Mon. Not. R. Astron. Soc. **000**, 1–5 (2006) Printed 13 September 2006 (MN LATEX style file v2.2)

A near-infrared spectroscopic detection of the brown dwarf in the post common envelope binary WD 0137-349

M. R. Burleigh[1] E. Hogan[1] P. D. Dobbie[1] R. Napiwotzki [2] P. F. L. Maxted[3]
[1] *Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK*
[2] *Centre for Astrophysics Research, STRI, University of Hertfordshire, College Lane, Hatfield AL10 9AB, UK*
[3] *Astrophysics Group, Keele University, Keele, Staffordshire, ST5 5BG, UK*

Accepted 2100 December 32. Received 2099 December 25; in original form 1888 October 11

ABSTRACT

We present a near-infrared spectrum of the close, detached white dwarf + brown dwarf binary WD 0137-349 (Maxted et al. 2006), that directly reveals the substellar companion through an excess of flux longwards of $\approx 1.95\mu$m. We best match the data with a white dwarf + L8 composite model. For ages ~ 1 Gyr, the spectral type of the cool secondary is in agreement with the mass determined by Maxted et al. (2006) from radial velocity measurements (0.053 ± 0.006M$_\odot$), and supports an evolutionary scenario in which the brown dwarf survived a previous phase of common envelope evolution which resulted in the formation of this close binary. The brown dwarf is the lowest mass companion to a white dwarf yet found, and the lowest mass object known to have survived a common envelope phase. At $1300 < T_{\rm eff} < 1400$ K WD 0137-349B is also the coolest known companion to a white dwarf. At a separation $a = 0.65$R$_\odot$ the hemisphere of the brown dwarf facing the $16,500$K white dwarf is being heated through irradiation. We discuss the possible effects of this additional heating, with particular relevance to those other close binaries with substellar companions, the hot Jupiters. We propose future observations to investigate the likely temperature differences between the "day" and "night" sides of the brown dwarf.

Key words: Stars: white dwarfs, low-mass, brown dwarfs

1 INTRODUCTION

Detached brown dwarf companions to white dwarfs are rare (Farihi, Becklin & Zuckerman 2005). Proper motion surveys and searches for infra-red (IR) excesses have so far found only three confirmed examples: GD 165 (DA+L4, Becklin & Zuckerman 1988), GD 1400 (DA+L6/7, Farihi & Christopher 2004; Dobbie et al. 2005), and WD 0137-349 (Maxted et al. 2006), the subject of this paper. GD 165 is a widely separated system (120 AU); the separation of the components in GD 1400 is currently unknown. In contrast, WD 0137-349 is a close binary (orbital period $P \approx 116$ minutes).

Optical spectra of the H-rich DA white dwarf WD 0137-349 show a narrow H$_\alpha$ emission line due to irradiation of the surface of the unseen companion. Radial velocities measured from this line and the white dwarf's intrinsic Hα absorption line allowed Maxted et al. (2006) to determine the mass ratio of the system. Using the white dwarf mass (0.39 ± 0.035M$_\odot$), derived from an analysis of its optical spectrum, Maxted et al. (2006) then determined the mass of the companion to be 0.053 ± 0.006M$_\odot$. This is well below the limit of 0.075M$_\odot$ commonly used to distinguish stars from brown dwarfs. The substellar nature of WD 0137-349B was reinforced by an analysis of its 2MASS near-IR JHK fluxes (Figure 2, Maxted et al. 2006). The J and H band photometry can be fit by a model consistent with the white dwarf alone. There is a slight excess of flux at $K_{\rm S}$, which can be matched by a model consisting of the white dwarf plus a brown dwarf spectral type mid-L or later. This is consistent with the radial velocity determined mass measurement for WD 0137-349B.

