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Near-infrared spectroscopy of the very low mass companion to the hot DA white dwarf PG 1234+482

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ABSTRACT

We present a near-infrared spectrum of the hot ($T_{\rm eff} \approx 55\,000$ K) hydrogen atmosphere (DA) white dwarf PG 1234+482. We confirm that a very low mass companion is responsible for the previously recognized infrared photometric excess. We compare spectra of M and L dwarfs, combined with an appropriate white dwarf model, to the data to constrain the spectral type of the secondary. We find that uncertainties in the Two-Micron All-Sky Survey *HK* photometry of the white dwarf prevent us from distinguishing whether the secondary is stellar or substellar, and assign a spectral type of L0±1 (M9–L1).Therefore, this is the hottest and youngest ($\approx 10^6$ yr) DA white dwarf with a possible brown dwarf companion.

Key words: binaries: spectroscopic – stars: low-mass, brown dwarfs – white dwarfs.

1 INTRODUCTION

Observations of substellar companions to white dwarfs allow the investigation of a variety of aspects of binary formation and evolution. Since a white dwarf is up to ~10 000 times fainter than its progenitor, the contrast gain also facilitates direct detection of very low mass secondaries. White dwarfs with brown dwarf secondaries can be used to place constraints on the fraction of their main-sequence progenitors with substellar companions. For example, radial velocity and imaging surveys indicate a discrepancy between the brown dwarf companion fraction at small separations (1 ± 1 per cent at <10 au, Marcy & Butler 2000; McCarthy & Zuckerman 2004) and large radii (a > 1000 au; 10–30 per cent; Gizis et al. 2001). The closest white dwarf + brown dwarf binaries might also represent either another channel for cataclysmic variable (CV) evolution (Politano 2004) or the end state of CV evolution, in which the secondary has become highly evolved through mass transfer. In close detached binaries, the brown dwarf is expected to be irradiated by the white dwarf's high-ultraviolet (high-UV) flux, possibly leading to substantial differences between the 'day' and 'night' hemispheres. Such contrasts have recently been reported in several hot Jupiters (e.g. HD 189733b, Knutson et al. 2007). Finally, we note that there are few observational constraints on brown dwarf evolutionary models at large ages, such as might be expected for most white dwarfs (>1 Gyr). Thus wide, detached white dwarf + brown dwarf binaries may provide 'benchmarks' for testing these models (Pinfield et al. 2006).

However, brown dwarf companions to white dwarfs are rare (Farihi, Becklin & Zuckerman 2005). To date only three such systems have been confirmed: GD 165 (DA+L4, Becklin & Zuckerman 1988), GD 1400 (DA+L6/7, Farihi & Christopher 2004; Dobbie et al. 2005) and WD0137−349 (DA+L8, Burleigh et al. 2006a; Maxted et al. 2006). GD 165 is a widely separated system (120 au), whereas WD 0137−349 is a close binary ($P_{\rm orb} = 116$ min). The separation of the components in the GD 1400 system is currently unknown. At $T_{\rm eff} \approx 55\,000$ K, PG 1234+482 is significantly hotter than GD 165 ($T_{\rm eff} \approx 12\,000$ K, McCook & Sion 1987), GD 1400 ($T_{\rm eff} \approx 11\,580$ K, Farihi & Christopher 2004), and WD 0137−349 ($T_{\rm eff} \approx 16\,500$ K, Maxted et al. 2006). Although there are many candidate substellar mass secondaries in CVs, it was only recently that one was finally confirmed (SDSS 103533.03+055158.4, Littlefair et al. 2006), though not through a direct spectroscopic detection.

