White dwarfs with unresolved substellar companions and debris disks in the UKIDSS Survey

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Abstract. We present a near-infrared (NIR) photometric search for substellar companions and debris disks around white dwarfs in the UKIRT Infrared Deep Sky Survey (UKIDSS). We cross-correlate the SDSS DR4 and McCook & Sion catalogues of white dwarfs with the UKIDSS DR3 database producing 408 and 133 matches respectively. Models are then fitted to Sloan photometry to identify those with NIR photometric excesses consistent with an unresolved sub-stellar companion or a debris disk. We present follow up photometry from targets previously identified in UKIDSS DR2 and the first results from DR3. In total we identify 8 potential white dwarf + very low mass binary systems, 2 potential white dwarf + disk systems, and 2 systems which require further investigation to clarify the source of the excess.

1. Introduction

The detection and observation of very low mass companions to white dwarfs allows us to investigate an extreme of binary formation and evolution. White dwarf + brown dwarf binaries also allows us also to investigate the fraction of main-sequence stars with substellar companions. This will give us further insight into the possible discrepancy between the brown dwarf companion fraction at small separations (1 ± 1% at < 10 AU, Marcy & Butler 2000; McCarthy & Zuckerman 2004) and large radii (a > 1000 AU; 10–30%, Gizis et al. 2001). In addition there are very few observational constraints on brown dwarf evolutionary models at large ages, such as those expected for most white dwarfs (> 1 Gyr). Thus wide, detached white dwarf + brown dwarf binaries can provide “benchmarks” for testing these models (Pinfield et al. 2006).

Near-infrared (NIR) photometry and spectroscopy allows for the detection and study of such systems. The spectral energy distribution of the white dwarf in this region is markedly different to that of a brown dwarf with the latter peaking at these wavelengths. As the white dwarf falls off in flux the two components of a binary system are easily separated in broadband photometry, facilitating detection and enabling straightforward spectroscopic followup. Close WD+BD are of interest as an outcome of common envelope (CE) evolution, another channel for cataclysmic variable (CV) evolution, or the end state of CV evolution. In the latter case the secondary will have become highly evolved through mass transfer, perhaps beginning its life at a much higher mass and earlier stellar class.
Unfortunately, brown dwarf companions to white dwarfs are rare (< 0.5%; Farihi et al. 2005) with only 3 systems confirmed: GD165 (DA+L4, Becklin & Zuckerman 1988), GD400 (DA+L6/7, Farihi & Christopher 2004) and WD0137−349 (DA+L8, Burleigh et al. 2006). GD165 is the only resolved widely separated system (120 AU) whereas WD0137 and GD400 (Burleigh et al., these proceedings) are close orbit binaries. Hence, large, deep near-IR surveys such as the UKIRT Infrared Deep Sky Survey (UKIDSS) are excellent databases to search for these objects.

Recently a number of white dwarfs have been found to harbour metal-rich debris disks (e.g. GD362; Kilic et al. 2005). These can be revealed optically by looking for distinct, double-peaked Ca II emission triplet at 850-866nm (e.g. Gaensicke et al. 2007), or through $K$-band excesses in the near-IR. Therefore, near-IR photometry and spectroscopy can also be used to search for these debris disks and, for those white dwarfs showing heavy element contamination in their photospheres, may provide an important diagnostic tool for distinguishing between disk accretion and accretion from very-low mass companions.

