Praesepe and the seven white dwarfs

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Accepted 2004 October 19. Received 2004 October 18; in original form 2004 August 31

ABSTRACT
We report the discovery, from our preliminary survey of the Praesepe open cluster, of two new spectroscopically confirmed white dwarf candidate members. We derive the effective temperatures and surface gravities of WD0837+218 and WD0837+185 (LB5959) to be 17845+555−565 K and log g = 8.48+0.07−0.08 and 14170+1380−1900 K and log g = 8.46+0.15−0.16, respectively. Using theoretical evolutionary tracks we estimate the masses and cooling ages of these white dwarfs to be 0.92 ± 0.05 M⊙ and 280−30 30 Myr and 0.90 ± 0.10 M⊙ and 500−100 170 40 Myr, respectively. Adopting reasonable values for the cluster age we infer the progenitors of WD0837+218 and WD0837+185 had masses of 2.6 ≤ M ≤ M_{crit} M⊙ and 2.4 ≤ M ≤ 3.5 M⊙, respectively, where M_{crit} is the maximum mass of a white dwarf progenitor. We briefly discuss these findings in the context of the observed deficit of white dwarfs in open clusters and the initial mass–final mass relationship.

Key words: white dwarfs – open clusters and associations: individual: Praesepe.

1 INTRODUCTION
The common age, metallicity and distance of their members make galactic open star clusters favourable environments in which to examine fundamental issues in stellar and galactic astrophysics e.g. the shape of the initial mass function (IMF) or the form of the initial mass–final mass relationship (e.g. Weidemann 1987). The modestly rich and well-studied Praesepe (NGC 2632) cluster at a distance of 177 pc, as determined from the He− line of HD183143 (van Leeuwen 1999). A more recent Hipparcos based study of Praesepe indicates the cluster is slightly metal rich with respect to the Sun ([Fe/H] = 0.038, [C/H] = 0.01; Friel & Boesgaard 1992). This is consistent with the conclusions reached by previous investigations of this type (e.g. Boesgaard & Budge 1988). However, there is still uncertainty as to the age of the cluster, with estimates ranging from 0.4–2 Gyr (e.g. Allen 1973; Mathieu & Mazeh 1988). Those determinations based on isochrone fitting generally support an age of between 0.7–1.1 Gyr (e.g. Anthony-Twarog 1982; Mazzei & Pigatto 1988), although Claver et al. (2001), hereafter C01, favour a value closer to that of the Hyades (625 Myr), on grounds that the two clusters have similar metallicity and that, kinematically, Praesepe is part of the Hyades moving group (Eggen 1960).

To date, five white dwarf members of Praesepe have been identified: LB390, LB5893, LB393, LB1847 and LB1876 (Luyten 1962; Eggen & Greenstein 1965; Anthony-Twarog 1982, 1984; C01). This is fewer than the 7–20 observable degenerates predicted from the extrapolation of the present-day cluster luminosity function, allowing for reasonable assumptions about the form of the IMF, the maximum progenitor mass (M_{crit}) and the binary fraction (Williams 2004, hereafter W04). Several explanations have been put forward to account for this shortfall and the deficit of white dwarfs observed in other open clusters such as the Hyades. For example, if M_{crit} ∼ 4 M⊙ there would have been fewer white dwarf progenitors in the first place (e.g. Tinsley 1974). However, the presence of the white dwarf LB1497 in the Pleiades with an estimated progenitor mass M ≥ 6 M⊙ argues against this (C01). It has recently been shown that asymmetry at a level of only 1 per cent in the post-main-sequence mass-loss process is sufficient to lead to the rapid loss of a significant fraction of the white dwarf population from an open cluster (Fellhauer et al. 2003). Alternatively, for Praesepe at least, it may be that no investigation to date has included a sufficient fraction of the

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To move towards a resolution of these issues we are embarking on a comprehensive search for additional white dwarf members of Praesepe. Here we report the discovery, from a preliminary version of this survey, of two new white dwarf candidate cluster members. For each object we present an optical spectrum, determine $T_{\text{eff}}$ and $\log g$ and, by comparing these measurements to evolutionary models, estimate mass and cooling time. We conclude by briefly discussing our findings in the context of the reported deficit of white dwarfs in Praesepe and the initial mass–final mass relationship.

