Detection limits for close eclipsing and transiting sub-stellar and planetary companions to white dwarfs in the WASP survey

F. Faedi[*,†], R. G. West[†], M. R. Burleigh[†], M. R. Goad[†] and L. Hebb[**,‡]

[*]*Astrophysics Research Centre, School of Mathematics and Physics, Queens University, Belfast, BT7 1NN, U.K.*
[†]*Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH, U.K.*
[**]*Department of Physics and Astronomy, Vanderbilt University, Nashville, TN 37235, U.S.A.*
[‡]*School of Physics and Astronomy, University of St. Andrews, North Haugh, Fife, KY16 9SS, U.K.*

Abstract.
We used photometric data from the WASP (Wide-Angle Search for Planets) survey to explore the possibility of detecting eclipses and transit signals of brown dwarfs, gas giants and terrestrial companions in close orbit around white dwarfs. We performed extensive Monte Carlo simulations and we found that for Gaussian random noise WASP is sensitive to companions as small as the Moon orbiting a V ∼12 white dwarf. For fainter stars WASP is sensitive to increasingly larger bodies. Our sensitivity drops in the presence of co-variant noise structure in the data, nevertheless Earth-size bodies remain readily detectable in relatively low S/N data. We searched for eclipses and transit signals in a sample of 194 white dwarfs in the WASP archive however, no evidence for companions was found. We used our results to place tentative upper limits to the frequency of such systems. While we can only place weak limits on the likely frequency of Earth-sized or smaller companions; brown dwarfs and gas giants (radius$\simeq$ R_{jup}) with periods $\leq$0.2 days must certainly be rare ($<$ 10%). More stringent constraints requires significantly larger white dwarf samples, higher observing cadence and continuous coverage. The short duration of eclipses and transits of white dwarfs compared to the cadence of WASP observations appears to be one of the main factors limiting the detection rate in a survey optimised for planetary transits of main sequence stars.

Keywords: methods: data analysis stars: white dwarfs stars: planetary systems occultations
PACS: 97.82.Cp, 97.82.Fs

INTRODUCTION

The transit technique involves searching for periodic dips in stellar light-curves due to the orbital revolution of a transiting body, blocking a fraction of the stellar light. For a given planetary radius, the transit depth (δ) is proportional to $(R_{pl}/R_*)^2$. Therefore, planets orbiting solartype stars have extremely shallow eclipses, blocking ∼1% of the light for a giant planet and ∼0.01% of the light for an Earth-sized planet. Current ground-based wide-field surveys can achieve the necessary photometric accuracy of better than 1%, only for the brightest stars (V ∼9-12 in the case of WASP), so the bulk of the planets discovered by transit surveys around main-sequence stars have radii in the range R_{pl} $\sim 0.8-1.8$ R_{jup}. A strong advantage over main sequence star primaries is offered by white dwarf stars. White dwarfs (WD) are compact degenerate objects, with approximately the same radius as the Earth, and represent the final stage of evolution of main-sequence stars with masses $< 8M_\odot$ (i.e. ∼97% of all stars in our Galaxy). Any sub-stellar or gas giant companion in orbit around a white dwarf will completely eclipse it, while bodies as small as the Moon will have relatively large transit depths ($\sim$ 3%), with the only caveat being that it remains unclear as to whether any such systems survive beyond the latter stages of stellar evolution.

Sub-stellar companions to white dwarfs are rare (Farihi et al. 2005 using 2MASS estimated that $< 0.5\%$ of WDs have L dwarf companions). At the time of writing only three wide white dwarf + brown dwarf (WD+BD) systems have been spectroscopically confirmed, GD 165 (Becklin and Zuckerman 1988), PHL5038 (Steele et al. 2009), and LSPM $1459+0857$ AB (Day-Jones et al. 2010) and two detached, non-eclipsing, short-period WD+BD systems are currently known, WD$0137-349$ (Maxted et al. 2006, Burleigh et al. 2006, P$\approx$116mins), and GD1400 (Farihi and Christopher 2004, Dobbie et al. 2005, Burleigh et al. 2010, P$\approx$9.9h). The latter, is currently the lowest mass ($\sim$50M_{jup}) object known to have survived CE evolution. Although infrared surveys such as UKIDSS, VISTA and WISE, and observatories such as Spitzer hope to reveal many more such binaries, they remain difficult to identify either as infra-red excesses or through radial velocity measurements. In addition the detection of a significant number of eclipsing WD+BD binary systems might help uncover the hypothesised population of 'old' cataclysmic variables (CVs) in which the companion has been reduced to a sub-stellar mass (e.g. Patterson 1998; Patterson et al. 2005; Littlefair et al. 2003). These systems are undetectable as X-ray sources and difficult to identify in optical and infra-red surveys. Littlefair et al. (2006) confirmed the first such system through eclipse measurements, while Littlefair et al. (2007) showed that another eclipsing CV, SDSS J$150722.30+523039.8$, was formed directly from a detached WD+BD binary.

