

# Does GD 356 have a terrestrial planetary companion?

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## ABSTRACT

GD 356 is unique among magnetic white dwarfs because it shows Zeeman-split Balmer lines in pure emission. The lines originate from a region of nearly uniform field strength ( $\delta B/B \approx 0.1$ ) that covers 10 per cent of the stellar surface in which there is a temperature inversion. The energy source that heats the photosphere remains a mystery but it is likely to be associated with the presence of a companion. Based on current models, we use archival *Spitzer* Infrared Array Camera (IRAC) observations to place a new and stringent upper limit of  $12 M_J$  for the mass of such a companion. In the light of this result and the recent discovery of a 115-min photometric period for GD 356, we exclude previous models that invoke accretion and revisit the unipolar inductor model that has been proposed for this system. In this model, a highly conducting planet with a metallic core orbits the magnetic white dwarf and, as it cuts through field lines, a current is set flowing between the two bodies. This current dissipates in the photosphere of the white dwarf and causes a temperature inversion. Such a planet is unlikely to have survived both the red and asymptotic giant branch phases of evolution so we argue that it may have formed from the circumstellar disc of a disrupted He or CO core during a rare merger of two white dwarfs. GD 356 would then be a white dwarf counterpart of the millisecond binary pulsar PSR 1257+12 which is known to host a planetary system.

**Key words:** planetary systems – white dwarfs.

## 1 INTRODUCTION

GD 356 was first noted to be peculiar among magnetic white dwarfs through the discovery of strong Zeeman split Balmer lines in pure emission (Greenstein & McCarthy 1985). The number of known magnetic white dwarfs has since increased to some 220 through surveys such as Sloan Digital Sky Survey (SDSS), but GD 356 remains unique in exhibiting these properties.

A detailed study of the atmosphere of GD 356 by Ferrario et al. (1997) established that the line and continuum spectra can be modelled with a white dwarf with an effective temperature  $T_{\text{eff}} = 7500$  K and an assumed gravity  $\log_{10}(g/\text{cm s}^{-2}) = 8$  with a centred dipole field structure and polar field strength  $B_p = 13$  MG. The emission lines arise from a ring like spherical sector or strip around the magnetic pole covering 10 per cent of the stellar surface. The lines are a result of a temperature inversion that begins deep within the photosphere at optical depths of 1.0. The remainder of the photosphere produces absorption lines broadened by the underlying dipolar field.

These lines are masked by the emission lines in the flux spectra, but are discernible in the polarization spectra. Barring the possibility of a rapid rotator, the observed lack of variability of the spectrum over periods of several hours to days must indicate that the spin and dipole axes are nearly aligned. Likewise, the absence of reports of significant changes in the occasional spectra taken over a 25-yr period (G. Schmidt and J. Liebert, private communication) suggests that the photospheric region that gives rise to the emission lines has a stable structure on this time-scale.

The fields of the high field magnetic white dwarfs of  $1 < B/\text{MG} < 1000$ , such as GD 356 are generally believed to be of fossilized origin rather than dynamo generated (Wickramasinghe & Ferrario 2000). They are most likely generated in a common envelope that left a very close binary or merged core (Tout et al. 2008). In this case, all single white dwarfs with high-magnetic fields have evolved from binary stars that merged during common envelope evolution or shortly afterwards. Though very uncertain, estimates of their number densities indicate that about three times as many systems that enter a common envelope phase of evolution end up merging as form cataclysmic variables. The long ohmic decay time-scales, 8–12 Gyr (Cumming 2002), of the dipolar component in magnetic

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white dwarfs and the lack of observational evidence for differences in the mean dipolar field strength along the white dwarf cooling sequence support this hypothesis. Cool white dwarfs develop convective envelopes that could potentially lead to generation of magnetic fields by a contemporary dynamo, but there is no evidence for an increase in the incidence of magnetism among the cooler and more convective stars in the well-studied high-field group of white dwarfs. It is of course possible that all cool white dwarfs with outer convective envelopes have dynamo generated fields that are below the current observational limit of detectability from Zeeman polarimetry of  $B \approx 10^3$  G (Jordan et al. 2007). However, attempts to detect X-ray emission from coronae that may be generated through magnetic activity in such stars have so far led to upper limits that are well below theoretical predictions (Musielak et al. 2003).

Since these early investigations there have been some new observations of this star. Brinkworth et al. (2004) reported the detection of low amplitude ( $\pm 0.2$  per cent) near sinusoidal variability in the  $V$  band with a period of 115 min. They attribute this to the rotation period of the star. They presented a model in which a dark spot covers 10 per cent of the stellar surface and is viewed nearly face on or edge on as the star rotates. They speculated that the temperature inversion required to explain the spectroscopic data must occur in this region. While the cause of the observed photometric variability may well be related to a temperature differential between the line emission region and the remainder of the star, the idea of a dark magnetic spot presumably with an enhanced field caused by magnetic activity as in the Sun and stable over some 25 yr is less attractive. The modelling shows no evidence for an enhanced field strength in the emission line region. Rather it is simply a specially heated region of the star with an otherwise approximately dipolar field structure. It is thus more likely that GD 356 has a fossil field like other white dwarfs of similar field strength.

