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THE DEARTH OF MASSIVE, HELIUM-RICH WHITE DWARFS IN YOUNG OPEN STAR CLUSTERS[1]

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ABSTRACT

Spectra have been obtained of 21 white dwarfs (WDs) in the direction of the young, rich open star cluster NGC 2099. This represents an appreciable fraction (>30%) of the cluster's total WD population. The mean derived mass of the sample is 0.8 $M_{\odot}$—about 0.2 $M_{\odot}$ larger than the mean seen among field WDs. A surprising result is that all of the NGC 2099 WDs have hydrogen-rich atmospheres (DAs); none exhibit helium-rich ones (DBs) or any other spectral class. The number ratio in the field at the temperatures of the NGC 2099 WDs is DA/DB ∼ 3.5. While the probability of seeing no DB WDs in NGC 2099 solely by chance is ∼2%, if we include WDs in other open clusters of similar age it then becomes highly unlikely that the dearth of DB WDs in young open clusters is just a statistical fluctuation. We explore possible reasons for the lack of DBs in these clusters and conclude that the most promising scenario for the DA/DB number ratio discrepancy in young clusters is that hot, high-mass WDs do not develop large enough helium convection zones to allow helium to be brought to the surface and turn a hydrogen-rich WD into a helium-rich one.

Subject headings: open clusters and associations: individual (NGC 2099) — white dwarfs

1. INTRODUCTION

It is by now well accepted that some white dwarfs (WDs) change their atmospheric chemical composition as they cool. The fact that the ratio of DA to non-DA stars changes as a function of effective temperature renders this conclusion indisputable (see, e.g., Bergeron et al. 1997). The distribution of WDs from the Sloan Digital Sky Survey (see Fig. 11 of Kleinman et al. 2004) clearly shows that the overall fraction of hot DO WDs (those showing He II lines) first peaks and then declines at a temperature where the DB WDs (those showing He I lines) begins to rise. At cooler temperatures, the DC WDs (featureless spectrum) increase in number in the same temperature range that the DBs begin to decline (the DBs being too cool to show He I spectral lines). However, the distribution of WDs of various spectral types as a function of mass is much less constrained. Both the DA and DB WD mass distributions show a primary peak at ∼0.6 $M_{\odot}$ (Bergeron et al. 2001). Very few, if any, massive DBs have been found with $M > 0.8\ M_{\odot}$.

NGC 2099 is a very rich (4000 stars), young open star cluster in which we have found 50 WD candidates through a Canada-France-Hawaii Telescope (CFHT) imaging project (Kalirai et al. 2001a). Given the age of this cluster (650 Myr), most of these WDs have temperatures of 13,000–18,000 K. At these temperatures, the number ratio of those exhibiting hydrogen-rich atmospheres (DAs) to those with helium atmospheres (DBs) is about 3.5/1 in the field (Kleinman et al. 2004). In this Letter, we present spectroscopy of 21 WDs in NGC 2099 (>30% of the entire cluster WD population). The effective temperatures are such that we might expect a number of DB white dwarfs among their number, assuming the same statistics as in the field. Furthermore, the contemporaneous nature of these stars may allow us to gather some insights into the poorly understood physical mechanisms that underlie the DA/DB distinction.

2. OBSERVATIONS

Imaging and spectroscopic observations of NGC 2099 were obtained with the Canada-France-Hawaii, Gemini North, and Keck I telescopes. In our wide-field CFHT imaging study (Kalirai et al. 2001a), we found 50 cluster WD candidates in the central 15′ of NGC 2099. In the companion Letter (Kalirai et al. 2005), we describe the current observations and data reduction. Summarizing, we obtained imaging and multiobject spectroscopy with both the Gemini Multi-Object Spectrograph on Gemini and the Low-Resolution Imaging Spectrometer on Keck of three small fields (5.′5 × 5.′5 for Gemini and 5′ × 7′ for Keck). These fields were chosen in an unbiased way to simply maximize the number of WD candidates for which we could obtain spectroscopy. The Gemini data have a high signal-to-noise ratio (22 1 hr exposures were obtained of the same field), whereas the Keck data (two fields were obtained) have both higher resolution and bluer spectral coverage, allowing the detection of higher order Balmer lines. The observations of the second field were taken at high air mass, and so the bluest flux has been lost as a result of atmospheric dispersion. This, however, does not affect the classification of these stars as DA or DB.