1.1. The UKIDSS survey

UKIDSS is the near-infrared counterpart to the Sloan Digital Sky Survey (SDSS: York et al. 2000) and the successor to the previous 2 Micron All Sky Survey (2MASS: Skrutskie et al. 2006). The UKIDSS began in May 2005 and aims to cover 7500 deg$^2$ of the Northern Sky in $YJHK$ down to $K = 18.4$, 3 magnitudes deeper than the 2MASS. The UKIDSS actually consists of a set of 5 complimentary surveys; the Large Area Survey (LAS), the Galactic Plane Survey (GPS), the Galactic Clusters Survey (GCS), the Deep Extragalactic Survey (DXS) and the Ultra-deep Extragalactic survey (UDS). Following a release of science verification data and an Early data release (Dye et al. 2006), UKIDSS has had 3 data releases (DR1: Warren et al. 2007b, DR2: Warren et al. 2007a, DR3: Warren et al. 2008 in prep.) in July 2006, March 2007, and December 2007. Each subsequent data release contains all data from the previous releases and at present represents 15% of the complete data set; that is 1100 deg$^2$ of sky coverage. The survey of most importance to this work is the Large Area Survey.

The LAS (PI: Richard Jameson) aims to cover 4000 deg$^2$ upon it’s 7 year completion down to 5σ limiting magnitudes of $Y = 20.5$, $J = 20.0$, $H = 18.8$ and $K = 18.4$ (Vega). The target 4000 deg$^2$ is a subsection of the SDSS. As of DR3 approximately 900 deg$^2$ has been completed.

2. Identifying white dwarfs

The UKIDSS LAS DR3 catalogue was cross correlated with two catalogues of white dwarfs: the on-line August 2006 version of the McCook & Sion catalogue of spectroscopically identified white dwarfs (McCook & Sion 1999) which contains 5557 stars, and the Eisenstein et al. (2006) catalogue of 9316 spectroscopically confirmed white dwarfs from the SDSS DR4. The McCook & Sion catalogue contains the brightest white dwarfs known, whilst the white dwarfs identified in the SDSS are constrained by an upper brightness limit ($g' \approx 15$) and the lower sensitivity limit ($g' \approx 21$) of that survey. The majority of the SDSS white dwarves are too faint to have been detected by the 2MASS survey, therefore UKIDSS allows the investigation of the NIR properties of a large number of new white dwarfs discovered in the SDSS, as well as significantly reducing the measurement errors on the NIR photometry of the brighter white dwarfs detected in 2MASS.

Many of the relatively bright white dwarfs have large and unmeasured proper motions, meaning their astrometry is often unreliable. For the McCook & Sion white dwarfs, a set of improved coordinates supplied by Jay Holberg (private communication) were utilised in the cross correlation with the UKIDSS DR3. The SDSS stars, being fainter and therefore more distant have more reliable astrometry. The cross correlation was performed using the on-line “CrossID” tool at the WFCAM science archive. The results were constrained to stars brighter
than the 5σ limiting magnitudes (Section 1.1) using a pairing radius of 5″ taking only the nearest IR source to each white dwarf’s coordinates as the primary result. In general, the UKIDSS and white dwarf coordinates agreed within 5″ and the SDSS images revealed the same object as in the corresponding UKIDSS images. The images of each cross matched object in both databases were inspected by eye to ensure the correct object had been identified. Six of the sample were rejected as being the wrong source in the UKIDSS when compared to the SDSS image.

The cross correlation produced 493 matches with the SDSS DR3, and 201 with the McCook & Sion white dwarf catalogues. Only 77 of the McCook & Sion white dwarfs were not found in the SDSS.

3. Identifying candidate systems
In order to efficiently process the cross-matched catalogue of white dwarfs it was decided to model each white dwarf independently and then inspect each for evidence of a NIR excess. To that end, a program was written to fit a blackbody continuum to the SDSS photometry of each white dwarf using a grid of models and performing a Chi squared minimisation to achieve the best fit. Candidate stars were identified as those that showed a significant (>3σ) excess in one or more of the UKIDSS bands. 12 such stars were identified with the blackbody fitting and the corresponding photometry is given in table 1. Out of these 12, 10 show evidence of multiple band excesses potentially indicating white dwarf brown + dwarf binaries, and 2 show only K-band excesses indicative of a debris disk.

