On the empirical evidence for the existence of ultra-massive white dwarfs

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ABSTRACT
We re-examine the evidence for the existence of ultra-massive ($M > 1.1 M_\odot$) white dwarfs based on gravitational redshift of white dwarfs in common proper motion binaries or in clusters, on parallax measurements, on orbital solutions, and, finally, on the analysis of hydrogen line profiles. We conclude that the best evidence is largely based on the analysis of Balmer line profiles although the companion to the A8V star HR 8210 is a compelling case made initially using the large binary mass function and confirmed by an analysis of the Lyman line spectrum. The confirmation and identification of high-mass white dwarfs, more particularly non-DA white dwarfs, using parallax measurements may prove critical in establishing the population fraction of these objects and in constraining the high-end of empirical initial-mass to final-mass relations. The existence of a substantial population of ultra-massive white dwarfs supports the concept of a steeper initial-mass to final-mass relations linking $6 M_\odot$ progenitors with $\gtrsim 1.1 M_\odot$ white dwarfs.

Key words: stars: evolution -- stars: fundamental parameters -- white dwarfs

1 INTRODUCTION
Ultra-massive white dwarfs, generally defined as having masses exceeding 1.1 $M_\odot$, remained relatively rare until deep spectroscopic surveys uncovered these intrinsically faint objects. The hot hydrogen-rich (DA) white dwarf GD 50 (Bergeron et al. 1993), the carbon-rich white dwarf G35-26 (Thejll et al. 1990), and two DA white dwarfs (PG 1658+441 and PG 0136+251) from the Palomar-Green survey (Schmidt et al. 1992) were rare examples of this phenomenon. Interestingly, spectroscopic follow-up of extreme ultraviolet (EUV) surveys of the local ($d \lesssim 100$ pc), hot white dwarf population managed to identify many new ultra-massive white dwarfs on the basis of a large, spectroscopically determined surface gravity ($\log g \gtrsim 9$). Based on the Extreme Ultraviolet Explorer (EUVE) and ROSAT Wide Field Camera (WFC) surveys, Vennes et al. (1996, 1997a, 1997b), Vennes (1999), Finley et al. (1997), and Marsh et al. (1997) added a dozen new objects to the population. More recently, a re-analysis of the Palomar-Green (PG) sample of DA white dwarfs (Liebert et al. 2005) and a study of the white dwarf mass distribution in the Sloan Digital Sky Survey (SDSS; Kepler et al. 2007) seem to generate similar yields of ultra-massive white dwarfs.

Are these objects products of single star evolution or double degenerate mergers? Weidemann (2000) reviews theoretical arguments in favour of an upper mass limit for white dwarf stars larger than the canonical upper limit of 1.1 $M_\odot$, and possibly as large as $\sim 1.3 M_\odot$. A limit of 1.1 $M_\odot$ is generally assumed because carbon ignition in high mass cores would lead to thermonuclear runaway or core collapse. However, the effect of mass loss may alter the scenario and lead to the formation of a massive oxygen-neon-magnesium white dwarf (Nomoto 1984). Garcia-Berro et al. (1997) and Ritossa et al. (1996) successfully evolved 9 and 10 $M_\odot$ stars, which, following an off-centre carbon ignition in partial electron degenerate conditions, generated oxygen-neon core white dwarfs with carbon-oxygen shells, and total masses of 1.15 and 1.26 $M_\odot$, respectively. On the other hand, the merger scenario proposed for the origin of Type Ia supernovae (Yungelson et al. 1994) also generates ultra-massive white dwarfs. However, the merger process itself and the fate of these objects are uncertain (Segretain et al. 1997).

We re-examine the evidence for the existence of ultra-massive white dwarfs. Mass measurements are based on gravitational redshift measurements (§2), radius (parallax) measurements (§3), orbital parameters (§4), and surface gravity measurements (§5). The gravitational redshift measurements ($\propto M/R$), radius measurements, and surface gravity measurements ($\propto M/R^2$) are converted into mass measurements by adopting mass-radius relations for a variety of model structures. We adopted the models of...
Table 1. The CPMB Sample

| WD            | CPMB          | Types                      |
|---------------|---------------|----------------------------|
| 0433+470      | LP 356-525/B  | DA +dK5                    |
| 0738−172      | LP 783-3/LP783-2 | DZAQ+dM6                |
| 0820−585      | LP 186-119/LP186-120 | DA+dM3             |
| 1750−098      | G140-B1B/G140-B1A | DC+dK2              |
| 2323−241      | G275-B16A/G275-B16B | F7+dK7            |
| 2323−241      | G275-B16A/G275-B16B | F7+dK7            |

a [Silvestri et al. (2001)].
b Not a white dwarf, see text.