Therefore, WD 0137-349 is the first close, detached binary to be discovered containing a confirmed substellar companion. The brown dwarf must have survived a previous phase of common envelope (CE) evolution during which it was engulfed by the red giant progenitor of the white dwarf (Politano 2004). The drag on the brown dwarf caused it to spiral in towards the red giant core from an originally much wider orbit. Some fraction of the orbital energy was released and deposited in the envelope, which was ejected from the system, leaving a close binary. Simple physical arguments suggest that low mass companions less than some limit $m_{\rm crit}$ will be evaporated during the CE phase. WD 0137-349B places an upper limit on $m_{\rm crit}$.

Alternatively, WD 0137-349B may have originally been a planet which accreted a substantial fraction of its mass during the CE phase (Livio & Soker 1983). In this scenario, WD 0137-349B would be expected to have an effective temperature $T_{\rm eff} > 2000$K, and a spectral type (early L) commensurate with the cooling age of the white dwarf (~ 0.25 Gyr). Maxted et al. (2006) concluded that this model was probably not applicable to WD 0137-349 since the 2MASS fluxes are inconsistent with a companion earlier than mid-L. However, they suggested that a definitive test would be provided by IR spectroscopy to directly determine an accurate spectral type for the brown dwarf.

In this paper we present a near-IR spectrum of WD 0137-349. In Section 2 we discuss the observations and data reduction, in Section 3 we present our analysis of these data, and in Section 4 we discuss the results and comment on the spectral type of WD 0137-349B.

2 OBSERVATIONS AND DATA REDUCTION

We were awarded Director's Discretionary Time at the 8m Gemini South telescope in November 2005, to obtain a near-IR spectrum of WD 0137-349 with the Gemini Near-IR Spectrometer (GNIRS, Elias et al. 1998) in programme GS-2005B-DD-9. We selected the cross-dispersed mode, using the short camera, the 32 lines/mm grating centred at 1.65μm, and the $0.3''$ (2 pixels) slit, which gives a resolution $R = 1700$. In this observing mode, the entire near-IR region from $\approx 0.9\mu$m to $\approx 2.5\mu$m is covered in a single observation with excellent transmission across almost the whole wavelength range. There is no inter-order contamination as in long slit mode over a single atmospheric window, and this mode is much more efficient than executing separate H and K band observations.

The observations were conducted in service mode on the night of 2005 November 22nd. Our observing condition requirements were met: 70%-ile image quality (seeing $< 0.6''$ at J) and 50%-ile cloud cover (i.e., photometric). The observations were obtained at a mean airmass of 1.12. We took 20×120s exposures, using two "nod" positions along the $6''$ long slit giving a total exposure time of 40 minutes. This did not cause any problems of order overlap during the data reduction, since the target is a point source and the seeing was good. With overheads for detector readout etc., the observations lasted for ≈ 55 minutes, covering $\approx 47\%$ of the binary orbit. An A1 V telluric standard was also observed (HD 10538) both before and after the target, at a similar airmass.

The data were initially reduced using the GNIRS sub-package of the Gemini IRAF package. Briefly, a correction was first applied to the raw science, standard star and arc lamp spectral images for the s-distortion in the orders. The data were then flat-fielded, taking care to flat-field each order with the corresponding correctly exposed flat. Subsequently, difference pairs were assembled from the science and standard star images and any significant remaining sky background removed by subtracting linear functions, fitted in the spatial direction, from the data. The spectral orders of the white dwarfs and the standard stars were then extracted and assigned the wavelength solution derived from the relevant arc spectrum.

Unfortunately, the GNIRS IRAF routines proved inadequate for removing the telluric features from the target spectra and providing an approximate flux calibration. Instead, at this stage we utilised standard techniques offered by software routines in the STARLINK packages KAPPA and FIGARO. Any features intrinsic to the energy distribution of the standard star were identified by reference to a near-IR spectral atlas of fundamental MK standards (e.g., Wallace & Hinkle 1997; Wallace et al. 2000; Meyer et al. 1998) 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 spectral orders were then divided by the corresponding standard star spectral orders and multiplied by a blackbody with the standard star's $T_{\rm eff}$, taking into account the differences in exposure times.