The source of energy that powers the emission line region in GD 356 remains a mystery. The observed luminosity in the Balmer lines is  $2 \times 10^{27}$  erg s $^{-1}$ , much larger than the stringent upper limit of  $6 \times 10^{25}$  erg s $^{-1}$  that has recently been placed on the X-ray luminosity of GD 356. So the source of heating is not an X-ray corona (Weisskopf et al. 2007). Given the implausibility of a single star interpretation, the most likely possibility is that the energy is extracted in some way from a companion. The lack of evidence for an accretion disc in the line spectrum or of emission from accretion shocks appears to preclude intermediate polar type and AM Her type models.

One of the more intriguing models that has been proposed for GD 356 assumes that it has a companion of planetary mass with a conducting composition in a close orbit (Li, Ferrario & Wickramasinghe 1998). Such a planet would act as a unipolar inductor generating an electrical current that flows between the two stars analogous to the model proposed for the Jupiter-Io system (Goldreich & Lynden-Bell 1969). Ohmic dissipation in the atmosphere of the white dwarf leads to a temperature inversion in a ring surrounding the magnetic pole as the planet orbits the white dwarf. This model, as it presently stands, hinges rather heavily on the possibility of the survival of such a planet through the RGB and AGB phases of evolution.

In this paper, we present an analysis of archival *Spitzer*/IRAC observations of GD 356 that rule out a companion of mass as greater than  $12 M_J$ , according to substellar cooling models. We then discuss possible accretion models and the unipolar inductor model in the light of the new mass limits and the recently discovered photometric period for this star. We argue that the ensemble of presently available observations is inconsistent with accretion from a gaseous planetary

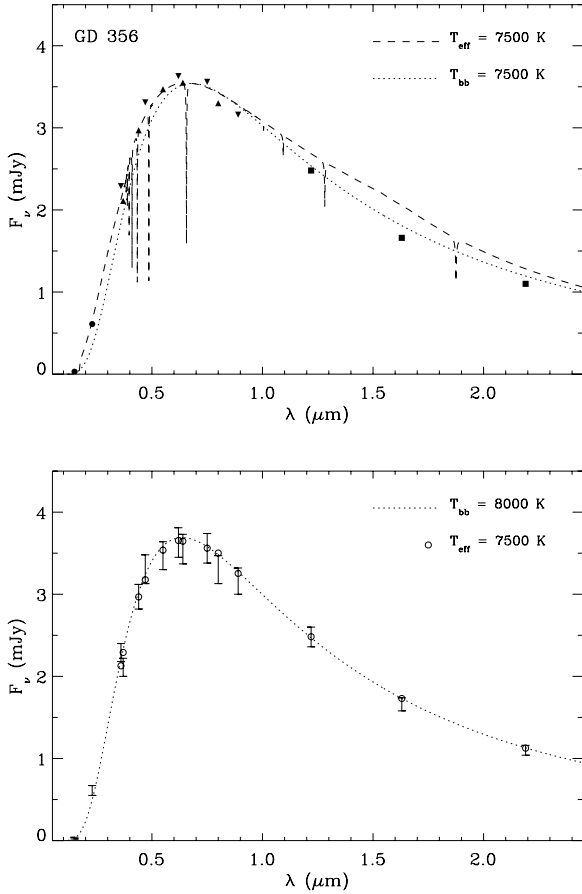
companion being the source of the anomalous line emission seen in GD 356. We then show that rocky planets are unlikely to survive the AGB phase of evolution and be dragged into a close orbit as is required in the unipolar inductor model. We propose that, for this model to be viable, the planet must have formed from material in a disc that resulted from the merging of two white dwarfs and argue that GD 356 may be the result of such a rare event akin to the event that resulted in the formation of planets around the millisecond pulsar PSR 1257+12 (Wolszczan & Frail 1992).

## 2 THE OBSERVATIONS, LIMITS ON COMPANION MASS AND IMPLICATIONS

We combine multiwavelength photometry from several sources in order to constrain the spectral energy distribution (SED) of GD 356, particularly the photospheric emission at infrared wavelengths. Far- and near-ultraviolet fluxes were obtained from the *Galaxy Evolution Explorer* (GALEX; Martin et al. 2005) data archive. These data are uncorrected for extinction and were assigned 10–30 per cent uncertainties (larger than their quoted errors) owing to this fact. Optical *BVRI* photometry was taken from Bergeron, Leggett & Ruiz (2001), supplemented with  $U$ -band measurements in McCook & Sion (2008), while *ugriz* photometry was available from the SDSS Data Release 7 (DR7; Abazajian et al. 2009). Near-infrared *JHK* fluxes were taken from the weighted average of photometry from Bergeron et al. (2001) and the Two Micron All-Sky Survey (Skrutskie et al. 2006). The optical and near-infrared fluxes shown in Fig. 1 are all weighted equally with assumed 5 per cent errors.

A thorough photometric and trigonometric parallax analysis of GD 356 by Bergeron et al. (2001) yields  $T_{\text{eff}} = 7510$  K,  $\log_{10}(g/\text{cm s}^{-2}) = 8.14$  and a helium-rich atmosphere for the DAe white dwarf. The top panel of Fig. 1 shows our first attempt to fit the data, represented by points, with a model photosphere with both a 7500 K,  $\log_{10}(g/\text{cm s}^{-2}) = 8.0$  DA spectral model (Koester 2008) and an identical temperature blackbody model. Neither of these models is sufficient to account for the entire SED simultaneously. In the absence of a full spectral model for helium atmosphere white dwarfs cooler than 10 000 K, in the lower panel we plot the *UBVRI* and *ugriz* model fluxes as open circles for a helium-rich white dwarf of 7500 K and  $\log_{10}(g/\text{cm s}^{-2}) = 8$  (Fontaine, Brassard & Bergeron 2001; Holberg & Bergeron 2006) against the photometry, represented as error bars. On the top of this is plotted an 8000 K blackbody model which mimics the 7500 K helium-rich model fluxes quite well. We use this blackbody fit to extrapolate towards longer wavelengths and iterate with the measured mid-infrared fluxes.

