Ensemble Properties of the White Dwarf Population of the Old, Solar Metallicity Open Star Cluster Messier 67*

Kurtis A. Williams1, Paul A. Canton2, A. Bellini3, Michael Bolte4, Kate H. R. Rubin5, Alexandros Gianninas3, and Mukremin Kilic2

1 Department of Physics & Astronomy, Texas A&M University-Commerce, P.O. Box 3011, Commerce, TX, 75429-3011, USA; Kurtis.Williams@tamuc.edu
2 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, 440 W. Brooks Street, Norman, OK 73019, USA
3 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
4 UCO/Lick Observatory, University of California, 1156 High Street, Santa Cruz, CA 95064, USA
5 Department of Astronomy, San Diego State University, San Diego, CA 92182, USA

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Abstract

White dwarfs (WDs) are excellent forensic tools for studying end-of-life issues surrounding low- and intermediate-mass stars, and the old, solar metallicity open star cluster Messier 67 is a proven laboratory for the study of stellar evolution for solar-type stars. In this paper, we present a detailed spectroscopic study of brighter ($M_r \lesssim 12.4$) WDs in Messier 67, and in combination with previously published proper motion membership determinations, we identify a clean, representative sample of cluster WDs, including 13 members with hydrogen-dominated atmospheres, at least one of which is a candidate double degenerate, and 5 members with helium-dominated atmospheres. Using this sample we test multiple predictions surrounding the final stages of stellar evolution in solar-type stars. In particular, the stochasticity of the integrated mass lost by $\sim 1.5$ solar mass stars is less than 7% of the WD remnant mass. We identify WDs likely resulting from binary evolution, including at least one blue straggler remnant and two helium-core WDs. We observe no evidence of a significant population of helium-core WDs formed by enhanced mass loss on the red giant branch of the cluster. The distribution of WD atmospheric compositions is fully consistent with that in the field, limiting proposed mechanisms for the suppression of helium atmosphere WD formation in star clusters. In short, the WD population of Messier 67 is fully consistent with basic predictions of single- and multiple-star stellar evolution theories for solar metallicity stars.

Key words: open clusters and associations: individual (M67) – stars: evolution – white dwarfs

Supporting material: machine-readable tables, tar.gz file

1. Introduction

Intermediate-age and old open star clusters (ages $\gtrsim 50$ Myr) are ideal laboratories for studying the late stages of intermediate- and low-mass stellar evolution. The stars within a given open cluster are coeval and nearly identical in elemental abundances, with most properties dependent primarily on the stellar mass. White dwarfs (WDs) are the remnants of stars with masses $M \lesssim 8M_\odot$. Therefore, the study of WD populations in open star clusters can be an exceptionally effective means of studying the late stages of stellar evolution, as the progenitor star properties of age, metallicity, and mass can be constrained tightly. In this paper, we present the results of combined photometric, spectroscopic, and astrometric studies of the WD population in the old open star cluster Messier 67 (M67, NGC 2682). The results of this study are useful in probing several different areas of stellar and WD evolution.

1.1. WD Masses

Much effort in the study of open cluster WD populations has gone into understanding the relationship between WD mass and the derived progenitor star mass, known as the initial-final mass relation (IFMR). A proper review of the IFMR literature and the contribution of the M67 WD population to the semi-empirical IFMR are given in a companion manuscript by P. Canton et al. (2018, in preparation; hereafter Paper II).

A topic closely related to the IFMR is the intrinsic scatter in the relationship. Given a fixed progenitor star mass and metallicity, is there any stochasticity in the resulting WD mass? Basic single star evolutionary theory predicts stellar evolution is uniquely determined by the zero-age main sequence mass and metallicity of a star, yet it is plausible that some randomness in the remnant WD mass could be introduced by events such as core mass loss during dredge up, the number of thermal pulses during the asymptotic giant branch phase, and the rate and timing of post main sequence mass loss. For such studies, a population of WDs arising from stars of nearly identical masses would be highly useful, especially for solar metallicity stars (some spectroscopic globular cluster WD mass measurements exist, e.g., Moehler et al. 2004; Kalirai et al. 2009).

M67 is among the oldest known open star clusters. Its age is typically quoted as being $\approx 4$ Gyr (e.g., Montgomery et al. 1993; Richer et al. 1998; VandenBerg & Stetson 2004; Sarajedini et al. 2009; Bellini et al. 2010), though the most recent studies using a variety of age dating techniques such as asteroseismology (Stello et al. 2016), main sequence fitting (Bonatto et al. 2015), and modified stellar models (Chen et al. 2014) lean toward a younger age of $\approx 3.5$ Gyr.

For this paper, the exact age is not crucial—the zero-age main sequence mass of a star at the tip of the AGB (i.e., those stars currently forming WDs) is only slowly evolving in time.
changing by $\lesssim 0.05 M_\odot$ (Chen et al. 2015) between cluster ages of 3.5 and 4.0 Gyr. More important in our study is the change in progenitor mass for WDs in our sample. The WDs used in the analysis in this paper have cooling ages $\lesssim 700$ Myr, and therefore have a spread in zero-age main sequence mass of $\lesssim 0.1 M_\odot$. Cluster WDs from more massive progenitors exist, but are fainter than the photometric limits of this study. We therefore will be able to measure the intrinsic spread in WD mass for stars of virtually identical composition and initial mass.

Another ancient metal-rich star cluster with a rich, spectroscopically well-studied WD sequence is NGC 6791, which has a super-solar metallicity ([Fe/H] $\approx +0.4$, e.g., Gratton et al. 2006; Origlia et al. 2006) and an age of $\sim 8$ Gyr. The spectroscopic WD study of Kalirai et al. (2007) found a majority of cluster WDs with masses $\lesssim 0.5 M_\odot$, consistent with these WDs harboring helium cores instead of the canonical carbon–oxygen cores formed by helium burning during the asymptotic giant branch phases of stellar evolution. Although He-core WDs can be formed by binary star evolution (see Section 1.2), the binary fraction of NGC 6791 is too low to explain the large fraction of He-core WDs in this cluster.

Hansen (2005) and Kalirai et al. (2007) hypothesize that the high metallicity of NGC 6791 may lead to excessive mass loss from stars ascending the red giant branch, resulting in stellar cores too low in mass to undergo a helium flash. Kilic et al. (2007) similarly invoke this mechanism to explain the large number of low-mass single WDs in the field. Enhanced mass loss on the red giant branch is also invoked to explain the large number of extreme horizontal branch (EHB) stars in NGC 6791 noted by Liebert et al. (1994) as red giants that retained just enough mass for a helium flash, and to explain the bimodal WD luminosity function (WDLF) reported by Bedin et al. (2005, 2008a). Other mechanisms such as double degenerates have been proposed to explain NGC 6791’s peculiar WDLF (Bedin et al. 2008b; García-Berro et al. 2010), and little evidence of ongoing enhanced red giant mass loss has been observed (van Loon et al. 2008; Miglio et al. 2012).

