Claver et al. (2001). Thus performing a linear least squares fit to the remaining twenty-seven white dwarfs we derive fit co-efficients $a_0=0.289\pm0.051$, $a_1=0.133\pm0.015$ (solid line). We note that had we adopted pure-C core white dwarf evolutionary models, the cooling times would have been systematically larger by between 5-30Myrs, resulting in shorter progenitor lifetimes, larger progenitor masses and a marginally flatter IMFR ($a_0=0.304$, $a_1=0.127$; dashed line). In either case our fit is somewhat steeper than the widely applied Weidemann (2000) relation, in particular at $M_{prog} \gtrsim 4M_\odot$ where the latter flattens slightly (dotted line).

In standard stellar evolutionary theory, the CO core of an intermediate mass star can grow to $\sim 1.1M_\odot$ before the carbon ignites. The resulting degenerate NeO core collapses, through electron capture onto Ne, to form a neutron star. Extrapolating our fit to the initial mass-final mass data we find that a $1.1M_\odot$ white dwarf is produced by a star with an initial mass of $\sim 6.1M_\odot$. However, more recent theoretical modelling by Garcia-Berro et al. (1997) have shown that it is possible for stable more massive NeO de-

generate cores to form via single star evolution. For example, their calculation of the evolution of a $10M_\odot$ star ends in the production of a $1.26M_\odot$ NeO white dwarf. However, a $1.37M_\odot$ degenerate NeO core produced in a similar computation for a more massive star collapses, resulting in a type II supernova explosion. These findings led Weidemann (2000) to suggest that the upper limit for a white dwarf mass is $\sim1.3M_\odot$. On the basis of an extrapolation of our fit this corresponds to progenitor masses of $7.6(6.8\text{-}8.6)M_\odot$, somewhat lower than the 10-11 $M_\odot$ suggested by the models of Garcia-Berro et al. (1997).

There is no observational evidence to indicate that the form of the IMFR can be represented by an extrapolation of our linear function for $M_{prog} \gtrsim 6M_\odot$. Nevertheless, if we were to assume that such an extrapolation is valid and that the maximum white dwarf mass is $1.3M_\odot$ then these results argue that the minimum mass of a core collapse supernova progenitor lies in the range $\sim6.8\text{-}8.6M_\odot$. We note that Ratnatunga & van den Bergh (1989) estimate a Galactic type II supernova rate of $1.1^{+1.5}_{-0.6}$ century^{-1} for a minimum progenitor mass of $8M_\odot$.

5 SUMMARY

We have spectroscopically confirmed four more white dwarf members of Praesepe and argued that there are at least eleven white dwarfs in this cluster. We find that this number is consistent with that expected if the initial mass function of Praesepe was Salpeter in form. We suggest that this consistency indicates that few white dwarfs have evaporated from the cluster since their formation. If this is correct then any recoil velocity kick arising from possible asymmetries in mass loss during the final stages of stellar evolution is likely smaller than ~2.5kms^{-1}. We find most stars appear to follow, relatively closely, a monotonic relation between their initial and final masses. This relation can be reasonably approximated by a linear function with coefficients a_0=0.289±0.051, a_1=0.133±0.015. Extrapolation of this linear function beyond initial masses $\sim6M_\odot$ supports a minimum mass for a type II supernova progenitor in the range $\sim6.8\text{-}8.6M_\odot$ for an assumed maximum white dwarf mass of $1.3M_\odot$.

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