White Dwarfs in Globular Clusters
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I. Introduction

Surrounding the galaxy, with an aloofness appropriate to their great age, the globular clusters have played a starry role in the development of much of modern astronomy. In particular, they continue to be vital laboratories for testing our ideas of stellar evolution (Renzini and Fusi Pecci 1988). Through the study of cluster color-magnitude diagrams (CMD's), all the major phases in the life of a common low mass star can be traced, save one. The final sequence, the locus of cooling white dwarfs, remains unexplored. We are forced to glean our knowledge of this evolutionary phase from the study of a heterogeneous sample of relatively nearby stars. Although remarkable progress has been made, the prospect of observing white dwarfs in globular clusters offers the potential for new insights into old problems; e.g., the DA/DB dichotomy, and perhaps a resolution of some of the outstanding issues connected with the clusters themselves.

The advantages of using globular clusters for the study of white dwarfs include the following. (i) White dwarfs are the only known endpoint for the current population of stars in globular clusters. Indeed, this has been true for many billions of years and hence globulars should be _full_ of white dwarfs. Estimates of their numbers will be given shortly. (ii) The clusters are rich and compact stellar systems so that a limited search area can be effective in discovering large numbers of white dwarfs. (iii) The white dwarfs in any one cluster are derived from a chemically homogeneous (with the known exception of ω Cen) and coeval parent population whose distance and age are reasonably well known. (iv) Given the apparently low incidence of duplicity in globular clusters, the evolutionary path of most stars should be unaffected by the complications of binary star evolution.

On the other hand, there are two serious obstacles to be faced. (i) The clusters are distant: the nearest has an apparent distance modulus of 12.3 mag. and a typical value is perhaps 15.0 mag. Even the brightest cluster white dwarfs appear as very faint objects. Direct observation of the vast majority of the white dwarf population is simply not feasible now or in the forseeable future. (ii) The stellar density within the cluster is high. Deep photometric fields are invariably crowded and therefore our ability to see the faint white dwarfs is severely compromised.

To the above, we might add that the globular clusters exhibit a metal deficiency compared to the disk stars and that there is a range of about 2 dex in metallicity among them. We should remain alert to the possibility that there could be systematic differences between the cluster white dwarfs and those commonly observed in the solar neighbourhood and further, that similar differences might exist from cluster to cluster.

II The Expected Number of White Dwarfs

There are two issues to be discussed: (i) the number of observable white dwarfs and (ii) the total number of white dwarfs in a cluster. The technique of estimating the number of bright and hence observable white dwarfs has been thoroughly discussed by Renzini (1985) following an earlier presentation by Fusi Pecci and Renzini (1979). Briefly, the method is based on the assumption that stars are conserved during their relatively rapid post main sequence (pms) evolution. Consequently the number of stars in any given pms phase is simply proportional to the time spent in that phase. The 'constant' of proportionality can be written as the product of the specific evolutionary flux and the visual luminosity of the cluster (Renzini and Buzzoni 1986, Renzini 1988).

We can take a more direct tact starting with the expression

$$N_{wd}(<M_v) = N_{hb} \, t_c(<M_v) \, / \, t_{hb} \qquad (1)$$

where $N_{wd}(<M_v)$ is the number of white dwarfs brighter than absolute magnitude M_v; N_{hb}, the total number of stars now on the horizontal branch; $t_c(<M_v)$, the cooling time to reach M_v and t_{hb}, the horizontal branch lifetime. This expression is valid as long as the present value of N_{hb} does not differ sensibly from the past values, an assumption which is quite reasonable for any observable extent of the cooling sequence. Convenient expressions for the cooling times can be obtained from Green (1980):

$$
\begin{aligned}
\log t_c &= 4.85 + 0.32 \, M_v & M_v &> 11.3 \\
\log t_c &= -1.01 + 0.84 \, M_v & M_v &< 11.3
\end{aligned}
\qquad (2)
$$

and for t_{hb} a value of 10^8 yrs may be used (Renzini 1977).

In principle N_{hb} can be obtained by simply counting the number of horizontal branch stars but this is generally practical only in a limited area of any given cluster. A summary of available data can be found in Buzzoni et al (1985).

