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On the origin of the ultramassive white dwarf GD50 *

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ABSTRACT

We argue on the basis of astrometric and spectroscopic data that the ultramassive white dwarf GD50 is associated with the star formation event that created the Pleiades and is possibly a former member of this cluster. Its cooling age ($\sim$60Myrs) is consistent with it having evolved essentially as a single star from a progenitor with a mass M$>$6M$_{\odot}$ so we find no need to invoke a white dwarf-white dwarf binary merger scenario to account for its existence. This result may represent the first direct observational evidence that single star evolution can produce white dwarfs with M$>$1.1M$_{\odot}$, as predicted by some stellar evolutionary theories. On the basis of its tangential velocity we also provisionally identify the ultramassive (M$\sim$1.2M$_{\odot}$) white dwarf PG0136+251 as being related to the Pleiades. These findings may help to alleviate the difficulties in reconciling the observed number of hot nearby ultramassive white dwarfs with the smaller number predicted by binary evolution models under the assumption that they are the products of white dwarf mergers.

Key words:
stars: white dwarfs

1 INTRODUCTION

GD50 (WD0346-011) is a well studied nearby hot H-rich white dwarf with a mass of M$>$1.1M$_{\odot}$ (e.g. Giclas, Burnham & Thomas 1965, Bergeron et al. 1991; Table 1). Extrapolation of recent determinations of the initial mass-final mass relation (IFMR; e.g. Dobbie et al. 2006) suggest that if it evolved via single star evolution then its progenitor likely had a mass M$\gtrsim$6M$_{\odot}$. However, it appears to reside well away from any known star forming region, stellar association or young ($\tau\lesssim$200Myrs) open star cluster. This is somewhat surprising as current observational evidence indicates that massive stars are born predominantly within rich stellar associations or star clusters (e.g. Lada & Lada 2003, de Wit et al. 2004).

More generally, the observed number of massive white dwarfs, M$>$0.8M$_{\odot}$, may be too large for them all to have evolved as single stars from OB type progenitors, for reasonable assumptions about the Galactic star formation history and the form of the IFMR. Accordingly, it has been suggested that GD50 and a large proportion of the massive white dwarfs may have formed through binary evolution ($\approx$80%; Liebert et al. 2005a). For example, these objects may be born from the merger of two white dwarfs (either He+CO or CO+CO) each with a mass closer to the canonical value of 0.6M$_{\odot}$ (e.g. Segretain, Chabrier & Mochkovitch 1997, Mochkovitch 1993). The detection in an Extreme Ultraviolet Explorer spectrum of GD50 of what appeared to be rotationally broadened (1000kms^{-1}) absorption lines of photospheric helium lent credance to this hypothesis (Vennes et al. 1996) since it might be expected that these merger products are rapid rotators with unusual atmospheric compositions. However, a more recent and detailed high resolution study of the spectral energy distribution of this star centered on the H-α line failed to corroborate this result and has set an upper limit on the rotational velocity of $v\sin i\lesssim$35kms^{-1} (Vennes 1999). Furthermore, an extreme-ultraviolet spectroscopic survey of a further eight ultramassive white dwarfs failed to reveal compelling evidence for the presence of helium in the atmospheres of any of these objects (Dupuis, Vennes & Chayer 2002). Thus the origin of GD50 and ultramassive white dwarfs in general is still an open question.

In this short communication we argue, based on astrometric and spectroscopic data and our recent re-evaluation of the form of the IFMR, that GD50 is associated with the Pleiades open cluster and is possibly a former member with properties consistent with having evolved essentially as a single star. We briefly discuss the implications of this result for stellar evolution theory.

2 THE HELIOCENTRIC SPACE VELOCITY OF GD50

We have obtained estimates of the proper motion of GD50 from the SuperCOSMOS Sky Survey database

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Table 1. Summary details of GD50 (WD0346$-$011) including coordinates, apparent visual magnitude (Marsh et al. 1997), distance, proper motion, radial velocity and heliocentric space velocity.