2 A PRELIMINARY SEARCH FOR PRAESEPE WHITE DWARFS

We have utilized the USNO-B1.0 catalogue to undertake a survey of a $5^\circ \times 5^\circ$ region centred on the Praesepe open cluster ($\alpha = 08^h40^m, \delta = +19^\circ40', \text{J2000.0}$). The USNO-B catalogue contains astrometric information and photographic magnitudes for over a billion objects, gleaned from digitally scanned photographic plates spanning a baseline of $\sim 50$ yr. The internal astrometric accuracy and the dispersion in the photometry are estimated to be $\sim 0.2$ arcsec and $\sim 0.3$ mag, respectively (for details see Monet et al. 2003).

In this preliminary effort we have extracted all sources with $19 \geq O \geq 17$, $O-E \leq 0$ and with proper motions $-25 \geq \mu_\alpha \cos \delta \geq -45$ mas yr$^{-1}$, $0 \geq \mu_\delta \geq -20$ mas yr$^{-1}$. This encompasses the magnitude range of known cluster white dwarfs and is virtually coincident with the astrometric range sampled by Hambly et al. (1995). Further, the survey should be near complete for $O-E \gtrsim -1$ (Hambly et al. 1995). Subsequently, the POSS II J and F images of each candidate have been inspected to eliminate extended sources, blended objects and spurious detections originating in the diffraction spikes of bright stars. As an additional check, candidates have been cross-referenced against the 2MASS Point Source Catalogue (Skrutskie et al. 1997), keeping only those which are either non-detections or have blue near-infrared (near-IR) colours within the photometric errors. Finally, we have used photographic photometry measured by SuperCOSMOS to compare the location of our new candidates to the locus of cluster white dwarfs in the $B_1$, $R_F$ colour–magnitude diagram (Fig. 2). The external accuracy of individual passband

Figure 1. 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 C01 (grey shading). The region included in this investigation is outlined (dashed grey line). All objects listed in Table 1 (open circles) and the known white dwarf cluster members (open stars) are also overplotted. The locations of the two new spectroscopically confirmed white dwarf candidate members are highlighted (open triangles).

Figure 2. A $B_1$, $B_1 - R_F$ colour–magnitude diagram of the 11 objects remaining after cross-referencing against the 2MASS Point Source Catalogue (PSC; open circles). The thick line represents a linear least-squares fit to SuperCOSMOS photometry of the known degenerate members (open circles + stars) and objects drawn from the 20-pc sample of Holberg et al. (2002) with trigonometric parallax determinations (filled triangles). The magnitudes of the latter have been scaled to correspond to a distance of 177 pc. Note that LB5893 (filled square) has been excluded from the fit.
The spectra were extracted using the APEXTRACT package and wavelength-calibrated by comparison with the CuNe arc standards. The CuAr arc was treated by means of the occupation probability formalism of Lanz (1995) and SYNSPEC (v48; Hubeny & Lanz, private communication). We have employed a state-of-the-art model H atom incorporating the eight lowest energy levels and one superlevel extending to the observed Balmer lines (thick grey lines).