For candidate white dwarfs with $T_{\text{eff}} > 16,000$ K we improved the determination of the size of the excess by calculating a synthetic spectrum at the temperature and gravity determined by Eisenstein et al. (2006) (Table 2). For the candidates with effective temperatures $\leq 16,000$ K we have generated blackbody models at the temperatures given in table 2. The synthetic spectra were then normalised to the Sloan $g'$ magnitude of the corresponding white dwarf (Table 2).

3.1. Identifying sub-stellar companions
For each candidate white dwarf + brown dwarf binary the SDSS optical spectrum was first examined for evidence of a low mass main-sequence companion. An increase in flux of the spectral energy distribution towards longer wavelengths or spectral features indicative of early-mid M dwarfs (e.g. Hα emission and/or TiO absorption bands) were searched for by eye. None of our candidates exhibited these features definitively and so none were removed from our sample at this stage. Empirical models for late M to T spectral types were then added to the white dwarf synthetic spectrum and these composites were compared to UKIDSS photometry to obtain an approximate spectral type for the potential companion.

The empirical models were constructed using the NIR spectra of late M, L and T dwarfs from the IRTF spectral library (Cushing et al. 2005, Rayner et al. in prep.). Subsequently, these fluxes were scaled to the distance of the relevant white dwarf (Table 2) and, starting with T5, earlier types were progressively added until a match could be made with the UKIDSS photometry.

3.2. Identifying debris disks
We could not match any substellar model to the white dwarfs displaying only K-band excess emission. For these objects, it is plausible that the excess is due to the presence of a warm debris disk (e.g. GD362). We estimate the temperature of the putative disk by fitting combined white dwarf + blackbody models.

4. Results
After matching these models to the stars showing near-IR excesses, we confirmed that 8 potentially harbour very low mass or substellar companions, 2 show K-band only excesses
The results are summarised in table 3.

Table 1. UKIDSS Photometry of candidate binary/disk systems

| SDSS J | WD | Y | J | H | K |
|--------|----|---|---|---|---|
| 003902.47−003000.3 | - | - | 18.39 ± 0.08 | 17.87 ± 0.11 | 17.42 ± 0.10 |
| 003923.04+003534.7 | - | - | - | 17.49 ± 0.05 | 17.05 ± 0.06 |
| 090759.59+053649.7 | - | 18.79 ± 0.05 | 18.64 ± 0.08 | 18.61 ± 0.16 | 18.39 ± 0.19 |
| 092452.73+020712.2 | 0922+006 | - | - | 18.21 ± 0.12 | 17.63 ± 0.11 |
| 101532.10+042507.5 | - | - | - | 18.42 ± 0.17 | 18.17 ± 0.19 |
| 120212.00+082244.6 | 1159+086 | 18.02 ± 0.04 | 18.14 ± 0.07 | 18.23 ± 0.10 | 17.88 ± 0.13 |
| 120503.99+070031.0 | - | - | - | 17.76 ± 0.08 | 17.72 ± 0.13 |
| 131724.75+002373.3 | 1314+003 | 16.77 ± 0.01 | 16.91 ± 0.02 | - | 16.84 ± 0.08 |
| 132044.68+001855.0 | 1318+005 | 17.64 ± 0.02 | 17.64 ± 0.04 | 17.76 ± 0.11 | 17.40 ± 0.11 |
| 155720.77+091624.7 | - | 18.82 ± 0.04 | 18.82 ± 0.06 | 19.03 ± 0.14 | 18.34 ± 0.15 |
| 222030.68−004107.9 | - | 16.97 ± 0.01 | 16.76 ± 0.02 | 16.45 ± 0.03 | 16.38 ± 0.04 |
| 222551.65+001637.7 | - | 18.60 ± 0.05 | 18.52 ± 0.07 | 18.16 ± 0.13 | 17.63 ± 0.13 |

Table 2. Physical parameters of the candidate white dwarfs showing near-infrared excesses. Temperatures and surface gravities are from Eisenstein et al. (2006) unless otherwise stated. Distances are calculated through evolutionary models.