We note that N_{hb} should be equal to the number of stars which evolve off the main sequence over the time t_{hb}. Turning to the isochrones of VandenBerg and Bell (1985), (for definiteness, we use the metal rich isochrone with Z=0.003, appropriate to M71; there will be some metallicity dependence in the following results), we find that the stellar mass at the turnoff (defined as the bluest point in the isochrone) changes by only $\Delta m_{hb} \approx 1.6 \times 10^{-3} \, M_\theta$ over the time t_{hb} at an age of 16 Gyr. While continuity of the mass spectrum of the cluster is debatable over such a small range, we nevertheless will assume that $N_{hb} = A \, f(m) \, \Delta m_{hb}$ where A is a normalization constant and $f(m)$ is the functional form of the mass distribution. The constant A can be obtained by counting stars over some convenient interval. With CCD detectors, it is possible to reach well below the main sequence in many clusters and a suitable range to determine A would be from the turnoff to 3 magnitudes below. Designating this number by N_{-3}, we have

$$N_{hb} = N_{-3} \, \Delta m_{hb} \, / \, \Delta m_{-3} \approx 7.4 \times 10^{-3} \, N_{-3} \qquad (3)$$

where $\Delta m_{-3} = 0.22$ from the isochrones. Substituting into equation (1), we find

$$N_{wd}(<M_v) = 6.8 \times 10^{-11} \, N_{-3} t_c \, (<M_v) \qquad (4)$$

That this estimate of N_{wd} is consistent with Renzini's prescription can be shown as follows. A detailed study of the stellar population in M71 by Richer and Fahlman (1988b) demonstrates that essentially all the visible stellar luminosity comes from stars more massive than 0.33 $M_{\odot}$. Moreover, in that cluster the visible mass to light ratio is 0.57 and the mean mass of the stars involved is 0.63 $M_{\odot}$ so that $N(>0.33\ M_{\odot})$ = 0.9 L_v. We find that $N(>0.33\ M_{\odot})$ = 2.5 N_{-3} and therefore

$$N_{wd}(<M_v) = 3.0 \times 10^{-11}\ L_v\ t_c\ (<M_v). \tag{5}$$

This agrees completely with Renzini's (1988) result for M3. Although it must be admitted that exact agreement is fortuitous, our result certainly supports the basic correctness of Renzini's approach based on the concept of specific evolutionary flux.

Using the star counts of Lee (1977a,b,c), we have calculated the expected numbers of white dwarfs in three clusters with more or less complete data using equation (1). These are listed in Table 1. Taking the necessary data from the compilation of Webbink (1985), we have used equation (5) to estimate the number of bright white dwarfs in some nearby clusters. These are in Table 2. Since M4 (NGC 6121) appears in both tables, the difference in the estimates probably reflects the inherent uncertainty in these formulae.

Table 1

Predicted Number of White Dwarfs

Cluster	$(m-M)_v$	N_{HB}	$N_{WD}(M_v<)$		$N_{WD}(V<26)$
			10	12	
NGC 3201	14.15	175	43	857	767
NGC 6121	12.75	148	34	676	1699
NGC 6809	13.80	209	51	1024	1186

Table 2

White Dwarfs in Nearby Clusters

Cluster	$(m-M)_v$	$\log L_c/L_0$	$N_{WD}(M_v<10)$	$N_{WD}(V<26)$
47 Tuc	13.46	5.79	453	13400
ω Cen.	13.98	6.10	925	18929
NGC 6121	12.75	4.73	39	1982
NGC 6397	12.30	4.56	27	1850
NGC 6752	13.20	5.02	77	2800

In order to estimate the total population of white dwarfs, two important parameters are needed: (i) m_c, the upper mass limit for white dwarf progenitors and (ii) x, the mass spectral index, defined by a power law parameterization of the mass function, $dN/dm = A\ m^{-(1+x)}$. Neither of these parameters is without controversy and

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the assumption of a power law may be particularly egregious. The total number of white dwarfs is then obtained from

$$N_d = A \int_{m_o}^{m_c} m^{-(1+x)} \, dm \tag{6}$$

where m_o is the present day turnoff mass.