Clues to the existence of other white dwarf + brown dwarf binaries might be provided by the degenerate stars themselves. White dwarfs are expected to have either pure-H or pure-He atmospheres. However, in some apparently isolated white dwarfs there are unusually high metal abundances. This is somewhat unexpected as the gravitational settling times of such elements are much less than the cooling time-scale of the white dwarf. For example, in H-rich hydrogen atmosphere with metal absorption lines (DAZ) white dwarfs with $T_{\rm eff} \lesssim 20\,000$ K Ca and Mg are seen in optical spectra, despite these elements having a residence time in the atmosphere of days. This strongly implies that the polluting material is being directly accreted from some unseen source. Zuckerman et al. (2003), Gianninas, Dufour & Bergeron (2004) and Kilic & Redfield (2007) argue that interstellar material is an unlikely source of accretion, implying that the metals are being accreted from a source associated with the white dwarf itself. The detection of dust and gas discs around some DAZs provides the source for this material in these cases (e.g. GD 362, Becklin et al. 2005; Kilic et al. 2005; SDSSJ 104341.53+085558.2, Gaensicke, Marsh & Southworth 2007), but Zuckerman et al. (2003) have also noted the high

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frequency of DAZ stars which are part of known binary systems and suggest that wind-driven mass loss from the companion may be responsible for a proportion of the observed DAZ stars.

Barstow et al. (2003) used far-UV spectra to measure the metal abundances for a group of hotter DA white dwarfs in the range $20\,000 < T_{\rm eff} < 110\,000$ K. They showed that the photospheres of all DAs $\gtrsim$50 000 K contain heavy elements which can be adequately supported against gravitational settling by radiation pressure. In most cases, these metals presumably remain from the pre-white dwarf evolution of the star. Therefore, a difficulty may arise in easily identifying candidate hot stars that might be accreting small amounts of material from an unseen dust or gas disc, or the wind of a close companion, unless the latter is of spectral type mid M or earlier. For example, the hot DA white dwarfs Feige 24 ($T_{\rm eff} \approx 60\,000$ K, Vennes et al. 2000; Barstow et al. 2003) and RE J 0720−318 ($T_{\rm eff} \approx 55\,000$ K Dobbie et al. 1999; Vennes, Thorstenson & Polomski 1999) have close, early-M companions which are possibly supplying at least a fraction of the heavy elements detected in the white dwarfs' photospheres. It is plausible that a proportion of the apparently single metal-polluted hot DA white dwarfs may also be accreting from as-yet-unseen low-mass companions (Dobbie et al. 2005).

PG 1234+482 (hereafter PG 1234) is a hot ($T_{\rm eff} \approx 55\,000$ K) DA white dwarf with some evidence for metal pollutants in its photosphere. Jordan, Koester & Finley (1996) reported the detection of Fe in an *Extreme Ultraviolet Explorer* spectrum of the star, and Wolff et al. (1998) give the overall metallicity as 20 per cent that of the archetypal metal-rich hot DA G191−B2B using the same data (a pure-H atmosphere overpredicts the extreme-UV continuum flux and metal opacities are required to satisfactorily model these data). However, Barstow et al. (2003) did not detect any heavy elements in a noisy *International Ultraviolet Explorer* far-UV spectrum, and only give upper limits on the abundances of C, N, O, Si, Fe and Ni. A quick analysis of the *FUSE* spectrum of PG 1234 also failed to reveal any obvious photospheric metal lines.

PG 1234 was first observed in the near-infrared (near-IR) by Green, Ali & Napiwotzki (2000), who reported a small 1.3σ *K*-band excess and thus did not claim any evidence for a companion. Debes, Sigurdsson & Woodgate (2005) later noted significant *H*- and *K*-band excess from the more precise Two-Micron All-Sky Survey (2MASS) photometry and suggested the presence of a companion spectral type M8V. More recently, Mullally et al. (2006) measured a mid-IR excess in two *Spitzer* IRAC bands (4.5 and 8.0 μm). They modelled the excess using a companion with $T_{\rm eff} < 2000$ K, assigning a spectral type of early L.

Here we report near-IR spectroscopy of PG 1234 to confirm the presence of the very low mass companion and to better constrain its spectral type.

