Low Mass Companions to White Dwarfs

J. Farihi[1,2], B. Zuckerman[2], and E.E. Becklin[2]

[1] Gemini Observatory, Northern Operations, 670 North A'ohoku Place, Hilo, HI 96720
[2] Department of Physics & Astronomy, University of California, 430 Portola Plaza, Los Angeles, CA 90095

Abstract. This paper summarizes the results of over 17 years of work searching for low mass stellar and substellar companions to more than 370 nearby white dwarfs. Roughly 60 low mass, unevolved companions were found and studied all together, with over 20 discovered in the last few years, including the first unambiguous brown dwarf companion to a white dwarf, GD 1400B. The resulting spectral type distributions for companions to white dwarfs and nearby cool field dwarfs are compared, and the implications for binary star formation are discussed. A brief analysis of GD 1400B, including new data, is also presented.

arXiv:astro-ph/0509165 v1   7 Sep 2005

1. Introduction

Searching for brown dwarfs as companions to stars offers the opportunity to search systems near to Earth and requires less time than field or cluster searches covering a relatively large portion of the sky. The first serious brown dwarf candidate was discovered as a companion to the white dwarf GD 165 (Becklin & Zuckmerman 1988). GD 165B ($M \sim 0.072$ $M_\odot$, $T_{\rm eff} = 1900$ K) remained unique for a number of years but eventually became the prototype for a new spectral class of cool stars and brown dwarfs, the L dwarfs. The first unambiguous brown dwarf was also discovered as a companion to a star, Gl 229 (Nakajima et al. 1995). Gl 229B ($M \sim 0.040$ $M_\odot$, $T_{\rm eff} = 950$ K) became the prototype T dwarf, the coolest known spectral class, all of whose members are brown dwarfs.

The study of low mass stellar and substellar companions to white dwarfs yields useful information regarding the initial mass function near the bottom of the main sequence and below, the overall binary fraction of intermediate mass stars, the long term stability and survivability of low mass objects in orbit about post-asymptotic giant branch stars, and has a few advantages over similar searches around main sequence stars (Zuckerman & Becklin 1987; 1992; Schultz et al. 1996; Farihi 2004; Farihi et al. 2005).

Correspondence to: jfarihi@gemini.edu

This paper summarizes results for 371 white dwarfs which were searched for low luminosity companions using near-infrared imaging arrays at several facilities (mainly Steward, Keck, & IRTF) over the past 17+ years. For full details on the survey, including data acquisition, reduction and analyses, comprehensive information on all targets, photometry and spectra of companions as well as extensive notes on individual objects and systems, the interested reader is referred to Farihi (2004); Farihi et al. (2005).

2. A Kinematically Young White Dwarf Sample

The white dwarf targets selected for the survey were taken almost exclusively from McCook & Sion (1987; 1999). In general, the selection was guided by: (1) proximity to the Earth; (2) small to moderate proper motions; (3) youth indicators such as mass, temperature, or cluster membership. Selecting nearby targets has obvious sensitivity advantages over more distant targets of a similar nature, while selecting white dwarfs with relatively smaller proper motions aimed to cull a sample that is not kinematically old (i.e. not thick disk stars).