3 ANALYSIS OF THE DATA

3.1 Model white dwarf spectra

A glance at Fig. 3 reveals broad hydrogen Balmer lines consistent with both objects being DA white dwarfs. Therefore, we have generated a grid of pure-H synthetic spectra covering the $T_{\text{eff}}$ and surface gravity ranges 14 000–20 000 K and log $g$ = 7.0–9.0, respectively. 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 & Lanz, private communication). We have employed a state-of-the-art model H atom incorporating the eight 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), generalized to the non-LTE situation by Hubeny, Hummer & Lanz (1994). All calculations were carried out under the assumption of radiative equilibrium, included the bound-free and free-free opacities of the H$^-$ ion and incorporated a full treatment for the blanketing effects of H$^+$ lines and the Lyman $\delta$, $\beta$ and $\gamma$ satellite opacities as computed by N. Allard (e.g. Allard et al. 2004). During the calculation of the model structure the lines of the Lyman and Balmer series were treated by means of an approximate Stark profile but in the spectral synthesis step
the effects of the wiggles in the response of the ISIS dichroic around uncertainties.

white dwarf members of Praesepe, for reasonable values of the maximum investigated by W04 that was consistent with his assumption of seven. Similarly, because both Luyten’s and the current work utilized blue surveys of C01 and Anthony-Twarog. White dwarfs with more massive main sequence extending out to at least the tidal radius should be undertaken before 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

We carried out comparisons between models and data 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 \chi^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 \chi^2 is minimized. Errors are calculated by stepping the parameter in question away from its optimum value until the difference between the two values, \Delta \chi^2, corresponds to 1\sigma for a given number of free model parameters (e.g. Lampton et al. 1976). The errors in \text{Teff} and \log g quoted here are formal 1\sigma fit errors and may underestimate the true uncertainties.

Preliminary fitting of our model grid to the observed Balmer line profiles (He–Hα) in both spectra revealed that our efforts to remove the effects of the wiggles in the response of the ISIS dichroic around 4400 Å had not been entirely successful. Therefore, we excluded the Balmer \gamma line from our subsequent analyses, determining \text{Teff} and \log g from the four remaining profiles. The results are given in Table 2 and shown overplotted in Fig. 3.

### 4 DISCUSSION

#### 4.1 Cluster membership and the white dwarf deficit

A steep power law (\Gamma = 2) was the only shape of IMF for the four investigated by W04 that was consistent with his assumption of seven white dwarf members of Praesepe, for reasonable values of the maximum progenitor mass (6 \text{M}_\odot \leq \text{M}_{\text{crit}} \leq 10 \text{M}_\odot). The ‘Naylor’ IMF, a broken power law with index \Gamma = 0.2 (M \leq 1 \text{M}_\odot) and \Gamma = 1.8 (M > 1 \text{M}_\odot) was found to be consistent only for \text{M}_{\text{crit}} = 6 \text{M}_\odot. However, in a subsequent paper, Williams, Bolte & Liebert (2004) show LB6037 and LB6072 to be quasi-stellar objects (QSOs), reducing the number of bona fide white dwarf members of Praesepe unearthed to date to only five. In this case, only the steep power-law form with \text{M}_{\text{crit}} \leq 8 \text{M}_\odot can be considered consistent with the observations.

Nevertheless, we have presented evidence here that the number of Praesepe white dwarfs is at least seven. As a further check of the membership status of our two new spectroscopic candidates we constrain their distances using the measured \text{Teff} and \log g and radii derived from evolutionary tracks. From the ‘thick H layer’ models of Wood (1995) we determine R = 0.0093 ± 0.0020 \text{R}_\odot and R = 0.0091 ± 0.0009 \text{R}_\odot for LB5959 and WD8037+218, respectively. Subsequently, we estimate the absolute visual magnitude of LB5959 to be \text{M}_V = 12.0 ± 0.5 and that of WD8037+218 to be \text{M}_V = 11.7 ± 0.2. Referring to the synthetic photometry of Bergeron, Wesemael & Beauchamp (1995, also private communication) we estimate \text{B} – \text{V} \approx +0.15 and +0.05 for the cooler and hotter degenerate, respectively. Thus from the SuperCOSMOS data, \text{B}_1 = 18.3 ± 0.3 and \text{B}_2 = 18.0 ± 0.3, we determine \text{V} magnitudes of 18.15 ± 0.3 and 18.0 ± 0.3. Hence, we estimate these white dwarfs to reside at 170 +20 −10 and 180 +40 −30 pc, respectively.