An upper limit to m_c of about 8-9 $M_\odot$ is set by the ability of a star to form a degenerate CO core after the exhaustion of central helium (Iben and Renzini 1983). Observationally, the existence of massive white dwarfs in the open cluster NGC 2516 shows convincingly that progenitor masses of up to 8 $M_\odot$ are possible at least in population I stars (Weidemann and Koester 1983). A value of $m_c = 5 M_\odot$ is sometimes used as in Meylan (1988). This limit is based on the linear relationship between the initial, m_i, and final mass, m_{wd} proposed by Iben and Renzini (1983)

$$m_{wd} = 0.53\eta^{-0.082} + 0.15\eta^{-0.35}(m_i - 1) \tag{7}$$

where η is a parameter scaling the mass loss rate. A value of $\eta = 1/3$ is generally consistent with the distribution of white dwarf masses (Weidemann and Koester 1983) and also with the masses of the nuclei of population II planetary nebulae (Heap and Augensen 1987). With $\eta = 1/3$, the above formula yields an upper limit of $m_i = m_c \approx 5 M_\odot$. While equation (7) is certainly a convenient parameterization of a complex relationship, it is becoming evident that the mass lost is a function of the initial mass; i.e., $\eta = \eta (m_i)$ (Weidemann 1984, 1987). For this reason, the 5 $M_\odot$ limit is somewhat artificial. In practise the estimated numbers are not strongly dependent on m_c for values of $x \geq 1$.

One of the most remarkable results to emerge from the CCD studies of globular cluster luminosity functions is the apparent relationship between x and the cluster metallicity (McClure et al 1986). Metal rich clusters tend to have flat luminosity functions ($x \approx 0$) whereas the metal poorest have the steepest functions ($x \geq 1$). The initial result has been softened somewhat because of the question of mass segregation corrections (Pryor, Smith and McClure 1986) and some of the recent results on metal poor clusters are ambiguous (at best): see Richer, Fahlman and VandenBerg (1988) for a discussion of M30 and the results of Stetson and Harris (1988) for M92. It may well turn out that a single power law representation of the mass function is generally inappropriate as indicated for M13 by Drukier et al (1988). What does seem to be clear is that the metal rich clusters 47 Tuc (Hesser et al 1987) and M71 (Richer and Fahlman 1988b) have essentially flat luminosity functions to well below the turnoff.

We have calculated the expected number and total mass of white dwarfs in a strawman cluster with a luminosity of $10^5 L_\odot$ where the light is assumed to come from stars between 0.8 and 0.4 $M_\odot$ with a mean mass of 0.6 $M_\odot$. The white dwarfs are assumed to have a mean mass of 0.6 $M_\odot$ and $m_c = 8 M_\odot$. The results are shown in Table 3 where we have also listed the total mass of the progenitor stars, M_{pg}, and the mass lost by the cluster in forming the remnants, ΔM. It can be seen that the extrapolation of the flat mass functions, as seen in the metal rich clusters, implies an uncomfortably large mass lost during the early evolution of the cluster. A continuation of the mass function to even more massive stars, which presumably produce heavy remnants, exacerbates the problem.

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Table 3

Total Number of White Dwarfs

X	N_{WD}	$M_{WD}/M_\odot$	$M_{pg}/M_\odot$	$\Delta M/M_\odot$
0	3.4×10^5	2.1×10^5	1.1×10^6	8.7×10^5
1	9.7×10^4	5.8×10^4	2.0×10^5	1.4×10^5
2	3.7×10^4	2.2×10^4	5.4×10^4	3.2×10^4

III Expected Properties of the White Dwarfs

Fusi Pecci and Renzini (1979) pointed out that the cosmic scatter in the masses of the observable white dwarfs is expected to be very small. They estimated $m_{wd} = 0.515 \pm 0.015 M_\odot$, where the uncertainty reflects primarily the metallicity variation among the clusters.

Such a small spread is not an obvious result. The isochrones of VandenBerg and Bell (1985) show that a coeval population of clusters with a metallicity range $-0.49 > [Fe/H] > -2.27$ will have a systematic variation of about $0.08 M_\odot$ in their turnoff masses at 16 Gyr. A strictly linear relationship between initial and final masses would give a corresponding systematic variation in the white dwarf masses.

Such a naive interpretation is unlikely to be correct. Before reaching the white dwarf state, the star must lose approximately $0.3 M_\odot$ and even a slight differential mass loss with metallicity could well narrow (or broaden!) the original mass difference. Evidence that the initial mass range is ultimately narrowed comes from two observations discussed in Renzini and Fusi Pecci (1988): (i) the maximum luminosity on the AGB can be used to infer the mass of the CO degenerate core destined to become the white dwarf, and (ii) the eight post-AGB stars observed by de Boer (1985) appear to span a very small mass range, $\Delta m \approx 0.02 M_\odot$ when compared to the corresponding Schönberner (1983) models. With regard to the former, the small number of identified AGB stars mitigates against finding the absolutely brightest possible star. For the latter, an additional point is the determination of the stellar luminosity contribution below the Lyman limit; de Boer assumed that this was the same as that for population I stars at the same effective temperature. In spite of these caveats, the observations do currently support the hypothesis of a small mass range among the white dwarfs in different clusters. The higher luminosities of the AGB stars in metal rich clusters suggests that they will have slightly more massive white dwarfs than their metal poorer cousins (see also Schönberner 1987).