Figure 1 displays the Galactic UVW space motions for the entire sample of white dwarfs (assuming zero radial velocity for uniform treatment), plotted together with contours for old, metal-poor disk stars. The sample white dwarfs have kinematics offset from the thick disk, and centered about
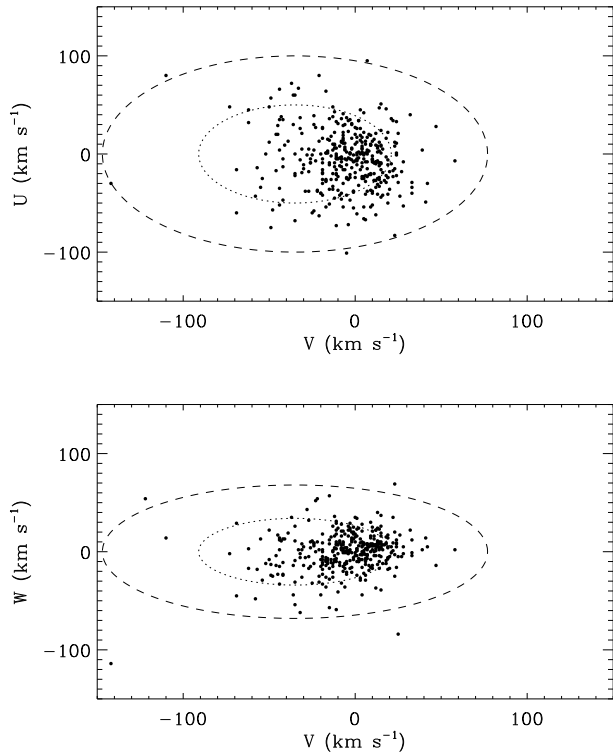
Fig. 1. Galactic space velocity distribution in the UV and WV planes for all 371 white dwarfs in the sample, assuming $v_r = 0$. The ellipses represent the 1 and 2 σ contours for old, metal-poor disk stars from Beers et al. (2000)

zero in UVW - values that represent the undisturbed circular Galactic disk orbits of younger stars (Mihalas & Binney 1981; Binney & Merrifield 1998).

Comparing the resulting kinematical statistics of the white dwarf sample with values for stellar populations of known ages, from $Hipparcos$ measurements of nearby stars, yields additional evidence that the white dwarf sample contains young disk stars (see Farihi 2004; Farihi et al. 2005). The average UVW, their dispersions, and the total velocity dispersion values of the entire sample are consistent with those of disk stars of intermediate age ($\tau = 2 - 5$ Gyr), but inconsistent with stars of age $\tau = 5$ Gyr due to the relatively small negative value of $\langle V \rangle$ (Wielan 1974; Jahreiß & Wielen 1997). In fact, a subsample of 330 white dwarfs with $\mu < 0.50''$ yr^{-1}, is quite consistent with stars of age $\tau \sim 2$ Gyr (Wielan 1974; Jahreiß & Wielen 1997).

Are the cooling ages of the sample white dwarfs consistent with a relatively young disk population? Is the $2 - 5$ Gyr total age range estimate significantly greater than the typical sample white dwarf's cooling age? Exactly 90% of the sample stars have temperatures above 8000 K – implying cooling ages less than 1.1 Gyr for typical hydrogen atmosphere white dwarfs (Bergeron et al. 1995). Moreover, 67% of the sample stars have temperatures above 11,500 K and hence typical cooling ages less than 0.4 Gyr. Therefore the cooling ages of the sample stars are consistent with the total age estimate inferred from kinematics – that of a relatively young disk population.

Since one does not know the main sequence progenitor ages for the white dwarf sample, caution must be taken not to over interpret the kinematical results. In principle, any individual star of any age can have any velocity. While the sample white dwarf cooling ages are consistent with young disk objects, a conservative approach would be to explore a range of ages when interpreting the implications of the survey results. Realistically, a typical white dwarf in the sample is likely to be between $\tau = 2 - 5$ Gyr old.

3. Initial Mass Function for Companions

The completeness limits are listed in Table 1 for a typical sample white dwarf at the average distance of 57 pc and a total age of 3 Gyr. The sensitivity was often greater than these conservative limits, especially at closer distances and for younger ages. In Figure 2 is plotted the number of unevolved low mass companions versus spectral type for objects studied in this work. Despite excellent sensitivity to late M dwarfs and early L dwarfs at all telescopes, very few were detected. Additionally, both M & L dwarfs were detectable at arbitrarily close separations as excess near-infrared emission (Farihi 2004, Farihi et al. 2005), whereas T dwarfs were only detectable as resolved, wide companions.