With its solar metallicity, lack of EHB stars (Liebert et al. 1994), and unimodal WDLF (Richer et al. 1998; Bellini et al. 2010), the enhanced mass loss mechanism would suggest that M67 should have a lower He-core WD fraction than NGC 6791; a detailed study of WD masses to determine this fraction is therefore in order, especially since recent asteroseismological studies of M67 red giants has found no evidence of strong mass loss (Stello et al. 2016).

### 1.2. Products of Binary Star Evolution

Open star clusters have significant binary star fractions; M67 itself has a main sequence binary fraction of $\gtrsim 38\%$ (e.g., Montgomery et al. 1993; Fan et al. 1996). Signs of binary interaction are common among open cluster member populations. Blue stragglers are stars with masses significantly higher than the main sequence turnoff mass; these are thought to be the result of significant mass transfer (e.g., Chen & Han 2008; Geller & Mathieu 2011; Gosnell et al. 2014) and binary coalescence (e.g., Hurley & Shara 2002; Hurley et al. 2005; Perets & Fabrycky 2009). If the mass transfer/merger results in significant mixing of unburned hydrogen into the stellar core, in essence resetting the clock on stellar evolution, a blue straggler with a mass greater than the main sequence turnoff mass will produce a more massive WD than the single stars completing their evolution at that point in time.

M67 is known to have a significant blue straggler population (e.g., Mathieu & Latham 1986; Milone 1992; Landsman et al. 1998), including evolved blue stragglers such as S1237 (Leiner et al. 2016) and S1040 (Landsman et al. 1997). Given the presence of evolved blue stragglers in the cluster, it is highly likely that additional blue straggler stars have completed their evolution and evolved into WD remnants. Further, since many blue stragglers have low-mass, helium-core WD companions, the WD progeny of blue straggler stars are likely to appear to be single WDs. This is because low-mass WDs have a large surface area and He-core WDs have significant lower heat capacity than the typical carbon–oxygen core WDs, resulting in He-core WDs cooling and fading below our detection limits quite rapidly.

The presence of helium-core WDs in an open cluster can be another sign of binary interactions. The minimum core mass required for helium ignition in an evolved star is $\approx 0.45 M_\odot$ (e.g., Sweigart 1994; Fontaine et al. 2001). WDs more massive than this limit are composed primarily of carbon and oxygen, the primary results of core helium burning. Less massive WDs, not having ignited helium, should have core compositions of helium. However, stellar evolution models predict that the nuclear lifetime of a single star with insufficient mass for core helium ignition is significantly longer than a Hubble time, therefore any He-core WDs in the present day universe cannot have arisen by standard stellar evolution. Close binary evolution is one source of He-core WDs; if a common envelope forms around a red giant star and a companion, the envelope can be ejected and nuclear evolution halted prior to the helium flash (e.g., Iben &Livio 1993). The fact that a large fraction of low-mass He-core WDs in the field are short-period binary systems is strong evidence of this mechanism (e.g., Marsh et al. 1995; Brown et al. 2010; Gianninas et al. 2015).

Finally, we note that one cataclysmic variable system is known in M67, EU Cnc (Gilliland et al. 1991; Pasquini et al. 1994). Our observations and analysis of this system are presented in Williams et al. (2013) and are not discussed further in this paper.

### 1.3. WD Atmospheric Composition

The high surface gravity of WDs results in highly stratified atmospheres usually dominated by a single atomic species. The two most common atmospheric types of WDs are the hydrogen-dominated atmospheres (spectral-type DA) and helium-dominated atmospheres (almost all non-DA spectral types). The accepted formation scenario of most non-DA WDs is the “born again” scenario, in which a late thermal pulse results in the loss of the WD’s hydrogen layer (Iben et al. 1983).

The ratio of DA to non-DA WDs is a function of temperature, with most changes explicable by the mixing or gravitational separation of atmospheric layers by the competing effects of diffusion and changing convection zone depth (e.g., Fontaine & Wesemael 1987; Bergeron et al. 2011), but for warmer WDs such as those presented in this paper, the fraction of DA WDs is $\approx 80\%$ (e.g., Koester & Kepler 2015).

Kalirai et al. (2005a) and Davis et al. (2009) have proposed that some intermediate-age open star clusters and some globular clusters exhibit a dearth of non-DA WDs, requiring a mechanism suppressing non-DA formation in the star cluster.
environment. However, some non-DA WDs are known to exist in intermediate-age open star clusters at a fraction comparable to the field if the “DB gap” and the different cooling rates of DA and non-DA WDs are appropriately considered (Williams et al. 2006). Again, a large sample of WDs with solar metallicity progenitors, like we present in this paper, could be key to proper determination of whether open cluster environments exhibit any difference of DA to non-DA ratio from the field population.

1.4. Improved Cluster Membership Determination

In most work involving open cluster WDs, cluster membership is determined solely by cuts in apparent distance modulus (e.g., Williams et al. 2009; Dobbie et al. 2012; Cummings et al. 2016). Dobbie et al. (2009), Tremblay et al. (2012), and Bellini et al. (2010), among others, demonstrate that proper motion membership determinations are crucial in investigating open cluster WD populations. Proper motion memberships not only reliably reduce field contamination in IFMR studies, but they also permit identification of other astrophysically interesting WDs for which knowledge of progenitor mass, system age, and primordial metallicity are important but typically unknown quantities. These include WDs with differing atmospheric compositions, cataclysmic variables, and double degenerates (e.g., Williams et al. 2006, 2013, 2015). However, most open clusters lack precise proper motions for faint stars such as WDs; most open cluster WDs located at distances \( \gtrsim 1 \text{kpc} \) are fainter than the likely ultimate limits of \( \text{GAIA} \) astrometry \( (V \lesssim 21.5) \).

Precision proper motion membership measurements for open cluster WDs require multi-epoch wide-field imaging of clusters using 4 m class telescopes or larger. After the advent of large-format CCDs in the mid-to-late 1990s, a first epoch of deep open cluster imaging dedicated to WD studies was obtained by multiple groups (e.g., Claver et al. 2001; Kalirai et al. 2001; Williams 2002). Since then, enough time has passed that the accumulated WD proper motions are measurable from second- and third-epoch imaging with sufficient precision to separate cluster and field WDs.

Bellini et al. (2010) use multi-epoch wide-field imaging to measure proper motions for sources in the field of M67 brighter than \( V \sim 26 \). They identify cluster members iteratively via their position in the \( V, B - V \) color–magnitude diagram (CMD) and their position in the proper motion vector-point diagram, but the Bellini et al. analysis focuses on identifying the faintest (oldest) WDs in order to compare the cluster age derived from WD cooling to the age determined by main sequence fitting. In this paper, we expand the use of Bellini et al.’s proper motion measurements to constrain cluster membership of the brighter, younger WDs in our sample. This proves to be crucial to producing a clean sample of cluster member WDs and permit studies of the stellar evolutionary topics detailed above.