Lastly, we have analysed archival *Spitzer* IRAC images of GD 356 following the methods of Farihi, Jura & Zuckerman (2009). It is worth remarking that these images were free of potential flux-contaminating sources within the  $r = 3.6$  arcsec photometric aperture and that the signal to noise was sufficiently high that the flux errors at all wavelengths are dominated by IRAC calibration error. These previously unpublished fluxes are listed in Table 1 and plotted in the upper panel of Fig. 2 together with the shorter wavelength photometry and our selected model. The entire photometric SED, except possibly the  $7.9 \mu\text{m}$  flux which appears to be in excess at the  $2.0\sigma$  level, is fitted well by the 8000 K blackbody model. The stellar image at this longest wavelength is both highly symmetric and sufficiently bright to show a faint Airy ring in the  $0.6$  arcsec pixel $^{-1}$  mosaic, but we are cautious about the interpretation of an excess at this level without more data (see the lower panel of Fig. 2).



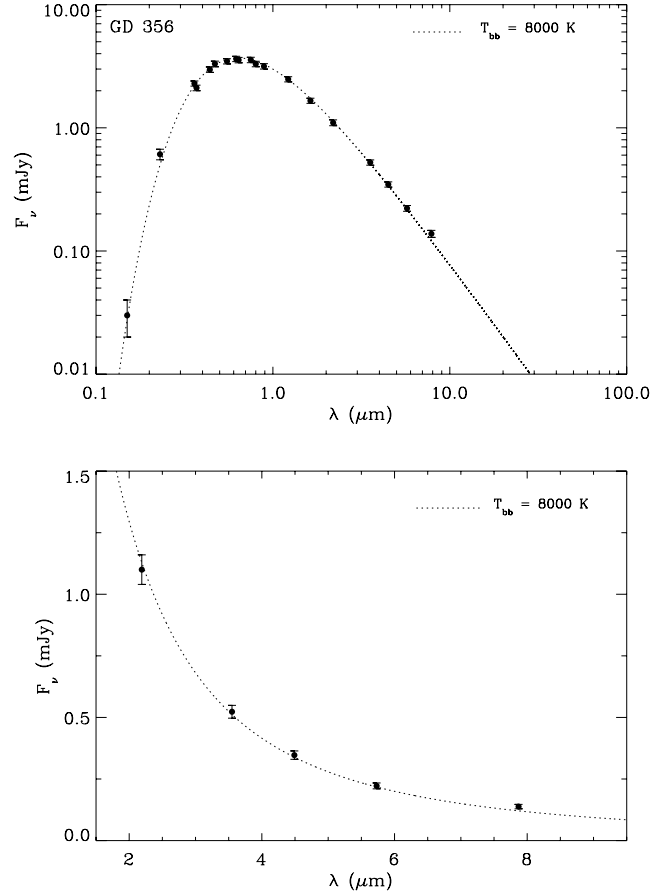
**Figure 1.** Ultraviolet to near-infrared SED of GD 356. The upper panel displays all available photometric data (filled symbols) for the white dwarf plotted beside a 7500 K hydrogen-rich model (dashed line) and a 7500 K blackbody (dotted line). Circles are *GALEX*, upward triangles are *UBVRI*, downward triangles are *ugriz*, and squares are *JHK* photometry. The lower panel shows fluxes for a 7500 K helium-rich model (open circles) at the optical and near-infrared bandpasses, together with an 8000 K blackbody model (dotted line). This reproduces the helium atmosphere model fluxes rather well.

**Table 1.** Mid-infrared fluxes for GD 356.

Wavelength $\lambda/\mu\text{m}$	Model flux $F_v/\mu\text{Jy}$	Measured flux $F_v/\mu\text{Jy}$
3.6	512	$523 \pm 26$
4.5	339	$347 \pm 17$
5.7	218	$222 \pm 12$
7.9	121	$138 \pm 9$

Note: – There is a  $2.0\sigma$  excess measured at 7.9  $\mu\text{m}$ .

We follow Farihi, Becklin & Zuckerman (2008a) and use the measured photospheric flux at 4.5  $\mu\text{m}$  to place an upper limit to the mass of a possible substellar companion to GD 356. For a white dwarf of mass  $0.67 M_{\odot}$  and effective temperature 7500 K, the cooling age is 1.6 Gyr (Bergeron, Saumon & Wesemael 1995). The main-sequence progenitor of GD 356 should have had a mass  $M_{\text{MS}} = 3.25 M_{\odot}$  according to the initial-to-final mass relation (Dobbie et al. 2006; Kalirai et al. 2008; Williams, Bolte & Koester 2009) and hence an estimated total lifetime of 2.1 Gyr. According to models, at the  $d = 21.1$  pc trigonometric parallax distance to the white dwarf, an unseen  $3\sigma$  (15 per cent) excess at 4.5  $\mu\text{m}$  places a companion upper



**Figure 2.** Full SED of GD 356. The upper panel shows all photometry (filled circles), now including the *Spitzer* IRAC flux measurements and the 8000 K blackbody model, normalized to the same level as in Fig. 1. The lower panel is a linear plot of the infrared data and the potential modest excess at 8  $\mu\text{m}$ .

mass limit of  $M_p < 12 M_J$  for an age of 2.1 Gyr (Baraffe, private communication; Baraffe et al. 2003).