Benvenuto & Althaus (1999) with a C/O core and zero metallicity, a helium mantle (log g(He) = −2), and with a thick (log g(H) = −4) hydrogen layer to describe hydrogen-rich DA white dwarfs or without a hydrogen layer to describe non-DA white dwarfs. In §5, we also present evidence that deep surveys of high-proper motion white dwarves are now extending the ultra-massive population toward lower temperatures, and it is estimated that approximately 10% of white dwarves have masses in excess of 1.1 \( M_\odot \). We summarize and conclude in §6.

2 BASED ON GRAVITATIONAL REDSHIFT: THE CPMB SAMPLE AND CLUSTER MEMBERS

The massive white dwarf and member of the Pleiades LB 1497 (Wegner et al. 1999) remained a unique candidate for having a mass in excess of 1.0 \( M_\odot \) and possibly in excess of 1.1 \( M_\odot \) among stars with gravitational redshift measurements (Wegner & Reid 1999; Bergeron et al. 1999; Reid 1996). However, applying the same techniques to white dwarves in common proper motion binaries Silvestri et al. (2001) proposed new ultra-massive white dwarf candidates (Table 1). We demonstrate that this is not the case and that the ultra-massive white dwarf sequence presented by Silvestri et al. (2001) and based on gravitational redshift measurements does not exist. We also re-evaluate the mass of LB 1497 and show that its case remains compelling.

2.1 WD 0433+470: LP 356-525

The hydrogen-rich (DA) white dwarf WD 0433+470 is part of a CPMB with the putative Hyades member LB 26+730. However, the presence of a cool, presumably old white dwarf in the Hyades poses a chronology problem that Catalán et al. (2008b) tentatively resolved by substituting a normal C/O core with a Fe core thereby shortening the cooling age of the white dwarf from 4 Gyr to 1 Gyr. Their analysis is based on the Balmer line profile fits of Bergeron et al. (2001) and Zuckerman et al. (2003). Adopting a straight average of these measurements, \( T_{\text{eff}} = 5527±130 \) K and \( g = 8.08±0.10 \), we determined a mass \( M = 0.63±0.06 \) \( M_\odot \) and absolute visual magnitude \( M_V = 14.78±0.30 \) using the DA mass-radius relations of Benvenuto & Althaus (1999). The resulting mass is well below the mass based on the gravitational redshift measurements of Silvestri et al. (2001) \( M = 1.12±0.01 \) \( M_\odot \). Moreover, the apparent \( (V = 15.81) \) magnitude combined with the absolute visual magnitude for the low-mass solution corresponds to a distance modulus of \( m - M = 1.03±0.30 \) (\( d = 16±2 \) pc) in agreement with the Hipparcos parallax measurement for BD+26 730, \( \pi = 56.0±1.2 \) mas (Gould & Chaname 2004) or \( d = 17.9±0.4 \) pc, and the white dwarf parallax measurement, \( \pi = 60±3 \) mas (Harrington & Dahn 1980) or \( d = 16.6±0.8 \) pc. According to Catalán et al. (2008a), the mass of an iron core white dwarf would be lower by approximately 0.2 \( M_\odot \) for the same temperature and surface gravity. The white dwarf radius inferred for this configuration would also decrease by 18% resulting in a closer distance for the white dwarf \( d = 13±2 \) pc that is marginally consistent with the parallaxes measurements.

2.2 WD 0738−172: LP 783-3

The metal-rich hydrogen-poor white dwarf LP 783-3 (DZAQ6) is paired with the dM star LP 783-2. The parallax of the white dwarf, \( \pi = 112±3 \) mas (van Altena et al. 1993), translates into a distance modulus of \( m - M = -0.25±0.06 \) and, using \( V = 13.03 \), we determined the absolute magnitude \( M_V = 13.28±0.07 \).

By fitting optical/infrared spectral energy distribution and by constraining the absolute magnitude to \( M_V = 13.31±0.05 \) (Bergeron et al. 2001) determined \( T_{\text{eff}} = 7710±220 \) K and \( g = 8.09±0.03 \).