### 1.5. Adopted Cluster Parameters for M67

For this work we adopt the second-ranked cluster photometric parameters from Bonatto et al. (2015), which are consistent with those of Chen et al. (2014): \( d = 880 \pm 20 \text{ pc} \), \( E(B - V) = 0.02 \pm 0.02 \), \( Z = 0.019 \pm 0.003 \), and \( \text{age} = 3.54 \pm 0.15 \text{ Gyr} \). This choice was guided in large part by the desire to use a consistent set of isochrones (the PARSEC 1.2S isochrones, Chen et al. 2015) for the different open cluster WD populations analyzed in Paper II. As mentioned in Section 1.1, the exact choice of cluster parameters has little impact on our conclusions beyond the precise values of derived WD progenitor masses. We use the \( \lambda / (E(B - V)) \) determinations from Schlafly & Finkbeiner (2011) for the SDSS filters to calculate apparent distance modulus \( (m - M)_A = 9.784 \pm 0.05 \) and color excesses \( E(u - g) = 0.019 \pm 0.019 \) and \( E(g - r) = 0.02 \pm 0.02 \). The stated errors are obtained by propagating the published uncertainties of Bonatto et al. (2015) through the entire analysis; these errors are treated as Gaussian distributions in magnitude space in the analysis below.\(^6\)

### 2. Observations

#### 2.1. MMT Megacam Imaging

We obtained imaging data with the Megacam wide-field CCD imager on the MMT 6.5 m telescope over three nights in 2004 and 2005. Megacam, described fully in McLeod et al. (2015), consists of 36 2 k \( \times \) 4 k CCDs with a scale of \( 0.08 \text{ pix}^{-1} \), resulting in a \( 25^\prime \times 25^\prime \) field of view. Images were dithered using a five-point pattern to fill in CCD chip gaps. Total exposure times were \( 21,000 \text{ s} \) in \( u \), \( 2400 \text{ s} \) in \( g \), and \( 1800 \text{ s} \) in \( r \). A summary of the imaging is given in Table 1.

| UT Date | Filter | Exposure Times \( N_{\text{exp}} \times t_{\text{exp}} \) (s) | FWHM (arcsec) |
|---------|--------|--------------------------------------------------|---------------|
| 2004 Mar 22 | \( g \) | 10 \( \times \) 240 | 0.6 |
| 2004 Mar 22 | \( r \) | 10 \( \times \) 180 | 0.8 |
| 2005 Jan 11 | \( u \) | 17 \( \times \) 600 | 1.3 |
| 2005 Jan 13 | \( \mu \) | 18 \( \times \) 600 | 1.3 |

\(^6\) Since the original submission of this paper, \( \text{GAIA} \) Data Release 2 parallaxes for M67 have been published in Gaia Collaboration et al. (2018). Their measured parallax of \( \pi = 1.1325 \pm 0.0011 \text{ mas} \) and log(age) = 9.54 are consistent with those we have adopted and do not affect our analysis significantly, so we retain our original age and distance adoptions.

\(^7\) IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
We obtain aperture photometry via DAOPHOT II (Stetson 1987). We set the aperture radius equal to the measured FWHM in the stacked image of the corresponding filter (see Table 1). In order to appear in the final catalog, objects were required to appear in both the g and r photometric catalogs.

We exclude extended objects by using two-aperture photometry in the g image with aperture radii of 1 × and 2 × FWHM. Point sources have empirically determined magnitude differences in the two apertures of 0.28 ± 0.035 mag, while extended objects have aperture magnitude differences $\geq$0.5 mag. All objects with aperture magnitude differences $\geq$0.42 mag are therefore considered to be extended and excluded from further analysis. While this excludes close blends of point sources, the aperture photometry of all such sources is contaminated by the close neighbor and uncontaminated spectroscopy is not easily obtained.

As the images were obtained on non-photometric nights, we calibrate the photometry using photometric data from the SDSS Data Release 12 (DR12) SkyServer (Alam et al. 2015). Stars with clean SDSS ugr photometry are selected from the DR12 catalog and matched with stars in our aperture photometry catalog. Zero points and color terms are obtained by fitting the following linear functions for all stars with photometric errors $\leq$0.1 mag:

$$u_{\text{SDSS}} = u_{\text{MMT}} + 2.5 \log_{10} t_{\text{exp}} + a_0 + a_1(u_{\text{SDSS}} - g_{\text{SDSS}})$$

$$g_{\text{SDSS}} = g_{\text{MMT}} + 2.5 \log_{10} t_{\text{exp}} + b_0 + b_1(g_{\text{SDSS}} - r_{\text{SDSS}})$$

$$r_{\text{SDSS}} = r_{\text{MMT}} + 2.5 \log_{10} t_{\text{exp}} + c_0 + c_1(g_{\text{SDSS}} - r_{\text{SDSS}}).$$

The photometric coefficients are given in Table 2. The residuals to these linear fits exhibit no trends with magnitude, color, or spatial coordinate, though we note that the u-band fits are poorly constrained for objects with $(u - g) \leq 0.75$. The resulting CMD and color–color diagram are presented in Figures 1 and 2.

### Table 2

| Filter | Zero Point a (mag) | Color Term (mag) |
|--------|-------------------|-----------------|
| u      | $a_0 = 24.784 \pm 0.012$ | $a_1 = 0.004 \pm 0.006$ |
| g      | $b_0 = 26.159 \pm 0.006$ | $b_1 = -0.079 \pm 0.008$ |
| r      | $c_0 = 26.023 \pm 0.006$ | $c_1 = 0.114 \pm 0.008$ |

Note. a Nights were not photometric.

2.2. Keck Spectroscopy

#### 2.2.1. Candidate WD Selection

We select spectroscopic targets guided by a comparison of photometric data with predicted WD cooling models while avoiding portions of color space inhabited by main sequence stars. The selection region spans the most common masses and spectral types of WDs while excluding thick disk MS turnover stars and unresolved blue galaxies. A handful of objects with blue $u - g$ colors but red $g - r$ colors are also selected as potential WD+M binary systems. We select spectroscopic targets without consideration of proper motion memberships, as these memberships were not available to us prior to spectroscopic observations.

Our initial target selection criteria were defined prior to finalization of photometric calibrations and did not apply a limiting magnitude. Guided by subsequent evolution of the photometric calibrations and the need for high signal-to-noise (S/N) spectral data, we define post factum quantitative photometric criteria for WD candidates: all unresolved objects with $g \leq 22.2$, $-0.6 \leq u - g \leq 0.7$, and $1.05 + 2.05(g - r) \leq u - g \leq -0.03 + 1.214(g - r)$ are considered to be candidate WDs.

This post facto selection region is shown in the color–color diagram in Figure 3, which presents the color–color diagram for bluer point sources in the MMT imaging, along with representative 0.6 $M_\odot$ DA and DB WD cooling curves for cooling ages less than 4 Gyr. Positional and photometric data for the candidates thus selected are given in Table 3 and are plotted in the center panel of Figure 1. Data for the 17 spectroscopically targeted sources not meeting the post facto selection criteria are given below the bar in Table 3.