We note that there are no white dwarfs with *Spitzer*-only excesses owing to companions (Mullally et al. 2007; Farihi et al. 2008a, 2009). All known infrared excesses from substellar companions reveal themselves in the near-infrared by 2  $\mu\text{m}$  at the latest (Becklin & Zuckerman 1988; Farihi, Zuckerman & Becklin 2005; Burleigh et al. 2006; Farihi, Burleigh & Hoard 2008b; Steele et al. 2009). These results give strict upper limits to the mass of Jupiter-sized companions to white dwarfs of typically between 5 and 20  $M_J$  from young, less than 1 Gyr, to intermediate, 2–5 Gyr, total ages. The limits at GD 356 are therefore commensurate with other 4.5  $\mu\text{m}$  excess searches.

The stringent upper limit that we have deduced for the mass of a possible secondary places new constraints on a binary accretion model for GD 356. First suppose that the substellar type companion is gaseous with  $M_p \leq 12 M_J$ . We expect such a companion to be tidally locked with the orbital period just as in cataclysmic variables. For a Roche lobe filling gaseous companion of mass  $M_p$  orbiting a white dwarf of mass  $M_{\text{wd}}$  with separation  $a$ , the equivalent spherical Roche lobe radius  $R_{L2}$  is given by

$$\frac{R_{L2}}{a} = \frac{2}{3^{4/3}} \left( \frac{M_p}{M_p + M_{\text{wd}}} \right)^{1/3} \quad (1)$$

(Paczynski 1971). For  $M_p \ll M_{\text{wd}}$  Kepler's third law gives

$$R_{L2} = 0.05 \left( \frac{M_p}{10 M_J} \right)^{1/3} \left( \frac{P}{1 \text{ h}} \right)^{2/3} R_{\odot}. \quad (2)$$

For  $0.1 \leq M_p/M_J \leq 70$ , the radius of a planetary secondary is  $R_2 \approx 0.1 R_{\odot}$  (Hubbard 1994). If such a secondary is to just fill its Roche lobe or lie within it the orbital period must satisfy

$$P \geq 2.83 \left( \frac{10 M_J}{M_p} \right)^{1/2} \text{ h}. \quad (3)$$

The limit of  $M_p < 12 M_J$  could therefore be consistent with a gaseous planet in a binary system with an orbital period  $P_{\text{orb}} \geq 2.7 \text{ h}$  in which the white dwarf rotates at a period of 115 min (Brinkworth et al. 2004) asynchronously with the orbit. Such a system could in principle be a post-period bounce cataclysmic variable in which the companion mass has been reduced to low values by mass transfer. In such a case, the white dwarf need not be tidally locked and should be rotating faster than the orbit because it is still accreting angular momentum, albeit at a slow rate. However, the time-scale to reach post bounce periods of greater than 2.7 h would typically exceed a Hubble time (Kolb & Baraffe 1999) so that this possibility can actually be eliminated given the youth of the white dwarf. Alternatively, a gaseous planet may have been dragged in to a close orbit during AGB evolution but not evaporated or it could have formed in a disc following a merger of two stars.

However, for gaseous planets with  $P_{\text{orb}} \geq 2.7 \text{ h}$ , the mass transfer rate by Roche lobe overflow would be less than  $10^{-13} M_{\odot} \text{ yr}^{-1}$  when the orbital evolution is driven by gravitational radiation. For this white dwarf, the corresponding specific accretion rate per unit area would be about  $10^{-6} \text{ g cm}^{-2} \text{ s}^{-1}$  if accreting material were to flow on to the 10 per cent of the surface area of the white dwarf where a temperature inversion is seen. At these accretion rates, a shock would not form and the atmosphere would be heated by particle bombardment and cooled by cyclotron emission. Deep heating would not be expected in the bombardment regime and heating to optical depths of order unity, as is required to explain the emission lines in GD 356, is excluded (Ferrario et al. 1997). Accretion from a companion at higher rates, perhaps by an irradiation induced wind, can also be rejected because the usual indicators of disc or funnel accretion are not seen in this system either.