In total, we obtained spectroscopy of 24 individual WD candidates in the field of NGC 2099 (three stars turned out not to be WDs). Therefore, despite sampling only 14% of the total cluster area, we include more than 30% of the total WD population (cluster and field) given the careful positioning of the fields. This is therefore the largest individual star cluster WD sample that has ever been spectroscopically acquired. We present the 25 spectra for the 21 WDs (four stars are in common between the Gemini and Keck data) in Figure 1. Surprisingly, all stars show hydrogen Balmer absorption lines and are of DA

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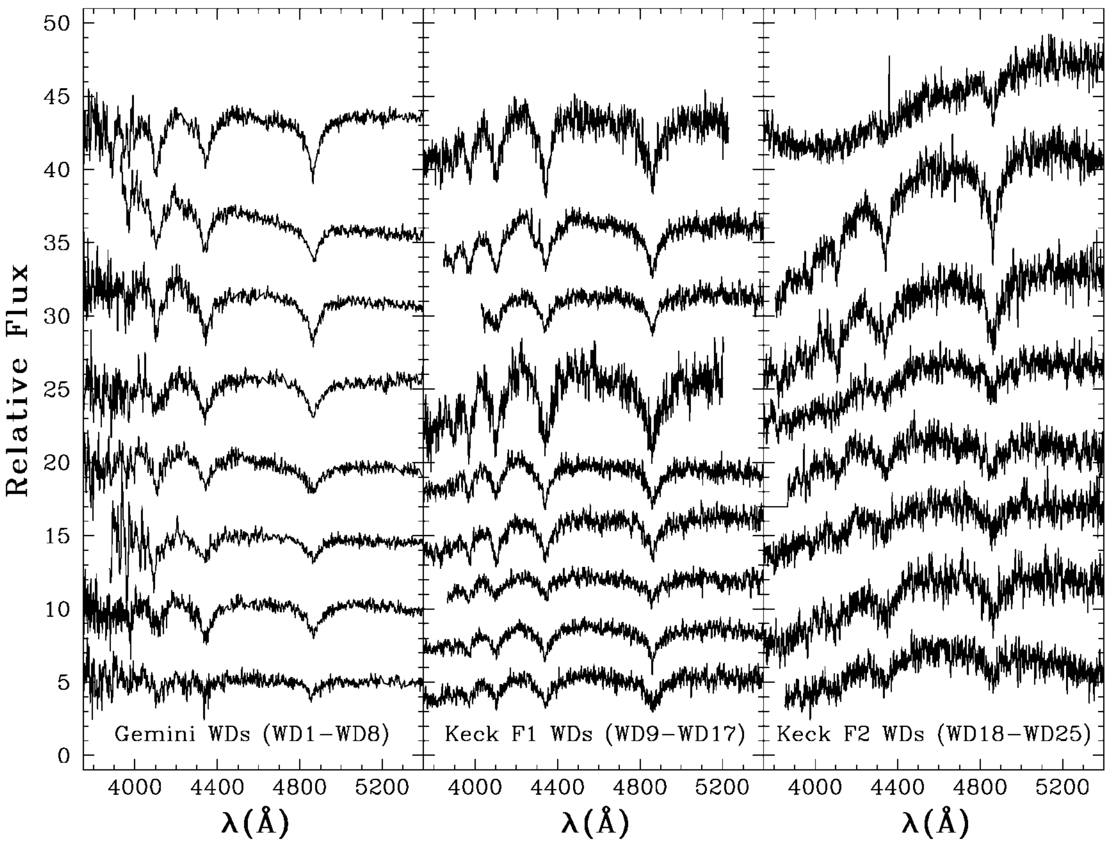

Fig. 1.—Spectra of the 21 WDs observed in the direction of NGC 2099 shown in order of decreasing brightness from top (e.g., WD1) to bottom (e.g., WD8), within each panel (all with $22.46 \leq V \leq 23.66$). Four of the spectra are shown twice: WD19 is the same star as WD1, WD20 is WD2, WD22 is WD5, and WD23 is WD6. It is probable that four or five of the WDs are field objects. Note that all of the WDs are DA spectral type.

spectral type. A table of the derived temperatures and masses for most of this sample of WDs is given in Kalirai et al. (2005).