Spectroscopic target selection was also influenced by slitmask placement and orientation. These were determined by qualitatively maximizing the number of highest priority targets (i.e., candidate WDs selected by the photometric criteria) that could fit on a slitmask. The primary selection bias for M67 member WDs is therefore based on luminosity, with potential but likely minimal secondary biases due to binarity and any differences in spatial distributions of WD subpopulations.

#### 2.2.2. Observing Details

We obtained spectroscopic data with the Low-Resolution Imaging Spectrograph (LRIS; Oke et al. 1995; McCarthy et al. 1998; Steidel et al. 2004; Rockosi et al. 2010) on the Keck I telescope over four nights in 2007 and 2010. A run in 2006 February was lost to thick clouds. We obtained most spectra using slitmasks with 1″ wide slits, though we used a 1″ wide long slit for spectrophotometric calibrators and for LB 3600. Although we collected data using both the red and blue arms of LRIS, only the blue arm data are presented here. An observing log for the 2007 and 2010 runs is presented in Table 4.

The spectroscopic configuration used the 400/3400 grism and D560 dichroic. The 400/3400 grism was selected over the higher-resolution 600/4000 grism due to its higher throughput shortward of 4000 Å, where the mass-sensitive higher order Balmer lines are located. Resulting spectral resolutions, as measured by the FWHM of the 5577 Å night sky emission line, are $\approx$8.0 Å, with some variation depending on the slitlet location.

We designed slitmasks using the Autoslit3 program provided by J. Cohen. Slitmask position and orientations were varied to permit as many WD candidates as possible to fit on a slitmask; typically three to five high priority candidates were present on a slitmask. If WD candidate slit placement was not affected, additional slitlets were milled for serendipitous studies of other objects, such as galaxies and unresolved objects outside the stellar locus in the color–color diagram. Data from these extra slitlets are not presented in this paper. The Keck I atmospheric dispersion corrector was in use and operational, so little heed was paid to parallactic angle. A pickoff mirror was attached to each slitmask for purposes of guiding.
We reduced the spectroscopic data using standard techniques in the IRAF twodspec and onedspec packages. We used overscan regions to subtract amplifier bias from individual images; we then used the L.A.Cosmic cosmic-ray rejection routine (van Dokkum 2001) to flag and remove cosmic rays from the two-dimensional spectra. We median combined internal flat field exposures for each slitmask and normalized these via a polynomial fit in the spectral direction over wavelengths where the flat field counts were higher than 300 cts, corresponding to wavelengths $\geq 3600$ Å. Residuals to the polynomial fit had an rms $\leq 0.5\%$. The normalized spectroscopic flat fields were applied to each individual exposure.

Spectrograph flexure in the spatial direction was significant. We determined the centroids of the spectroscopic traces of mask alignment stars to determine individual shifts in the spatial direction for each exposure prior to combining the exposures. In order to avoid interpolation issues, we rounded these shifts to the nearest integer number of pixels and shifted each image in the spatial direction by this amount. Since the spatial scale of the blue arm of LRIS is $0.135$ pix$^{-1}$ and typical seeing was $\approx 1''$, any distortions in the spatial direction are minimal.

We combined the spectra by averaging the resulting images, masking pixels flagged as cosmic rays by L.A.Cosmic, to produce a single deep spectroscopic exposure for each slitmask. We then extracted one-dimensional spectra from each slitlet and applied a wavelength solution derived from Hg, Cd, and Zn arclamp spectra. A zeropoint wavelength offset was applied to the arclamp solution to ensure that the centroid of the peak of the [O I] auroral line was 5577.338 Å (Osterbrock et al. 1996). We used 1'' long-slit spectra of G 191-B2B obtained with the same spectral setup to determine a spectral

**Figure 1.** The $g - r, g$ color–magnitude diagram for the field of M67. The magenta solid line is a 0.6 $M_\odot$ DA WD cooling curve for cooling ages $\leq 4$ Gyr; the magenta dotted line is a 0.6 $M_\odot$ DB WD cooling curve for the same age range. The long-dashed orange line is a PARSEC 1.2S isochrone for a $Z = 0.0152$, 3.5 Gyr old stellar population at the adopted distance and extinction. The left panel shows all unresolved sources with good photometry. The central panel indicates the post facto photometrically selected WD candidates described in Section 2.2.1 with large points; all other unresolved sources with good photometry are small points. The right panel identifies objects by spectral type. Green circles are DA WDs, purple diamonds are non-DA WDs, red crosses are non-WDs, black circles are photometric targets without spectral identifications, and the black triangle is a photometric target with neither spectral identification nor proper motion data. Filled symbols indicate cluster members, while open symbols indicate nonmember objects. The green asterisks indicate the potential double degenerates.
response function; we applied this to our extracted slitlet spectra to achieve relative flux calibration. We note that some objects have spectral slopes inconsistent with their photometric colors, most commonly with apparently missing blue flux (e.g., see WD15 in Figure 4 for an egregious example). The cause of this is unclear but is almost certainly due to instrumentation or human error. Caution should be exercised in interpretation of the spectral slopes.

2.2.4. Spectroscopic Completeness

Of the 35 photometric WD candidates in the our post facto candidate sample, 29 had successful spectroscopic observations for an 83% success rate. An additional 17 objects not meeting the post facto selection criteria resulted in successful spectroscopic data as well. We consider a “successful” spectroscopic observation of a target to have resulted in sufficient S/N to permit spectral identification. WDs exhibiting the hydrogen Balmer line series are identified as spectral-type DA; WDs clearly exhibiting at least one absorption line of He I are identified as DB, and WDs with no obvious spectral features are identified as DC. Because our spectra do not cover H\textalpha, it is possible that one or more of our DBs and DCs have H\textalpha absorption. One faint DB, WD23, appears to have additional significant absorption features in addition to He I λ 4471 Å, but the wavelengths of these features do not precisely match any common strong stellar absorption features. We therefore identify this star as a DB: following the revised spectral classification scheme presented in McCook & Sion (1999) and references therein.

Of the six photometric candidates for which we were unable to obtain successful spectroscopic observations, three have identifications published in the literature. Objects 206310 and 202440 are both listed in the DR10 version of the SDSS quasar catalog (Pâris et al. 2014); visual inspection of the SDSS spectra for both objects confirms they are indeed QSOs. Object 203493 (WD33) is a DA WD in the DR10 WD catalog of Kepler et al. (2015), though the S/N of the SDSS spectrum is very low. Therefore, only three unresolved objects meeting the post facto candidate selection criteria lack spectral identification: Objects 292232, 17303, 8 and 15623, for an incompleteness of 9%.

We do not quantify the completeness of the photometric catalog, but as the MMT images are very deep and are not crowded, and as our spectroscopic magnitude limit (g ≤ 22.2) is well above the photometric limit of g ≤ 25.25, we do not expect any significant systematics to be introduced by photometric incompleteness.

