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Four faint T dwarfs from the UKIRT Infrared Deep Sky Survey (UKIDSS) Southern Stripe

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ABSTRACT
We present the optical and near-infrared photometry and spectroscopy of four faint T dwarfs newly discovered from the UKIDSS first data release. The sample, drawn from an imaged area of ~136 deg2 to a depth of Y = 19.9 (5σ, Vega), is located in the Sloan Digital Sky Survey (SDSS) Southern Equatorial Stripe, a region of significant future deep imaging potential. We detail the selection and followup of these objects, three of which are spectroscopically confirmed brown dwarfs ranging from type T2.5 to T7.5, and one is photometrically identified as early T. Their magnitudes range from Y = 19.01 to 19.88 with derived distances from 34 to 98 pc, making these among the coldest and faintest brown dwarfs known. The T7.5 dwarf appears to be single based on 0.05-arcsec images from Keck laser guide star adaptive optics. The sample brings the total number of T dwarfs found or confirmed by UKIDSS data in this region to nine, and we discuss the projected numbers of dwarfs in the future survey data. We estimate that ~240 early and late T dwarfs are discoverable in the UKIDSS Large Area Survey (LAS) data, falling significantly short of published model projections and suggesting that initial mass functions and/or birth rates may be at the low end of possible models. Thus, deeper optical data have good potential to exploit the UKIDSS survey depth more fully, but may still find the potential Y dwarf sample to be extremely rare.

Key words: techniques: photometric – techniques: spectroscopic – catalogues – surveys – stars: low-mass brown dwarfs – infrared: stars.

1 INTRODUCTION
Members of the coldest brown dwarf spectral type currently observed, the ‘T’ class (Kirkpatrick 2005), are now being discovered quite regularly thanks to a growing archive of optical and near-infrared survey data. As a result, this sample of once-rare objects has increased dramatically from the handful known only a few years ago (Nakajima et al. 1995; Burgasser et al. 1999; Cuby et al. 1999; Strauss et al. 1999) to the dozens gradually retrieved by searches through dedicated surveys (Burgasser et al. 2002; Geballe et al. 2002; Knapp et al. 2004; Chiu et al. 2006; Stern et al. 2007), and ultimately towards what is predicted to be the bulk discovery of hundreds in the next few years (Deacon & Hambly 2006, hereafter DH06). As the growth of this discovered population continues, the study of T dwarfs has also naturally expanded to ever more detailed examination of their physical properties, and has fuelled observations of rarer, but highly interesting, properties, such as binarity (e.g. Liu et al. 2006).

The advance in the discovery rate of T dwarfs has been a direct product of the coupling of optical and near-infrared survey techniques. With the development of the UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007), the opportunity for automated candidate identification has grown enormously. The first T dwarf discoveries from UKIDSS are confirming the survey’s powerful red object finding capability (e.g. Kendall et al. 2007; Lodieu et al. 2007; Warren et al. 2007b).

In this Letter, we present the first results of our ongoing search for the reddest objects in the UKIDSS data: the coolest brown dwarfs and very high redshift quasars. We have found three spectroscopically confirmed early to late T dwarfs in the UKIDSS first data release (DR1) area of approximately 150 deg2, and one strong photometrically/spectroscopically identified early T candidate, and we

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describe the techniques used to identify these objects, their follow up and their characterization. We also compare the sample with other discovered brown dwarfs in this area, and discuss predictions of brown dwarf discovery rates for the full UKIDSS project. In this Letter, all near-infrared magnitudes are expressed in the UKIDSS Vega-normalized system. (Note that the Y-band photometry used here does not include a possibly necessary correction of 0.1 mag; see Warren et al. 2007a for details.) However, accompanying photometry in the optical i/c bands is on the AB system, as used by the SDSS project (Fukugita et al. 1996; Lupton, Gunn & Szalay 1999).