2 OBSERVATIONS AND DATA REDUCTION

We observed PG 1234 on 2007 March 5 using the Long-slit Intermediate Resolution Infrared Spectrograph (LIRIS) during service time on the 4.2-m William Hershel Telescope (WHT). LIRIS is a near-IR imager/spectrograph which uses a 1024 × 1024 pixel array HAWAII detector. The pixel scale is 0.25 arcsec pixel^{-1}, giving a field view of 4.27 × 4.27 arcmin^2. Data were acquired using the *HK* grism providing a wavelength coverage of 1.39–2.42 μm. Observations were taken using the standard technique of nodding the point-source targets along the spectrograph slit in an ABBA pattern. For PG 1234, 18 × 100 s exposures were taken (nine AB pairs) for a total exposure time of 1800 s, followed by 4 × 10 s exposures of an A3V telluric standard. The average airmass over the course of the observations was 1.06. To reduce the data, we first corrected the bottom left-hand quadrant pixel 'scrambling' (the image is constructed after readout with a 1-pixel dislocation) in all images using the LCPIXMAP function of the IRAF package LIRISDR.[1] We then applied standard reduction techniques using software routines in the STARLINK packages KAPPA and FIGARO. In brief, a bad pixel map was constructed and applied to all the data. The science, standard star and arc lamp spectral images were flat-fielded with a normalized response map. Difference pairs were then assembled from the science and standard star images and any significant remaining sky background was removed by subtracting linear functions, fitted in the spatial direction, from the data. The spectra of the white dwarf and the standard star were then extracted and assigned the wavelength solution derived from the arc spectrum. Any intrinsic features of the standard star's energy distribution were identified by reference to the near-IR spectral atlas of fundamental Morgan and Keenan standards (Wallace et al. 2000; Meyer et al. 1998; Wallace & Hinkle 1997) and were removed by linearly interpolating over them. The spectrum of the white dwarf was then co-aligned with the spectrum of the standard star by cross-correlating the telluric features present in the data. The science spectrum was divided by the standard star spectrum and multiplied by a blackbody with $T_{\rm eff}$ of the standard. Finally, the flux levels were scaled to achieve the best possible agreement between the spectral data and the *H* and $K_{\rm s}$ photometric fluxes of the object derived from the 2MASS All-Sky Data Release Point Source Catalogue magnitudes (Skrutskie et al. 1997).

3 ANALYSIS

To assist in spectrally typing the companion, we compare the data to combined white dwarf and M/L dwarf models.

We have generated a pure-H synthetic spectrum for PG 1234 at $T_{\rm eff} = 55\,040$ K and $\log g = 7.78$ (Liebert, Bergeron & Holberg 2005) using the plane-parallel, hydrostatic, non-local thermodynamic equilibrium (non-LTE) atmosphere and spectral synthesis codes TLUSTY (v202; Hubeny 1988; Hubeny & Lanz 1995) and SYNSPEC (v49). The synthetic flux has been normalized to $V = 14.45$ (Liebert et al. 2005).

Empirical companion models have been constructed using the near-IR spectra of M and L dwarfs from the IRTF spectral library (Cushing, Rayner & Vacca 2005; Rayner et al., in preparation). The fluxes of the empirical models have been scaled to a level appropriate to a location at $d = 10$ pc using distances estimated from the parallax of each object. Subsequently, these fluxes have been re-scaled to be consistent with the Liebert et al. (2005) distance estimate of 144 pc. The final distance scaled models were then added to our synthetic white dwarf spectrum.

We also compare the PG 1234 *Spitzer* photometry of Mullally et al. (2006) to archival *Spitzer* IRAC photometry of observed M and L dwarfs (Table 1; Patten et al. 2006). Again, these values have been appropriately scaled to the distance given previously. We added these fluxes to expected values for PG 1234 calculated by integrating our synthetic spectrum folded through the appropriate filter transmission response.

4 RESULTS

Fig. 1 shows our extracted spectrum for PG 1234. It is not possible to scale the spectrum to match the *H* and *K* 2MASS photometry

[1] http://www.iac.es/proyect/LIRIS/index.html

Table 1. Photometric fluxes in mJy of combined PG 1234 (predicted) + M and L dwarfs compared to those of PG 1234 (observed).