Eliminating these possibilities, we are once again led to favour the hypothesis of a conducting planet orbiting the magnetic white dwarf, with the excess emission powered by the unipolar inductor mechanism (Li et al. 1998). The planet must have a conducting core and be free of any atmosphere so that the inducted current dissipates in and heats the white dwarf atmosphere. At the mass of the Earth, even a rocky planet in a close orbit would assume the shape of a Roche potential because tidal forces would be sufficient to melt any solid crust. For such a planet, of mean density of  $\rho_p$ , the Roche limit obtained with equation (1) is

$$P^2 > 4\pi \left( \frac{3}{2} \right)^5 \frac{1}{G \rho_p}. \quad (4)$$

This allows orbital periods of greater than about 4.7 h for  $\rho_p = 5 \text{ g cm}^{-3}$ . We have estimated the contribution that this planet would make to the observed energy distribution. For a rocky planet with an albedo  $\epsilon$  in orbit at a distance  $a$  from the white dwarf, the equilibrium effective temperature is given, to a first approximation, by

$$T_p = (1 - \epsilon)^{1/4} \left( \frac{R_{\text{wd}}}{2a} \right)^{1/2} T_{\text{wd}}. \quad (5)$$

For a bond albedo of 0.3, we find a planet temperature of 560 K for an orbital period of 4 h. Such a planet would contribute

1 per cent of the white dwarf flux at  $7.9 \mu\text{m}$  if it had a radius of  $1.4 R_{\oplus}$ . The  $2\sigma$  excess observed at  $7.9 \mu\text{m}$  could in principle be consistent with the presence of the hypothesized rocky planet, although other interpretations of this excess are also possible.

### 3 DISCUSSION

We must now ask how such a planet-like object can find itself so close to a white dwarf. We first show that it could not have been dragged in from a larger orbit by the progenitor of the white dwarf and then discuss the likelihood that it formed when a less massive companion white dwarf merged with GD 356.

#### 3.1 Planets orbiting white dwarfs

The discoveries of Jovian planets orbiting evolved giant stars at distances of the order of 1 au demonstrate that such planets can survive at least the early giant phases of evolution. Lovis & Mayor (2007) estimate that at least 3 per cent of evolved giant stars ( $M \geq 1.8 M_{\odot}$ ) have companions, including brown dwarfs, with  $M_p \sin i > 5 M_J$ . These results show that planets form in intermediate stars that evolve into white dwarfs. Some evidence that Jovian mass planets may survive through the RGB and AGB phases to the white dwarf phase comes from the timing of pulsations in ZZ Cet stars. It has been estimated that GD 66 may have a planet with  $M_p \geq 2.11 M_J$  orbiting at 2.4 au. However this is based on only one measured turning point of the orbit and is therefore not well constrained (Mullally et al. 2008). Likewise V391 Pegasi, which is an extreme horizontal branch star, appears to have a planet with  $M_p \geq 3.2 M_J$  orbiting at about 1.7 au (Silvotti et al. 2007). However, most SdB stars are in binaries so this particular system is likely to have been the end product of binary evolution.

Gaseous planets that are initially close enough to interact with the expanding RGB or AGB star could simply be dragged into a closer orbit by bow-shock and tidal drag during an ensuing common envelope phase of evolution or be completely destroyed by evaporation depending on their initial mass. The critical mass below which a Jovian planet is expected to evaporate in the envelope of the giant star before the envelope itself can be ejected is estimated to be about  $15 M_{\text{Jup}}$  for a  $1 M_{\odot}$  star, but there are large uncertainties in this estimate related to parameters such as efficiency of common envelope ejection (Nelemans & Tauris 1998; Siess & Livio 1999). This estimate increases to  $120 M_J$  for a  $5 M_{\odot}$  star. If the time-scale for the common envelope phase were short enough it might be envisaged that a larger mass planet might have been partially evaporated down to about  $10 M_J$ . However, given that evaporation should accelerate as the planet loses mass, it is very unlikely that such fine tuning could have occurred. A main-sequence star–planet system that evolves through these phases would be seen either as a single white dwarf or as a white dwarf with a close planetary companion with a mass above this critical value. GD 1400 and WD 0137 are close binaries with orbital periods of 10 and 2 h, respectively (Farihi & Christopher 2004; Maxted et al. 2006). GD 1400 is a CO white dwarf, which is the remnant of AGB phase of evolution, while WD 1037 is a He white dwarf which has only passed through the RGB phase of evolution. The companions are 50–60  $M_J$  brown dwarfs. Thus, the empirical evidence appears to be that a companion of this mass can survive evaporation and in-spiralling during RGB/AGB evolution, eject the envelope and be seen as a close binary now. We note, however, that Villaver & Livio (2007) have questioned whether such a close companion could survive the intense radiation to which it would be subjected by the newly formed

white dwarf and have proposed that such systems are more likely to have arisen from a merger of two white dwarfs. Against this hypothesis is the observation that main-sequence star–brown dwarf pairs appear to occur with about the same frequency as white dwarf–brown dwarf pairs indicating that the latter can form without the need for strong binary interaction.