We revisited this result by computing a H/He model grid for effective temperatures \( 7000 \leq T_{\text{eff}} \leq 8500 \) K and surface gravities \( 7.0 \leq \log g \leq 8.5 \), and a hydrogen abundance \( \log H/He = −3 \) consistent with the measurements of Bergeron et al. (2001). The absolute magnitudes were calculated using the mass radius relations of Benvenuto & Althaus (1999) for non-DA stars. We adopted the temperature of Bergeron et al. (2001), \( T_{\text{eff}} = 7710±220 \), and the absolute magnitude \( M_V = 13.28±0.07 \) and propagated the errors. We determined a surface gravity \( g = 8.12±0.09 \) that corresponds to a mass of \( M = 0.64±0.06 \) \( M_\odot \). The mass of the white dwarf is normal.

Adopting the distance modulus for the white dwarf \( (m - M = -0.25±0.06) \) we estimate an absolute luminosity for the red dwarf companion \( M_V = 16.92±0.06 \) that corresponds to a spectral dM6.5 (Kirkpatrick & McCarthy 1994).

2.3 WD 0820−585: LP 186-119

The DA white dwarf (L186-119) is paired with a dM star (L186-120). We obtained a low-dispersion (\( \approx 6 \) Å) EFOSC2 spectrum from the ESO archives and fitted the Balmer line profiles from H/3 to H9 using our most recent pure hydrogen model atmosphere grid (Kawka & Vennes 2004). Figure 1 shows the results of our analysis. Using the DA mass-radius relations of Benvenuto & Althaus (1999), the surface gravity and effective temperature measurements (\( \log g = 8.12±0.08 \), \( T_{\text{eff}} = 9310±70 \) K) correspond to a mass \( M = 0.67±0.05 \) \( M_\odot \) well below the mass of \( M = 1.10±0.03 \) \( M_\odot \) estimated by Silvestri et al. (2001) and based on their gravitational redshift measurement. The calculated absolute magnitude is \( M_V = 12.66±0.22 \) and corresponds to a distance modulus \( m - M = 3.9±0.2 \) (\( d = 60±6 \) pc).

1 Based on observations made with ESO telescopes at the La Silla Paranal Observatory under programme 078.D-0824.
Silvestri et al. (2001) listed the spectral type of the companion as dM5. We revised this estimate using their V photometry as well as 2MASS JHK measurements (Cutri et al. 2006). The measured $V$ photometry and 2MASS JHK measurements correspond to a white dwarf mass $M_\text{WD} = 12.05$ (Kirkpatrick & McCarthy 1994) and the corresponding distance modulus $(m - M = 3.8)$ confirms the physical association of the two stars and the normal mass ($M \approx 0.7 \, \text{M}_\odot$) for the white dwarf component.

2.4 WD 1750+098: G140-B1B

The DC white dwarf G140-B1B is paired with the K star G140-B1A (HD 162867). The optical/2MASS colour index $V - J = 1.68 \pm 0.08$ of G140-B1A constrains the spectral type to K2 (Bessell & Brett 1988) and the absolute magnitude to $M_V = 6.2 \pm 0.2$ (Dotter et al. 2008). Therefore, the distance modulus is $m - M = 3.2 \pm 0.2$ and corresponds to a distance of $d = 44$ pc. Adopting $V = 15.72$ for the white dwarf (Eggen & Greenstein 1965), the absolute luminosity is $M_V = 12.5 \pm 0.2$. To determine the corresponding stellar parameters we computed a grid of pure He models at $900 \leq T_\text{eff} \leq 11000$ K and surface gravities $8.0 \leq \log g \leq 9.0$ and calculated the absolute magnitudes using the non-DA mass-radius relations of Benvenuto & Althaus (1993). Combined with the colour index $V - I = 0.178 \pm 0.060$ (Silvestri et al. 2001), the absolute magnitude corresponds to $T_\text{eff} = 9200 \pm 600$ K and $\log g = 8.14 \pm 0.25$ that translate into a mass of $M = 0.66 \pm 0.16 \, \text{M}_\odot$. The presence of Hα in the white dwarf spectra is uncertain as Silvestri et al. (2001) and Wegner & Reid (1991) claim Hα detections while Reid (1996) does not report the detection. The absence of Hα would invalidate the white dwarf gravitational redshift measurement of Silvestri et al. (2001). However, the coincident proper motions and the normal mass for the white dwarf, which implies similar distance moduli for the two stars, strongly favour a physical association for the pair.