8 Object ID 17303 is coincident with an X-ray source (van den Berg et al. 2004) and is therefore likely an active galactic nucleus, but there is no optical confirmation.
We also expect no systematic incompleteness due to atmospheric composition. The selection criteria include the cooling tracks for both DA and non-DA WDs. In addition, although WDs with H-dominated and He-dominated atmospheres cool at different rates over different magnitude ranges, this selection effect is not important for our selection range. Taking $g = 22.2 (M \approx 12.4)$ as our magnitude limit and using the 0.6 $M_\odot$ evolutionary models of Fontaine et al. (2001), we find that the cooling time of a DA at our magnitude limit is 698 Myr, while the cooling time for a DB of this magnitude is 696 Myr, nearly identical.

Spectral identifications are presented in Table 5 for WDs and in Table 6 for non-WDs. Spectra for DA WDs are plotted in Figure 4, non-DA WD spectra are plotted in Figure 5, and spectra for non-WDs are plotted in Figure 6. These identifications are also illustrated in the right-hand panels of the cluster CMD and WD color–color plots (Figures 1 and 3, respectively). The 46 reduced spectra shown in these figures are provide in a tar.gz supplementary archive file.

2.2.5. WD Atmospheric Parameters

Atmospheric parameters for DA WDs are determined using the techniques described in detail in Paper II. In short, we fit normalized Balmer line profiles from one-dimensional atmospheric models using the methodology and software of Gianninas et al. (2011) to obtain $T_{\text{eff}}$ and $\log g$; their methods are refinements of those presented by Bergeron et al. (1992, 1995). We note that the uncertainties in the fitted parameters include the external errors estimated by Liebert et al. (2005), though using the corrected values of 1.4% in $T_{\text{eff}}$ and 0.042 dex in $\log g$ as discussed in Bédard et al. (2017). We then apply the 3D $T_{\text{eff}}$ and $\log g$ corrections from Appendix C of Tremblay et al. (2013) to those WDs with $T_{\text{eff}} \leq 15,000$ K to account for the known shortcomings mixing length theory produces in one-dimensional DA WD atmospheric models.

We obtain synthetic photometry for each DA WD for comparison to observed photometry for the purposes of identifying potential binary systems and cluster membership. Synthetic photometry is calculated using tabulated color tables (2016 October vintage) provided by P. Bergeron.9 These evolutionary models and color calculations are detailed in Holberg & Bergeron (2006), Kowalski & Saumon (2006), Tremblay et al. (2011), Bergeron et al. (2011). We calculate uncertainties in the synthetic photometry by simulating 1000 observations of the WD with $T_{\text{eff}}$ and $\log g$ drawn from a Gaussian distribution centered on the derived $T_{\text{eff}}$ and $\log g$

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9 http://www.astro.umontreal.ca/~bergeron/CoolingModels/
| Object ID | R.A. (J2000) | Decl. (J2000) | g  | dg | u – g | d(u–g) | g – r | d(g–r) | Cross ID |
|----------|--------------|--------------|----|----|-------|--------|-------|--------|---------|
| 207325   | 8:50:29.47   | 11:52:49.5   | 20.671 | 0.032 | -0.152 | 0.032 | -0.329 | 0.045 | MMJ 5011 (1) |
| 206310   | 8:50:35.21   | 11:50:33.9   | 20.024 | 0.032 | 0.669  | 0.032 | 0.250  | 0.045 | MMJ 5055 (1) |
| 207569   | 8:50:39.43   | 11:53:26.8   | 21.342 | 0.032 | 0.415  | 0.034 | -0.165 | 0.045 | ... |
| 203383   | 8:50:47.60   | 11:43:30.0   | 21.883 | 0.032 | 0.423  | 0.035 | -0.131 | 0.046 | ... |
| 203493   | 8:50:48.28   | 11:43:47.8   | 21.665 | 0.032 | 0.423  | 0.034 | -0.149 | 0.045 | SDSS J085048.27+114347.7 (7) |
| 207278   | 8:50:51.65   | 11:42:06.5   | 21.526 | 0.032 | 0.071  | 0.033 | -0.235 | 0.045 | ... |
| 202432   | 8:50:56.29   | 11:44:43.1   | 21.257 | 0.032 | 0.190  | 0.033 | -0.144 | 0.045 | LB 6310 (3) |
| 206986   | 8:50:52.52   | 11:52:06.8   | 21.436 | 0.032 | 0.399  | 0.033 | -0.147 | 0.045 | ... |

Notes. Entries below the bar do not meet the post facto photometric criteria but were targeted spectroscopically either due to results of first-iteration photometric reduction or the desire to fill slitmasks with targets to explore parameter space outside the formal selection criteria.

* Running index from DAOphot photometry files used as identifier in slitmask design.

** Simbad coordinate matches within 3° radius.

References. (1) Montgomery et al. (1993), (2) van den Berg et al. (2004), (3) Luyten (1963), (4) Pasquini et al. (1994), (5) Fleming et al. (1997), (6) Fan et al. (1996), (7) Kepler et al. (2015), and (8) Páris et al. (2014).

(This table is available in machine-readable form.)
with stated errors, propagating these through all photometric calculations, and then deriving the standard deviation of the output synthetic photometry.

An apparent distance modulus for each DA WD is determined by subtracting the $g$-band apparent magnitude from the synthetic absolute $g$ magnitude. Color excesses are also calculated by subtracting synthetic colors from the observed colors. Errors on the apparent distance moduli and color excesses are determined by adding observational uncertainties, cluster distance and reddening uncertainties, and synthetic model uncertainties in quadrature.

3. The WD Population of M67

3.1. Cluster Membership Determination

We determine cluster membership for each WD as follows. For DA WDs with proper motion measurements, we require the WD to be a proper motion cluster member as defined by Bellini et al. (2010) and to have an apparent distance modulus within 3 standard deviations of our adopted value. Eighteen of the 24 (75%) spectroscopically confirmed DA WDs have spectra of sufficient quality to permit photometric membership determination. A search of the Gaia DR2 catalog is unable to better constrain cluster membership—none of our WDs have sufficiently precise parallax measurements, and only WD15 and WD21 have significant proper motions, both of which are consistent with cluster membership in both the Gaia and Bellini et al. (2010) catalogs.

Candidate double degenerates are identified as DA WD proper motion members with distance moduli inconsistent with cluster membership yet foreground to the cluster up to a maximum of 0.75 mag (i.e., those less than a factor of 2 overluminous). We note that the spectrum of any true double
degenerate system will be a flux-averaged combination of the two components, and that these two components need not be the same mass or luminosity. Therefore, the derived atmospheric parameters of candidate double degenerates should be considered unreliable.

To date we have not attempted to determine atmospheric parameters for non-DA WDs; we hope to revisit this issue in future study. For now, non-DA cluster membership is based solely on the WD’s proper motion membership from Bellini et al. (2010). The information relevant to membership determination is presented in Table 7 for DA WDs and in Table 8 for non-DA WDs.