A related question is the mass spread among the stars in a given cluster. For guidance here, we appeal to the recent models of synthetic horizontal branches reported by Lee, Demarque and Zinn (1988). These calculations are based on the assumption that the HB stars have a (truncated) Gaussian distribution in mass. The mass dispersion required for most clusters leads to a full width at half maximum in the distribution of $0.14 M_\odot$. According to Renzini (1977), the mass spread in the resulting white dwarfs should be reduced by a factor of $\approx 1/6$ due to mass loss during the final AGB phases. Therefore, within the cluster, the typical mass spread should be $\Delta m \approx 0.02 M_\odot$.

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We conclude from this discussion that one can anticipate cluster cooling sequences to be very tightly delineated and to define almost identical loci irrespective of cluster metallicity. Of course, if observations should indicate otherwise, two possible culprits can be readily identified: (i) the mass loss mechanism, and (ii) non standard evolution.

The existence of a mass spread on the HB is direct evidence that the mass loss process must involve an unaccounted for stochastic component which allows rather substantial variations in the total mass lost. If similar stochastic factors apply along the AGB, it is not completely clear that the mass spread introduced along the HB will be decreased by the full factor of 1/6. Given that the termination of the AGB phase is controlled by the mass remaining in the envelope, it does seem reasonable to expect <u>some</u> reduction to occur.

The question of non standard evolution includes a number of issues. For example, a cluster like M15 has an extended blue HB which cannot be modelled with the parameters appropriate to other clusters (Lee, Demarque and Zinn 1988). Indeed, the whole issue of why differences exist in the HB morphology of clusters with similar metallicity (cf Buonanno, Corsi and Fusi Peci 1985) remains unresolved and points to a deficiency in our understanding of the parameters which control the late stages of stellar evolution (Fusi Pecci 1986). Whether such unknowns might manifest themselves in the white dwarf sequence is a moot point.

The possibility that stars may bypass the AGB or even the HB on their route to the white dwarf stage must be entertained. This can occur in the course of binary star evolution (Iben and Tutukov 1986) and is possibly the explanation for the two anomalous planetary nebula central stars described by Mendez et al (1988) which surely will become white dwarfs. We have already noted that binaries seem to be rare in globulars but there are two situations to be wary of: (i) the very open globulars tend to contain blue straggler stars whose masses appear to be about twice that of the subgiants (Nemec and Harris 1987), and (ii) those clusters in an advanced state of dynamical evolution, like M15, in which a large number of binaries may form in the core (see Elson, Hut and Inagaki 1987). A second possibilty is that HB stars with very small envelopes may evolve to the blue, through the sdB and sdO regions, and then to the white dwarf region (Schönberner and Drilling 1984, Heber et al 1987). This consideration is relevant to those clusters with extended blue horizontal branches, like M15 or NGC 6752.

An imaginative suggestion made by Bailyn et al (1988) is that the extended blue horizontal branch stars are the result of a collision between a main sequence star and a white dwarf. This leaves the latter with a small envelope and appearing as a blue drooper off the horizontal branch. It is interesting to note that the merger of two helium dwarfs considered by Iben and Tutukov (1986) would also result in an object appearing as an sdB which, as Caloi et al (1986) show, is just what a blue drooper looks like. These ideas raise the intriguing possibility that the blue droopers of horizontal branch are generically (if not filially) related to the blue stragglers of the main sequence.

Finally we note that Renzini (1985) has suggested that perhaps 20% of the post AGB stars might experience a final helium shell flash which could turn the star onto the path leading to a non-DA white dwarf. Given the observed difference between the high luminosity end of the DA and DB/DO sequences (Greenstein 1988), it appears that a

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significant fraction of non-DA white dwarfs could confuse an intrinsically narrow cooling sequence.