2.5 2323–241: G275-B16A

Silvestri et al. (2001) estimated a white dwarf gravitational redshift $v_g = 132 \pm 1 \, \text{km} \, \text{s}^{-1}$ that translated into a mass $M = 1.19 \pm 0.01 \, \text{M}_\odot$. This conclusion is based on the assumption that the star is a white dwarf part of a common proper motion binary and that the velocity differential is entirely caused by the gravitational redshift of the white dwarf. The companion is a late type star. We now re-examine the evidence.

First, Figure 2 shows a comparison between two model spectra and the UVES spectrum from the ESO archive for G275-B16A. The model spectra were obtained from the library of Munari et al. (2005), which is based on Kurucz models. Models and data are presented at a resolution of 1 Å. The Balmer line series clearly extends to H15 and implies a normal main-sequence surface gravity and a low metallicity. Indeed, we estimate $\text{[M/H]} = -1.5$ and $\text{[M/H]} = -2.0$ (shifted up by $1.0$ in relative flux units).

$\text{[M/H]} = -1.5$ for G275-B16A and G275-B16B, respectively. The colours correspond to spectral types of F7 and K7, respectively (Bessell & Brett 1988). Using the low metallicity ($\text{[M/H]} = -1.5$) models of Dotter et al.

2 Based on observations made with ESO telescopes at the La Silla Paranal Observatory under programme 165.H-0588.

3 Available at http://archives.pd.astro.it/2500-10500/
for the F star, the colour index \( V - J = 0.99 \) corresponds to an absolute magnitude \( M_V = 5.2 \) (or \( T_{\text{eff}} = 6200 \) K). A somewhat brighter absolute magnitude \( M_V = 4.9 \) is obtained with the model at \( T_{\text{eff}} = 6500 \) K. Note that low-metallicity stars are fainter than their solar-metallicity counterparts. Using the solar-metallicity models for the K star we determined a temperature of \( T_{\text{eff}} = 4200 \) K and an absolute magnitude \( M_V = 8.0 \). Therefore, the F star is at a considerably larger distance \((m-M) = 10.6-10.9, \, d = 1.3-1.5 \, \text{kpc}\) than the K star \((m-M) = 7.7, \, d = 350 \, \text{pc}\) and the pair is purely coincidental.

This conclusion is supported by proper motion and radial velocity measurements that place the F star on a different course than the K star. Zacharias et al. (2002) list the proper motions (in mas yr\(^{-1}\)) as \( \mu_\alpha = 0 \pm 3 \) and \( \mu_\delta = -36 \pm 5 \) for the F star, \( \mu_\alpha = -5 \pm 5 \) and \( \mu_\delta = -64 \pm 5 \) for the K star. Consequently, the difference in velocities, \( v(\text{F star}) - v(\text{K star}) \approx 132 \, \text{km s}^{-1} \) (Silvestri et al. 2001), may no longer be interpreted as being due to the effect of gravitational redshift, but as being due to diverging space motions.

The F star space motion is characteristic of low-metallicity stars (Chiba & Beers 2000). Adopting a distance of 1.4 kpc the radial velocity (\( v_\text{rad} = 133 \, \text{km s}^{-1} \)) and proper-motion correspond, following Johnson & Soderblom (1987), to a Galactic velocity \((U, V, W) = (145, -185, -138)\), which confirms its membership into the old disk or possibly the halo.

### 2.6 WD 0349+247: LB 1497

LB 1497 is a member of the Pleiades and Wegner et al. (1991) reported a gravitational redshift of \( v_g = 84 \pm 9 \) km s\(^{-1}\) for this DA white dwarf. Bergeron et al. (1993) also resorted a temperature \( T_{\text{eff}} = 31660 \pm 350 \) K and a high gravity of \( \log g = 8.78 \pm 0.05 \). Using the DA mass-radius relations of Benvenuto & Althaus (1999) and the temperature from Bergeron et al. (1993) we obtain a mass of \( M = 1.03 \pm 0.04 \, M_\odot \) based on the redshift measurement in agreement with the mass of \( M = 1.10 \pm 0.03 \, M_\odot \) based on the surface gravity measurement. The weighted mass average is \( M = 1.075 \pm 0.024 \, M_\odot \), close to the ultra-massive range.