3. THE SIGNIFICANCE OF OUR SAMPLE

Given our sample of 21 DA WDs, the 3.5/1 field DA/DB ratio at these temperatures suggests that we should see approximately four DB WDs (considering that four or five of our 21 WDs are field objects). Assuming that binomial statistics are applicable, the probability of a sample producing zero stars by chance with this expectation is ∼1.4%. We can improve the statistics significantly by including spectroscopy from other young open clusters. The full sample in a search of the literature is shown in Table 1. All of the turnoff stars in these clusters have masses above 2 $M_{\odot}$ so that the WDs are all likely to be massive, just as in our sample. The total number of hot, massive WDs observed rises to 61, where 13.5 are expected to be DBs, and none are found. The likelihood of this happening purely by chance is now 0.00002%.

TABLE 1
White Dwarfs in Young Open Clusters

Cluster	Number of DAs	Number of DBs	References
Hyades	6	0	1
Pleiades	1	0	2
Praesepe	6	0	3
IC 2391	1	0	4
NGC 1039	1	0	5
NGC 2099	21	0	6
NGC 2168	8	0	7
NGC 2287	2	0	8
NGC 2422	1	0	8
NGC 2451	3	0	9
NGC 2516	4	0	10, 11
NGC 3532	6	0	12, 13
NGC 6405	1	0	12
NGC 6633	1	0	14
NGC 6633	2	0	5
NGC 7063	1	0	5

References.—(1) Eggen & Greenstein 1965; (2) Luyten & Herbig 1960; (3) Claver et al. 2001; (4) Koester & Reimers 1985; (5) Williams 2002; (6) this work (four or five are field objects); (7) Williams et al. 2004; (8) Koester & Reimers 1981; (9) Koester & Reimers 1985; (10) Reimers & Koester 1982; (11) Koester & Reimers 1996; (12) Reimers & Koester 1989; (13) Koester & Reimers 1993; (14) Reimers & Koester 1994.

Thus, it appears as though massive open cluster WDs are always DAs, in contradiction to the expectation from the overall field fraction. DBs are not normally found immediately above a temperature of 30,000 K (the DB gap) nor are they found below a temperature of 12,000 K at which point helium lines become spectroscopically invisible (Bergeron et al. 1997). (Of course, the stars may still possess helium atmospheres at these cool temperatures.) All of our stars are between these temperatures, where DBs are abundant in the field. One possibility is that this indicates a hitherto unappreciated mass dependence to the phenomenon (§ 5). Another is that the cluster environment may somehow lead to larger hydrogen envelope masses.

4. THE ROLE OF THE CLUSTER ENVIRONMENT

Are cluster WDs really representative of field WDs? The cluster environment is unlikely to give the WDs a common property (such as angular momentum, magnetic field, or rotation) as the initial conditions from the cloud collapse should be washed out by the huge disparity between cluster and stellar length scales (see, e.g., Ménard & Duchêne 2004). White dwarfs in a given cluster will all have the same metallicity; however, our sample contains 15 clusters with different metallicities ranging from at least $Z = 0.008$ to $Z = 0.024$. Thus, it is reasonable to treat the 61 WDs as *individual* data points—an assumption necessary for the statistical veracity of our result.

The fact that star clusters are bound by their own gravity might lead one to imagine that they would trap gas lost in the advanced stages of stellar evolution and that this would lead to an enhanced accretion of gas (largely hydrogen) by the WDs in the cluster. However, this notion is problematic from the outset. Open star clusters have low-velocity dispersions (NGC 2099 has $\sigma = 2.5$ km s^{-1}), much lower than the wind velocities from evolved 2–4 $M_\odot$ stars (~10–30 km s^{-1}; e.g., Barnbaum et al. 1991). As a result, the mass lost from the cluster is unbound, and so the cluster WDs do not accrete from a gravitationally trapped reservoir of gas. The WDs will, nevertheless, accrete some material from the escaping collective mass outflow. To determine whether cluster WDs or field WDs have thicker hydrogen layers, we consider accretion from a "cluster wind."