For comparison, Figure 3 shows similar statistics for cool field dwarfs within 20 pc of Earth taken from Reid & Hawley (2000); Cruz et al. (2003). The data plotted in Figure 3 have been corrected for volume, sky coverage, and estimated completeness. Can one reconcile Figure 3 with the common notion that there are at least as many brown dwarfs as low mass stars (Reid et al. 1999)? To resolve this possible discrepancy, most field brown dwarfs would have to be of spectral type T or later, since it is clear from the figure that, in the field, L dwarfs are much less common than stars.

However, there are several things to keep in mind regarding the relative number of field brown dwarfs versus stars. There should be a relative dearth of L dwarfs compared to T type and cooler brown dwarfs in the field because cooling brown dwarfs pass through the L dwarf stage relatively rapidly. The lower end of the substellar mass function is poorly constrained at present (Burgasser 2004) and the relative number of substellar objects versus low mass stars in the field depends on the shape of the mass function in addition to the unknown minimum mass for self-gravitating substellar objects (Reid et al. 1999; Burgasser 2004). Furthermore, even for only moderately rising mass functions, such as those measured for substellar objects in open clusters (Hillenbrand & Carpernter 2000; Luhman et al. 2000; Hambly et al. 1999; Bouvier et al. 1998), there will be more brown dwarfs than stars if the minimum self-gravitating substellar mass is $< 0.010 \, M_\odot$. Ongoing and future measurements of the local T dwarf space density will constrain the substellar field mass function.

Figures 2 & 3 are quite similar. Clearly, the peak frequency in spectral type occurs around M3.5 for both field dwarfs and companions to white dwarfs. In fact, the peak is

Table 1. Survey Completeness for $d = 57$ pc, $\tau = 3$ Gyr

Survey	a_{in} (AU)	a_{out} (AU)	m_{abs} (mag)	SpT	M ($M_{\odot}$)	N
IRTF	0	700	$M_K = 12.2$	L6	0.065	82
Steward	110	4700	$M_J = 14.2$	L7	0.060	261
Keck	55	1100	$M_J = 17.2$	T9[†]	0.030	86
All	0	110	$M_H = 13.5$	L8	0.058	371

[†] No objects are known with spectral type later than T8. However, the average limiting magnitude of the Keck survey probed ~ 1.5 magnitudes deeper than that of any known brown dwarf (Vrba et al. 2004; Legget et al. 2002).

This table presents only average separations and sensitivities. The actual values depend on each individual white dwarf distance and age. The "All" entry refers to detection in 2MASS of an H band excess above that expected from the white dwarf photosphere (see Farihi 2004; Farihi et al 2005).

identical; 25.6% for both populations. By itself, this could imply a common formation mechanism, a companion mass function similar to the field mass function in this mass range, approximately $0.15 - 0.60$ $M_{\odot}$ for spectral types M0−M5 (Farihi 2004, Farihi et al. 2005). But, relative to the peak, there are $\sim 2 - 3$ times more L dwarfs and $\sim 4 - 5$ times more M6−M9 dwarfs in the field than companions. For the T dwarf regime, uncertainty remains because only the Keck portion of the white dwarf survey was sensitive to such cool brown dwarfs (and only for certain separations) plus the current incomplete determination of the field population density.

Hence, binary systems with small mass ratios ($q = M_2/M_1 < 0.05$) are rare for white dwarf progenitors (which typically have main sequence masses ~ 2 $M_{\odot}$). Although there exists some speculation regarding the possibility that brown dwarfs are ejected in the early stages of multiple system or cluster formation, there is currently no evidence of this occurring. It is conceivable that low mass companions in very wide orbits may be lost to gravitational encounters in the Galactic disk over a few billion years, but given the fact that there are a dozen or so known L and T dwarfs in wide binaries, this seems like a rare mechanism, if it occurs at all.

In a way, the relative dearth of late M dwarfs alleviates a potential interpretation problem. Had it been the case that many late M dwarfs were detected but only one or two L dwarfs, it might have been argued that the L dwarfs were cooling beyond the sensitivity of the search. Since all M dwarfs (and the first few L dwarf subclasses) at $\tau \geq 1$ Gyr are stellar according to theory, this concern does not exist. The measured dearth is real and is not caused by brown dwarf cooling and the resulting lower sensitivity.