We found that the flux levels of the three brightest spectral orders (number 3, covering $\approx 1.95\mu$m to $\approx 2.5\mu$m, number 4 covering $\approx 1.4\mu$m to $\approx 1.8\mu$m, and number 5 covering $\approx 1.2\mu$m to $\approx 1.35\mu$m) were well matched to each other. However, it was necessary to scale these fluxes by a single, constant normalisation factor to obtain the best possible agreement between the spectral data and the J, H and $K_{\rm S}$ photometric fluxes derived from the 2MASS All Sky Data Release Point Source Catalogue magnitudes (Skrutskie et al. 1995) where zero magnitude fluxes were taken from Zombeck (1990). The reduced GNIRS spectrum and 2MASS fluxes are shown in Figure 1.

3 ANALYSIS

We have analysed the GNIRS near-IR spectrum of WD 0137-349 following the method of Dobbie et al. (2005). We calculated a pure-hydrogen synthetic white dwarf spectrum for the temperature ($T_{\rm eff} = 16,500 \pm 500$ K) and surface gravity (log $g = 7.49 \pm 0.08$) determined by Maxted et al. (2006). We used recent versions of the plane-parallel, hydrostatic, non-local thermodynamic equilibrium (non-LTE) atmosphere and spectral synthesis codes TLUSTY (V200; Hubeny & Lanz 2001 and SYNSPEC (v48; ftp:/tlusty.gsfc.nasa.gov/synsplib/synspec). The synthetic spectral fluxes have been normalised to the white dwarf's V magnitude (15.33 ± 0.02). The synthetic white dwarf spectrum is shown overplotted the GNIRS data in Figure 1.

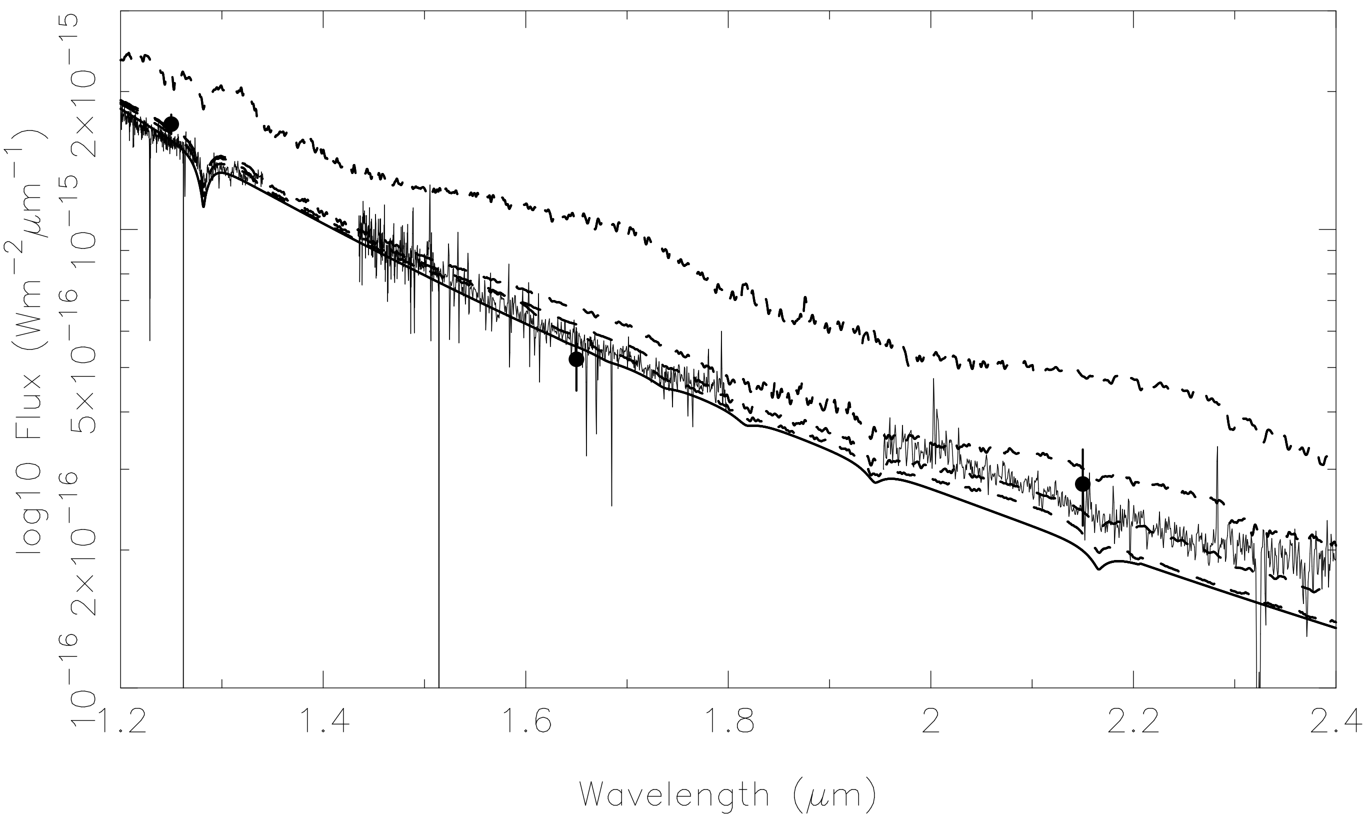
Examination of Figure 1 reveals a clear difference in the overall shape and level of the synthetic white dwarf spectrum and the observed data in the K band (below $\approx 1.95\mu$m). In contrast, we do not readily observe any spectral features typical of the energy distributions of L or T dwarfs, e.g. Na I absorption at 2.20μm, CH_4 or CO at 1.6μ and 2.3μm respectively and H_2O centred on 1.15, 1.4 and 1.9μm. We estimate the signal-to-noise ratio at 2.2μm ≈ 12.