### 3 BASED ON PARALLAX MEASUREMENTS

Preliminary parallax information on G35-26 (Thejll et al. 1998), GD 50 and PG 1658+441 was provided by Dahn (1999). Reading from Dahn’s Figure 3, the absolute V magnitudes of these three objects are 12.9, 11.5, and 12.4, respectively. Although, the original measurements are not listed the absolute magnitudes may be converted into masses using published effective temperatures and the mass-radius relations of Benvenuto & Althaus (1999). Adopting \( T_{\text{eff}} = 43200 \) K for GD 50 (Vennes et al. 1997a) and \( T_{\text{eff}} = 30510 \) K for PG 1658+441 (Schmidt et al. 1992) we obtain masses of \( M = 1.24 \, M_\odot \) and \( M = 1.29 \, M_\odot \), respectively. These values are in good agreement with the spectroscopic masses (Schmidt et al. 1992; Vennes et al. 1997b).

Similarly, employing the effective temperature considered by Thejll et al. (1994), \( T_{\text{eff}} = 14000 \) K, and the non-DA mass-radius relations, the absolute visual magnitude of G 35-26, interpolated using a grid of helium model atmospheres at \( 7.0 \leq \log g \leq 9.5 \) and \( \log H/He = -3 \) and at a temperature of 14000 K, also suggest a high-mass of \( M = 1.16 \, M_\odot \). This mass is somewhat lower than the spectroscopic mass obtained by Thejll et al. (1990), \( M = 1.2-1.33 \, M_\odot \).

These comparisons and the analysis of LHS 4033 (Dahn et al. 2004), and G47-18 and ESO439-26 (Bergeron et al. 2001) show that, although limited in scope, parallax measurements confirm the spectroscopic masses and the existence of a population of ultra-massive white dwarfs.

### 4 BASED ON ORBITAL SOLUTIONS

EUV surveys also uncovered a population of white dwarfs paired with early-type stars (Vennes et al. 1993; Barstow et al. 2001). Initial-mass to final-mass relations (Catalán et al. 2008a) for white dwarf stars indicate that the progeny of early-type stars (A, B) would retain a mass above average and in excess of \( 1 \, M_\odot \) for progenitors with \( M \geq 5 \, M_\odot \). The massive subluminous companion of the A8V star HR 8210 is such a relevant case. Far and extreme ultraviolet spectroscopy uncovered a DA white dwarf companion to HR 8210 (Landsman et al. 1993; Barstow et al. 1994; Vennes et al. 1998). The mass function, \( f(M_{WD}) = 0.219 \pm 0.004 \) (Vennes et al. 1998), and the constraint placed on the orbital inclination (\( i < 88^\circ \)) by the lack of an eclipse (Landsman et al. 1993) restricts the mass of the white dwarf to \( M(\text{WD}) \geq 1.19 \, M_\odot \) if \( M(\text{A8V}) = 1.6 \, M_\odot \).

We confirmed the high mass for the white dwarf using Far Ultraviolet Spectroscopic Explorer (FUSE) spectra that cover the white dwarf spectral energy distribution from \( \approx 900 \, \text{Å} \) to \( \approx 1180 \, \text{Å} \) (Fig. 3). The spectra (data id A0540909000) were obtained with FUSE on 2001 July 12 (UT) for a total exposure time of 4199 s using the LWRS aperture, and were processed using CalFUSE v3.2. The FUSE instrumentation is briefly described by Moos et al. (2000). We fitted the Lyman line series observed with FUSE with sets of grid of models to constrain the effective temperature and surface gravity of the white dwarf. In total we used 4 sets of grids, which either include or exclude the effect of Lyman satellite features and where line merging is treated either by using the formalism of Inglis & Teller (1993) (hereafter IT) or of Hummer & Mihalas (1988) (hereafter HI), which follows the treatment of Hubeny et al. (1994). The latter is described in more detail in Kawka & Vennes (2008) and Kawka et al. (2007). Figure 3 shows the analysis of the Lyman line spectra using the grid of model spectra that excludes Lyman satellites and used IT. The best fit model to the spectra corresponds to an effective temperature of \( T_{\text{eff}} = 35490 \pm 70 \) and a surface gravity of \( \log g = 8.85 \pm 0.04 \). We repeated the fit using a grid of models that include Lyman satellites and use HI to obtain \( T_{\text{eff}} = 33450 \pm 100 \) and \( \log g = 9.04 \pm 0.05 \). The grid of models that exclude Lyman satellites and use HI result in a best fit with \( T_{\text{eff}} = 3500 \pm 80 \) and \( \log g = 8.75 \pm 0.03 \). And finally the grid of models that include Lyman satellites and use IT result in a best fit with \( T_{\text{eff}} = 34800 \pm 90 \) and \( \log g = 9.13 \pm 0.04 \). The series of analyses show that the two different treatments of
Figure 3. Analysis of the Lyman line profiles of the DA white dwarf in HR 8210. Six separate *FUSE* spectroscopic channels are labelled and included in the analysis. Spectral ranges contaminated by geocoronal line emission were excluded from the analysis. The observed spectrum has been shifted by $-0.5 \, \text{Å}$.