| SDSS J | WD | g' | Teff (K) | log g | D (pc) |
|--------|----|----|---------|-------|-------|
| 003902.47−003000.3 | - | 18.74 | 12314 ± 268 | 7.39 ± 0.08 | |
| 003923.04+003534.7 | - | 19.09 | 10080 ± 81 | 7.99 ± 0.11 | 269 |
| 090759.59+053649.7 | - | 18.17 | 19474 ± 293 | 7.82 ± 0.05 | 323 |
| 092452.73+020712.2 | 0922+006 | 18.55 | 15231 ± 147\(^1\) | 8.49 ± 0.10\(^1\) | 209 |
| 101532.10+042507.5 | - | 17.63 | 35073 ± 195 | 7.38 ± 0.04 | 604 |
| 120212.00+082244.6 | 1159+086 | 17.63 | 16400\(^2\) | - | - |
| 120503.99+070031.0 | - | 18.89 | 8688 ± 61 | 8.21 ± 0.12 | 185 |
| 131724.75+000237.3 | 1314+003 | 15.75 | 60000\(^3\) | 7.8\(^3\) | 262 |
| 132044.68+001855.0 | 1318+005 | 17.10 | 19649 ± 130 | 8.36 ± 0.02 | 133 |
| 155720.77+091624.7 | - | 18.43 | 21990 ± 403 | 7.67 ± 0.06 | 437 |
| 222030.68−004107.9 | - | 17.44 | 8037 ± 31 | 8.28 ± 0.07 | 84 |
| 222551.65+001637.7 | - | 18.80 | 10640 ± 94 | 8.16 ± 0.09 | 216 |

\(^1\) Helium fit.

\(^2\) Blackbody fit of SDSS photometry.

\(^3\) Werner et al. (2004).

indicative of debris disks, and 2 objects show H and K-band excesses that can be explained by either a companion or a disk. Figures 1-12 show each white dwarf’s modelled spectrum plotted with both SDSS and UKIDSS photometry. The model used to match the excess(es) are identified in each plot (the vertical order of the labels matches the vertical order of the empirical models). The results are summarised in table 3.
5. Notes on Individual Objects

5.1. SDSS J 003902.47−003000.3

This white dwarf’s optical spectrum (Figure 1) shows no evidence for an M dwarf companion. When compared to a model spectrum (Figure 1) a small excess emission can be identified in
the optical $z$-band, with strong excesses clearly visible in the UKIDSS $YJHK$ photometry. The photometry is best matched by the addition of either an M8 or M9.5 dwarf, placed at the distance predicted by the star’s temperature and surface gravity (Table 2).

This result was first identified in UKIDSS DR2 (Burliegh et al. 2008, in prep.) and follow-up
Table 3. Table of Results identifying binary and disk candidates.

| SDSS J | WD | Binary | Spectral Type | Disk | Temperature (K) |
|--------|----|--------|--------------|------|-----------------|
| 003902.47−003000.3 | - | Yes | M8±1 | - | - |
| 003923.04+003534.7 | - | Yes | M9±1 | - | - |
| 090759.59+053649.7 | - | Yes | L6±2 | - | - |
| 092452.73+020712.2 | 0922+006 | Yes | L6±2 | - | - |
| 101532.10+042507.5 | - | Yes | L0±2 | - | - |
| 120212.00+082244.6 | 1159+086 | - | Yes | <600 K |
| 120503.99+070031.0 | - | Yes | L6±2 | - | - |
| 131724.75+000237.3 | 1314+003 | Yes | L4±1 | Yes | <800 K |
| 132044.68+001855.0 | 1318+005 | - | Yes | <600 K |
| 155720.77+091624.7 | - | Yes | L4±1 | Yes | <700 K |
| 222030.68−004107.9 | - | Yes | T0±1 | - | - |
| 222551.65+001637.7 | - | Yes | L8±1 | - | - |

$JHK$ photometry was obtained using SOFI on the NTT on October 25th 2007 (Figure 1). No exact match is obtained with either model but the SOFI photometry confirms the presence of a NIR excess and indicates the companion is of spectral type M8±1. As this is a late-M it is doubtful that this companion can be identified as a brown dwarf.