Several theoretical studies discuss post-main sequence evolution of planetary systems and show that planetary survival is not beyond possibility (Duncan and Lissauer 1998; Debes and Sigurdsson 2002; Burleigh et al. 2002; and Villaver and Livio 2007). Radial velocity observations of red giants indicate that planets in orbits beyond the red giant's envelope can survive stellar evolution to that stage (see Frink et al. 2002; Hatzes et al. 2005, Sato et al. 2003). Moreover, Silvotti et al. (2007) reported the detection of a $\sim$3M_{jup} planet orbiting an extreme horizontal branch star, and Mullally et al. (2008) found convincing evidence of a 2M_{jup} planet in a 4.5 year orbit around a pulsating WD. Furthermore, Beuermann et al. (2010) reported the detection of two planetary companions (M_c=6.9M_{Jup} and M_d=2.2M_{Jup}) in the post common envelope binary NN Ser (ab) via measurements of a light-travel-time effect superposed on the linear ephemeris of the binary; showing that planets do survive stellar evolution.

Short-period rocky companions to white dwarfs may seem less likely. Villaver and Livio (2007) suggested that planets in orbit within the reach of the AGB envelope will either evaporate or in rare cases, more massive bodies may accrete mass and become close companions to the star. Planets in wide orbits that escape engulfment by the red giant or asymptotic giant will move outwards to conserve angular momentum (as described by Jeans 1924). Duncan and Lissauer (1998) found that for WD progenitors experiencing substantial mass loss during the AGB phase, planetary orbits become unstable on timescales of $\leq 10^8$ year. Debes and Sigurdsson (2002) found that the mass loss is sufficient to destabilise planetary systems of two or more planets and that the most likely result is that one planet would be scattered into an inner orbit (occupied, before the RGB phase, by a 'now evaporated' inner planet), while the other would either be boosted into a larger orbit, or ejected from the system altogether.

The above scenario provides a plausible explanation for the recent detection of silicate-rich dust discs around a growing number of white dwarfs at orbital radii up to $\sim 1R_\odot$ (e.g. Reach et al. 2005; Farihi et al. 2007, 2008; Jura 2003). Jura (2003) suggests that the formation of dust discs around white dwarfs is most probably due to the tidal disruption of an asteroid or larger body which has strayed too close to the parent star. (Jura et al. 2009) suggest that the disc around GD362 originated from the tidal destruction of a single massive body such as Callisto or Mars.

The detection of short period sub-stellar and planetary mass companions to white dwarfs, will open an exciting chapter in the study of exoplanet evolution, constraining theoretical models of CE evolution and helping us to understand the ultimate fate of hot Jupiter systems as well as the fate of our own solar system in the post main-sequence phase. Here we present some of the results of our study which investigated the detection limits for transiting sub-stellar and terrestrial companions in close orbits around white dwarfs (for more details see Faedi et al. 2010).

In §2 we discuss the characteristics of the transit signals, the parameter space investigated and our detection method. In §3 we analysed a sample of 194 WDs in the WASP archive. Finally in §4 we discuss our conclusions.