In Figure 7, we plot the apparent distance modulus for each DA WD as compared to the cluster distance modulus. This figure highlights the utility of combining photometric and proper motion membership determinations. Fully half of the nonmembers (based on proper motions) would have been considered cluster member WDs based on distance modulus criteria alone, and the resulting contamination would have been ~30%. Additionally, there is one DA WD, WD15, that has a proper motion consistent with M67 membership but a distance modulus that is significantly background to the star cluster. Such an interloper is not surprising due to the overlap of the field star and cluster star proper motion vectors as seen in Figure 4(d) of Bellini et al. (2010). The combination of distance modulus and proper motion measurements is therefore a powerful tool in producing an uncontaminated sample of cluster member WDs.

Of the six post facto photometric WD candidates without new spectroscopy, three are proper motion nonmembers (Objects 206310, 292440, and 17303); two are proper motion members (the DA WD33 and Object 292232); and one, Object 15623, is outside the footprint of the Bellini et al. (2010) proper motion data.

Notes on individual objects:

WD10—This WD is a proper motion member and candidate double degenerate, as it is otherwise overluminous for a cluster member WD with the derived atmospheric parameters. However, if a binary, its spectrum would be a composite; our spectral analysis assumes it is a single star.

WD15—This DA is a proper motion member, but its distance modulus is 0.77 mag (~8σ) background to the cluster, which would imply it is a field star. This would not be unexpected, since the cluster member proper motion distribution in Bellini et al. (2010) does overlap with the field proper motion distribution, though to date we have not calculated proper motion membership probabilities. Additionally, even though the spectral S/N is high, the Balmer line fits are mediocre for this star, meaning that the derived parameters (and therefore distance modulus) could be in error. Because of these ambiguities, we do not include it in our further analysis of cluster members.
WD19—This DA is a proper motion member, but two different $T_{\text{eff}}$ and $g$ solutions are equally good matches to the spectroscopic and photometric data (see Paper II). Both spectral solutions have synthetic photometry consistent with cluster membership, though the cooler solution is also consistent with a potential double degenerate solution. The derived WD masses are consistent each other to within 2σ. We therefore consider this WD a cluster member, but we exclude it from the WD mass distribution discussed below.

WD24—This faint DA is a proper motion member, but the low S/N spectrum does not permit precise determinations of mass or synthetic photometry. We therefore exclude this WD from further discussion.

WD28—This DA does not have a proper motion measurement from Bellini et al. (2010). Photometrically, it is 1.22 mag background to the cluster, but the S/N of the spectrum is very low, resulting in poor constraints on the synthetic photometry. We exclude this WD in all further analysis.

WD32—This DA shows unambiguous spectroscopic evidence of an unresolved M-star companion redward of the H$\beta$ line. Given that the WD is not a proper motion member and is significantly foreground to the cluster, we do not analyze the spectrum any further.

WD33—This DA was not observed spectroscopically by us but has spectral data from the SDSS DR10 WD catalog of Kepler et al. (2015), and it is a proper motion member of the cluster. Kepler et al. (2015) derive spectral parameters of $T_{\text{eff}} = 9914 \pm 284$ K and $\log g = 8.310 \pm 0.300$ using the spectral models of Koester (2010) and 3D corrections, which generally results in parameters consistent with published results from our methodology (see Paper II, and references therein). Due to the very low S/N of the SDSS spectrum ($S/N = 3$), the mass and the synthetic photometry are poorly constrained. We therefore exclude this WD from further discussion.

### 3.2. DA WD Mass Distribution

Stellar evolution theory predicts that, for a simple stellar population, single star evolution should produce WD remnants with masses only dependent on the progenitor star’s zero-age main sequence mass. Therefore, all stars with the same progenitor mass should have the same WD mass. So far, this assertion has been difficult to test via open cluster WD populations, either because the WDs in a given cluster have significantly different progenitor masses or because the sample size is too small.

The progenitor mass of a WD can be determined from WD parameters, albeit in a strongly model-dependent way. This methodology is discussed in Paper II and references therein; we especially point out the discussion of the limitations as discussed by Salaris et al. (2009). In brief, the derived $T_{\text{eff}}$
and log\( g \) of DA WDs translate directly into a WD mass and cooling age (time since the cessation of the majority of nuclear burning) via WD evolutionary models. We subtract this cooling age from the star cluster age to get the nuclear lifetime of the progenitor star. We then use the PARSEC 1.2S stellar evolutionary models (Chen et al. 2015) to determine the zero-age main sequence mass of a star with this nuclear lifetime. As we mention above, the discussion below is not strongly dependent on the exact value of the initial masses for each WD but rather the relative values.

Since M67 is an old cluster, the main sequence turnoff mass is changing relatively slowly, and all of the WDs in our spectroscopic sample should have nearly identical progenitor masses; this idea is clearly illustrated in the IFMR discussion of Paper II. Our sample of 13 cluster member DAs with well-determined masses therefore permits us to test whether there is any evidence for additional scatter in the WD masses beyond that due to observational errors.

We start with the sample of cluster member DA WDs given in Table 7. We exclude WD19 from consideration since we are unable to choose unambiguously which atmospheric parameter solution is correct, and we exclude WD10 since it is a potential double degenerate. This leaves us with a sample of \( N = 11 \) WDs. We calculate the mean of the WD masses weighted by the mass uncertainties in Table 7 to be \( \bar{M}_{\text{DA}} = 0.594 \pm 0.011 \, M_\odot \) (formal error on the mean) with a standard deviation of \( \sigma_{M_{\text{DA}}} = 0.106 \, M_\odot \). Three WDs are clear outliers in this distribution: WD20 (\( M = 0.429 \pm 0.066 \, M_\odot \)) and WD22 (\( M = 0.390 \pm 0.034 \)) are significantly less massive than the mean, and WD29 is significantly more massive than the mean with \( M = 0.759 \pm 0.039 \, M_\odot \). We discuss these further below.

If we remove the three outlier WDs from the sample (now \( N = 8 \)), we find a weighted mean mass \( \bar{M}_{\text{DA}} = 0.610 \pm 0.012 \, M_\odot \) (formal error on the mean) with a standard deviation of \( \sigma_{M_{\text{DA}}} = 0.043 \, M_\odot \); the distribution is consistent with a Gaussian with the same standard deviation (see Figure 8). The mean mass is \( \approx 0.08 \, M_\odot \) higher than that predicted by the linear semi-empirical IFMR of Williams et al. (2009) of 0.53 \( M_\odot \) for a 1.5 \( M_\odot \) progenitor mass; this is discussed further in Paper II.