The fate of rocky planets, particularly that of the Earth itself, during the late stages of stellar evolution has been looked at in some detail. Sackmann, Boothroyd & Kraemer (1993) thought that the Earth would escape because mass loss increases the orbital separation faster than the Sun grows on both the RGB and AGB. Rasio et al. (1996) went on to point out that tides, if a little stronger than expected, induced by the Earth on the Sun might actually cause the Earth to spiral in during the RGB phase. Like Sackmann et al. (1993) they worked with Reimers' (Reimers 1975) mass-loss rates and so claimed that survival of the RGB would lead to an orbit wide enough to survive the AGB too. Rybicki & Denis (2001) used more realistic thermally pulsing AGB models with weak mass loss on the RGB and so their stars experience many more thermal pulses and grow fast enough to swallow the Earth before the end of the AGB. Schröder & Conan Smith (2008) invoke even stronger mass loss towards the luminous tip of the RGB so that their Sun grows large enough to engulf a tidally spiralling Earth on the RGB but not on the AGB. The orbital angular momentum of a low-mass terrestrial planet that is engulfed during the RGB phase is insufficient to eject the common envelope. The orbit rapidly decays owing to tidal and bow-shock drag and the planet plunges into the central star and is destroyed. A planet that is first engulfed only during a thermal pulse on the AGB phase might have a better chance of survival. Rybicki & Denis (2001) suggest that such a planet would be dragged in by 10–70  $R_{\odot}$  per thermal pulse, and is also likely to be destroyed. Willes & Wu (2005) went back to the older AGB models of Sackmann et al. (1993) to argue that a fraction of such systems may survive stellar evolution and end up as close companions to the white dwarfs. However, these models had fewer thermal pulses and did not grow as much on the AGB as is now thought. Indeed, Willes & Wu (2005) relied on the star shrinking sufficiently over the last few pulses. Our models (Stancliffe, Tout & Pols 2004; Stancliffe & Glebbeek 2008) show AGB stars growing rapidly at the end of their lives after the onset of a superwind. In which case engulfment cannot be avoided if a planet is dragged in. While uncertainty remains in the evolution of AGB stars it is possible that planets within a narrow range of separations from their stars might actually be dragged in to closer orbits. However, the fine tuning of the orbital decay that would be required from pulse to pulse makes it very unlikely that the orbit could be reduced as much as required for GD 356.

Assuming that any planet that might be sufficiently dragged in would be engulfed by the star's envelope, we must then consider the implicit assumption that an Earth-like planet is likely to evaporate during such periods of engulfment and so would not survive. To totally evaporate a planet, of mass  $M_p$  and radius  $R_p$ , it must absorb sufficient thermal energy to overcome its gravitational binding energy

$$E_{\text{gr}} = \frac{\zeta G M_p^2}{R_p} = 10^{38} \zeta \left( \frac{M_p}{M_{\oplus}} \right)^2 \left( \frac{R_{\oplus}}{R_p} \right) \text{ erg}, \quad (6)$$

where  $\zeta = 3/5$  for a uniform density body. For a typical rocky planet, this is much larger than the total energy, of less than  $10^{36}$  erg, to sublimate, dissociate and ionize the planet. As long as the planet's core remains at a temperature significantly lower than the ambient temperature bath, the time-scale for evaporation is just the Kelvin–Helmholtz time-scale for the planet if it were radiating as a

blackbody with the temperature of the bath. Thus, the evaporation time-scale

$$t_{\text{evap}} = \frac{\zeta G M_p^2 / R_p}{4\pi\sigma R_p^3 T_*^4}, \quad (7)$$

where  $T_*$  is the temperature of the ambient giant stellar material. In equilibrium, the thermal energy of the planet would exceed the gravitational binding energy when

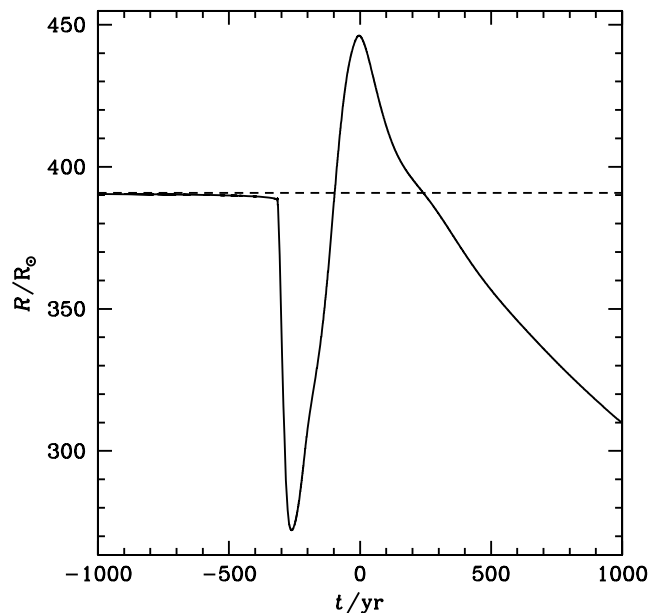
$$\frac{3}{2} \frac{R}{\mu} T_{\text{eq}} M_p > E_{\text{gr}}, \quad (8)$$

where  $R$  is the gas constant. The mean molecular weight  $\mu$  depends on the composition and ionization state of the planetary material. At  $10^4$  K, most constituents of the Earth are at least singly ionized and for a typical composition this gives  $\mu \approx 15$ . At higher temperatures  $\mu$  approaches two. Thus,

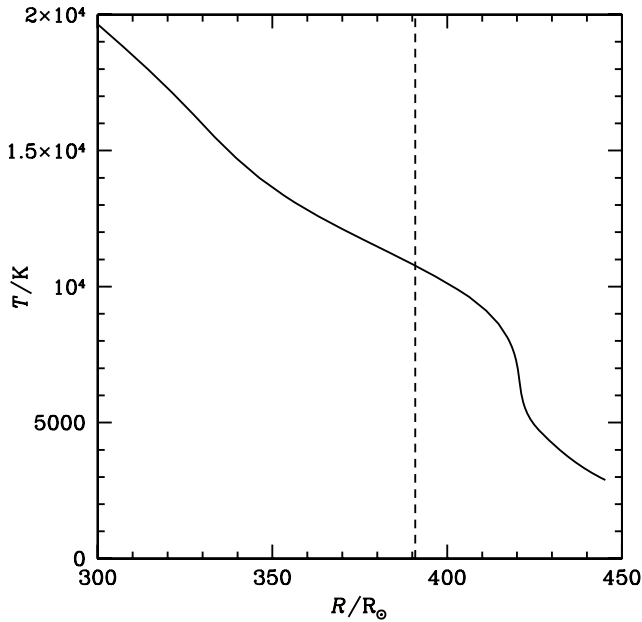
$$T_{\text{eq}} < 30\,000 \frac{M_p}{M_{\oplus}} \frac{R_{\oplus}}{R_p} \text{ K}. \quad (9)$$