Indeed, the favourable success rate of our preliminary survey in unearthing cluster white dwarfs suggests several of the remaining four new candidates will also prove to be degenerate members. However, as confirmation of this must await further spectroscopy, for now we consider the observed number of Praesepe white dwarfs, N, to lie in the range 7 \leq N \leq 11. Based on the Williams simulations we find the steep power-law form of the IMF is consistent with the observed number for any reasonable value of \text{M}_{\text{crit}}. Similarly, if N \geq 8, the ‘Naylor’ form can be considered consistent for any reasonable value of \text{M}_{\text{crit}}. We note that one requires to detect at least 10 white dwarf members for the Salpeter form of the IMF to be regarded at best, in Williams scheme, as mildly inconsistent with the observed number (P \approx 0.07). As our preliminary results indicate white dwarf members are to be found outwith the well-studied inner regions of the cluster (Fig. 1 shows WD0837+218 lies at a projected separation of \sim 2\') more likely await discovery. A detailed survey extending out to at least the tidal radius should be undertaken before any firm conclusions are drawn regarding the form of the IMF.

Prior to this work only the ‘Naylor’ form of the IMF was found to be consistent with the non-detection of cluster white dwarfs residing in unresolved binary systems (W04). However, there is no evidence to suggest that either of the two new confirmed white dwarfs resides in a binary. We find a white dwarf with \text{Teff} = 17 000 K and \log g = 8.0, typical of the Praesepe population, has \text{M}_V = 11.0, \text{M}_B = 11.0 and \text{M}_{\text{U}} = 10.2 (Bergeron et al. 1995) and a young disc M3 dwarf has \text{M}_V = 10.7, \text{M}_B = 12.3 and \text{M}_{\text{U}} = 13.4 (Leggett et al. 1992). An unresolved binary consisting of these two objects has \text{U} – \text{B} = -0.6, \text{B} – \text{V} = 0.6. It thus lies on the fringes of the W04 criteria for being ‘observable’ (\text{U} – \text{B} \leq 0.0, \text{B} – \text{V} \leq 0.6), which were chosen to approximate the limits of the \text{UBV} surveys of C01 and Anthony-Twarog. White dwarfs with more massive main sequence companions are unlikely to have been identified by these surveys. Similarly, because both Luyten’s and the current work utilized blue and red photographic plates, selecting objects with colours I.C. \leq 0.2 (\approx \text{B} – \text{V} \leq 0.5) and O–E \leq 0 respectively, these too are likely

### Table 2

Details of the two new spectroscopically confirmed white dwarf candidate cluster members. Masses and cooling times are derived from the ‘thick H layer’ evolutionary calculations of Wood (1995).

<table>
<thead>
<tr>
<th>WD</th>
<th>\text{Teff}(K)</th>
<th>\log g</th>
<th>\text{M}(\text{M}_\odot)</th>
<th>\text{t}_c (\text{Myr})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0837+185</td>
<td>14170 ^{+380}_{-1590}</td>
<td>8.46 ^{+0.15}_{-0.16}</td>
<td>0.90 ± 0.10</td>
<td>500 ^{+170}_{-100}</td>
</tr>
<tr>
<td>0837+218</td>
<td>17845 ^{+555}_{-565}</td>
<td>8.48 ^{+0.07}_{-0.08}</td>
<td>0.92 ± 0.05</td>
<td>280 ^{+40}_{-30}</td>
</tr>
</tbody>
</table>

Note. *Extrapolated.*

### Table 3

Progenitor lifetimes and corresponding masses for various adopted cluster ages.