To test whether the flux excess in the K band is due to the brown dwarf companion, and to constrain its spectral type, we have added empirical models for substellar objects to the white dwarf synthetic spectrum and compared these composites to the near-IR spectrum (Figure 1). The empirical models have been constructed using the near-IR spectra of L and T dwarfs presented by McLean et al. (2003). In brief, the data have been obtained with the NIRSPEC instrument on the Keck Telescope, cover the range 0.95μm $- 2.31\mu$m with a resolution of $\lambda/\delta\lambda \approx 2000$ and have been flux calibrated using J, H and $K_{\rm S}$ photometric fluxes derived from the 2MASS magnitudes as described by McLean et al. (2001). To extend these data out to 2.4μm, our effective red limit, we have appended to them sections of UKIRT CGS4 spectra of late-type dwarfs obtained by Leggett et al. (2001) and Geballe et al. (2002).

The fluxes of the empirical models have been scaled to a level appropriate to a location at d=10pc using the 2MASS J magnitude of each late-type object and the polynomial fits of Tinney et al. (2003) to the $M_{\rm J}$ versus spectral type for L0-T8 field dwarfs/brown dwarfs. Subsequently, these fluxes have been re-calibrated to be consistent with the distance of WD 0137-349, as derived from its measured V magnitude, effective temperature and theoretical $M_{\rm V}$ and radius.

In Figure 1 we compare the observed GNIRS near-IR spectrum of WD 0137-349 to a range of these empirical composite

Figure 1. The GNIRS spectrum of WD 0137-349 from $1.2\mu m - 2.4\mu m$ compared to a synthetic white dwarf spectrum from a pure-H model atmosphere normalized using the observed V band magnitude (solid line). Also shown are the synthetic white dwarf spectrum combined with spectra of known brown dwarfs scaled to the appropriate distance as follows (dashed lines, top-to-bottom): L0, L6, L8 and T5. Note the telluric water bands between $1.35\mu m - 1.42\mu m$ and $1.8\mu m - 1.95\mu m$ have been omitted.



white dwarf + brown dwarf models (WD+L0, L6, L8 and T5). We find the best match to the data is provided by a white dwarf + L8 composite model. The lack of an obvious CO edge at $2.3\mu m$ supports this conclusion.