Thus, for an Earth-like planet at a depth that takes it to  $T_* > 30\,000$  K, we may apply equation (7) and  $t_{\text{evap}}$  is only about two days so the planet could not survive such conditions.

Fig. 3 illustrates the evolution of the stellar radius of an initially  $3 M_{\odot}$  star with a current core mass of  $0.65 M_{\odot}$  through a single AGB pulse calculated with the Cambridge Stars code (Stancliffe et al. 2004). A planet that is located just outside the star prior to a pulse is engulfed by the expanding envelope for a period of more than 300 yr. Even if the planet were not dragged in, Fig. 4 demonstrates that it would be exposed to ambient temperatures of 10 000 K for long enough to evaporate the more volatile elements. As the pulses proceed, the mass of the planet would fall and the temperature and depth in the stellar envelope required for complete evaporation would rapidly diminish. We would not expect a rocky Earth-like planet to survive more than the first few pulses that engulf



**Figure 3.** The evolution of radius with time during the 15th thermal pulse of an initially  $3 M_{\odot}$  star when it has a core mass of  $0.65 M_{\odot}$ . The star is beginning to lose mass in a superwind and so is expanding rapidly from pulse to pulse. The dashed line marks the maximum radius reached during the previous interpulse period. A planet at this radius is engulfed for more than 300 yr and reaches a depth of more than  $50 R_{\odot}$  in the AGB envelope.



**Figure 4.** The temperature structure with radius for the 15th pulse of our initially  $3 M_{\odot}$  star at  $t = 0$  in Fig. 3 when the star reaches its maximum radius. The dashed line marks the maximum radius reached during the previous interpulse period and so corresponds to the depth of a planet that just survived the 14th pulse.

it. If the planet is dragged in, it is exposed to yet higher temperatures for even longer. The temperature at the base of an AGB star's envelope is in excess of  $10^7$  K so a planet dragged into a close orbit within the giant envelope could not survive.

For the extreme case of a planet engulfed at the very end of the thermally pulsing AGB when only about  $0.05 M_{\odot}$  of stellar envelope remains the planet might survive partial immersion. However, the binding energy of such an envelope is only about one-thousandth of that required to bring the planet in to a close enough orbit around the white dwarf. We therefore conclude that a rocky, Earth-like planet cannot both survive evaporation and end up in a very close orbit.

### 3.2 Merging double white dwarfs

We consider a binary evolution scenario which leads to the formation of a CO white dwarf with a lower mass He or CO white dwarf companion through common envelope evolution. The two stars are subsequently drawn together by gravitational radiation and merge. During the merging, this companion breaks up and forms a massive disc around the remaining CO white dwarf. Such a disc could be composed of CO-rich or He-rich material. The mass of the disc is somewhat more than one-tenth of that of the accreting star and so becomes unstable to its own self gravity. The disc expands and cools as the central star accretes matter. When the temperature in the outer disc is cool enough dust and rocks formed and these clump to form a rocky planetary core. This model is very similar to that initially proposed to explain planetary companions to millisecond pulsars (Podsiadlowski, Pringle & Rees 1991).

In order for the two white dwarfs to merge the common envelope process must leave them close enough for gravitational radiation to act quickly. Tout et al. (2008) have demonstrated how high magnetic fields in white dwarfs are almost certainly generated in common envelopes from which the cores emerge already close together. Thus,

the high field in this system is evidence that the white dwarf most likely emerged from common envelope evolution with a close companion, in this case a second, less massive white dwarf. The mass of GD 356 of  $0.67 M_{\odot}$  is already above the average for CO white dwarfs. In order to leave two white dwarfs that can merge the system must originally have been close enough that the evolution of both stars was curtailed by mass transfer. Thus, we might envisage mass transfer from the initially more massive star to begin when it has a CO core of say  $0.4 M_{\odot}$ . If this leads to a mild common envelope phase, the orbit would then shrink so that the second star fills its Roche lobe early on red giant branch with a He core of about  $0.3 M_{\odot}$ . Alternatively, the first star might have filled its Roche lobe as a subgiant, evolved through an Algol phase to a helium white dwarf. Its rejuvenated companion could then go on to fill its own Roche lobe on the AGB followed by common envelope evolution that leaves its CO core in a close orbit. In either case for the final common envelope must leave the two cores sufficiently close that they can be driven together by gravitational radiation and their mass ratio must be less than 0.628 so that the ensuing mass transfer is dynamically unstable.