RA	Dec	V	d	$\mu_\alpha \cos\delta$	μ_δ	RV	U	V	W
J2000.0			pc	mas yr^{-1}		kms^{-1}		kms^{-1}	
03 48 50.20	-00 58 31.2	14.04±0.02	31.0±1.7	+86.6±6.8	-164.4±5.0	+13.8±12.2	-3.8±9.2	-28.0±2.2	-11.8±7.9

($\mu_\alpha \cos\delta$=+75.1±16.4mas yr^{-1}, μ_δ=$-$155.9±18.1mas yr^{-1}; Hambly et al. 2001), the Lick Northern Proper Motion Program ($\mu_\alpha \cos\delta$=+89.4±5.5mas yr^{-1}, μ_δ=$-$165.6.9±5.5mas yr^{-1}; Klemola et al. 1987) and from our own measurements of the Palomar Sky Sky (E932, 1953/12/31) and UK Schmidt Telescope (9597, 1986/09/22) survey plates ($\mu_\alpha \cos\delta\approx$+86±4mas yr^{-1}, $\mu_\delta\approx-$164±6mas yr^{-1}). These values are consistent with each other within their respective uncertainties: we determine a weighted mean proper motion for GD50 of $\mu_\alpha \cos\delta$=+86.6±6.8mas yr^{-1}, μ_δ=$-$164.4±5.0mas yr^{-1}, where the final uncertainties have been estimated from the scatter of the individual measurements.

From a high S/N UVES spectrum of the white dwarf taken in the course of the SPY programme (Napiwotzki et al. 2003) we have determined the weighted mean redshift of the H-α and H-β line cores to be +176.0±4.3kms^{-1}, in excellent agreement with the earlier measurement of Vennes (1999). Additionally, by determining the weighted means of the robust estimates found in the refereed literature of the last 15 years and new measurements obtained from our independent analysis of the FORS1 spectrum of GD50 detailed in Aznar-Cuadrado et al. (2004) we have estimated the effective temperature and surface gravity of this object to be T$_{\rm eff}$=41550±720K and log g=9.15±0.05, respectively. As listed in Table 2, the errors in the individual determinations of effective temperature and surface gravity have been assumed to be at least 2.3% and 0.07 dex, respectively (e.g. see Napiwotzki et al. 1999), while the scatter of these measurements has been used to estimate the final uncertainties in the mean parameters. The measurements of Barstow et al. (1993) were rejected from the calculation as they were found to lie $>3\sigma$ in both effective temperature and surface gravity from an initial estimate of the means.

Using CO core, thick (thin) H-layer, white dwarf evolutionary models (e.g. Fontaine, Brassard & Bergeron 2001) we infer the mass, the radius and the cooling time of GD50 to be 1.264±0.017 (1.253±0.018)M$_\odot$, 0.00495±0.00034 (0.00493±0.00034)R$_\odot$ and 61±6 (58±6)Myrs, respectively. We note that the specific choice of core composition, CO or ONe, is believed to make little difference these values (e.g. van Kerkwijk & Kulkarni 1999, Hamada & Salpeter 1961). We determine the gravitational contribution to the line core redshift to be +162.2±11.4 (+161.4±11.4)kms^{-1}. Thus we estimate the radial velocity of GD50 to be +13.8±12.2 (+14.6±12.2)kms^{-1}. Based on a modern grid of white dwarf synthetic photometry (Holberg & Bergeron 2006; Bergeron et al. 1995), the above effective temperature and surface gravity estimates and the V magnitude from Marsh et al. (1997) we determine the distance of GD50 to be 31.0±1.7 (30.9±1.7)pc. Following the prescription given by Johnson & Soderblom (1987) we calculate the heliocentric space velocity of GD50 to be U=$-$3.8±9.2 ($-$4.4±9.2)kms^{-1}, V=$-$28.0±2.2 ($-$28.1±2.2)kms^{-1} and W=$-$11.8±7.9 ($-$12.3±7.9)kms^{-1} (see Table 1).