2 CANDIDATE SELECTION

This work is based on the UKIDSS DR1, and was aimed at mining the Southern Equatorial Stripe, pioneered by the SDSS (Stripe 82). The Large Area Survey (LAS), the wide and shallow subsurvey of UKIDSS, imaged this area partially over the 2005B semester, covering approximately 136 deg$^2$ to a depth of \[ [Y, J, H, K] = [20.2, 19.6, 18.8, 18.2] \] (5σ, Vega).

For the science user seeking the reddest objects, the most important attribute of the UKIDSS data base is the matching of SDSS photometry with LAS-detected objects (Hambly et al. 2008; Irwin et al., in preparation). This non-trivial cross-matching feature, operated on \( N \sim 10^8 \) objects, allows the identification of sources displaying flux decrements of interest, and most importantly for this work, across the optical and near-infrared bands; e.g. brown dwarfs and high-redshift quasars.

Using the merged UKIDSS/SDSS photometry, we ranked LAS-detected point-source objects with a priority based on several factors. The UKIDSS Y and/or J magnitudes were sorted, giving emphasis in followup observations to the brightest candidates first, typically down to a magnitude limit of \( Y = 19.9 \) dictated by the feasibility of spectroscopic observations. Photometric errors were examined to measure the confidence of weak detections given the varying depth of exposures. The \( i - Y \) colour then yielded the primary ranking, with high values indicating candidates with the greatest potential. A limit of \( i - Y > 3.5 \) was imposed to produce manageable candidate numbers, and when a UKIDSS point source lacked an SDSS source within several arcseconds, a lower limit on the \( i - Y \) value was calculated, generally implying a large and interesting but uncertain \( i - Y \) value. The nominal SDSS flux limits reach \( [u, g, r, i, z] = [22.0, 22.2, 22.2, 21.3, 20.5] \) (5σ, AB).

Imposing the \( i - Y \) and magnitude criteria, the surface density of candidates from the data base was \( \sim 5 \text{ deg}^{-2} \). Candidates were then subjected to automated as well as visual inspection against their archived imaging to check for defects, among which cosmic rays, interpolation artefacts, cross-talk and persistence features are the most common in the UKIDSS and SDSS imagery. In addition, deeper imaging data from repeated scans of the SDSS were used to verify photometry and colour decrement in \( i - z \). In some areas, where 10 or more SDSS runs contributed to the deeper imaging, this allowed verification to 1.25 mag deeper than the normal SDSS survey depth, as has been demonstrated in a few searches to date (Jiang et al. 2006, 2007).

3 OBSERVATIONS

The preliminary inspection procedures reduced candidate numbers dramatically, and a more restricted list of good objects, numbering \( \sim 1 \text{ deg}^{-2} \), was subjected to followup imaging. This was undertaken to measure the faint \( i/c \) flux of the objects, and to confirm the near-infrared photometry of the new WFCAM images. As detailed in Table 1, these observations were taken at several facilities: the UFTI instrument (at UKIRT), IRIS2 (AAI) and SOI (SOAR). Finding charts for the four T dwarfs, based on the UFTI J imaging, are displayed in Fig. 1. Typical exposure times in the near-infrared and optical were 300 s. Based on these imaging trials and other work with larger samples (e.g. Chiu et al. 2007), the UKIDSS photometry is found to be relatively reliable at the \( > 5\sigma \) detection level, as long as images are not affected by artefacts. However, some larger discrepancies were encountered, such as with the \( H \)-band measurements of J0139-0048.

Following imaging verification, 20 objects continued to display interesting colours, including two T dwarfs later spectroscopically observed in collaboration with Lodieu et al. (2007) and Warren et al. (2007b) – ULAS J2239+0032 (T5.5) and J0034-0052 (T8.5). In addition, among these objects was the \( z = 5.86 \) quasar confirmed by Venemans et al. (2007). Optical spectroscopy was then carried out on the remaining candidates using the EMMI instrument at the European Southern Observatory (ESO) 3.6-m New Technology Telescope (NTT) telescope in the \( R \sim 600 \) RILD mode (program 078.A-0398), or the MARS red spectrograph at Kitt Peak National Observatory (\( R \sim 450 \)), both covering \( 5500-9500 \) Å. Candidates typically received \( 3 \times 15 \) min exposure each, and the MARS nod-and-shuffle mode was employed to improve sky line background subtraction in the troublesome \( \lambda < 8000 \) Å region.