4. GD 1400B

Discovered 17 years after GD 165B (Becklin & Zuckerman 1988), GD 1400B is a long sought datum in the search for low mass companions to white dwarfs (Farihi 2004; Farihi et al. 2005). Little is known about the probable white dwarf plus brown dwarf spectroscopic binary, GD 1400. The cool
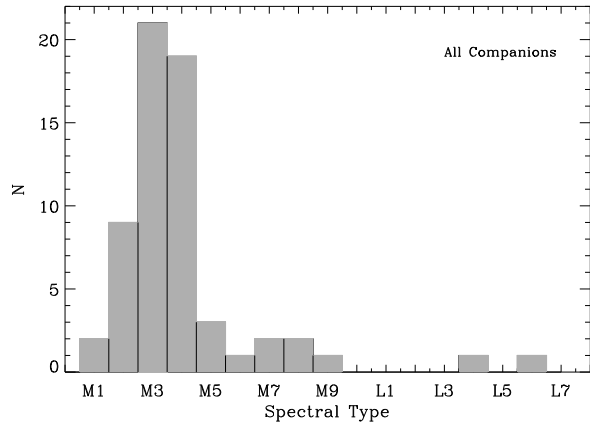
Fig. 2. The number of cool dwarf companions versus spectral type for objects discovered and studied in the search.
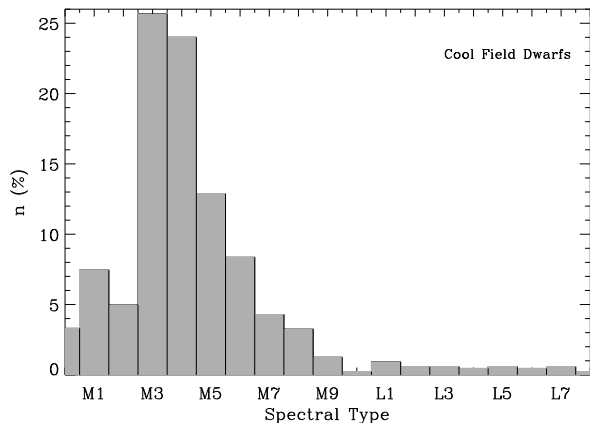
Fig. 3. The frequency of cool field dwarfs within $d = 20$ pc versus spectral type (Reid & Hawley 2000; Cruz et al. 2003). The data have been corrected for volume, sky coverage, and estimated completeness.

companion was discovered, then confirmed, through photometric excess and subsequent spectroscopy in the 2.2μm region (Farihi & Christopher 2004). Its apparent lack of excess emission at 1.2μm implies that GD 1400B has a spectral type of L5.5 or later and the lack of Na in its K band spectrum indicates it cannot be an early L dwarf. Utilizing the best available data on the white dwarf primary to assess its distance and to account for its contribution at near-infrared wavelengths, the absolute magnitude of GD 1400B would place it around spectral type L6 (Farihi & Christopher 2004). Subsequently, an independent spectroscopic study estimated GD 1400B at spectral type L7 through simultaneous fits of the white dwarf and brown dwarf components in an HK grism observation, with model and empirical template spectra respectively (Dobbie et al. 2005).

GD 1400 has been observed with *Spitzer*/IRAC at $3 - 8\mu$m as part of an ongoing program searching for substellar companions to nearby white dwarfs. The IRAC measurements of GD 1400 presented in Figure 4 have S/N > 15 at all wavelengths. The deconvolved magnitudes of GD 1400B

imply $2 - 8\mu$m colors consistent with a spectral type of L5 or later, corroborating previous findings by alternate methods (Patten et al. 2004; Farihi et al. 2005, submitted).
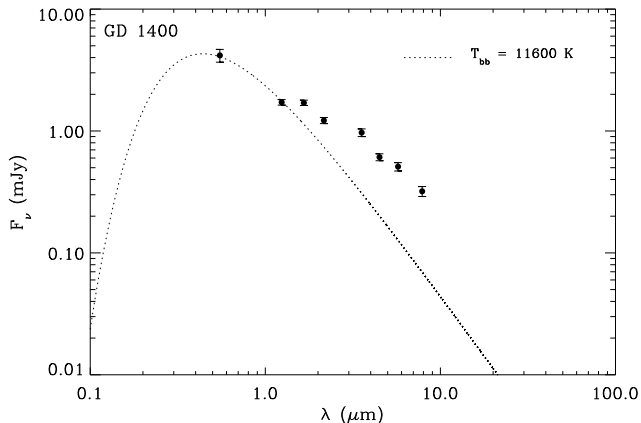