The recent kinematical study performed by Pauli et al. (2006) of 398 field white dwarfs drawn from the catalogue of McCook & Sion (2000) reveals that $\sim$75% have V>-25kms^{-1}. Additionally, the error bounds on the U,V and W velocity components of only 3 of these stars overlap with the range defined by the above values and their associated uncertainties (assuming a solar velocity with respect to the local standard of rest of U=10.00kms^{-1}, V=5.25kms^{-1} and W=7.17kms^{-1}; Dehnen & Binney 1998). Thus we conclude that GD50 lies in a region of velocity space which is not heavily populated by white dwarfs. However, we note that the space velocity of this object is strikingly close to that of Pleiades open star cluster and also the AB Dor moving group (Zuckermann et al. 2004). The Pleiades is the closest rich young ($\tau\approx$125Myrs) open cluster to GD50. We determine its space motion to be U=$-$6.5±0.5kms^{-1}, V=$-$27.8±1.1kms^{-1} and W=$-$14.6±0.5kms^{-1}, for a distance of 134±5pc (the weighted mean of recent ground based estimates e.g. Percival et al. 2005, Southworth et al. 2005, Pan et al. 2004, Munari et al. 2004, Zwahlen et al. 2004, Gatewood et al. 2000), a radial velocity of +5.7±0.5kms^{-1} and a proper motion of $\mu_\alpha \cos\delta$=+19.15.1±0.23mas yr^{-1},μ_δ=-45.72±0.18mas yr $^{-1}$ (Robichon et al. 1999). Luhman et al. (2005) estimate the space motion of the AB Dor moving group, within which the Sun resides, to be U=$-$7.7±0.4kms^{-1}, V=$-$26.0±0.4kms $^{-1}$ and W=$-$13.6±0.3kms^{-1}.

3 DISCUSSION

3.1 The Local Association

The Pleiades and the AB Dor moving group are part of the Local Association, a large scale “supercluster” structure consisting of a gravitationally unbound collection of open clusters, stellar associations and moving groups with comparable space motions (e.g. Sco-Cen, IC2602, Per OB3, Cas-Tau and NGC2516; Eggen 1992). While this could be taken as evidence of a common ancestry (e.g. Weidemann et al. 1992), the age of the members of this supercluster is estimated to span the relatively broad range of $\sim$few Myrs to $\sim$few 100Myrs (e.g. Eggen 1992, Asiain et al. 1999). Chereul et al. (1998) argue that the Local Association may just be the result of the chance superposition in phase space of several smaller stellar streams, each associated with a star formation event which if sufficiently massive manufactured a gravitationally bound star cluster. Indeed, Hipparcos observations of open clusters within the Local Association reveal that at a level of <10kms^{-1} their space velocities are quite distinct e.g. Pleiades, U=$-$6.5±0.5kms^{-1}, V=$-$27.8±1.1kms^{-1} and W=$-$14.6±0.5kms^{-1}, Per OB3 (α-Per), U=$-$15.3±0.7kms^{-1}, V=$-$25.8±1.0kms^{-1}, W=$-$7.9±0.4kms^{-1}) and NGC2516, U=$-$17.4±1.4kms^{-1}, V=$-$23.7±0.4kms^{-1}, W=$-$3.9±0.4kms^{-1} (Robichon et al. 1999).

Other recent extensive analyses of the velocity and age distributions of stars in the solar neighbourhood confirm the existence of this significant substructure within the Local Association. For example, based on a study of nearby early-type stars, Asiain et al. (1999) resolve the supercluster into 4 distinct components in

Table 2. Temperature and gravity determinations of GD50 in the refereed literature of the last 15 years used in deriving the means. The values of Barstow et al. (1993) were excluded from the calculation as they lie $>3\sigma$ from an initial estimate of the means. We assume a minimum uncertainty in all temperature and gravity determinations of 2.3% and 0.07dex, respectively.