Name	Spectral type	2MASS			*Spitzer* IRAC channel	
		J(error)	*H*(error)	K_s(error)	4.5 µm(error)	8.0 µm(error)
PG 1234 (observed)	DA	1.628(28)	1.067(21)	0.707(13)	0.2116(75)	0.085(15)
PG 1234 (predicted) + BRI 0021–0214	DA + M9.5	1.549(27)	1.035(20)	0.729(13)	0.240(10)	0.010(18)
PG 1234 (predicted) + 2MA 1439+1929	DA + L1.0	1.512(26)	0.946(19)	0.631(12)	0.191(8)	0.072(12)

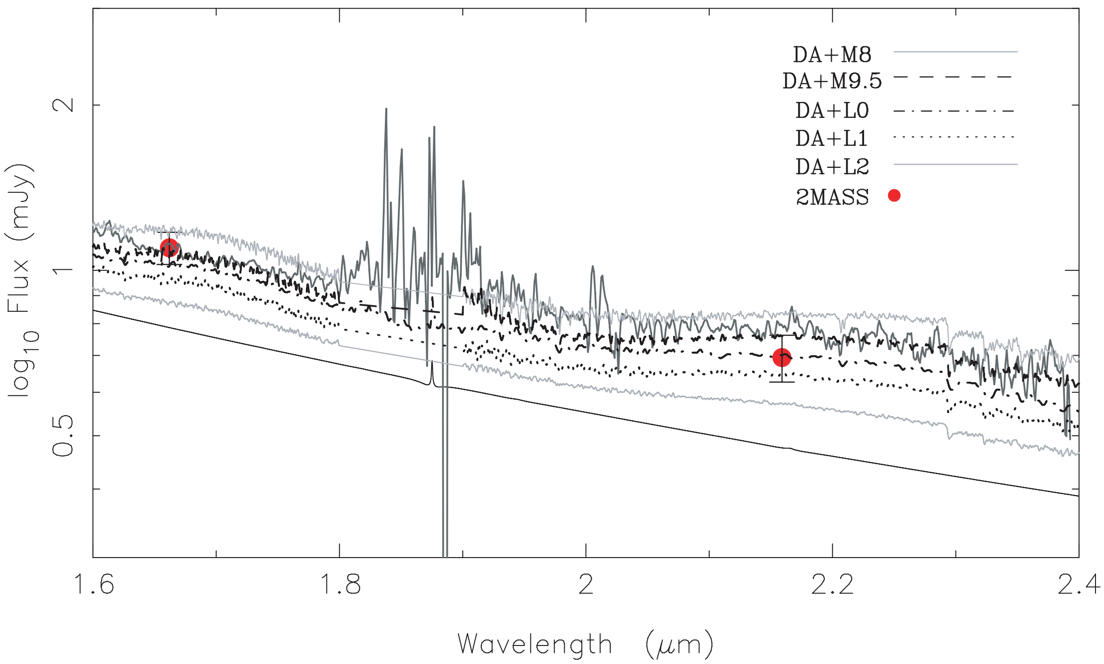

Figure 1. Observed near-IR spectrum of PG 1234+482 scaled to the 2MASS *H* flux. The predicted white dwarf model alone is shown by the solid line. We also compare the data to the white dwarf model combined with late-M and early-L dwarfs, all scaled to a distance of 144 pc (Liebert et al. 2005). The upper and lower grey spectra are PG 1234+M8 and PG 1234+L2 spectra, respectively. The 1.87-µm H Paschen α emission line in the predicted white dwarf spectrum is due to non-LTE effects in the upper atmosphere.

simultaneously, although when scaling to one the other is only off by $<2\sigma$. This may indicate either a residual error in the reduction of the spectrum or errors in the 2MASS photometry. At $K_s = 14.937 \pm 0.106$, PG 1234 does not meet the 2MASS Point Source Catalog level 1 requirements [signal-to-noise ratio (S/N) > 10] and Tremblay & Bergeron (2007) have shown that lower quality 2MASS data should be treated with caution when interpreting near-IR excesses to white dwarfs. In Fig. 1, we show the data scaled to the *H* photometry. Fig. 1 also shows combined white dwarf + dwarf spectra of spectral types M 9.5, L0 and L1. The light grey spectra above and below are of M8 and L2 types, respectively, and are added to show that our data do not match either of these types. When normalized to the *H*-band flux, the observed spectrum is best approximated by a WD + M9.5 companion, whereas if normalized to the *K*-band flux the spectrum would be closer to that of a WD + L0 or WD + L1.

