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 (~60Myrs) is consistent with it having evolved essentially as a single star from a progenitor with a mass M>1.1M⊙ 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⊙, as predicted by some stellar evolutionary theories. On the basis of its tangential velocity we also provisionally identify the ultramassive (M~1.2M⊙) 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⊙ (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≥6M⊙. However, it appears to reside well away from any known star forming region, stellar association or young (τ<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⊙, 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 (~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⊙ (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 (1000km s⁻¹) absorption lines of photospheric helium lends credence 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≤35km s⁻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

* Based on observations collected at the European Southern Observatory, Chile. ESO No. 072.D-0362
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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 pc | $\mu_\alpha \cos \delta$ mas yr$^{-1}$ | $\mu_\delta$ mas yr$^{-1}$ | RV kms$^{-1}$ | U   | V   | W   |
|------|------|---------|------|---------------------------------|-----------------|--------------|-----|-----|-----|
| 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 |

($\mu_\alpha \cos \delta=+75.1±16.4$ mas yr$^{-1}$, $\mu_\delta=-155.9±18.1$ mas yr$^{-1}$, Hambly et al. 2001), the Lick Northern Proper Motion Program ($\mu_\alpha \cos \delta=+89.4±5.5$ mas yr$^{-1}$, $\mu_\delta=-165.6±9.5$ mas yr$^{-1}$, Klemola et al. 1987) and from our own measurements of the Palomar Sky Survey (E932, 1953/12/31) and UK Schmidt Telescope (1997, 86/09/22) survey plates ($\mu_\alpha \cos \delta=+86.4±4.6$ mas yr$^{-1}$, $\mu_\delta=-164.6±6.9$ mas yr$^{-1}$). These values are consistent with each other within their respective uncertainties: we determine a weighted mean proper motion for GD50 of $\mu_\alpha \cos \delta=+86.6±6.8$ mas yr$^{-1}$, $\mu_\delta=-164.4±5.0$ mas 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-$\alpha$ and H-$\beta$ line cores to be $+176.0±17.6$ km s$^{-1}$. These values are consistent with each other with their respective uncertainties: we determine a solar velocity with respect to the local standard of rest of $V=+10.0±1.0$ km s$^{-1}$ (Robichon et al. 1999). Luhman et al. (2005) estimate the space motion of GD50 to be $U=+6.5±0.5$ km s$^{-1}$, $V=+27.8±1.1$ km s$^{-1}$ and $W=+14.6±0.5$ km s$^{-1}$, for a distance of 134±5 pc (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, Gatewood et al. 2000), a radial velocity of $+5.7±0.5$ km s$^{-1}$ and a proper motion of $\mu_\alpha \cos \delta=+19.5±1.0$ mas yr$^{-1}$, $\mu_\delta=+45.7±0.1$ mas 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 $U=-7.7±0.4$ km s$^{-1}$, $V=-26.0±0.4$ km s$^{-1}$ and $W=-13.6±0.3$ km s$^{-1}$.

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 ~few Myrs to ~few 100 Myrs (e.g. Eggen 1992, Asai 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, Hipparchos observations of open clusters within the Local Association reveal that at a level of <10 km s$^{-1}$ their space velocities are quite distinct e.g. Pleiades, $U=-6.5±0.5$ km s$^{-1}$, $V=-27.8±1.1$ km s$^{-1}$ and $W=-14.6±0.5$ km s$^{-1}$, Per OB3 ($\alpha$-Per), $U=-15.3±0.7$ km s$^{-1}$, $V=-25.8±1.0$ km s$^{-1}$, $W=-7.9±0.4$ km s$^{-1}$) and NGC2516, $U=-17.4±1.4$ km s$^{-1}$, $V=-23.7±0.4$ km s$^{-1}$, $W=-3.9±0.4$ km s$^{-1}$ (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, Asai 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 >3σ 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.

| $T_{\text{eff}}$ (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 $U=−4.5±4.7\text{km s}^{-1}$, $V=−20.1±3.3\text{km s}^{-1}$ and $W=−5.5±1.9\text{km s}^{-1}$, consists of a very young population ($20±10\text{Myrs}$) and is attributable to the Scorpio-Centaurus OB association, while moving group B4, with $U=−8.7±4.8\text{km s}^{-1}$, $V=−26.4±3.3\text{km s}^{-1}$ and $W=−8.5±4.7\text{km s}^{-1}$, is substantially older ($150±50\text{Myrs}$). 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 $\sim2\text{km s}^{-1}$ (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 $\sim2\text{km s}^{-1}$ with respect to the cluster for $\sim55\text{Myrs}$ for the two to be separated by $>100\text{pc}$ 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 its 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 $\sim30$ 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 $\sim50$ 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...
show that once the helium exhausted cores of some stars exceed
merger rate (10^{-2}–10^{-3} yr^{-1}), under the assumption that
these objects are the products of coalesced double degenerate sys-
tems. For example, for a Galactic merger rate of 10^{-2} yr^{-1}
and a cooling time scale of the order 20 Myrs, Segretain, Chabrier
& Mochkovitch (1997) estimate that the average distance to the closest
hot ultramassive white dwarf merger product is ~70 pc. The
probability of there being 3 within 40 pc (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 (Segre-
tain, 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 for-
mation event that created the Pleiades open cluster and has prop-
ties consistent with having evolved essentially as a single star.
We believe this to be the first compelling observation evidence di-
rectly 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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