$T_{\rm eff}$(K)	log g	Reference
40538±932	9.22±0.08	1
38088±876	8.87±0.07	2
43102±1982	9.09±0.09	3
43200±994	9.21±0.07	4
39508±908	9.07±0.07	5
43170±993	9.08±0.07	6
41480±954	9.19±0.07	7
<41550±720>	<9.15±0.05>	

(1) Bergeron et al. (1991), (2) Barstow et al. (1993), (3) Bragaglia et al. (1995), (4) Vennes et al. (1997), (5) Napiwotzki et al. (1999), (6) Aznar-Cuadrado et al. (2004) and (7) This work

U,V,τ space, each with a lower velocity dispersion and a more restricted age range than the Local Association as a whole. Moving group B1, with U=-4.5 ± 4.7kms^{-1}, V=-20.1 ± 3.3kms^{-1} and W=-5.5 ± 1.9kms^{-1}, consists of a very young population (20±10Myrs) and is attributable to the Scorpio-Centaurus OB association, while moving group B4, with U=-8.7 ± 4.8kms^{-1}, V=-26.4 ± 3.3kms^{-1} and W=-8.5 ± 4.7kms^{-1}, is substantially older (150±50Myrs). Given the similarities between the space velocities and ages of this moving group and the Pleiades open cluster, it is likely the two are related (Asiain et al. 1999).

Luhman et al. (2005) and Luhman & Potter (2006) have recently shown that the stellar sequences of the AB Dor moving group (including AB Dor Ba and Bb) and the Pleiades open cluster are coincident in M_K,V$-$K and M_K,J$-$K colour-magnitude diagrams. Thus not only do the AB Dor moving group members and the Pleiades have very similar space velocities, there is compelling evidence that the former also have an age in the range 100-125Myrs. It is argued by these authors that the AB Dor moving group is thus likely to be the remnants of an OB and T association related to the formation and evolution of the Pleiades open cluster, a more mature version of the relationship which exists today between the Per OB3 open cluster and the Cassiopeia-Taurus Association (de Zeeuw et al. 1999). In this framework, presumably the bulk of the B4 moving group is also part of this unbound remnant.

3.2 GD50 and the Pleiades star formation event

We find, in the context of the substantial velocity substructure of the Local Association, the kinematics of GD50 are most closely matched to those of the B4 moving group/Pleiades open cluster stream. To further examine the possibility that GD50 is related to this particular episode of star birth we have examined it's location in initial mass-final mass space under the assumption that it is coeval with the Pleiades (125±25Myrs; Ferrario et al. 2005). Noting that the determination of initial mass is extremely sensitive to the adopted age of the progenitor population (see Dobbie et al. 2006 for details), the proximity of GD50 to an extrapolation of the linear fit to the initial mass-final mass data for 27 white dwarfs in open clusters and the Sirius binary system (Dobbie et al. 2006, Liebert et al. 2005b, Williams, Bolte & Koester 2005, Claver et al. 2001, Koester & Reimers 1996), indicates that it's cooling age is entirely consistent with it being associated with this star formation event and having evolved essentially as a single star (see Figure 1).

To get further insights we calculated the Galactic orbits of GD50 and the Pleiades back in time. We used the code ORBIT6 of Odenkirchen & Brosche (1992) for our calculations. ORBIT6 computes the trajectory of a star in the Galactic potential for a given set of initial coordinates and space velocities. Please refer to Pauli et al. (2003) for further details. For every time step we calculated the distance between the orbits of GD50 and the Pleiades. Errors in the estimated distance and space velocities were propagated by means of a Monte Carlo simulation. The results of this modelling are consistent with GD50 having formed within the Pleiades and having been subsequently ejected. Indeed, the escape velocity from the center of the present day cluster is only ~2kms^{-1} (Dehnen, priv. comm) and while the Pleiades is relatively young and one white dwarf member has already been firmly identified (LB1497; Luyten & Herbig 1960), it is estimated, based around an extrapolation of the present day mass function, that a small number of other massive members could by now have evolved to this configuration (e.g. Williams 2004). As dynamical evolution would have likely led the relatively massive progenitor of this white dwarf to settle towards the most densely populated central regions of the cluster, it might be that, after formation, GD50 gained sufficient kinetic energy through an interaction with another star or a binary system to allow it to escape the Pleiades. Alternatively, some massive white dwarfs may receive a small recoil velocity kick during the final stages of their (super)-AGB evolution due to low level point-asymmetries in the outflowing material (e.g. Fellhauer et al. 2003). We note that GD50 need only have been moving at a mean velocity, post ejection, of ~2kms^{-1} with respect to the cluster for ~55Myrs for the two to be separated by >100pc as observed today.