Fig. 2 shows the 2MASS *JHK* and the *Spitzer* IRAC 4.5- and 8.0-µm photometry (Mullally et al. 2006) of PG 1234 with the combined predicted PG 1234 fluxes + BRI 0021−0214 (M 9.5) and 2MA 1439+1929 (L1). It can be seen that the 2MASS fluxes are more closely approximated by the WD + M9.5 spectral type, whereas *Spitzer* fluxes are overpredicted by our WD + M9.5 model, but are underpredicted by our WD + L1 model. Thus, the *Spitzer* data are likely best matched with a WD + L0.

5 CONCLUSIONS

We have attempted to determine the spectral type of the low-mass companion to PG 1234+482 using *H*- and *K*-band spectroscopy obtained from the WHT LIRIS instrument and the *Spitzer* IRAC 4.5- and 8.0-µm photometry. Due to uncertainty in the 2MASS photometry used to place these data on an absolute flux scale, we estimate the spectral type as L0±1 (M9–L1), making PG 1234 the hottest and youngest ($t_{cool} \approx 10^6$ yr; Liebert et al. 2005) DA white dwarf with a possible brown dwarf companion.

Whether the companion is substellar then depends on its age, which we can estimate as follows. The mass of the progenitor to PG 1234 can be estimated using the initial–final mass relationship of Dobbie et al. (2006), which holds down to an initial mass of 2.7 $M_\odot$, but has recently been shown to extend down to an initial mass of 1.6 $M_\odot$ by Kalirai et al. (2007). The mass of PG 1234 is $0.61 \pm 0.02\,M_\odot$ (Liebert et al. 2005) yielding an initial mass of $2.4 \pm 0.1\,M_\odot$. An approximate main-sequence lifetime can then be calculated from

$$t_{ms} = 10\left[(M_*/M_\odot)^{-2.5}\right]\ \mathrm{Gyr},$$

(Wood 1992). Therefore, the age of the system is ≈1 Gyr as the cooling age is negligible.

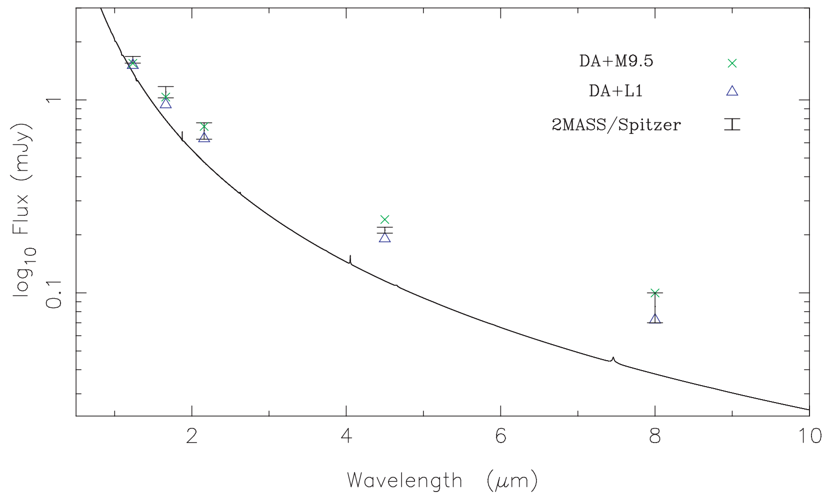

Figure 2. 2MASS and *Spitzer* IRAC (4.5 and 8.0 μm) photometric fluxes of PG 1234+482 with M9.5 and L1 fluxes scaled appropriately. The symbols for the combined WD + M and L dwarf models do not represent the actual errors which can be seen in Table 1.