4 DISCUSSION

We can estimate the temperature of the brown dwarf from its spectral type. From astrometric and photometric observations of L dwarfs Vrba et al. (2004) give the mean effective temperature of an L8 dwarf as 1390K, although they caution that their derived values should be treated as schematic results only, and note that late L and early T dwarfs appear to occupy a fairly narrow temperature range from $1200 < T_{\rm eff} < 1550$ K. The temperatures computed by Golimowski et al. (2004) for a small sample of late L and early T dwarfs are in agreement with these estimates. For example, they estimate the effective temperature of the L8 dwarf Gl 584C, whose age is constrained by its main sequence companion to $1 - 2.5$ Gyr (Kirkpatrick et al. 2001), as $1300 < T_{\rm eff} < 1400$ K.

Using the evolutionary models of Burrows et al. (1997) and their on-line calculator[1], we find that for a $0.053 M_\odot$ brown dwarf to have a temperature in the range $1300 < T_{\rm eff} < 1400$ K it must be ~ 1.0 Gyr old. The COND models of Baraffe et al. (2003) also suggest that this mass and temperature range are consistent only for a cooling age ~ 1.0 Gyr.

The low temperature of WD 0137-349B therefore supports the conclusion of Maxted et al. (2006) that it is an old brown dwarf that survived a phase of CE evolution some ≈ 0.25 Gyr ago, and does not support the rather more exotic evolutionary scenario of Livio & Soker (1983) in which a lower mass planet or brown dwarf accreted substantial mass during the CE. In that case the temperature would be substantially higher ($T_{\rm eff} > 2000$ K) and the spectral type would be early L.

If the brown dwarf is ~ 1.0 Gyr old, then the main sequence lifetime of the white dwarf progenitor was ≈ 0.75 Gyr, in which case the progenitor's mass was just over $2M_\odot$. During the CE phase, some fraction of the orbital energy released, $\alpha_{\rm CE}$, will be deposited as kinetic energy in the envelope, which is ejected from the binary. A progenitor mass of $2M_\odot$ requires a value of $\alpha_{\rm CE} > 2$ to explain the formation of the WD 0137-349 system. However, we note that the cooling age of the brown dwarf does not necessarily set an upper limit on the system age, since it may have been reheated during the immediate post-CE phase when the white dwarf was very hot. The system may be older, in which case the white dwarf progenitor mass and the required value of $\alpha_{\rm CE}$ are lower.

The brown dwarf hemisphere facing the $16,500$K white dwarf is currently intercepting $\approx 1\%$ of its light. This irradiation is seen as weak Hα emission in the optical spectrum. Therefore, WD 0137-349 is an interesting system for studying the effects of irradiation on the atmosphere of a substellar object, and can potentially be used as a comparison for differ-

[1] http://zenith.as.arizona.edu/~burrows/cgi-bin/browndwarf3.cgi

ent theoretical models of the effects of irradiation on lower-mass hot Jupiters. The heated atmospheres of the transiting planets HD 209458b and TrES-1 have both been detected by the *Spitzer Space Telescope* in the mid-IR during secondary eclipse (Deming et al. 2005, Charbonneau et al. 2005). Irradiation can increase the photospheric temperature by an order of magnitude compared to isolated planets, decrease the cooling rate and alter the planet's radius and atmospheric structure (e.g. Guillot et al. 1996, Baraffe et al. 2003, Arras & Bildsten 2006). Severe irradiation could even lead to atmospheric evaporation (Baraffe et al. 2004), for which evidence has been found through the discovery of an extended atmosphere for HD 209458b (Vidal-Madjar et al. 2003; Vidal-Madjar et al. 2004). In these synchronously rotating systems, substantial temperature differences are expected between the "day" and "night" sides, possibly leading to strong winds transporting heat to the "night" side (Showman & Guillot 2002, Barman, Hauschildt & Allard 2005). Similar effects may occur for more massive brown dwarfs (Hubeny, Burrows & Sudarsky 2003).