The mass estimates for the bulk of the cooler white dwarfs depend on the initial-final mass relationship discussed in the last section. The practical issue is the number of white dwarfs whose masses exceed the mass of the visible stars. Such high mass remnants will be segregated in the central region of the cluster and, if sufficiently numerous, can have a significant influence on the dynamical evolution of the cluster. The linear relationship of Iben and Renzini (1983) predicts a rather larger number of higher mass remnants than the non-linear relationship favoured by Weidemann (1984). In any case, the mean mass of the white dwarfs is not expected to be very different from that of the luminous main sequence stars and so they should be distributed throughout the cluster, more or less following the surface brightness profile.

IV Observational Evidence for White Dwarfs in Globular Clusters

There are basically three approaches for studying the white dwarf population in globular clusters: (i) indirect, based on dynamical models of the cluster, (ii) semi-direct, based on observations of individual objects related to white dwarfs including immediate precursors and binary systems, and (iii) direct observation of individual white dwarfs. Each of these is discussed in turn below.

(1) Indirect Studies based on Globular Cluster Dynamics.

The basic mechanism forcing the evolution of a globular cluster is thought to be long range, gravitational two body encounters. This process, known as dynamical relaxation, drives the cluster toward a state of energy equipartition; a state which it can never achieve. The cluster developes a core-halo structure. The cores are collapsing toward, or have already reached, an almost singular state while the halo suffers a truncation from the tidal field of the Galaxy (see Elson, Hut and Inagaki 1987 for a recent review of this field).

In general, the structure of any cluster can be reasonably well represented by the well known King (1966) models. One important point to realize is that most of the available observational data pertains only to the luminous stars, chiefly those at the turnoff and the evolved stars above. These span an extremely narrow mass range. For this reason, the apparent agreement between the data and the single mass King models is somewhat illusionary. Dynamical relaxation leads to mass segregation in the cluster; the heavier stars are more centrally concentrated than the lighter stars. The bulk of the cluster mass may well be distributed quite differently from the relatively bright stars. However the internal motions of the stars depend on the total mass in the cluster and therefore information about the unseen mass, including the white dwarfs, can be obtained through kinematical studies.

Illingworth (1976), Pryor et al (1988) and Peterson and Latham (1987), among others, have measured the central velocity dispersion in a number of clusters. The results, interpreted with King models, show that the central values of the cluster mass to light ratio are in the range 1 - 3. Given that the visible stars typically have $M/L \leq 0.6$, this is clear evidence that about 2/3 of the cluster mass is

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unaccounted for by the brighter stars. Of course the dim stars on the lower main sequence contribute to the mass. In principle, given a mass spectrum and a plausible low mass cutoff, it is possible to calculate their contribution and hence determine at least the total mass of dark remnants in the cluster. In practise, this is not likely to be a very meaningful exercise for two reasons. (i) The low mass stellar population is very poorly constrained by current data and may not be simply related (i.e., with a power law) to the more visible stars (Drukier et al 1988). (ii) Mass segregation must be taken into account. To model this, one needs to assume a global mass function and thus the problem becomes circular. Evidently more constraints are needed.

One approach is indicated by Richer and Fahlman (1988b) who were able to derive surface density profiles for stars in separate mass bins. Mass segregation is clearly seen but, within the framework of multimass King models, the data appears most consistent with a large population of low mass (<0.3 M_θ) stars. We were unable to place meaningful constraints on a dark remnant population.

A complementary technique is to observe the velocity dispersion <u>profile</u>. A few studies of this type have been done and are conveniently collected in Meylan (1987). Both the kinematical and surface brightness profiles (of the brighter stars) are simultaneously fit with a series of multimass King models. This exercise involves varying a number of parameters describing the mass spectrum, including dark remnants. A recent example is Meylan's (1988) discussion of 47 Tuc. He used equation (7) with $\eta = 1/3$ to specify the white dwarf population. From a grid of some 400 models, his best 15 all have about 1/3 of the present cluster mass in the form of white dwarfs. Unfortunately, what is not clear from this work (or other similar studies) is whether one is <u>compelled</u> by the data to include such a large white dwarf component.

In contrast to the above work, which is all based on King models, Murphy and Cohn (1988) have used the Fokker-Planck equation to model the evolution of a multimass component cluster through to the core collapsed phase, where the cluster exhibits a power law surface brightness profile near the center. Observations of the power law in two well observed clusters (M15 and NGC 6624) are shallower than the predicted slope for a single component cluster. Murphy and Cohn attribute this to the fact that dark heavy remnants can dominate the potential in the central power law region whereas the lighter, luminous stars are more dispersed. Both the apparent slope and the radial extent of the power law depend fairly sensitively on the fraction and maximum mass of the dark remnants. This result, upon development of the model to more closely match the evolution in real clusters, holds considerable promise for quantifying at least part of the remnant population.