A further possibility, which is less favoured but not ruled out by our Galactic orbit modelling, is that GD50 or more particularly it's progenitor star, may have originated in an unbound OB association related to formation of the Pleiades open cluster. While the AB Dor moving group has only ~30 known members with spectral types from F5-M6 (Zuckermann et al. 2004, Luhman & Potter 2006), the B4 moving group is known to contain at least ~50 objects of spectral types A and B (Asiain et al. 1999). Furthermore, detailed simulations of the early evolution of a rich stellar aggregate like the nascent Pleiades, suggest that when the ignition of the OB stars drives away the mass dominating primordial gas, as many as 2/3 of the initial constituents may become part of an unbound and expanding association. Over a period comparable to the age of the B4 stream this structure can disperse over scales well in excess of 100pc (Kroupa, Aarseth & Hurley 2001).

3.3 Stellar evolution

Although the available data do not allow us to pin down the details of the history of GD50, as a whole, the evidence presented here provides a relatively compelling argument that it is associated with the star formation event that created the Pleiades. Clearly there is no need to invoke a binary white dwarf merger scenario to account for its evolution, if as supported by its location in Figure 1, it has evolved essentially as a single star. Liebert et al. (2005a) have recently noted the apparent projected spatial coincidence between many of the hot massive white dwarfs detected in the ROSAT WFC and EUVE surveys and Gould's Belt, a rich band of OB stars tilted at 18° with respect to the Galactic Plane which represents a ring of nearby recent star formation. This has led them to suggest that

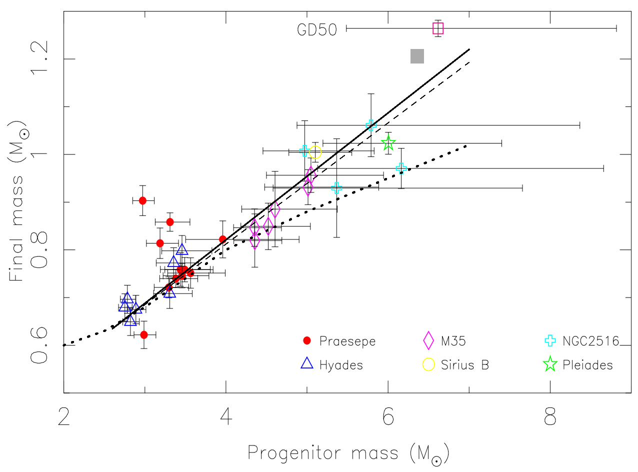

Figure 1. The white dwarf members of the Hyades, Praesepe, M35, NGC2516 and Pleiades open clusters and the Sirius binary system in initial mass-final mass space (see text for references). A linear fit to the data derived by Dobbie et al. (2006) and the relation of Weidemann (2000; dotted line) are overplotted as solid and dotted lines, respectively. The location of GD50, derived assuming it to be coeval with the Pleiades, is consistent with it having evolved essentially as a single star (open square). The approximate location of PG0135+251 is also shown (filled square).

significantly more than 20% of these objects may be the progeny of single stars. Furthermore, based on their recent determination of the form of the IFMR, Ferrario et al. (2005) predict that ∼28% of objects in the white dwarf mass distribution have M$\gtrsim$0.8M$_\odot$.