<table>
<thead>
<tr>
<th>Progenitor of WD</th>
<th>8.80 (log10 Myr)</th>
<th>8.92 (log10 Myr)</th>
<th>9.04 (log10 Myr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{t}_\text{prog} (Myr)</td>
<td>\text{M}<em>\text{prog} (\text{M}</em>\odot)</td>
<td>\text{t}_\text{prog} (Myr)</td>
<td>\text{M}<em>\text{prog} (\text{M}</em>\odot)</td>
</tr>
<tr>
<td>0837+185</td>
<td>130^{+30}_{-170}</td>
<td>4.9^{+0.4}_{-1.0}</td>
<td>330^{+100}_{-170}</td>
</tr>
<tr>
<td>0837+218</td>
<td>350^{+30}_{-40}</td>
<td>3.3^{+0.2}_{-0.1}</td>
<td>550^{+30}_{-40}</td>
</tr>
</tbody>
</table>

biased against finding white dwarfs residing in binaries with stars of spectral type earlier than mid-M.

Farhi, Becklin & Zuckerman (2003) report a deficit of objects of spectral type later than mid-M paired to field white dwarfs at separations of ~ a few 100 au. Furthermore, radial velocity surveys point towards a drop in the relative frequency of main-sequence binaries with mass ratios $M_2/M_1 \lesssim 0.2$, at separations $\lesssim 5$ au (Hab- wachs et al. 2003; Marcy & Butler 2000). Hence, it seems plausible, particularly as the progenitors of the Praesepe and Hyades white dwarfs had $M \gtrsim 2.5 \, M_\odot$, that by including a population of zero-age binaries consisting of randomly paired stars, the simulations of W04 overpredict the number of detectable white dwarfs in unresolved binaries with main-sequence companions. This assumption was acknowledged by W04 as a possible shortcoming in their modelling. Our forthcoming GALEX survey of Praesepe will expand the parameter space in which we are able to search for white dwarfs to include those in unresolved systems with K-, G- and F-type companions. It will reveal important additional information on the form of the IMF and the binary fraction of this cluster.

4.2 White dwarf masses and the initial mass–final mass relationship

We have estimated the masses of the two new white dwarfs by comparing their measured $T_{\text{eff}}$ and $\log g$ to the predictions of evolutionary calculations (Wood 1995). As expected for their progenitor masses, $M \gtrsim 2.5 \, M_\odot$, these two objects have masses greater than the canonical white dwarf value of $M \approx 0.6 \, M_\odot$ (see Table 2). We have also used the evolutionary tracks to estimate the cooling times of these objects, determining $500^{+100}_{-100}$ Myr and $280^{+170}_{-160}$ Myr for LB5959 and WD0837+218, respectively. As the age of the cluster is rather uncertain we have used three different estimates encompassing the likely value ($\log \tau_{\text{cluster}} = 8.80, 8.92$ and 9.04) to derive the progenitor lifetimes. Using cubic splines to interpolate between the lifetimes calculated for stars of solar composition by Girardi et al. (2000), we constrain the masses of the progenitors of LB5959 and WD0837+218 to be $2.6 \leq M \leq 3.5 \, M_\odot$, respectively.

Examining the location of these objects in fig. 11 of C01 we find that while LB5959 fits in comfortably with a monotonic relationship between initial mass and final mass, like LB5893, WD0837+218 appears to be too hot and hence too young for its high mass. We note there are five blue stragglers members of Praesepe (e.g. Andrievsky 1998). The evolution of these objects appears to have been delayed, either through binary interaction or another as yet unidentified mechanism. We suggest that LB5893 and WD0837+218 may be related to this population. Alternatively, as suggested by Reid (1996), perhaps at least some stars do not subscribe to a simple monotonic relationship between their mass and the mass of their resulting white dwarf remnant.

ACKNOWLEDGMENTS

PDD and DJP are sponsored by PPARC postdoctoral grants. RN and MRB acknowledge the support of PPARC advanced fellowships. The WHT is operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. We thank the anonymous referee for timely and useful comments.

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