The Origins of the Ultramassive White Dwarf GD 50

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Abstract. On the basis of astrometric and spectroscopic data we argue that the ultramassive white dwarf GD 50 is associated with the star formation event that created the Pleiades and is potentially a former cluster member. Its cooling time ($\sim$60Myrs) is consistent with it having evolved essentially as a single star from a $M > 6M_{\odot}$ progenitor so there appears to be no need to invoke a white dwarf–white dwarf binary merger scenario to account for its existence. Our 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. Additionally, our findings may help towards alleviating 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.

1.   Massive White Dwarfs

The well studied nearby hot H-rich white dwarf GD 50 has a mass of $M > 1.1M_{\odot}$ (Bergeron et al. 1991). If it evolved via single star evolution then given our current understanding of stellar evolution, its progenitor likely had a mass $M \geq 6M_{\odot}$ (e.g. see Dobbie et al. 2006a). Somewhat surprisingly, however, it is not a member of any known stellar association or young ($\tau \leq$200Myrs) open star cluster, where most massive stars are born (e.g. de Wit et al. 2004). In a broader sense, the observed number of massive white dwarfs, $M > 0.8M_{\odot}$, seems to 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 initial mass–final mass relation (IFMR). Accordingly, it has been suggested that a large proportion ($\approx$80%; Liebert, Bergeron, & Holberg 2005) of these objects may have formed via the merging 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).

    Degenerates which have evolved through this latter channel might be expected to rotate rapidly and possess unusual atmospheric compositions. Thus the alleged detection of the rotationally broadened ($v \sin i \sim 1000$km s^{-1}) absorption lines of photospheric helium in the extreme ultraviolet spectral energy distribution of GD 50 was of great interest (Vennes et al. 1996). However, it was subsequently shown, via a detailed study of the H-α line core, that GD 50 is

probably not a rapid rotator ($v \sin i \leq 35 \mathrm{km\,s}^{-1}$; Vennes 1999) and that there is no compelling evidence for the presence of helium in the photospheres of ultramassive white dwarfs in general (Dupuis, Vennes, & Chayer 2002). Hence the origins of GD 50 and other ultramassive white dwarfs is still an open question.

Here, we use astrometric and spectroscopic data and our recent re-evaluation of the form of the IFMR, to argue that GD 50 is associated with Pleiades open cluster and is possibly a former member with properties consistent with having evolved essentially as a single star.

2.   The Space Velocity of GD 50

We have used the SuperCOSMOS Sky Survey (Hambly et al. 2001), the Lick Northern Proper Motion Program (Klemola et al. 1987) and our own measurements to determine the proper motion of GD 50 to be $\mu_\alpha \cos \delta = +86.6 \pm 6.8 \mathrm{mas\,yr}^{-1}$, $\mu_\delta = -164.4 \pm 5.0 \mathrm{mas\,yr}^{-1}$. Analysis of a high S/N UVES spectrum of the white dwarf taken in the course of the SPY programme (Napiwotzki et al. 2003) reveals the weighted mean redshift of the H-α and H-β line cores to be $+176.0 \pm 4.3 \mathrm{km\,s}^{-1}$. Applying our refined estimate of the effective temperature and surface gravity of GD 50 ($T_{\mathrm{eff}} = 41550 \pm 720 \mathrm{K}$ and $\log g = 9.15 \pm 0.05$) and the CO core white dwarf evolutionary models of Fontaine, Brassard, & Bergeron (2001) we determine the mass, the radius and the cooling time of this object to be $1.264 \pm 0.017 M_\odot$, $0.00495 \pm 0.00034 R_\odot$ and $61 \pm 6 \mathrm{Myrs}$, respectively. Thus we estimate the radial velocity of GD 50 to be $+13.8 \pm 12.2 \mathrm{km\,s}^{-1}$. We derive the distance of the white dwarf to be $31.0 \pm 1.7 \mathrm{pc}$ based on the V magnitude from Marsh et al. (1997) and the white dwarf synthetic photometry of Holberg & Bergeron (2006). Finally, following the prescription of Johnson & Soderblom (1987), we calculate the heliocentric space velocity of GD 50 to be $U = -3.8 \pm 9.2 \mathrm{km\,s}^{-1}$, $V = -28.0 \pm 2.2 \mathrm{km\,s}^{-1}$ and $W = -11.8 \pm 7.9 \mathrm{km\,s}^{-1}$. We note that this 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 ($\tau \approx 125 \mathrm{Myrs}$) open cluster to GD 50. We determine its space motion to be $U = -6.5 \pm 0.5 \mathrm{km\,s}^{-1}$, $V = -27.8 \pm 1.1 \mathrm{km\,s}^{-1}$ and $W = -14.6 \pm 0.5 \mathrm{km\,s}^{-1}$.