We can estimate the effective temperature of an object on the substellar boundary using the DUSTY models of Chabrier et al. (2000) and Baraffe et al. (2001). At an age of 1 Gyr and the commonly used upper mass limit for brown dwarfs of 0.075 $M_{\odot}$, we expect an effective temperature of ≈2200 K. At this temperature, the observations of Vrba et al. (2004) suggest a spectral type of L1–L2, and Golomowski et al. (2004) an L1. Using the empirical formula of Stephens et al. (2001):

$$T_{\rm eff} = 2220 - 100 L_n \text{ where } L_n = \text{L0–L8},$$

we would expect a spectral type of L0–L1. Thus, the expected spectral type of a 1-Gyr object on the substellar boundary is ≈L1 ±1.

Therefore, we do not have sufficient evidence to state conclusively if the companion is stellar or substellar in nature – that is, a brown dwarf. To further constrain the spectral type, we suggest higher resolution, higher S/N *H*-band and more importantly *K*-band spectroscopy. An accurate spectral type could then be determined from the relative strength of the CO absorption edges at 2.3 μm.

The confirmation of a very low mass, possibly substellar, companion to PG 1234 leads us to speculate whether the metals in the hot white dwarf's atmosphere are at least in part being accreted from the companion's wind. To answer this, we will need to constrain the separation of the pair, by either high-resolution imaging and/or radial velocity measurements. Farihi et al. (2005) did not resolve the two, indicating that the separation is less than or approximately 1 arcsec. Consideration of the post-main-sequence evolution of these systems and observations by Farihi et al. (2006) suggests that there may be a bimodal distribution of orbital separations among binaries containing at least one white dwarf: wide pairs with orbits >10 au and very close systems (less than few solar radii) in which the companion was dragged in during the common envelope phase. The failure to resolve the system by Farihi et al. (2005) might be indicating that PG 1234 is a close binary, but we caution that the pair also may be aligned by chance. Whether it is wide or close, and a possible survivor of common envelope evolution, PG 1234+482 B is one of the lowest-mass companions to a white dwarf currently known. We list the known lowest-mass detached companions to white dwarfs in Table 2, and the lowest-mass companions to CVs in Table 3.

Table 2. The lowest-mass detached companions to white dwarfs.

Name	Spectral types	Separation	Reference
WD 2151–015	DA+M8	23 au	1
WD 2351–335	DA+M8	2054 au	2
WD 1241–010	DA+M9	284 au	2
PG 1234+482	DA+L0±1	Unresolved	3
GD 165	DA+L4	120 au	4
GD 1400	DA+L6/7	Unresolved	5, 6
WD 0137–349	DA+L8 (0.053 $M_{\odot}$)	$0.65 R_{\odot}$ (P = 116 min)	7, 8

References. 1: Farihi, Hoard & Wachter (2006); 2: Farihi et al. (2005); 3: this work; 4: Becklin & Zuckerman (1988); 5: Farihi & Christopher (2004); 6: Dobbie et al. (2005); 7: Maxted et al. (2006); 8: Burleigh et al. (2006a).

Table 3. The lowest-mass companions to CVs

Name	Spectral types	Period	Reference
OY Car	CV+M6	91 min	1
EX Eri	CV+L0.084 $M_{\odot}$ star	∼90 min	2
SDSS 1212	DA+L8-T2	88.4 min	3, 4
SDSS 1035	CV+0.052 $M_{\odot}$ BD	82 min	5
SDSS 1507	CV+0.056 $M_{\odot}$ BD	66.61 min	6

References. 1: Wood & Horne (1990); 2: Feline et al. (2004); 3: Burleigh et al. (2006b); 4: Farihi, Burleigh & Hoard (2007); 5: Littlefair et al. (2006); 6: Littlefair et al. (2007).

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