The standard deviation of 0.043 \( M_\odot \) is very similar to the average of the WD mass measurement uncertainties (0.039 \( M_\odot \)), suggesting any additional source of scatter in the WD mass distribution beyond observational uncertainties must be \( \lesssim 0.02 \, M_\odot \), assuming the intrinsic scatter and observational errors can be added in quadrature. In other words, single stars in M67 near the current main sequence turnoff mass result in WD remnants with an intrinsic scatter of less than 3% in the WD mass—if we have estimated our observational errors.
Table 7
Derived Quantities and Cluster Membership for DA WDs

| ID | $M_{WD}$ ($M_\odot$) | $dM_{WD}$ ($M_\odot$) | $M_\gamma$ mag | $dM_\gamma$ mag | $\Delta(m - M)_\gamma$ * mag | $d(m - M)_\gamma$ mag | PM Memberb,c | Phot. Memberb |
|----|----------------|----------------|--------------|--------------|----------------|----------------|-------------|-------------|
| WD3 | 0.696 | 0.032 | 12.213 | 0.084 | −0.118 | 0.090 | Y | Y |
| WD6 | 0.591 | 0.026 | 12.657 | 0.143 | −0.318 | 0.147 | Y | Y |
| WD9 | 0.563 | 0.023 | 11.251 | 0.095 | 0.294 | 0.100 | Y | Y |
| WD10 | 0.795 | 0.025 | 12.240 | 0.068 | −0.624 | 0.071 | Y | B |
| WD14 | 0.627 | 0.025 | 11.464 | 0.071 | −0.123 | 0.075 | Y | Y |
| WD16 | 0.621 | 0.043 | 12.226 | 0.113 | 0.131 | 0.117 | Y | Y |
| WD17 | 0.625 | 0.026 | 11.819 | 0.071 | −0.177 | 0.078 | Y | Y |
| WD19 | 0.657d | 0.017d | 11.305d | 0.052d | 0.116d | 0.061d | Y | Y |
| WD20 | 0.429 | 0.063 | 12.426 | 0.187 | 0.071 | 0.190 | Y | Y |
| WD22 | 0.390 | 0.029 | 11.419 | 0.112 | 0.229 | 0.117 | Y | Y |
| WD25 | 0.612 | 0.009 | 10.529 | 0.028 | 0.151 | 0.043 | Y | Y |
| WD26 | 0.561 | 0.032 | 12.255 | 0.086 | 0.030 | 0.092 | Y | Y |
| WD29 | 0.759 | 0.031 | 12.294 | 0.082 | −0.182 | 0.088 | Y | Y |
| WD2 | 0.687 | 0.023 | 11.391 | 0.069 | 0.163 | 0.076 | N | Y |
| WD5 | 0.607 | 0.020 | 11.749 | 0.056 | −0.101 | 0.064 | N | Y |
| WD8 | 0.719 | 0.034 | 10.843 | 0.095 | 0.898 | 0.100 | N | N |
| WD15 | 0.548 | 0.017 | 8.128 | 0.094 | 0.769 | 0.099 | Y | N |
| WD32 | 0.561 | 0.014 | 12.173 | 0.036 | −2.847 | 0.048 | N | N |
| WD11 | 0.527 | 0.041 | 12.397 | 0.109 | −0.721 | 0.111 | N | ... |
| WD12 | 0.759 | 0.029 | 13.871 | 0.143 | −2.648 | 0.145 | N | ... |
| WD13 | 0.400 | 0.200 | 12.243 | 0.593 | 1.088 | 0.593 | N | ... |
| WD24 | 0.222 | 0.414 | 12.282 | 0.763 | 1.343 | 0.764 | Y | ... |
| WD28 | 0.530 | 0.132 | 12.442 | 0.364 | 1.217 | 0.366 | N | ... |
| WD33 | 0.795 | 0.182 | 12.703 | 0.521 | −0.822 | 0.524 | Y | ... |

Notes. Objects below the first horizontal line are considered field (nonmember) WDs. Objects below the second horizontal line have too large of errors in spectral parameters to constrain photometric membership meaningfully.

a Difference of WD and cluster apparent distance moduli.

b “Y” = yes, “N” = no, “B” = candidate binary member.

c From Bellini et al. (2010).

d Hot solution (see the text).

e Cool solution (see the text).

(This table is available in machine-readable form.)

Table 8
Cluster Membership for non-DA WDs

| ID | Spectral Type | PM Memberb |
|----|--------------|-------------|
| WD1 | DB | ... |
| WD4 | DB | N |
| WD7 | DB | N |
| WD18 | DB | N |
| WD21 | DB | Y |
| WD23 | DB: | Y |
| WD27 | DC | Y |
| WD30 | DB | Y |
| WD31 | DC | Y |

Notes.

a From Bellini et al. (2010).

b Outside the region studied by Bellini et al. (2010).

correctly. If our mass errors are significantly overestimated, then the intrinsic scatter could be as large as the observed scatter of $\approx 0.04 M_\odot$, or $\approx 7\%$.

Overall, one should expect that cooler WDs in a star cluster should have a larger mass than hotter WDs, since the cooler WDs came from progenitor stars with shorter nuclear lifetimes, implying a higher progenitor mass. Indeed, this effect is seen in younger open clusters such as NGC 2168 and NGC 2099 (Kalirai et al. 2005b; Williams et al. 2009; Cummings et al. 2015). Given the advanced age of M67 and the comparatively short cooling time of our spectroscopic sample, the derived progenitor masses for our WDs span less than 0.1 $M_\odot$, as seen in Paper II. Based on linear approximations to the semi-empirical IFMR (e.g., Williams et al. 2009; Cummings et al. 2016), one would expect only a change in WD masses of $\approx 0.015 M_\odot$ over the M67 sample initial mass range, significantly smaller than our observed scatter. Indeed, no significant correlation is found between the M67 WD masses and their initial mass—see Figure 9.

3.3. Two Candidate He-core WDs

As mentioned above, WD20 and WD22 are significantly less massive than the cluster mean. In fact, both WDs are less massive than the canonical mass required for He-core ignition of $\approx 0.45 M_\odot$ (e.g., Sweigart 1994; Fontaine et al. 2001), though these are only $\approx 2\sigma$ deviations. This would imply that a fraction $\approx 0.18$ of M67 WDs are He-core WDs, with a 90% upper confidence limit of $\approx 0.4$ assuming a binomial distribution.

Candidate He-core WDs have also been identified in the older, very metal-rich open cluster NGC 6791 by Kalirai et al. (2007),
who present evidence of a He-core WD fraction of greater 50%. They propose that mass loss during the first ascent of the red giant branch may be responsible for the He-core WDs in that cluster, though Miglio et al. (2012) find no evidence of such extreme mass loss by red giants in NGC 6791. Kalirai et al. (2007) also propose that the high He-core WD fraction is likely related to the known EHB stars known to be in the cluster.

Our measurement of the M67 He-core WD fraction is inconsistent with that observed in NGC 6791, and recent K2 asteroseismology results on the masses of giants in M67 likewise find no evidence of such extreme mass loss by red giants in NGC 6791. Kalirai et al. (2007) also propose that the high He-core WD fraction is likely related to the known EHB stars known to be in the cluster.

Another mechanism for the formation of He-core WDs is through binary interactions. Our spectra are too low of resolution to resolve radial velocity variations, but we can compare synthetic and observed photometry for inconsistencies with an appropriately reddened single WD model. In particular, we compare the color indices $\Delta(u-g) = (u-g)_{\text{WD}} - (u-g)_{\text{model}}$ and $\Delta(g-r) = (g-r)_{\text{WD}} - (g-r)_{\text{model}}$. WD20 has color indices fully consistent with the single star model: $\Delta(u-g) = 0.018 \pm 0.042$ and $\Delta(g-r) = 0.0040 \pm 0.047$. Therefore, any companion to WD20 must be extremely faint in our bandpasses.