CHARACTERISTICS OF THE TRANSIT SIGNAL

A transit signal is described by its *duration*, its *depth* and its *shape*. Extra-solar planets transiting main-sequence stars show signals characterised by an ingress, a flat bottom and an egress, with a typical durations of 2-3 hours and depths of about 1% (see for example Collier Cameron et al. 2007; Simpson et al. 2010; Barros et al. 2010; and Faedi et al. 2010). We modelled the synthetic dataset assuming circular orbits and fixed stellar parameters. We considered a typical 1 Gyr old carbon-core white dwarf of mass $M_* = 0.6M_\odot$ and radius $R_* = 0.013R_\odot$. We explored the detectability of planetary transits across the two-dimensional parameter space defined by the orbital period and the planet radius. Our simulations cover companions $\sim 0.3R_\oplus < R_{pl} < 12R_\oplus$, and orbital periods in the range $P \sim 2$ hours to 15 days (equivalent to orbital distances between $a \sim 0.003$ and 0.1 AU). We chose the minimum orbital period to yield an orbital separation close to the Roche radius of the WD, and the maximum period in order to have a reasonable chance of detecting five or more transits in a typical WASP season of 150 day.

In Figure 1 we show the probability that a given system will transit, and the duration of such transit across the parameter space defined above. It is evident from these diagrams that the signatures of transits of white dwarfs by typical planet-sized bodies will be rather different than those seen for typical transiting hot Jupiters. In particular the transit

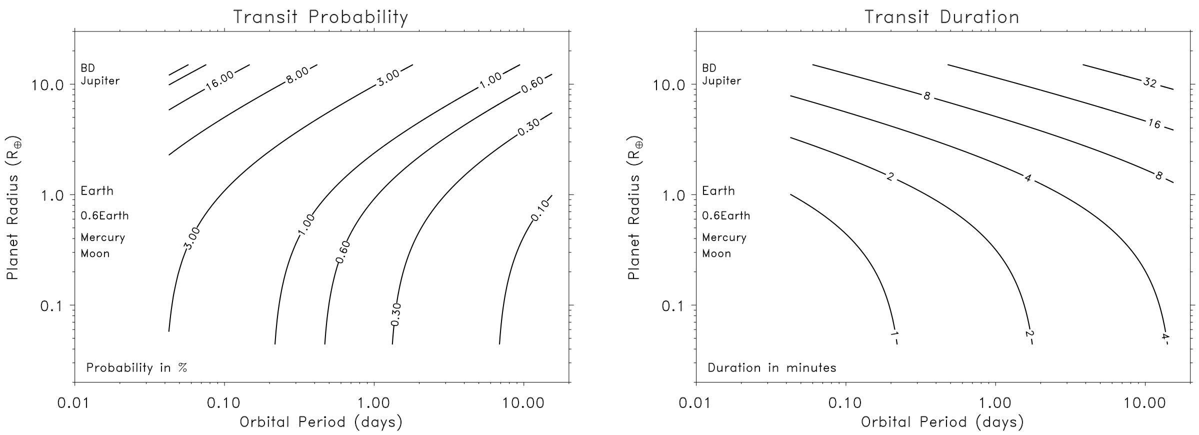

FIGURE 1. Contours of constant transit probability (left), and duration (right) in the parameter space defined by orbital period and planetary radius. The transit probability is expressed in percentage values. The transit duration is expressed in minutes.

duration is much shorter, from $\sim$1-30 min for companions with sizes ranging from Moon-size to Jupiter-size, compared to 2-3 hours for a typical hot Jupiter. In addition, Figure 2, left-panel, shows that the transit depths are much larger, from around 3% for a Moon-sized to 100% for any companion larger than the Earth, compared to $\sim$1% for a hot Jupiter.