   (2) Semi-Direct Observations.

We have already mentioned the eight cluster post-AGB stars studied by de Boer (1985) and shown by Renzini (1985) to place very tight constraints on the mass range of cluster white dwarfs. This is a list which surely can be added to.

Another interesting group of stars worth further exploration in this context are the extremely blue horizontal branch stars of the kind found, for example, in NGC 6752. These have been studied recently by Caloi et al (1986), Crocker, Rood and O'Connell (1986), and Heber et al (1987). These stars appear to be 'ordinary' horizontal branch stars with extremely small envelope masses and may be related

(cluster analogues) to the field sdB stars. For sufficiently small envelope masses ($\leq$0.01 $M_\odot$), such stars are expected to evolve to the blue, passing through a hot sdO phase on their way to becoming white dwarfs (Heber et al 1987, see also Schönberner and Drilling 1984).

There is only one planetary nebula known to be in a globular cluster, K648 in M15, recently discussed in some detail by Adams et al (1984). The central star is one of the post-AGB objects studied by de Boer (1985) and is also discussed by Schönberner (1987) and Clegg (1987).

There are two known; i.e., spectroscopically confirmed, cataclysmic variables which are probably members of globular clusters, M5 V101 (Margon, Downes and Gunn 1981) and V4 in M30 (Margon and Downes 1983). Both appear to be examples of dwarf novae. They are very faint objects and apart from their existence little else can be said. However it might be noted that these two dim stars are the most tangible evidence currently available that there are indeed white dwarfs in globular clusters. Shara et al (1986) have identified a candidate for Nova 1938 in M14. Spectroscopic confirmation is needed since their object has rather odd colors, $(B-V)_o = 0.8\pm0.4$, $(U-B)_o = -0.3\pm0.4$, suggesting that the putative white dwarf has an evolved companion. A nova was also observed in M80 in the year 1860 but, in view of its proximity to the cluster center, will probably never be recovered (see further discussion in Trimble 1980).

To the above list we can probably add the low luminosity x-ray sources observed in the direction of globular clusters (Hertz and Grindlay 1983). Krolik (1984) and Hertz and Wood (1985) have suggested that these are the high luminosity end of a population essentially similar to the field cataclysmic variables. The binaries are believed to be the result of encounters between main sequence stars and an ambient population of about 5000 white dwarfs per cluster. These observations are perhaps the best evidence that a significantly large number of white dwarfs inhabit the globular clusters. A cautionary note has been sounded by Margon and Bolte (1987) who were unable to identify plausible optical candidates for the five sources listed by Hertz and Grindlay (1983) in ω Cen.

(3) Direct Observations

We finally come to the holy grail of this subject, unambiguous evidence for the white dwarf cooling sequence in globular clusters. There are two parts to the observational problem: (i) identifying, through photometric studies, plausible candidates for cluster white dwarfs and (ii) obtaining some spectroscopic confirmation that we are indeed dealing with bonafide white dwarfs. We have yet to get convincingly past the first part.

A recent photographic study by Chan and Richer (1986) in M4 has revealed a surprisingly large population of blue objects whose spatial distribution, after background subtraction, appears to follow the cluster surface brightness profile. Calibrated three color photometry is available for a subset of these objects and allows a further discrimination between background QSO's and potential cluster white dwarfs. Among the white dwarf candidates, there appears to be two groups separated in color (they are shown in Figure 2). The bluest group was identified with cluster white dwarfs and the redder group, with foreground white dwarfs. The cluster white dwarf candidates, it will be noted, are rather luminous with $M_v \leq 9.0$. Given the Lee

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(1976b) counts of HB stars in M4, we would expect only 5 white dwarfs brighter than M_v=9.0 in the entire cluster. The five objects shown in the figure are certainly not a complete sample and therefore either there are many more luminous white dwarfs than expected or the observed objects are something else. The same problem, too many too bright candidates, also applies to an earlier study of NGC 6752 reported by Richer (1978).