The optical spectroscopy resulted in the preliminary identification of five L dwarfs and four T dwarfs. The T dwarfs are plotted in colour and magnitude in Fig. 2, showing that the sample extends to the range of the faintest late T dwarfs yet known. In addition, we note that the \( i - Y \) selection technique employed here is able to discover dwarfs outside the near-infrared selection box shown, which otherwise relies on the presence of flux in all of the \( YJH \) bands. The relatively well separated dwarf colour locus versus type allowed

Table 1. Observed T dwarf properties. Optical \( i/c \) photometry was obtained with the SOAR/IRIS instrument, and \( YJHK \) photometry was obtained from the UKIDSS data base, or UKIRT/UFTI and AAT/IRIS2 observations as indicated.

| Object ID | \( i \) (AB) | \( z \) (AB) | \( Y \) (AB) | \( J \) (Vega) | \( H \) (Vega) | \( K \) (Vega) |
|-----------|-------------|-------------|-------------|-------------|-------------|-------------|
| J222958.30 + 010217.2 | 24.38 ± 0.48 | 21.16 ± 0.06 | 19.01 ± 0.06 | 17.87 ± 0.03 | 17.48 ± 0.05 | 17.21 ± 0.09 |
| J013117.53 – 003128.6 | >24.5 | 22.78 ± 0.19 | 19.88 ± 0.21 | 18.78 ± 0.12 | 18.61 ± 0.15 | – |
| J013939.77 + 004813.8 | >25.0 | 22.55 ± 0.20 | 19.57 ± 0.13 | 18.60 ± 0.04 | 18.48 ± 0.04 | 18.41 ± 0.04 |
| J034832.97 – 001258.3 | >24.8 | 21.56 ± 0.12 | 19.73 ± 0.11 | 18.89 ± 0.08 | 19.12 ± 0.05 | 19.23 ± 0.06 |

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New Faint T Dwarfs in UKIDSS DR1

Figure 1. Finding charts for the four T dwarfs discovered in this work. Frames are from UKIRT UFTI followup imaging in J band. Images have been Gaussian smoothed by 2 pixels to enhance features. Each panel is 2 × 2 arcmin, oriented as north up and east towards left.

Figure 2. The four faint T dwarfs discovered in this work are plotted (red points with thick error bars) in \((Y - J)\) versus \(Y\) colour–magnitude (left-hand panel) and \(YJH\) colour–colour (right-hand panel) diagrams. Normal stars are shown as small points, and the concurrently discovered objects of Lodieu et al. (2007) are shown for comparison (black points with light error bars). The extremely late type T8.5 dwarf of Warren et al. (2007b) is the open square with error bars. The sample of Lodieu et al. includes: four new T dwarfs and one previously known SDSS T dwarf found in the same area as our sample, and four T dwarfs discovered in additional area of the UKIDSS DR1 not covered in the present work. In the left-hand panel, the dotted line indicates the typical \(Y - J > 0.6\) selection cut used to identify dwarf candidates. In the right-hand panel, the dotted rectangular region indicates the range of predicted colours for late T and Y dwarfs (Leggett et al. 2004). Small text labels follow the approximate locus of brown dwarf example types, selected from table 10 of Hewett et al. (2006). The normal stellar sample was retrieved from a match of unidentified point sources appearing in both UKIDSS and SDSS.