Synthetic WASP light-curves

The synthetic light-curves were generated using the time sampling of a typical WASP survey field, and with statistical S/N representative of magnitude spanning the range of brightness of WDs in the WASP survey. The corresponding photometric accuracy of WASP over this range is $\sim$1% to 10%. Because WASP data show residual covariant-noise structure we have tested the transit recovery rate in the case of both uncorrelated "white" noise and correlated "red" noise. To cover the orbital period-planet radius parameter space we selected seven trial periods spaced approximately logarithmically ($P = 0.08$, 0.22, 0.87, 1.56, 3.57, 8.30 and 14.72 days), and five planet radii $R_{pl} = 10.0$, 1.0, 0.6, 0.34 and 0.27 $R_{\oplus}$. We modelled the set of synthetic light-curves by injecting fake transit signals into phase-folded light-curves at each trial period with a random transit epoch t_0 in the range $0 < t_0 < P$. Because in the case of a WD host star considered here, the ingress and egress duration is typically short compared to cadence of the WASP survey (8-10 minutes), we ignored the detailed shape of the ingress and egress phases and modelled the transit signatures as simple box-like profiles. Figure 2, right-panel shows two examples of our simulated transit light-curves. The top panel shows the synthetic light-curve of an hypothetical eclipsing WD+BD binary system with an orbital period of $P = 116$ mins, similar to WD0137 − 349 (a non-eclipsing system, Maxted et al. 2006). The lower panel shows the simulated transit light-curve for a rocky body of radius $1.2R_{\oplus}$ in a 5 hr orbit.

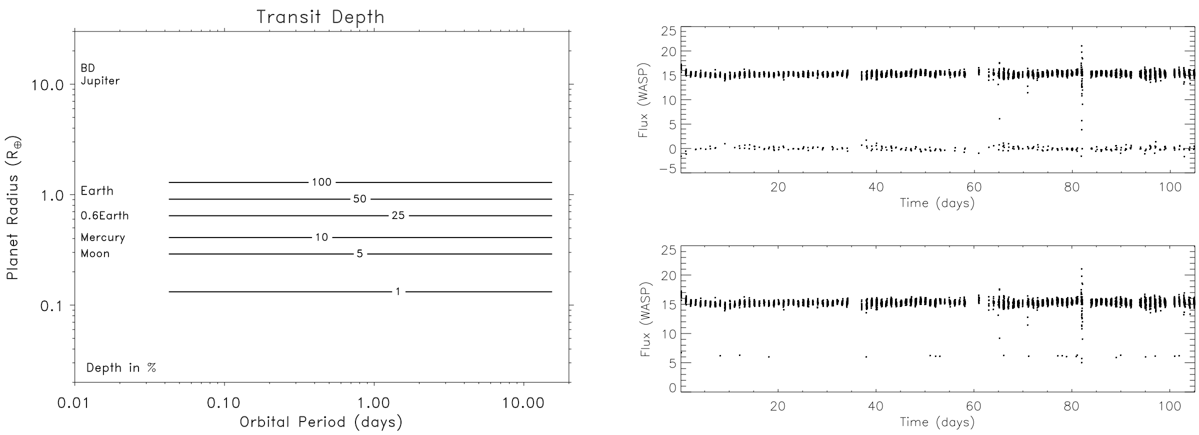

FIGURE 2. Left-panel: contours of constant transit depth; right-panel: examples of synthetic light-curves. Top, an eclipsing BD in orbit with 2 hr period. Bottom, a $1.2R_\oplus$ companion in 5 hr orbit.

Detecting transit signals

To recover the transit signals from the synthetic light-curves we used an implementation of the box-least-squares (BLS) algorithm (Kovács et al. 2002) commonly used to detect transits of main sequence stars. To ensure that the BLS search was sensitive across the expected range of transit durations, we chose to search a grid of box widths $W_b = \{1,2,4,8,16,32\}$ minutes, covering the range in transit durations over most of our parameter space (Figure 1). In addition, we used an optimised version of the BLS code which best accounted for the shape, duration and depth of the signals investigated in this work (Faedi et al. 2010).

We used the Signal Detection Efficiency (*SDE*) metric defined in Kovács et al. (2002) to assess the likely significance of a peak in a BLS periodogram. We evaluated *SDE* as follows:

$$SDE = \frac{S_{peak} - \bar{S}}{\sigma_S}$$

where S_{peak} is the height of the peak, and $\bar{S}$ and σ_S are measures of the mean level and scatter in the noise continuum of the periodogram. A detection is represented by the highest peak in the BLS power spectrum. We regard as a match any trial in which the most significant detected period is within 1% of being an integer fraction or multiple from $1/5\times$ to $5\times$ the injected transit signal. Details of the algorithm false alarm probability can be found in Faedi et al. (2010). The results of our simulations are illustrated in Figure 2, left-panel in the case of a $V \sim 12$ magnitude WD for light-curves with red noise. It is evident from Figure 2; Figure 6 and Table 1, 2, and 3 from Faedi et al. (2010), that transiting companions are essentially undetectable at our longest trial periods (8.30 and 14.72 days) in a WASP-like survey; the transits are too short in duration and too infrequent to be adequately sampled. In addition, we found that for