5.2. SDSS J 092452.73+020712.2

This is only one of two helium atmosphere (DB) white dwarfs in the list of candidates for low mass sub-stellar companions. The optical photometry shows no excess but there is a clear rise in the $H$ and $K$ band photometry. This is best matched by the addition of an L4-L6 dwarf scaled to the distance of the primary (Table 2), and would thus be the first DB white dwarf to potentially harbour a brown dwarf companion.

5.3. SDSS J 222030.68−004107.9

This white dwarf has the brightest NIR photometry out of the sample of candidates for sub-stellar binarity. Its optical spectrum reveals no evidence of a main-sequence companion. Eisenstein et al. (2006) give the physical parameters of this star as $T_{\text{eff}} = 8037 \pm 31$ K and $\log g = 8.28 \pm 0.07$ from an automated fit, also making this the coolest star in the sample. A comparison to a model for these parameters reveals a NIR excess which is best matched by the addition of an Late-L/early-T dwarf scaled to the distance of the primary star (Table 2). This would make this system the first white dwarf T dwarf binary detected and certainly the lowest mass object detected around a white dwarf to date.

However, UKIDSS classified this object as a merged source possibly indicating background contamination. A closer inspection of the UKIDSS images reveals the possibility that the system is becoming resolved in the longer wavelength $HK$-bands. This was indeed the case for a number of white dwarf M-dwarf binaries. Therefore this system could be a wider orbit Late-L/Early-T dwarf binary, however high resolution spectroscopy is needed to rule out the possibility of background sources.
5.4. SDSS J 222551.65+001637.7

This white dwarf shows no sign of an M dwarf in its optical spectrum and an atmospheric model (a cooler model was obtained in this case with parameters of $T_{\text{eff}} = 10,000$ K and $\log g = 8.00$, a close matched to the Eisenstein et al. (2006) autofit parameters of $T_{\text{eff}} = 10640 \pm 94$ K and $\log g = 8.16 \pm 0.09$) matches the SDSS photometry (Figure 12). A clear excess is then seen in the $H$ and $K$-band photometry that is best matched by the addition of companion of spectral type L6 scaled to the distance of the star.

This result was first identified in UKIDSS DR2 (Burleigh et al. 2008, in prep.) and follow-up $JHK$ photometry was obtained using SOFI on the NTT on October 2nd 2007 ($K$) and October 3rd 2007 ($JH$) — Figure 12. The $K$-band photometry agrees with the UKIDSS data within errors and indeed indicates an excess. However, the $JH$-band data matches the white dwarf model more closely when compared with the UKIDSS data. This could either indicate that there is only a $K$-band excess and therefore this system is most likely a disk candidate, or as the data was taken on separate nights the companion is in a close orbit and is variable due to heating on the hemisphere facing the white dwarf. Follow-up spectroscopy or time series NIR photometry is needed to confirm this scenario.

6. Conclusions

By cross-correlating the McCook & Sion and the SDSS DR4 catalogues of spectroscopically identified white dwarfs with the UKIDSS DR3 database, we have identified 12 systems with significant near-infrared excesses. 8 of these have multiple band excesses consistent with the presence of a low mass companion, these range in spectral type from M8-T0. Of notable interest are SDSS J 092452.73+020712.2 which is a potential DB+L binary and SDSS J 22030.68−004107.9 which is our latest typed companion (L8-T0). Two have a single $K$-band excess indicating they may harbour a debris disk, and 2 require further investigation to identify the exact source of the excess infrared emission.

We are now obtaining follow-up spectra for a number of these objects with Gemini North to confirm the nature of the excesses. This will allow us to place tighter constraints on the fraction of white dwarfs with substellar (L and T) companions.

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