WD22, on the other hand, does exhibit significantly different colors than predicted by synthetic photometry: $\Delta(u-g) = -0.145 \pm 0.040$ and $\Delta(g-r) = +0.328 \pm 0.052$. The significantly redder $g-r$ color could imply a faint, cool companion. No evidence of an M dwarf companion is obvious in the spectrum (see Figure 4), but the spectrum is relatively noisy and could hide a companion similar to that observed in the foreground WD+dM system WD32, which has a similar color excess. It is thus possible that the candidate He-core WD22 has an M dwarf companion.

### 3.4. WD(s) from Blue Stragglers

The other WD with a significantly discrepant mass is WD29, with $M_{WD} = 0.759 \pm 0.039 M_{\odot}$. We propose that this WD is the remnant of a blue straggler. M67 has a significant blue straggler population, some of which have measured masses. For example, S1237 is an evolved blue straggler with an

![Figure 7. Apparent distance moduli for DA WDs in the field of M67. Filled points are WDs that meet both proper motion and distance modulus criteria for membership; the cluster distance modulus is indicated by the vertical heavy dashed line with uncertainties of the vertical dotted lines. Open circles are WDs that are proper motion members but up to 0.75 mag foreground to the cluster (indicated by the light dashed vertical line); these are double degenerate candidates. WD15, indicated by an asterisk, is a proper motion member but significantly background to the cluster. The four DAs indicated by a cross are nonmembers according to proper motions. The two possible solutions for WD19 are shown as WD19H (hotter solution) and WD19C (cooler solution). Error bars indicate $2\sigma$ uncertainty. The combination of proper motion and distance modulus criteria identifies likely field WDs better than either criterion alone.](image-url)
and WD33, proper motion members whose spectra are too noisy to permit photometric membership determinations. For this case, we include WD19, the DA for which we could not select between hot and cold temperature solutions, since its spectral type is not in doubt. Our sample thus contains 12 DAs with $g \leq 22.2$. For non-DA spectral types, we include all proper motion members with $g \leq 22.2$; i.e., in the same apparent magnitude range as the DAs. Our sample thus consists of four non-DAs: WD18, WD21, WD30, and WD31. To first order, this gives us a DA:non-DA ratio of 4:1, nearly identical to that in the field, though with significant uncertainty ($\sim 50\%$) once small number statistics are considered. Given the high spectroscopic completeness for our post facto selected candidates, any effects due to incompleteness are far smaller than those due to small number statistics.

We note in Williams et al. (2006) that an appropriate accounting of non-DA WDs in a given open cluster requires consideration of the so-called “DB gap,” a noted change in the DA:non-DA ratio for WDs with $T_{\text{eff}} \approx 30,000$ to 45,000 K. The DB cooling models of Fontaine et al. (2001) show that a 0.6 $M_\odot$ WD will cool below 30,000 K in $\approx 14$ Myr, or roughly 2% of the cooling time of WDs at our limiting magnitude. Therefore, any DB gap correction will be on the order of this level, and insignificant compared to our statistical errors.

Therefore, we find no evidence that the DA to non-DA ratio differs in M67 as compared to the ratio in the field. This suggests that any proposed mechanism for suppressing non-DA formation in the cluster environment (e.g., as suggested in Davis et al. 2009) would need to explain this exception.

4. Summary

In this paper, we present the results of a spectroscopic study of the WD population in the field of the open cluster M67. A combination of proper motion and photometric distance determinations allows us to study an uncontaminated sample of cluster member WDs, including 13 DA (hydrogen-dominated atmosphere) WDs and four non-DA (helium-dominated atmosphere) WDs. Our spectroscopy is highly complete for non-binary cluster WDs; $\sim 90\%$ of photometrically selected candidates have spectroscopy, and 75% of the DAs in our sample have spectra of sufficient quality to permit photometric membership determination. While the photometric completeness is not quantified, it is likely to be high and relatively unbiased for $g \leq 22.2$ ($M_\odot \approx 12.4$). Because M67 is an old open cluster of solar metallicity, this sample provides unique insight into the end stages of stellar evolution for solar-type stars.

In particular, we find the following:

1. The mass distribution of DA WDs suggests that any scatter in integrated mass loss over the lifetime of a single, $\approx 1.5$ $M_\odot$ star is small—less than 7% of the WD mass, if our interpretation that the three significant outliers to this distribution are the result of binary evolution is correct. We find the average mass of the DA WDs to be $0.610 \pm 0.012$ $M_\odot$ with a standard deviation of $0.043$ $M_\odot$, comparable with our typical observational uncertainty in mass determination of $0.039$ $M_\odot$.

2. We identify two cluster member DA WDs that are consistent with being He-core WDs, for a He-core WD fraction of $\sim 20\%$, in contrast to others’ findings for the WDs in the super metal-rich cluster NGC 6791. Other

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**Figure 8.** The histogram of masses for the 11 well-measured cluster member DA WDs. The magenta curve is a Gaussian function with a mean value of $0.61$ $M_\odot$, a standard deviation of $0.043$ $M_\odot$, and normalized to a total of 8 WDs. The three outliers are WD20 and WD22 (low-mass end) and WD29 (high-mass end). When these three outliers are excluded, the measured standard deviation is very close to our calculated WD mass errors, consistent with the hypothesis that all WDs have the same mass to better than a few percent.
researchers find no observational evidence for strong mass loss on the M67 red giant branch, and M67 contains no EHB stars. If high metallicity can cause extreme mass loss on the red giant branch, the enhanced mass loss mechanism is not efficient at or below solar metallicity.

3. One or two M67 DA WDs have masses significantly higher than the cluster DA WD mean mass. These WDs are potential progeny of blue straggler stars. The WD masses are consistent with the expectation from the IMFR if their progenitor stars were twice as massive as expected from single star evolution.

4. The ratio of hydrogen- to helium-dominated atmosphere WDs (DA to non-DA ratio) is \(\sim 4:1\), consistent with that measured for field WDs. This argues against the proposal that a mechanism in clusters inhibits formation of non-DA WDs, at least for solar metallicity, low-mass stars.

5. We identify one DA WD that is a proper motion member of M67 but overluminous, indicating it is a candidate unresolved double degenerate.

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Facilities: Keck:I (LRIS-B), MMT (Megacam).

Software: IRAF (Tody 1986, 1993), SExtractor (Bertin & Arnouts 1996), SWarp (Bertin et al. 2002), DAOPHOT II (Stetson 1987), L.A.Cosmic (van Dokkum 2001).

ORCID iDs

Kurtis A. Williams https://orcid.org/0000-0002-1413-7679
A. Bellini https://orcid.org/0000-0003-3858-637X
Kate H. R. Rubin https://orcid.org/0000-0001-6248-1864
Alexandros Gianninas https://orcid.org/0000-0002-8655-4308
Mukremin Kilic https://orcid.org/0000-0001-6098-2235

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