Neglecting the contribution from the intrinsic luminosity of the brown dwarf, and assuming it is in thermal equilibrium with the stellar radiation, we can use the relation given by Arras & Bildsten (2006) to estimate the "equilibrium" temperature of the irradiated hemisphere:

$$T_{\rm eq} = T_*(R_*/2a)^{1/2} \quad (1)$$

Taking the white dwarf radius ($R_{\rm WD} = 0.0186{\rm R}_\odot$) and binary separation ($a = 0.65{\rm R}_\odot$) given by Maxted et al. (2006), we estimate the equilibrium temperature of the heated face of the brown dwarf to be $T_{\rm eq} \approx 2000$K. For ages ~ 1 Gyr, the spectral type of an object of this temperature would be early L. Clearly, we are not seeing a hemisphere at this temperature in our data. The GNIRS spectrum was obtained across 47% of the orbital period, so it is slightly possible that the heated face has not been observed. However, the 2MASS photometry are also not in agreement with a temperature this high, although the phase at which they were obtained is unknown. Eq. (1) assumes zero reflection of the stellar photons, and should be multiplied by $(1-A)^{1/4}$ for an albedo A (assuming isotropic emission from the brown dwarf). Substituting our estimated temperature of WD 0137-349B from the GNIRS spectrum ($T_{\rm eff} = 1300$K) for $T_{\rm eq}$ in Eq. (1), we find a high albedo $A \approx 0.8$. For comparison, Charbonneau et al. (2005) find that TrES-1 appears to be absorbing a high fraction of the incident stellar flux ($A \approx 0.3$), although we note that the spectrum of the light falling on the surface of WD 0137-349B is very different to that falling on a hot Jupiter.

None-the-less, there is likely some heating of the hemisphere facing the white dwarf. A fraction of the observed flux could originate from the heated face. This could mean that the underlying brown dwarf temperature might be lower than 1300K, and the deduced age should then be regarded as a lower limit.

We suggest that time series K-band photometry should reveal variability due to temperature differences between the "day" and "night" sides. *Spitzer* mid-IR observations should also reveal such temperature variations, allowing us to characterize the photometric properties of the brown dwarf WD 0137-349B across the whole orbit.

5 CONCLUSIONS

We have obtained a near-IR spectrum of the close, detached white dwarf + brown dwarf binary WD 0137-349 that reveals the substellar companion through an excess of flux longwards of $\approx 1.95\mu$m. We best match the data with a white dwarf + L8 composite model. This is the lowest mass, coolest and latest spectral type companion to a white dwarf yet discovered. For a cooling age ~ 1.0 Gyr, the temperature of the secondary ($1300 < T_{\rm eff} < 1400$ K) is in agreement with the mass determined by Maxted et al. (2006) from radial velocity measurements ($0.053 \pm 0.006{\rm M}_\odot$), and supports an evolutionary scenario in which the brown dwarf survived a previous phase of CE evolution ≈ 0.25 Gyr ago, which resulted in the formation of this close binary. The exotic alternative evolutionary scenario of Livio & Soker (1983), in which a lower mass planet or brown dwarf accreted substantial mass during the CE phase, is not supported. If the brown dwarf is ~ 1.0 Gyr old, then the main sequence lifetime of the white dwarf progenitor was ≈ 0.75 Myr and its mass was just over $2{\rm M}_\odot$, requiring a value of the CE parameter $\alpha_{\rm CE} > 2$ to explain the formation of the system. However, the brown dwarf may be older if it was re-heated by the very hot white dwarf immediately after the CE phase. The brown dwarf hemisphere facing the $16,500$K white dwarf is currently intercepting $\approx 1\%$ of its light, but does not appear to be substantially heated, although our spectroscopic observations only cover ≈ 0.5 of the orbital period.

6 ACKNOWLEDGMENTS

This paper was based on observations under programme GS-2005B-DD-9 obtained at the Gemini South Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the Particle Physics and Astronomy Research Council (PPARC, United Kingdom), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), CNPq (Brazil) and CONICET (Argentina).