Fig. 4. Spectral energy distribution of GD 1400, demonstrating the presence of the spatially unresolved cool brown dwarf companion. Optical and near-infrared data ($VJHK$) are from Farihi & Christopher (2004)

Because GD 1400AB has yet to be spatially resolved (Farihi & Christopher 2004), it remains possible that this spectroscopic binary is a radial velocity variable. It is perhaps more likely the system resides in close orbit due to the fact that post-asymptotic giant branch (AGB) evolution predicts a bimodal distribution of orbital semimajor axes for low mass, unevolved companions to white dwarfs (Farihi 2004). Specifically, companions close enough to orbit within the AGB envelope should spiral inward due to transfer of orbital energy into the envelope via friction, while those outside the envelope should spiral outward due to weakened gravity from mass loss (Zuckerman & Becklin 1987; Burleigh et al. 2002; Farihi 2004).

Further radial velocity monitoring of the white dwarf in the optical and/or its companion in the near-infrared, or high resolution ground- or space-based imaging should eventually reveal the nature of the current orbital separation of the binary. Resolving the pair would be advantageous because the companion could be directly studied. On the other hand, it would be fortuitous if the system were a radial velocity variable because then the mass and radius of the secondary could be estimated. Currently, there is only a single L dwarf (binary) system with a mass measurement (Bouy et al. 2004), and no mass estimates for old brown dwarfs. There exist two independent and reliable spectroscopic fits of $T_{\rm eff}$ and log g for GD 1400A, and hence the mass of the white dwarf is fairly well constrained near $M \approx 0.7 M_\odot$. A trigonometric parallax and high precision optical photometry would tighten up the primary mass estimate, making any secondary mass determination more reliable.

Determining the orbital parameters of this so far unique binary is critical to understanding the origin and evolution of the brown dwarf secondary. It is likely that the system formed as a extreme low mass ratio binary ($M_2/M_1 \approx 0.02$; Farihi & Christopher 2004), but it is conceivable that the companion formed in a massive disk around a ~ 3 $M_\odot$ main sequence star. There have been several substellar companions detected around K giants (Frink et al. 2002; Mitchell et al. 2003), which are the descendents of main sequence A & F stars. Presumably, these substellar companions formed in their respective primary progenitor disks based on their current orbital semimajor axes. Will these brown dwarfs survive the current first ascent and ensuing asymptotic giant branches to become companion systems similar to GD 1400? Although complete evaporation or inspiral collision with the stellar core is possible inside the AGB envelope, the higher mass brown dwarfs around these K giants may persist, as has GD 1400B, either by eschewing the greatly expanded photosphere or simply surviving the envelope itself (Farihi et al. 2005, submitted).

5. Conclusions

Together, the various phases of this survey discovered over 40 previously unrecognized white dwarf binary and multiple systems. The search conducted at Steward Observatory alone discovered at least 20 new white dwarf multiple systems. Based on the analysis of Farihi (2004); Farihi et al. (2005) there is no reason why all unevolved secondary stars should not be included in any initial companion mass function, for which Figure 2 is a good proxy (see Farihi 2004; Farihi et al. 2005 for details).