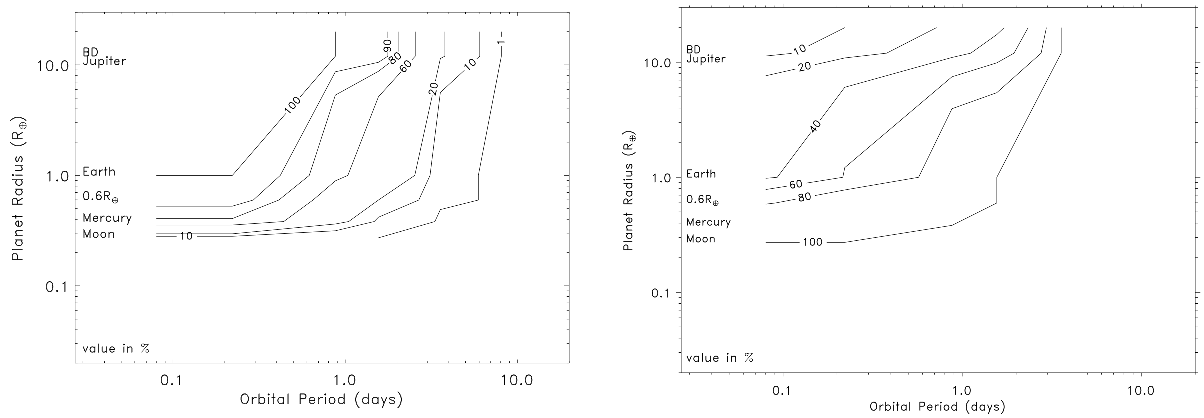

FIGURE 3. Left-panel: recovery rate for simulated transit signals injected into synthetic light-curves of a white dwarf of magnitude $V \simeq 12$; right-panel: upper-limits on companion frequency (95%) folding-in the detectability of transiting systems in a WASP-like survey. In both panels values are expressed in percent.

idealised photon-noise-limited cases, objects as small as Mercury could be detected to periods of around 1.5 d, and the Moon for periods less than 1 d. Once red noise is added, Moon-sized companions become almost undetectable. However, for companions around $1R_{\oplus}$ and larger there is a good chance of detection out to periods of around 4 days. Our key conclusion from these simulations is that for the case of transits of white dwarfs the degree of photometric precision delivered by a survey is of somewhat secondary importance compared to a high cadence and continuous coverage. For planet-sized bodies individual transits will be quite deep and readily detectable in data of moderate photometric quality, however it is the short duration of the transits that is the main factor limiting the transit detection rate in surveys optimised for main sequence stars.

SEARCHING FOR TRANSIT SIGNALS IN WASP SURVEY DATA

Encouraged by the results of our simulations we selected a sample of 194 WDs (with $V < 15$) which have been routinely monitored by WASP through the 2004 to 2008 observing seasons, and performed a systematic search for eclipsing and transiting sub-stellar and planetary companions. We selected the sample by cross-correlating the WASP archive with the McCook & Sion catalogue (McCook and Sion 2003). In addition to our authomated search, we have inspected each of the individual light-curves by eye. In both searches we found no evidence for any transiting and eclipsing companions. We have used this null result together with the results of simulations to estimate an upper-limit to the frequency of such close companions for the sample of WDs considered in this study.