MRB & RN acknowledge the support of PPARC Advanced Fellowships. EH acknowledges the support of a PPARC postgraduate studentship. PDD is also supported by PPARC. We thank Richard Jameson for illuminating discussions on the nature of WD 0137-359B. We thank the staff of the Gemini Observatory, and Phil Lucas (University of Hertfordshire, UK) for their advice and assistance with the GNIRS data reduction. We thank the referee, Kelle Cruz, for her timely and constructive comments.

REFERENCES

Arras P., Bildsten L., 2006, ApJ, in press
Baraffe I., Chabrier G., Barman T. S., Allard F., Hauschildt P. H., 2003, A&A, 402, 701
Baraffe I., Selsis F., Chabrier G., Barman T. S., Allard F., Hauschildt P. H., Lammer H., 2004, A&A, 419, L13
Barman T. S., Hauschildt P. H., Allard F., 2005, ApJ, 632, 1132
Becklin E. E., Zuckerman B., 1988, Nature, 336, 656
Burrows A., et al., 1997, ApJ, 491, 856
Charbonneau D., et al., 2005, ApJ, 626, 523
Deming D., Seager S., Richardson L. J., Harrington J., 2005, Nature, 434, 740
Dobbie P. D., Burleigh M. R., Levan A. J., Barstow M. A., Napiwotzki R., Holberg J. B., Hubeny I., Howell S. B., 2005, MNRAS, 357, 1049
Elias J. H., et al., 1998, SPIE, 3354, 555

Farihi J., Becklin E. E., Zuckerman B., 2005, ApJS, 161, 394
Farihi J., Christopher M., 2004, AJ, 128, 1868
Geballe T. R., et al., 2002, ApJ, 564, 466
Golimowski D. A., et al., 2004, AJ, 127, 3516
Guillot T., Burrows A., Hubbard W. B., Lunine J. I., Saumon D., 1996, ApJ, 459, L35
Hubeny I., Burrows A., Sudarsky D., 2003, ApJ, 594, 1011
Hubeny I., Lanz T., 2001, ApJ, 439, 875
Kirkpatrick J. D., Dahn C. C., Monet D. G., Reid I. N., Gizis J. E., Liebert J., Burgasser A. J., 2001, AJ, 121, 3235
Leggett S. K., Allard F., Geballe T. R., Hauschild P. H., Schwietzer A., 2001, ApJ, 548, 908
Livio M., Soker N., 1983, A&A, 125, L12
Maxted P. F. L., Napiwotzki R., Dobbie P. D., Burleigh M. R., 2006, Nature, 422, 543
McLean I. S., McGovern M. R., Burgasser A. J., Kirkpatrick J. D., Prato L., Kim S. S., 2003, ApJ, 596, 561
McLean I. S., Prato L., Kim S. S., Wilcox M. K., Kirkpatrick J. D., Burgasser A., 2001, ApJ, 561, L115
Meyer M. R., Edwards S., Hinkle K. H., Strom S. E., 1998, ApJ, 508, 397
Politano M., 2004, ApJ, 604, 817
Showman A. P., Guillot T., 2002, A&A, 385, 166
Skrutskie M. F., et al., 1995, in Garzon F., et al. eds, The Impact of Large Scale Near-IR Sky Surveys . Kluwer, Dordrecht, p. 25
Tinney C. G., Burgasser A. J., Kirkpatrick J. D., 2003, AJ, 126, 975
Vidal-Madjar A., et al., 2004, ApJ, 604, L69
Vidal-Madjar A., Lecavelier des Etangs A., Dsert J.-M., Ballester G. E., Ferlet R., Hbrard G., Mayor M., 2003, Nature, 422, 143
Vrba F. J., et al., 2004, AJ, 127, 2948
Wallace L., Hinkle K., 1997, ApJS, 111, 445
Wallace L., Meyer M. R., Hinkle K., Edwards S., 2000, ApJ, 535, 325
Zombeck M. V., 1990, Handbook of Astronomy and Astrophysics. Cambridge Univ. Press, UK