To confirm the T dwarf types, we obtained low-resolution (\(R \approx 100\)) near-infrared spectra on ut20061118 using the NASA IRTF. Conditions were photometric with excellent seeing at ~0.5 arcsec full width at half-maximum (FWHM) at K-band near zenith. We used the SpeX spectrograph (Rayner et al. 1998) in prism mode, obtaining 0.8–2.5 \(\mu\)m spectra in a single order, with the 0.8 arcsec slit oriented at the parallactic angle. Objects were nodded along the slit in an ABBA pattern with individual exposure times of 180 s, and observed over airmass 1.1–1.3. The typical on-source exposure time was 54 min, and A0 V stars were observed for flux and telluric calibration. All spectra were reduced using the SPEXTOOL software package (Vacca, Cushing & Rayner 2003; Cushing, Vacca & Rayner 2004), and are shown in Fig. 3. To our knowledge, these are the faintest spectra yet published from the IRTF/SpeX.

The spectral types of the T dwarfs were determined by matching to template dwarf spectra (Burgasser et al. 2006a), and have an uncertainty of 0.5 in type. Object J0348–0012 lacks a near-infrared spectrum, but is most likely an early T dwarf based on the absence of quasar emission features in the optical spectrum (Fig. 4), and its photometry as shown in Fig. 2. Using the spectral types of the three spectroscopically confirmed Ts, the photometric distances to each dwarf were derived from the relation of Liu et al. (2006), and are presented in Table 2.

We also undertook high angular resolution imaging of dwarf J0139+0048. Only six dwarfs of spectral type T7.5 or cooler have been imaged before at high angular resolution, with either Hubble Space Telescope (HST) (e.g. Burgasser et al. 2006b) or Keck Laser Guide Star (Liu et al., in preparation). We imaged J0139+0048 on ut20070906 using the sodium LGS adaptive optics system of Keck II. Conditions were photometric with excellent seeing, and we used the NIRC2 camera to obtain dithered K-band images, with a total on-source integration time of 720 s. The resulting data have FWHM of 0.050 ± 0.03 arcsec and Strehl ratios of 41 ± 11 per cent. The object appears single in our images, with no companions at 0.1–2.0 arcsec separation up to 3.5 mag fainter (\(K = 22.7\)). At 35 pc and an assumed age of 1–5 Gyr, this corresponds to companions of 12–30 \(M_J\), based on the models of Baraffe et al. (2003).
These four new faint T dwarfs were drawn from a searched area defined by the overlap of the UKIDSS DR1 data set with the SDSS Southern Equatorial Stripe, which ranges from RA ≈ 22° to 43°, and Dec. = ±1°.265. We calculate this overlap to be approximately 136 deg² by rectangular approximation using a 0.2 mesh, but with uncertainty of ±10 per cent due to incomplete UKIDSS tiling and areas lost due to extremely bright stars and other normal imaging defects. In this area, collaborators concurrently identified four other new T dwarfs ranging from type T4.5 to T8.5, which we also selected during this search, but did not pursue independently (see Lodieu et al. 2007; Warren et al. 2007b). One other T dwarf (T4, SDSS J0207+0000) was reconfirmed, having been found previously in the SDSS data alone (Geballe et al. 2002). Including our present sample then, this brings the total number of T dwarfs to nine in this area, down to a searched magnitude limit of Y = 19.9.

A recent estimate of T dwarf numbers in the UKIDSS LAS complete area is provided by DH06, based on a projection of 4000 deg² reaching a depth of \[ Y, J, H, K = [20.5, 20.0, 18.8, 18.4] \). Aside from the increased area, this differs from the present DR1 flux limits by an increase of 0.4 mag in depth of the J imaging (\( J = 19.6, 5\sigma; \)) Warren et al. 2007a). This is because the LAS J band is planned to have a second epoch of imaging to aid the determination of proper motions, among other goals. Also, their assumed limiting Y magnitude is slightly deeper than that actually achieved by the survey (\( Y = 20.2, 5\sigma; \)). With these flux limits, and depending on various assumed initial mass functions (IMF) and birth rates, the DH06 discovery estimates for the UKIDSS LAS survey are from 321 to 1375 early T dwarfs, 657 to 2014 late T dwarfs and 25 to 100 Y dwarfs, which Deacon and Hambly operationally define as objects with \( T < 770\ K \). At present, the actual spectral criteria and \( T_{\text{eff}} \) that would warrant a new type are unknown, though the presence of \( \text{NH}_3 \) absorption features is expected to be important (Leggett et al. 2007).