The wind velocity (~20 km s^{-1}) is larger than the WD space velocity, so that the wind accretion rate ($\dot{M} = 4\pi\,[(G^2M^2)/V^3]\,\rho$) onto a 0.85 $M_\odot$ WD is

$$\dot{M} = 5.5 \times 10^{-16}\ M_\odot\ \mathrm{yr}^{-1}\,\frac{n}{1\ \mathrm{cm}^{-3}}. \qquad (1)$$

The real unknown here is n, the local gas density due to the outflowing wind. Assuming the WD is located at a distance r from the cluster center (which is outside the majority of the mass-losing stars), n can be found from the cluster mass-loss rate $\dot{M}_{\mathrm{cl}} = 4\pi r^2 V \dot{m}_p n$, where V is the wind velocity. To get an expression for $\dot{M}_{\mathrm{cl}}$, we assume a Salpeter initial mass function for the cluster from 0.1 to 10 $M_\odot$. Since NGC 2099 is young enough that the remnant masses are small compared to the progenitor masses, we can also assume that all of the mass above the turnoff is lost. Finally, to make this a function of time, we assume the turnoff mass scales with time as $T = 6$ Gyr $(M/M_\odot)^{-2.5}$. Putting this together, we arrive at the present-day cluster mass-loss rate,

$$\dot{M}_{\mathrm{cl}} \sim 2.6 \times 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}\left(\frac{T}{650\ \mathrm{Myr}}\right)^{-0.86}, \qquad (2)$$

where we have used $M_{\mathrm{cl}} = 2515\ M_\odot$ and turnoff mass $M = 2.4\ M_\odot$ (Kalirai et al. 2001a).

Equation (2) can now be fed back to get n and $\dot{M}$ for the WD as a function of cluster age. This can then be integrated to yield the total amount of mass accreted by the WD,

$$M_{\mathrm{acc}} = 2.6 \times 10^{-8}\ M_\odot\left(\frac{r}{2\ \mathrm{pc}}\right)^{-2}\left(\frac{T}{650\ \mathrm{Myr}}\right)^{0.14}. \qquad (3)$$

The weak dependence on age is the result of the fact that the cluster mass-loss rate is higher at early times but lasts for a shorter period of time. Factors of 10 in age correspond to about a 30% variation in accreted mass.

The important result to note here is that equation (3) does not lead to more accretion than would occur in the field. For a young field WD, moving at 20 km s^{-1} through an interstellar medium of density 1 cm^{-3}, $\dot{M} \sim 5 \times 10^{-16}\ M_\odot$ yr^{-1}. Thus, it appears unlikely that our observational result can be explained by an enhanced accretion rate for cluster WDs. Thus, we turn to the properties of the WDs themselves for an explanation.

5. IS THE DB PHENOMENON A FUNCTION OF WHITE DWARF MASS?

If the incidence of non-DA stars is a strong function of WD mass, that may explain our data. In fact, the results of Beauchamp et al. (1996) contain a hint to this effect. They find that the mass distribution of DB stars lacks the tail to high masses that is seen in the DA mass distribution (and even in the smaller DBA sample). Our result makes this possibility much stronger statistically. What are the possible physical mechanisms for such a mass dependence?

5.1. *The Mass Dependence of Convective Mixing*

Although the chemical evolution of WDs is well known, the exact manner in which these transformations are achieved is still a matter of discussion. The appearance of DB stars at temperatures less than 30,000 K is thought to be due to the onset of convection in the helium layer that lies beneath the surface hydrogen layer (Liebert et al. 1987). If the hydrogen surface layer is thin enough (Liebert et al. 1987 considered very thin layers ~$10^{-14}\ M_\odot$), then it spans only a few pressure scale heights, and convective overshooting may overwhelm a surface hydrogen layer. The status of this idea in the face of later estimates of surface hydrogen layer masses (Clemens 1993) is unclear.