Line merging produces a difference of $\approx 0.1$ in the surface gravity, and that the inclusion of Lyman satellites increases the measured surface gravity by $\approx 0.3$. We find that the best agreement with Vennes et al. (1998) is obtained using models that include the Lyman satellites however the fit is unsatisfactory as several predicted features are stronger than observed. Similar difficulties were encountered by Dupuis et al. (2003) in the analysis of Lyman line profiles of the ultramassive DAp PG 1658+441.

Employing the mass-radius relations for DA white dwarfs (Benvenuto & Althaus 1999), we determined the mass and absolute magnitude of the white dwarf, $M = 1.08 - 1.24 \, M_\odot$ and $M_V = 10.96 - 11.76$. Vennes et al. (1998) already concluded that the distance modulus derived from the Hipparcos parallax of the A8 star would be consistent with the predicted distance modulus for an *ultra-massive white dwarf*.

To our knowledge, the case of HR8210 is rather unique with the possible exception of HD 209295. Based on their analysis of the 3.1 day binary period, Handler et al. (2002) inferred the presence of a companion to this A star. The measured UV excess and the constraints on the mass ($M >$...
1.01 $M_{\odot}$ suggest that the companion is a relatively hot massive white dwarf, although the flux deficit in the TD-1 measurement at 1565 Å conspires against this explanation. The case of the putative white dwarf component of the triple system λ Sco (Berghöfer et al. 2000) was put to rest by Uytterhoeven et al. (2004) who inferred the presence of a low-mass pre-main-sequence star rather than a hot ultra-massive white dwarf. No other ultra-massive white dwarfs were predicted based solely on orbital elements. It is worth noting that three other white dwarf companions to B type stars (HR 2875, θ Hya, 16 Dra; Vennes et al. 1997a; Burleigh & Barstow 1999, 2000) were uncovered from their extreme ultraviolet spectral signatures. Direct spectroscopic or orbital mass measurements are as yet unavailable.

5 BASED ON BALMER LINE SPECTROSCOPY

Figure 4 assembles the spectroscopic evidence gathered by Vennes et al. (1996), Vennes et al. (1997b), and Vennes (1999) based on EUV surveys and as revised by Vennes et al. (2008) for a total of 158 objects, and Kawka & Vennes (2006) and Kawka et al. (2007) based on the New Luyten Two-Tenths (NLTT) proper-motion catalog (66 objects). In the latter, using proper-motion as a proxy for distance, the white dwarf selection probability is primarily a function of distance and the NLTT survey is primarily volume limited. Due to the particular morphology of the local interstellar medium and the so-called local bubble (see Redfield & Linsky 2008), Vennes et al. (1997b) argued that the white dwarf selection in EUV surveys is confined to a volume of radius $\lesssim 100$ pc and characterized by low interstellar medium column density that does not hamper the EUV selection. They show that a white dwarf formation rate of $0.7 - 10 \times 10^{-12}$ pc$^{-3}$ yr$^{-1}$ is sufficient to account for all hot white dwarf stars detected within 100 pc. Incidentally, Liebert et al. (2003) determined a formation rate of $0.6 \times 10^{-12}$ pc$^{-3}$ yr$^{-1}$ for the DA white dwarfs in the PG survey. On this account, one may consider the EUV surveys to be volume limited as well and that few hot white dwarfs, irrespective of their radii (hence masses), were missing from within this volume. Interestingly, the yield in ultra-massive white dwarfs is very similar in both NLTT, 4 out of 66, and EUV, 17 out of 158, surveys. A total of 21 objects out of 224 sampled have masses in excess of 1.1 $M_{\odot}$, and, therefore, close to 10% of all white dwarfs maybe considered ultra-massive.

Liebert et al. (2003) and Kepler et al. (2007) built white dwarf mass distributions based on the PG and SDSS surveys, respectively. Figure 5 shows the sample of 347 DA white dwarfs analyzed by Liebert et al. (2003). Only seven ultra-massive white dwarfs are extracted from this survey due to the relative faintness of these objects and the magnitude-limited survey strategy. Both ultra-massive white dwarfs hotter than 30 000 K in the PG selection are also part of the EUV selection. However, by applying the $V/V_{\text{max}}$ correction to the number counts they conclude, as previously established in the EUV-selected count, that $\approx 10\%$ of white dwarfs maybe considered ultra-massive. A similar approach and conclusion was reached by Kepler et al. (2007).