The use of small field CCD's has largely supplanted photography and has been extensively used for deep photometric studies in globular cluster fields. Taking advantage of the superb imaging capability of the CFHT, we have made a detailed study of the relatively nearby cluster M71 using deep U,B,V exposures specifically to find the white dwarf cooling sequence (Richer and Fahlman 1988a). In that work we identified two groups of blue stars as shown in Figure 1.
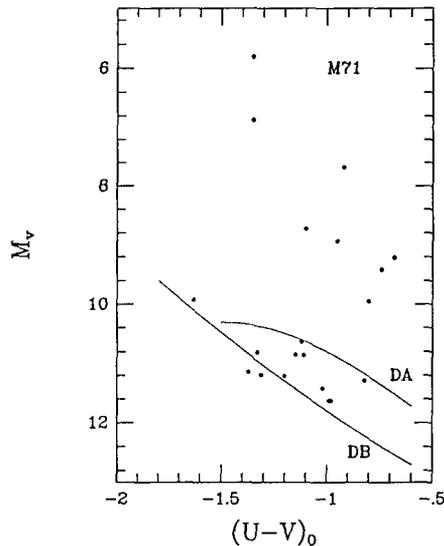
Figure 1.   The blue stars in M71 from Richer and Fahlman (1988a) are plotted.
The lines show the DA and DB (He) sequences defined by the
regression curves of Greenstein (1988).

The fainter group looks very much like a white dwarf cooling sequence. With our adopted distance modulus of 13.7, the sequence does not match the locus of the field DA stars but instead appears to be in better agreement with the field DB sequence. An alternate explanation is that the sequence members are DA's but more massive (by about $0.1M_\odot$) than the field stars. Unfortunately these objects are still beyond spectroscopic study and so the issue remains open.

Recently Ortolani and Rosino (1987) have claimed that they have detected white dwarfs in their deep V, B-V CMD of ω Cen. Taken at face value, their objects appear to be a mixture of DA and DB stars. However, in view of the large scatter apparent at the faint end of their diagram, there is a need for further photometric study, particularly with U, to confirm the reality of these candidates.

In addition to the possible white dwarfs, there is another 'sequence' of blue objects in M71 which is clearly seen in Fig. 1. These stars are far too bright to

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be cluster white dwarfs and too numerous to be foreground objects. Their colors
are similar to those of field cataclysmic variables and we suggested that they may
be cluster analogues of that group of objects. That this is no longer a viable
explanation will be made clear shortly.

For convenience, the Chan-Richer objects found in M4 and the M71 blue stars are
plotted together in Figure 2. Also shown are three hot sdO stars discovered by
Drilling (1983) and analysed by Schönberner and Drilling (1984), and a group of 10
faint ($M_v \geq 6.0$) sdB stars discovered by Downes (1986). This diagram raises the
interesting possibility that the three bright blue objects in M71 may be related to
the sdO/sdB stars. The remaining bright blue objects in M71 seem to be similar in
color to the 'foreground' group seen in M4. Finally, the faintest of the
Schönberner-Drilling stars, LSE 21, which they note is close to the transition
point between sdO's and the white dwarfs, is located near the luminous M4
candidates.
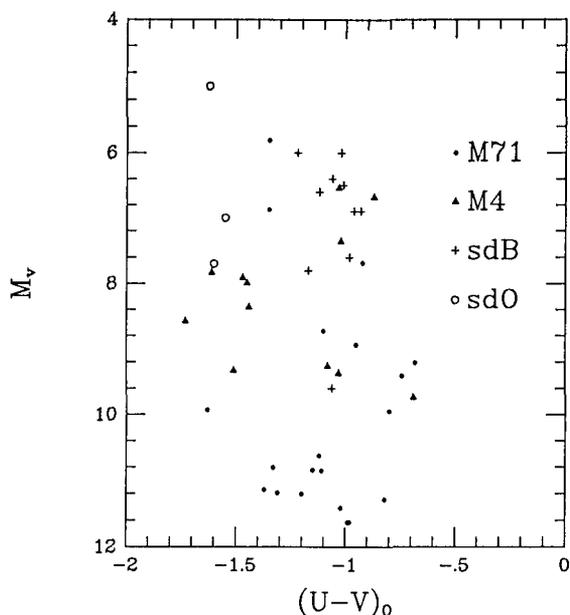
Figure 2.   The M71 blue stars, and the M4 white dwarf candidate from Chan and
             Richer (1986) are plotted together with a slection of 3 sdO stars
             and 10 sdB stars.