When two white dwarfs merge, the more massive, being larger in radius, fills its Roche lobe first. If the masses are sufficiently different stable mass transfer could follow with the orbit widening as the mass-losing star grows in radius. However, if the donor is more than 0.628 times the mass of the accretor, the mass transfer is unstable because the white dwarf grows faster than its Roche lobe expands. In this case, numerical simulations show that the less massive white dwarf is indeed tidally disrupted and accreted on to the more massive through a thick accretion disc (Mochkovitch & Livio 1989; Benz et al. 1990; Guerrero, García-Berro & Isern 2004). So the natural outcome is a hot white dwarf surrounded by a thin remnant disc that contains most of the angular momentum. The nature of this disc is likely to be very unusual, given that white dwarfs are composed primarily of carbon and oxygen, rather than the hydrogen and helium of more traditional circumstellar discs.

The formation of planets in such discs around neutron stars and white dwarfs has been discussed by Hansen (2002) and Livio, Pringle & Wood (2005). The expected outcome depends rather critically on the viscosity of the disc. Initially, it has an outer radius of  $10^9$ – $10^{11}$  cm, determined by the orbital angular momentum of the disrupted companion. As accretion proceeds the disc expands and cools. While the viscosity is determined by the magneto-rotational instability, it is strong only when the disc is ionized and the viscosity is negligible outside this region. Hansen (2002) found that, when sufficient gas persists, planets formed in the quiescent outer disc but at a higher temperature than for a hydrogen-rich composition, because of the higher ionization potential of carbon and oxygen, by processes similar to those that are believed to have occurred in the early solar system (Lissauer 1993). They predict that planets of  $30$ – $300 M_{\oplus}$  form in CO-rich discs and are located within 0.2 au. A similar scenario is appropriate for He-rich discs. Planet formation may take  $10^8$  yr. The temperature of the white dwarf indicates that it has been cooling in excess of  $10^9$  yr which easily accommodates this along with sufficient time for any remnant disc to disperse. We might further speculate that all volatiles, and perhaps some transitional elements, such as magnesium and silicon, may evaporate and be lost in the very near environment of a hot and relatively luminous, newly merged white dwarf, while refractories, such as calcium, titanium and aluminium, would more likely be retained, perhaps leading to a refractory-metal planet. In particular, much of the oxygen that would otherwise form oxides would almost certainly evaporate and be blown away by radiation pressure so that metals

that would otherwise oxidize would be left to form a substantial metallic core. Such a planet might be more like Mercury than the Earth in composition.

Such a planet would have a metallic core of mass  $0.03\text{--}1 M_{\oplus}$  (for a CO rich composition). Once within  $10 R_{\odot}$  of the highly magnetic white dwarf orbital energy can drive the unipolar induction current (Li et al. 1998). Owing to its atmosphere the planet's effective resistivity is initially larger than that of the white dwarf so that energy, which is extracted from the orbit, is mainly dissipated in the planet during the early phases of the magnetic interaction. As the planet drifts in, this heating facilitates the evaporation of its atmosphere, until the effective resistivity of the planet becomes smaller than that of the white dwarf's atmosphere. The heating then occurs mainly in the white dwarf atmosphere and the model presented by Li et al. (1998) for GD 356 becomes applicable.

Some observational support for the possibility of the formation of a second generation of planets around a star that is evolving into a white dwarf has been provided by the discovery of a substantial classical T Tauri-type dust disc surrounding an accreting first giant ascent giant star TYC 4144-329-2 (Melis et al. 2009). It has been speculated that the observed disc may have resulted from the common envelope interaction with a low-mass stellar or substellar companion.

#### 4 CONCLUSIONS

We have presented an analysis of archival *Spitzer* observations of GD 356 that shows that a firm upper limit of  $12 M_J$  can be placed on the mass of a possible companion. The new observations place further constraints on the orbital parameters of a possible binary companion. In agreement with previous investigators, we have again argued that accretion heating due to mass transfer from a companions is an implausible mechanism for explaining the anomalous line emission in this star. The unipolar inductor model, which requires GD 356 to have a rocky planet with a metallic core as a companion, remains the best explanation for the peculiar properties of this unique star.

Theoretical estimates indicate that it is unlikely that an Earth-type planet that was orbiting the main-sequence progenitor of a white dwarf, at a distance that would allow it to be engulfed by the expanding envelope during RGB/AGB phases of evolution, would survive the subsequent evolution of the parent star and be seen as a close companion to the white dwarf. Such a planet would either be evaporated as it is dragged into the core of the star during the RGB/AGB phases of evolution or be left in an orbit at a much larger radius of several hundred solar radii. If the unipolar inductor model for GD 356 is to be viable an alternative origin must be sort for its close companion. We have argued that the planet probably formed in an accretion disc following the disruption of a white dwarf in a rare merger event. GD 356 would thus be the white dwarf counterpart of the millisecond binary pulsar PSR1257+12 which is known to host a planetary system.

In conclusion, we note that the unipolar inductor model for GD 356 makes a definite prediction that could be verified by future observations. Two fundamental and distinct periods, the rotation period of the white dwarf and the orbital period of the planet around the white dwarf, are expected to be seen in the emission line flux or in any component of the continuum flux attributable to the heating. Livio, Pringle & Saffer (1992) argue that planets are most likely to be found around massive white dwarfs because these are more likely to have merged in the past. We would add that the white dwarf should not only be massive but also possess a high magnetic field, created

during the common envelope evolution that must have preceded the merging. It is around such white dwarfs that the search for planets should be concentrated and, if metallic, such systems might also show up as unipolar inductors.

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