Based on these nine T dwarfs found to date in the Southern Equatorial Stripe, we suggest that the eventual numbers of discovered dwarfs will not be able to reach the theoretical sky density of DH06, even after correcting for different assumptions about the increased expected depth of the full UKIDSS imaging. The nine T dwarfs found in 136 deg² suggest that by simple area scaling, approximately 264 dwarfs in the \textit{totalled early to late} T classes may be found in 4000 deg² of imaging to these depths (searched depth of \( Y = 19.9 \)), approximately an order of magnitude less than the typical numbers expected by DH06.

The difference in quoted survey limits must also be taken into account to correctly compare the samples. However, after doing so, a significant shortfall remains. Increasing the assumed searched depth from \( Y = 19.9 \) (actually searched in this sample) to \( Y = 20.5 \) (the flux limit of DH06), under an assumption of uniformly distributed objects, this would improve the limiting flux to 1/1.73 \( \times \) the present value, the probed distance to 1.31 \( \times \) and therefore the searched spherical volume to 2.29 \( \times \) the present value – 606 early-late T dwarfs. However, this still represents an approximately 3.5 \( \times \) deficiency compared to the average DH06 projections. In addition, if the expected vertical scaleheight for dwarfs were to differ from normal stars (such as a more rapid falloff), this could decrease the discovered numbers.

We note that while a future increase in survey \( J \) depth would increase the certainty of selected candidates through higher signal-to-noise ratio (S/N) detections, it would not increase the absolute numbers of discovered dwarfs as dramatically as the factor of 8 suggested by Lodieu et al. (2007), because the colours of T dwarfs are expected (and selected) to display \( Y = J > 0.5 \). As a result, in the current sample being searched to \( Y = 19.9 \), the survey depth of \( J = 19.6 \) has not been a limiting factor. Similarly, for the DH06 survey depth assumption of \( Y = 20.5 \) (which is corrected for above), the simultaneous \( J = 20.0 \) depth would not be limiting, and therefore the difference in survey \( Y \) depth can only account for one-sixth to one-half of the large discrepancy between the discovered dwarfs versus the DH06-predicted sky density. This shortfall, if affirmed as the UKIDSS dwarf census grows, may imply that the actual IMF/birth rate of early and late T dwarfs falls at the very low end of DH06
model scenarios, and that Y dwarfs (as defined by DH06) will be proportionally even more rare. The T8.5 dwarf (J0034−0052) of Warren et al. has an estimated $T_{\text{eff}}$ of 650–750 K but with spectral characteristics only slightly different from previously identified late-T dwarfs. Y dwarfs with NH$_3$ absorption features may thus be even rarer than the 25–100 predicted by DH06 in the full UKIDSS LAS – as challenging to find as $z > 6$ quasars.

5 CONCLUSION

We have conducted a search for high-redshift quasars and the coldest brown dwarfs in $\sim 136$ deg$^2$ of the UKIDSS DR1 in the Southern Equatorial Stripe (SDSS Stripe 82). Searching the combined UKIDSS and SDSS data bases, followed by dedicated imaging and spectroscopy, has yielded four newly discovered T dwarfs, three of which are spectroscopically identified and one is strongly inferred based on near-infrared photometry and optical spectroscopy. These are in addition to the four T dwarfs discovered independently by collaborators and one SDSS T dwarf previously known in this area. The four discovered dwarfs are among the faintest and coldest dwarfs found to date. From this ongoing search, we expect approximately $\sim 264$ early+late T dwarfs may be found in the total 4000 deg$^2$ of the final UKIDSS data. As deep optical data from SDSS become available, this search will continue to seek fainter and cooler dwarf types, in hopes of the still elusive Y dwarf class, and an ever-increasing number of these once-rare objects.

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