We now discuss the ultra-massive white dwarfs from the NLTT survey.

5.1 WD 0457−004: NLTT 14307

Kawka & Vennes (2006) measured a mass of 1.24±0.02 $M_{\odot}$.
With a temperature of 10 800 K, the white dwarf lies outside the ZZ Ceti instability strip but it remains useful in helping define the location of its red edge at high masses.

5.2 WD 1653+256: NLTT 43827

Kawka & Vennes (2006) measured a mass of 1.31 ± 0.01 $M_\odot$. As in the case of NLTT 14307 and with a temperature of 11 690 K, the white dwarf is useful in helping define the location of the red edge of the instability strip at high masses.

5.3 WD 1236−495: NLTT 31372

The star is also known as LTT 4816 and is the most massive ($M = 1.11 \pm 0.02 M_\odot$; Kawka et al. 2007) pulsating DA star and the only known to date ultra-massive member of this class (Gianninas et al. 2005).

5.4 WD 1729+371: NLTT 44986

The star is also known as GD 362 and is a peculiar ultra-massive ($M = 1.26 \pm 0.03 M_\odot$) DAZ white dwarf (Gianninas et al. 2004; Kawka & Vennes 2006). The star is also perceived as harboring a disk of debris (Kilic et al. 2003).

However, Zuckerman et al. (2007) recently obtained a high-dispersion, high signal-to-noise-ratio spectrum of GD 362 that revealed a rich heavy-element line spectrum, and one or possibly two He i lines. The helium abundance consistent with a weak He i λ5876 Å line has considerable effect on the effective temperature and surface gravity measurements. Zuckerman et al. (2007) measured (log He/H = 1.1) along with a temperature $T_{\text{eff}} = 10540$ and log g = 8.24. The mixing of hydrogen in an otherwise weakly detectable helium atmosphere has the effect of weakening the upper Balmer lines and of mimicking the effect of a high gravity. A parallax measurement is required to confirm the normal gravity for this object.

5.5 WD 2159−754: NLTT 52728

The star is also known as LTT 8816 and Kawka et al. (2007) determined a mass of $M = 1.17 \pm 0.04 M_\odot$. This estimate is supported by the peculiar radial velocity $v(\text{WD}) = 153 \pm 2$ km s$^{-1}$ (Maxted & Marsh 1999) that is much larger than normal. To illustrate this point we let the radial velocity of the star vary, while fixing its proper-motion to the observed value, $\mu = 504$ mas yr$^{-1}$ and $\theta = 277.9^\circ$ (Luyten 1976), and compute the corresponding $(U, V, W)$ vector. By minimizing the difference between this vector and the local disk vector of Chiba & Beers (2000) at $(U, V, W)_{\text{disk}} = (0, -35, 0)$ we estimate the most probable radial velocity for the star, $v_{\text{rad}} = 25$ km s$^{-1}$. Therefore, the excess $v(\text{WD}) - v_{\text{rad}} = 128$ km s$^{-1}$ represents the most likely gravitational redshift for the white dwarf. This redshift translates into a mass of 1.17 $M_\odot$. Of course, without a velocity reference point (cluster or binary memberships) it is not possible to confidently determine the gravitational redshift but it is likely to be large.

6 SUMMARY AND CONCLUSIONS

We critically reviewed current evidence for the existence of ultra-massive white dwarfs. First, we demonstrated that the high-mass white dwarfs listed in Silvestri et al. (2001) and presented as evidence for an ultra-massive white dwarf population in CPMB are in fact white dwarfs with normal masses ($\approx 0.6-0.7 M_\odot$), or, in the case of G275-B16A, a low-metallicity F star and possible halo member. The absence of any reliable candidates from this sample is puzzling considering the large number of objects identified using other methods. Improved radial velocity measurements of an enlarged sample of CPMB would help provide accurate gravitational redshifts and deliver the expected number of ultra-massive white dwarfs.