The calculated fraction of white dwarfs with substellar companions, within the range of masses and separations to which this work was sensitive, is $f_{bd} = 0.4 \pm 0.1\%$. This represents the first measurement of the low mass tail of the companion mass function for intermediate mass stars, main sequence A and F stars (plus relatively few B stars) with masses in the range 1.2 $M_\odot < M < 8$ $M_\odot$. This value is consistent with similar searches around solar type main sequence stars for comparable sensitivities in mass and separation (Oppenheimer et al. 2001; McCarthy & Zuckerman 2004). Therefore that the process of star formation eschews the production of binaries with $M_2/M_1 < 0.05$ is clear from the relative dearth of both L and late M dwarfs discovered in this work.

References

Becklin, E., & Zuckerman, B. 1988, Nature, 336, 656

Beers, T., Chiba, M., Yoshii, Y., Platais, I., Hanson, R., Fuchs, B., & Rossi, S. 2000, AJ, 119, 2866

Bergeron, P., Saumon, D., & Wesemael, F. 1995b, ApJ, 443, 764

Binney, J., & Merrifield, M. 1998, in Galactic Astronomy, (New Jersey: Princeton)

Bouvier, J., Stauffer, J., Martín, E., Barrado y Navascués, D., Wallace, B., & Béjar, V. 1998, A&A, 336, 490

Bouy, H., et al. 2004, A&A, 423, 341

Burgasser, A. 2004, ApJS, 155, 191

Burleigh, M., Clarke, F., & Hodgkin, S. 2002, MNRAS, 331, L41

Cruz, K., Reid, I., Liebert, J., Kirkpatrick, J., & Lowrance, P. 2003, AJ, 126, 2421

Dobbie, P., Burleigh, M., Levan, A., Barstow, M., Napiwotzki, R., Holberg, J., Hubeny, I., & Howell, S. 2005, MNRAS, 357, 1049

Farihi, J., Becklin, E.E., & Zuckerman, B. 2005, ApJS, in press

Farihi, J. 2004, Ph.D. Thesis, University of California, Los Angeles

Farihi, J., & Christopher, M. 2004, AJ, 128, 1868

Frink, S., Mitchell, D., Quirrenbach, A., Fischer, D., Marcy, G., & Butler, R. 2002, ApJ, 576, 478

Hambly, N., Hodgkin, S., Cossburn, M., & Jameson, R. 1999, MNRAS, 303, 835

Hillenbrand, L., & Carpenter, J. 2000, ApJ, 540, 236

Jahreiß, H., & Wielen, R. 1997, Hipparcos '97, ed. B. Battrick (Noordwijk: ESA), 675

Leggett, S., et al. 2002, ApJ , 564, 452

Luhman, K., Rieke, G., Young, E., Cotera, A., Chen, H., Rieke, M., Schneider, G., & Thompson, R. 2000, ApJ, 540, 1016

McCarthy, C., & Zuckerman, B. 2004, AJ, 127, 2871

McCook, G., & Sion, E. 1987, ApJS, 65, 603

McCook, G., & Sion, E. 1999, ApJS, 121, 1

Mihalas, D., & Binney, J. 1981, in Galactic Astronomy, (San Francisco: W. H. Freeman & Co.)

Mitchell, D., Frink, S., Quirrenbach, A., Fischer, D., Marcy, G., Butler, R., 2003, BAAS, 203, 1703

Nakajima, T., Oppenheimer, B., Kulkarni, S., Golimowski, D., Matthews, K., & Durrance, S. 1995, Nature, 378, 463

Oppenheimer, B., Golimowski, D., Kulkarni, S., Matthews, K., Nakajima, T., Creech-Eakman, M., & Durrance, S. 2001, AJ, 121, 2189

Patten, B., et al. 2004, BAAS, 36, 1353

Reid, I., & Hawley, S. 2000, in New Light on Dark Stars, (New York: Springer)

Reid, I., et al. 1999, ApJ, 521, 613

Schultz, G., Zuckerman, B., & Becklin E. 1996, ApJ, 460, 402

Vrba, F., et al. 2004, AJ, 127, 2948

Wielen, R. 1974, Highlights of Astronomy, Volume 3, (Dordrecht: D. Reidel), 395

Zuckerman, B., & Becklin, E. 1987, ApJ, 319, 99

Zuckerman, B., & Becklin, E. 1992, ApJ, 386, 260