Although WD models do not yet exist that contain a detailed treatment of convective overshooting, we can at least map the mass dependence of the onset of convection in the helium layer for a variety of hydrogen surface layer masses, using the models of Hansen (1999). For $q(\mathrm{H}) = M_{\mathrm{H}}/M = 10^{-7}$ or smaller, WDs with masses $\lesssim 1\ M_\odot$ will form convective zones in the subsurface helium layer (provided the WDs are cooler than ~25,000 K). However, as the surface hydrogen mass layer becomes larger, there is an upper mass limit [near 0.8 $M_\odot$ for $q(\mathrm{H}) = 10^{-6}$] above which a convective zone will never form in the helium layer. Therefore, given the higher masses of the NGC 2099 WDs (mostly 0.7–0.9 $M_\odot$; see Table 1 of Kalirai et al. 2005) compared to field WDs, the conversion of a DA to a DB WD through convective mixing may be inhibited by hydrogen layer masses that would still allow the transformation of 0.6 $M_\odot$ WDs. Note, however, that these layers are considerably thicker than in the original proposal of Liebert et al. (1987), and we are unaware of any quantitative model that has yet demonstrated the kind of mixing required in models with these parameters.

5.2. *Mass Dependence of Hydrogen Removal*

It is also possible that the mechanisms that determine the final hydrogen surface mass are mass-dependent as well. The most likely value of $q(\mathrm{H})$ from stellar evolution is $q(\mathrm{H}) \sim 10^{-4}$ (Iben & Tutukov 1984), a value high enough that it is likely to resist any attempt at convective mixing. The mechanisms that produce lower hydrogen masses are poorly understood, but some are indeed likely to depend on mass. For example, Lawlor & MacDonald (2003) show that "born-again" stars will be devoid of hydrogen after leaving the asymptotic giant branch for the final time. These stars evolve through this phase as a result of changes in the efficiency of convective mixing, which may be mass-dependent. Other mechanisms, such as the "self-induced nova" of Iben & MacDonald (1986), rely on shell flashes powered by CNO burning and so may be more easily quenched in more massive WDs where the heavier elements separate out more rapidly in the higher gravity. The competition between nuclear burning and gravitational separation in massive WDs is another issue that needs to be investigated anew in the light of these results.

5.3. *Binary Evolution*

Finally, it is possible that a number of WDs in NGC 2099 have been affected by some type of binary star evolution (interacting, merging, etc.). There is evidence to suggest binary evolution results in fewer DB white dwarfs (Liebert et al. 2005, § 5.2), and this could alter the cluster DA/DB ratio (although binaries with non-DA components do exist; e.g., Wood & Oswalt 1992). Hurley & Shara (2003) have recently modeled the WD cooling sequence of NGC 6819 (see Kalirai et al. 2001b) using *N*-body simulations, and they found that the observed morphology of the cooling sequence can be understood by invoking a large double-degenerate and/or mass transfer WD binary population. These simulations include contributions from a number of different binary evolutionary scenarios, such as common-envelope evolution and mass transfer systems. Such effects could also play a role in the evolution of NGC 2099 WDs, which do not exhibit a tight sequence of points on the color-magnitude diagram but rather a more diffuse clump (see Kalirai et al. 2001a). For a 40% primordial binary fraction, Hurley & Shara (2003) estimate that 12% of all WDs will be double degenerates after 0.5 Gyr (J. Hurley 2004, private communication). However, up to 39% of the WDs are nonstandard single WDs (i.e., they were in binaries at some point and may have suffered mass exchange) in which evolution may have resulted in mass transfer and thick H envelopes.

6. CONCLUSIONS

Spectroscopic observations in a sample of young open star clusters have shown that all cluster WDs exhibit hydrogen-rich atmospheres. This is in contrast to WDs in the field, where at temperatures between 13,000 and 18,000 K, about 25% are of DB type. The statistics are now good enough that the probability of this happening purely by chance is vanishingly small. A potential explanation is that the cluster environment might be the culprit. However, the only likely physical mechanism here—the accretion of H-rich gas produced by massive evolving stars—is found to be not higher than the rate for field objects. The most promising scenario appears to be related to the fact that these cluster WDs are, on average, more massive than those in the field because of the young ages of their parent clusters. Cooling models (Hansen 1999) suggest that the underlying helium convection zone may not easily break through to the surface hydrogen layer in massive WDs as it does for average mass WDs. This scenario makes two clear testable predictions: (1) field DB WDs should be less massive on average than field DAs at temperatures below about 20,000 K, and (2) the field DA/DB ratio ought to be found in older clusters whose turnoff stars produce WDs nearer to the canonical 0.6 $M_\odot$.

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