The study of the peculiar DBAZ GD 362 exposes potential difficulties in surface gravity, hence mass measurements based on hydrogen line profiles. Although spectroscopically evanescent at an effective temperature of 10 000 K, helium was found to be the dominant constituent in the atmosphere of that star. Zuckerman et al. (2007) demonstrated that the reduced hydrogen abundance had the consequence of lowering the surface gravity measurement to almost a normal level. Although helium lines are considerably stronger at temperatures in excess of 15 000 K, it is possible that some cooler ultramassive white dwarfs are in fact helium dominated but with a normal mass.

Next, we examined the evidence based on parallax measurements and found that the small number of measurements, and the white dwarf masses inferred from these measurements are in good agreement with the spectroscopic masses. Table 2 lists spectroscopically-identified ultra-massive white dwarfs for which parallax measurements are desirable. Indeed, there remain some questions concerning the validity of our approaches. Hummer & Mihalas (1988) or Inglis & Teller (1993), for Balmer and Lyman line merging at high density and temperature. The effect of perturbers on upper energy levels is essentially calibrated using normal gravity white dwarfs (log g = 8) and this calibration may not apply well at higher gravities potentially causing a systematic shift in mass measurements. However, a case-by-case review of the few spectroscopically identified high-mass white dwarfs with parallax measurements shows good agreement between the two methods. Table 2 lists the absolute visual magnitude and predicted parallax for each star based on parameters provided in the listed references. In addition to the calculated masses that we determined using the mass-radius relations assuming a CO core, we have also calculated mass estimates using mass-radius relations for white dwarfs with an ONe core (Athaus et al. 2005), which may be more appropriate for massive white dwarfs. The mass-radius relations for ONe cores, predict masses that are systematically $\approx 0.02 M_\odot$ lower than those predicted by CO mass-radius relations. For masses larger than 1.3 $M_\odot$, we used the mass-radius relations of Hamada & Salpeter (1961).

We also confirmed the high mass for the hot white dwarf in the binary HR 8210. A high mass was initially implied by the binary mass function (Landsman et al. 1993). We fitted the Lyman line spectrum of the white dwarf and constrained the mass to be $M = 1.08 - 1.24 M_\odot$ in agreement, in the upper mass range, with the binary parameters.

Finally, we show that the EUV-selected population
of white dwarf stars is composed of \( \approx 10\% \) objects with masses in excess of \( 1 M_\odot \). A similar yield was obtained by Liebert et al. (2003) based on the PG survey and by Kepler et al. (2007) based on SDSS after large corrections were applied due to the magnitude-limited nature of the samples collected. In particular, it should be noted that only seven objects out of 347 from the Palomar-Green sample, or a fraction of \( 2\% \), met the criterion. By applying corrections due to incompleteness at fainter magnitudes, the estimated fraction was re-evaluated at \( 10\% \) in agreement with the yield directly measured in the EUV selection.

The origin of ultra-massive white dwarfs remains uncertain. Initial-mass to final-mass relations (Catalán et al. 2008a) indicate that main sequence stars with masses in excess of \( \approx 6 M_\odot \) generate white dwarfs with masses in excess of \( 1 M_\odot \), a situation best illustrated by the massive white dwarf (LB 1497) member of the Pleiades. By re-evaluating available cluster data (Catalán et al. 2008a), revised the final masses upward, and managed to reproduce the high-mass peak in both SDSS and PG empirical mass distributions. It is therefore possible that white dwarfs with masses in excess of \( 1 M_\odot \) are the products of single star evolution and that the binary merger scenario may only apply to a minority of peculiar objects such as the fast rotating magnetic white dwarf WD 0325–857 (see Vennes et al. 2003, and references therein).

The existence of a substantial population of ultra-massive white dwarfs supports the concept of a steeper initial-mass to final-mass relations linking \( 6 M_\odot \) progenitors with \( \gtrsim 1.1 M_\odot \) white dwarfs as proposed by Catalán et al. (2008a). Ultra-massive white dwarfs in close binaries are also likely Type Ia supernova progenitors (Parthasarathy et al. 2007).

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Using the mass-radius relations for a ONe core (Athaus et al. 2005). For masses above 1.2\(M_\odot\), mass-radius relations of Hamada & Salpeter (1961) were used.

Using the mass-radius relations for a CO core (Benvenuto & Athaus 1999). For masses above 1.3\(M_\odot\), mass-radius relations of Hamada & Salpeter (1961) were used.

Based on the model fit of Kawka & Vennes (2006) assuming \(He/H = 0\).

\(1\) Kawka & Vennes (2006); (2) Kawka et al. (2007); (3) Vennes et al. (2008); (4) Vennes et al. (2003).