Very recently, we were able to obtain low dispersion spectroscopic observations
at the CFHT of the three bright blue stars in M71 and two stars in M4, one
belonging to the 'foreground' group and the other belonging to the 'cluster' group.
The data has not been fully analysed and so only very preliminary results can be
discussed here.

The best data, naturally enough, was obtained for the brightest blue star in
M71. A calibrated spectrum of this star is shown in Fig. 3 together with a
spectrum of the standard sdB star F108. The Balmer lines, while noisy, are

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clearly evident, He II lines cannot be convincingly identified and the general
shape of the continuum suggests that the candidate is somewhat cooler than F108.
It appears to be an sdB star. We emphasize that this data is a 'quick look' and
will very likely be improved upon with further processing. The spectra of the
other two M71 candidates are essentially similar but, as yet, too noisy to identify
absorption lines with any confidence. However, they too are likely to be sdB
stars.
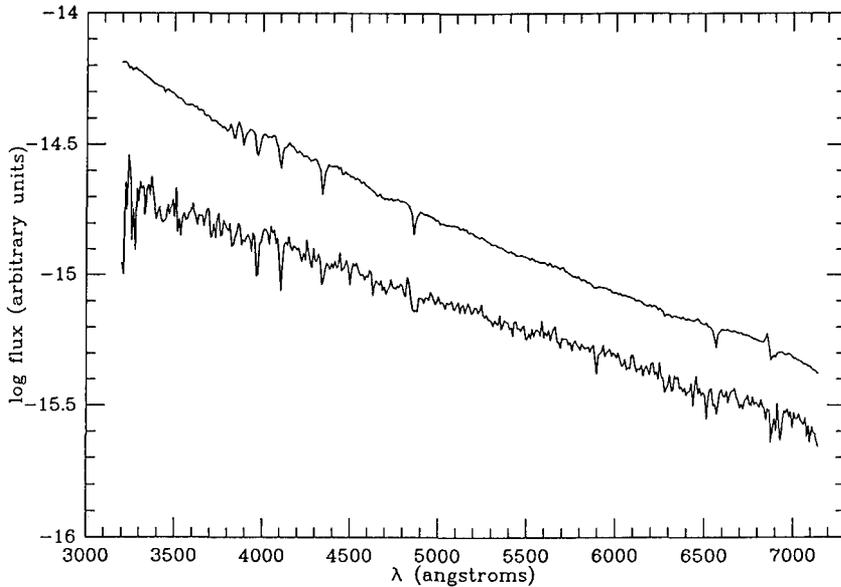
Figure 3. *The spectrum of the brightest blue star in M71 is shown together with*
the spectrum of the sdB standard star Fiege 108.

The cluster membership of these stars is questionable. Downes (1986) finds
that the space density of sdB's is about 2×10^{-6} pc^{3}. Given the distance to M71,
3.7 kpc, and the area of the sky surveyed, 24', we expect to see only 0.07 sdB
stars in the foreground. However, the three stars could be in the background. The
nearest would be at a distance of about 8.3 kpc and, if identified with the
brightest star, have $M_v \approx 4.0$, somewhat brighter than the mean magnitude of Downes'
(1986) sample. The only mitigating factor is that the height of the object above
the plane, at 660 pc, is higher than the sdB scale height of 325 pc found by Green,
Schmidt and Liebert (1986).

The spectrum of brighter and redder M4 star, Chan-Richer #774, was poor because
of some moonlight contamination but nevertheless it is clearly not the spectrum of a
white dwarf. The bluer M4 candidate, CR-831, appears to be rather flat and
featureless. For now its true nature remains unknown.

The bottom line is that we have not yet clearly identified a <u>single</u> white dwarf
in any of the galactic globular clusters.

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V Concluding Remarks

Where do we go from here? There is still very useful work to be done on the ground. The present generation of 4-m class telescopes, equipped with CCD detectors, is capable of identifying white dwarf candidates with deep broad band photometry in the nearer globular clusters. It is clear, however, that a convincing delineation of a white dwarf cooling sequence requires a dedicated effort, both to survey a sufficiently large area and to beat down the photometric errors. While expensive in terms of telescope time, such programs are far cheaper than the cost of making similar observations from space. When the planned new generation of large telescopes come on stream, deeper surveys will be possible and spectroscopic confirmation will become feasible. Of course, when HST (or perhaps its successor) is finally operational, many of the issues discussed here will be settled.

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