In order to estimate an upper limit to the frequency of close sub-stellar and planetary companions to white dwarfs, we used the detection limits derived from our simulations and the results obtained from the analysis of the sample of 194 white dwarfs. Although our complete sample numbers $N = 194$ stars, only a fraction $p_{tr}(R_{pl}, P)$ will exhibit a transit, and of those only a fraction $p_{det}(R_{pl},P)$ would be detectable in a WASP-like survey. Both these factors act to reduce the total number of transiting companions detected in the survey, or in the case of a null result will tend to weaken the constraints that can be placed on true companion frequency by such a survey. We incorporate these factors and we modified our effective sample size as $N' = N \times p_{tr}(R_{pl},P) \times p_{det}(R_{pl},P)$. We combined the magnitude-specific p_{det} maps obtained from our simulations for WDs of magnitude $V \sim 12$, 13, 15 into a single map by interpolating/extrapolating according to the magnitude of each object in our sample and combining these to form an averaged map which can be folded in to our calculation of the upper-limits. The resulting limits corresponding to the 95% of the integrated probability, are shown in the right panel of Figure 3. Our results show that for rocky bodies smaller than the size of Mercury no useful upper limits to the frequency of companions to white dwarfs can be found, and that for Earth-sized companions only weak constraints can be imposed. However, it does suggest that objects the size of BDs or gas giants with orbital periods P$< 0.1-0.2$ days must be relatively rare (upper limit of ∼10%).

CONCLUSION

We have investigated the detection limits for sub-stellar and planetary companions to white dwarfs using in the WASP survey. We found that Mercury-sized bodies at small orbital radii can be detected with good photometric data even in the presence of red noise. For smaller bodies red noise in the light-curves becomes increasingly problematic, while for larger orbital periods, the absence of significant numbers of in-transit points, significantly decreases our detection sensitivity. Application of our modified BLS algorithm to search for companions to WDs in our sample of 194 stars available in the WASP archive, did not reveal any eclipsing or transiting sub-stellar or planetary companions. We have used our results, to place upper limits to the frequency of sub-stellar and planetary companions to WDs. While no useful limits can be placed on the frequency of Mercury-sized or smaller companions, slightly stronger constraints can be placed on the frequency of BDs and gas giants with periods $< 0.1-0.2$days, which must certainly be relatively rare ($< 10\%$). More stringent constraints would requires significantly larger WD samples. Our key conclusion from simulations and analysis, using WASP data, suggests that photometric precision is of secondary importance compared to a high cadence and continuous coverage. The short duration of eclipses and transits of WDs compared to the WASP observing cadence, appears to be the main factor limiting the transit detection rate in a survey optimised for planetary transits of main sequence stars. Future surveys such as Pan-STARRS and LSST will be capable of detecting tens of thousands of WDs. However, we emphasise the importance of high cadence and long baseline observation when attempting to detect the signature of close, eclipsing and transiting sub-stellar and planetary companions to WDs. Space missions such as *COROT*, *Kepler* (see Di Stefano et al. 2010) and, especially, *PLATO* may therefore be better suited to a survey of white dwarfs as they deliver uninterrupted coverage at high cadence and exquisite photometric precision ($\sim 10^{-4}-10^{-5}$) and could at least in principle detect the transits of asteroid-sized bodies across a white dwarf.