Indeed, the formation of ultramassive white dwarfs from single stars is predicted by the stellar evolutionary modelling of a number of research groups. For example, Garcia-Berro et al. (1997) show that once the helium exhausted cores of some stars exceed ∼1.1M$_\odot$, a series of carbon-burning shell flashes can lead to a super-AGB phase of evolution and ultimately to the formation of degenerate ONeMg cores with masses in the range ∼1.1-1.4M$_\odot$. Alternatively, if a star has significant rotational angular momentum, then the pressure lifting effect of this can allow the CO core, which will ultimately become the white dwarf, to grow to M>1.1M$_\odot$ (e.g. Dominguez et al. 1997). We believe the present result represents the first compelling observational evidence directly linking ultramassive white dwarfs and single star evolution.

We also note that PG0136+251, with T$_{\rm eff}$=39640K, log g=8.99 and M=1.20$_\odot$ (Liebert et al. 2005a), has, as listed in the USNO-B1.0 catalogue, a proper motion of $\mu_\alpha \cos\delta$=+52±2mas yr^{-1}, μ_δ=−46±1mas yr^{-1} and is thus moving on a bearing which points within 10° of the convergent point of the Pleiades (e.g. Makarov & Robichon 2001). Additionally, the distance calculated using the moving clusters method (Equation 1), which assumes the white dwarf to be affiliated kinematically to this cluster,

$$d_{\rm mc} = v\sin\lambda/4.74\mu \approx 97{\rm pc} \qquad (1)$$

where v is the space velocity of the Pleiades (∼32kms^{-1}; Luhman et al. 2005), λ the angular separation between the white dwarf and the convergent point (∼95°) and μ the tangential motion (∼0.07arcsec yr^{-1}), is remarkably close to the spectrophotometrically derived value of ≈93pc. The mass and the cooling time of this white dwarf can also be considered consistent with it having evolved essentially as a single star born at about the same time as the Pleiades open cluster (see Figure 1). A firm conclusion regarding the origins of PG0136+251 must, however, await a radial velocity measurement for this object.

Both GD50 and PG0136+251 are sometimes touted as possible examples of white dwarf binary mergers (e.g. Bergeron et al. 1991, Mochkovitch 1993, Segretain, Chabrier & Mochkovitch 1997). However, the observed number of nearby hot ultramassive white dwarfs is difficult to reconcile with the population predicted by binary evolution models which adopt a plausible Galactic white dwarf merger rate (10^{-2}–10^{-3} yr $^{-1}$), under the assumption that these objects are the products of coalesced double degenerate systems. For example, for a Galactic merger rate of 10^{-2}yr^{-1} and a cooling time scale of the order 20Myrs, Segretain, Chabrier & Mochkovitch (1997) estimate that the average distance to the closest hot ultramassive white dwarf merger product is ∼70pc. The probability of there being 3 within 40pc (e.g. GD50, PG1658+441; Green, Schmidt & Liebert 1986, and RE0317-854; Barstow et al. 1995) is a mere ∼0.1%. However, this difficulty must be alleviated to some extent if a significant proportion of these hot ultramassive white dwarfs have instead formed via single star evolution (Segretain, Chabrier & Mochkovitch 1997).

A detailed study of the heliocentric space velocities of a large sample of hot young massive white dwarfs is clearly warranted. This would address additional questions regarding the end points of the evolution of intermediate mass stars, Type Ia supernovae progenitors and more generally the recent history of the local star formation rate.

4 SUMMARY

We have argued using astrometric and spectroscopic data that the ultramassive white dwarf GD50 is likely related to the star formation event that created the Pleiades open cluster and has properties consistent with having evolved essentially as a single star. We believe this to be the first compelling observation evidence directly linking ultramassive white dwarfs and single star evolution. This result can help to reconcile the observed population of nearby hot ultramassive white dwarfs with the number predicted by binary evolution models, under the assumption that these objects are the products of coalesced double degenerate systems.

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