3.   The Pleiades Supercluster

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, IC 2602, Per OB3, Cas–Tau and NGC 2516; Eggen 1992). Hipparcos observations of the Pleiades supercluster reveal that at a level of $<10 \mathrm{km\,s}^{-1}$ the space velocities of the component open clusters are quite distinct e.g. Pleiades, $U = -6.5 \pm 0.5 \mathrm{km\,s}^{-1}$, $V = -27.8 \pm 1.1 \mathrm{km\,s}^{-1}$ and $W = -14.6 \pm 0.5 \mathrm{km\,s}^{-1}$, Per OB3 ($\alpha$-Per), $U = -15.3 \pm 0.7 \mathrm{km\,s}^{-1}$, $V = -25.8 \pm 1.0 \mathrm{km\,s}^{-1}$, $W = -7.9 \pm 0.4 \mathrm{km\,s}^{-1}$; Robichon et al. 1999). This is consistent with the findings of other recent extensive analyses of the velocity and age distributions of stars in the solar neighbourhood, e.g. Asiain et al. (1999). These authors resolve the Local Association into 4 distinct components in U,V,τ space. Moving group B4, with $U = -8.7 \pm 4.8 \mathrm{km\,s}^{-1}$, $V = -26.4 \pm 3.3 \mathrm{km\,s}^{-1}$
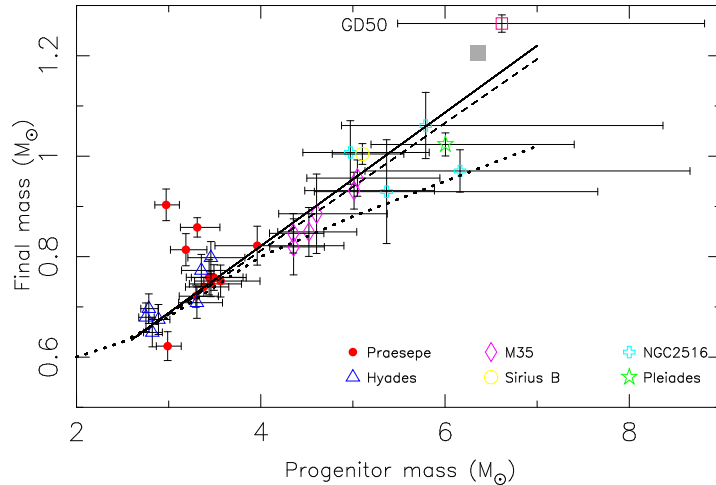
Figure 1.   Location of GD 50 in initial mass–final mass space, under assumption that it is coeval with the Pleiades open cluster. See Dobbie et al. (2006b) for full details and references relating to data points.

and $W = -8.5 \pm 4.7 \mathrm{km\,s}^{-1}$, is substantially older (150 ± 50Myrs) than the other components. 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).

4.   GD 50 and the Pleiades

Since the kinematics of GD 50 are a close match to those of the B4 moving group/Pleiades open cluster stream, 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; see Figure 1). Of immediate note is its proximity to an extrapolation of the linear fit to the data for 27 white dwarfs in open clusters and the Sirius binary system (see Dobbie et al. 2006a for full references), indicating that GD 50's cooling age is entirely compatible with it being associated with this star formation event and having evolved essentially as a single star. The results of our Galactic orbit modelling, undertaken with the ORBIT6 code of Odenkirchen & Brosche (1992), are consistent with GD 50 having formed within the Pleiades and having been subsequently ejected. Since dynamical evolution would have likely led the relatively massive progenitor of this degenerate to settle towards the most densely populated central regions of the cluster, it might be that after formation, GD 50 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 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). It is worth noting that the escape velocity from the centre of the present day cluster is only $\sim$2km s^{-1} (Dehnen, priv. comm) and GD 50 need only have been moving at a mean velocity, post ejection, of $\sim$2km s^{-1} with

respect to the cluster for ∼55Myrs for the two to be separated by >100pc as observed today. A further possibility, which is also compatible with our Galactic orbit modelling, is that the progenitor star of GD 50 may have originated in an unbound OB association related to formation of the Pleiades open cluster. 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).

5.   Implications

The evidence presented here provides a relatively compelling argument that GD 50 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. 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 $\sim 1.1 M_\odot$, 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 $\sim 1.1 - 1.4 M_\odot$. The present result, we believe, represents the first compelling observational evidence directly linking ultramassive white dwarfs and single star evolution.

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 three within 40pc (e.g. GD 50, PG 1658+441; Green, Schmidt, & Liebert 1986, and RE J0317−854; Barstow et al. 1995) is a mere ∼0.1%. However, this difficulty must be alleviated to some extent if a proportion of these hot ultramassive white dwarfs have instead formed via single star evolution (Segretain, Chabrier, & Mochkovitch 1997).

6.   Summary

We have argued that the ultramassive white dwarf GD 50 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 is the first compelling observation evidence directly linking ultramassive white dwarfs and single star evolution. This result can help towards reconciling the observed population of nearby hot ultramassive white dwarfs with the number predicted by binary evolution models, under the assumption that the merging of double

degenerate systems manufactures such objects. More comprehensive details of this work may be found in Dobbie et al. (2006b)

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