REFERENCES

J. Farihi, E. E. Becklin, and B. Zuckerman, *ApJ* **161**, 394–428 (2005), arXiv:astro-ph/0506017.
E. E. Becklin, and B. Zuckerman, *Nature* **336**, 656–658 (1988).
P. R. Steele, M. R. Burleigh, J. Farihi, B. T. Gänsicke, R. F. Jameson, P. D. Dobbie, and M. A. Barstow, *A&A* **500**, 1207–1210 (2009), 0903.3219.
A. Day-Jones, et al., *MNRAS* **in press** (2010).
P. F. L. Maxted, R. Napiwotzki, P. D. Dobbie, and M. R. Burleigh, *Nature* **442**, 543–545 (2006), arXiv:astro-ph/0608054.
M. R. Burleigh, E. Hogan, P. D. Dobbie, R. Napiwotzki, and P. F. L. Maxted, *MNRAS* **373**, L55 (2006).
J. Farihi, and M. Christopher, *AJ* **128**, 1868–1871 (2004), arXiv:astro-ph/0407036.
P. D. Dobbie, M. R. Burleigh, A. J. Levan, M. A. Barstow, R. Napiwotzki, J. B. Holberg, I. Hubeny, and S. B. Howell, *MNRAS* **357**, 1049 (2005).
M. R. Burleigh, J. Farihi, R. Napiwotzki, T. R. Marsh, and P. D. Dobbie, *MNRAS* **in prep.** (2010).
J. Patterson, *PASP* **110**, 1132–1147 (1998).
J. Patterson, J. R. Thorstensen, and J. Kemp, *PASP* **117**, 427–444 (2005), arXiv:astro-ph/0502392.
S. P. Littlefair, V. S. Dhillon, and E. L. Martín, *MNRAS* **340**, 264–268 (2003), arXiv:astro-ph/0211475.
S. P. Littlefair, V. S. Dhillon, T. R. Marsh, B. T. Gänsicke, J. Southworth, and C. A. Watson, *Science* **314**, 1578– (2006), arXiv:astro-ph/0612220.
S. P. Littlefair, V. S. Dhillon, T. R. Marsh, B. T. Gänsicke, I. Baraffe, and C. A. Watson, *MNRAS* **381**, 827–834 (2007), arXiv:0708.0097.
M. J. Duncan, and J. J. Lissauer, *Icarus* **134**, 303–310 (1998).
J. H. Debes, and S. Sigurdsson, *ApJ* **572**, 556–565 (2002), arXiv:astro-ph/0202273.
M. R. Burleigh, F. J. Clarke, and S. T. Hodgkin, *MNRAS* **331**, L41–L45 (2002), arXiv:astro-ph/0202194.
E. Villaver, and M. Livio, *ApJ* **661**, 1192–1201 (2007), arXiv:astro-ph/0702724.
S. Frink, D. S. Mitchell, A. Quirrenbach, D. A. Fischer, G. W. Marcy, and R. P. Butler, *ApJ* **576**, 478–484 (2002).
A. P. Hatzes, E. W. Guenther, M. Endl, W. D. Cochran, M. P. Döllinger, and A. Bedalov, *A&A* **437**, 743–751 (2005).
B. Sato, et al., *ApJ* **597**, L157–L160 (2003).
R. Silvotti, et al., *Nature* **449**, 189–191 (2007).
F. Mullally, D. E. Winget, S. Degennaro, E. Jeffery, S. E. Thompson, D. Chandler, and S. O. Kepler, *ApJ* **676**, 573–583 (2008), 0801.3104.
K. Beuermann, F. V. Hessman, S. Dreizler, T. R. Marsh, S. G. Parsons, D. E. Winget, G. F. Miller, M. R. Schreiber, W. Kley, V. S. Dhillon, S. P. Littlefair, C. M. Copperwheat, and J. J. Hermes, *A&A* **521**, L60+ (2010), 1010.3608.
W. T. Reach, M. J. Kuchner, T. von Hippel, A. Burrows, F. Mullally, M. Kilic, and D. E. Winget, *ApJ* **635**, L161–L164 (2005), arXiv:astro-ph/0511358.
J. Farihi, B. Zuckerman, E. E. Becklin, and M. Jura, "Spitzer Observations of GD 362 and Other Metal-Rich White Dwarfs," in *Astronomical Society of the Pacific Conference Series*, edited by R. Napiwotzki, and M. R. Burleigh, 2007, vol. 372, p. 315.
M. Jura, *ApJ* **584**, L91–L94 (2003), arXiv:astro-ph/0301411.
M. Jura, J. Farihi, and B. Zuckerman, *AJ* **137**, 3191–3197 (2009), 0811.1740.
F. Faedi, R. G. West, M. R. Burleigh, M. R. Goad, and L. Hebb, *MNRAS* pp. 1810–+ (2010), 1008.1089.
A. Collier Cameron, et al., *MNRAS* **380**, 1230–1244 (2007), 0707.0417.
E. K. Simpson, F. Faedi, S. C. C. Barros, et al., *ArXiv e-prints* (2010), 1008.3096.
S. C. C. Barros, F. Faedi, et al., *ArXiv e-prints* (2010), 1010.0849.
G. Kovács, S. Zucker, and T. Mazeh, *A&A* **391**, 369–377 (2002), arXiv:astro-ph/0206099.
G. P. McCook, and E. M. Sion, *VizieR Online Data Catalog* **3235**, 0 (2003).
R. Di Stefano, S. B. Howell, and S. D. Kawaler, *ApJ* **712**, 142–146 (2010), 0912.3253.