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Two T dwarfs from the UKIDSS Early Data Release

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ABSTRACT

Context. We report on the first ultracool dwarf discoveries from the UKIRT Infrared Deep Sky Survey (UKIDSS) Large Area Survey Early Data Release (LAS EDR), in particular the discovery of T dwarfs which are fainter and more distant than those found using the 2MASS and SDSS surveys.

Aims. We aim to show that our methodologies for searching the $\sim 27\,\mathrm{deg}^2$ of the LAS EDR are successful for finding both L and T dwarfs *via* cross-correlation with the Sloan Digital Sky Survey (SDSS) DR4 release. While the area searched so far is small, the numbers of objects found shows great promise for near-future releases of the LAS and great potential for finding large numbers of such dwarfs.

Methods. Ultracool dwarfs are selected by combinations of their $YJH(K)$ UKIDSS colours and SDSS DR4 $z-J$ and $i-z$ colours, or, lower limits on these red optical/infrared colours in the case of DR4 dropouts. After passing visual inspection tests, candidates have been followed up by methane imaging and spectroscopy at 4m and 8m-class facilities.

Results. Our main result is the discovery following CH_4 imaging and spectroscopy of a T4.5 dwarf, ULAS J 1452+0655, lying ~ 80 pc distant. A further T dwarf candidate, ULAS J 1301+0023, has very similar CH_4 colours but has not yet been confirmed spectroscopically. We also report on the identification of a brighter L0 dwarf, and on the selection of a list of LAS objects designed to probe for T-like dwarfs to the survey J-band limit.

Conclusions. Our findings indicate that the combination of the UKIDSS LAS and SDSS surveys provide an excellent tool for identifying L and T dwarfs down to much fainter limits than previously possible. Our discovery of one confirmed and one probable T dwarf in the EDR is consistent with expectations from the previously measured T dwarf density on the sky.

Key words. infrared: stars – surveys: stars: low mass, brown dwarfs

1. Introduction

The goals of the UKIRT Infrared Deep Sky Survey (UKIDSS) have been described by Lawrence et al. (2006) and a full technical description of the Early Data Release (EDR) is given by Dye et al. (2006). One of the prime science drivers for the UKIDSS Large Area Survey (LAS) is to search for large numbers of brown dwarfs, including those cooler than any known hitherto, i.e. with effective temperatures less than the latest T dwarfs ($\sim$ 700–800K). This is made possible by the depth and coverage of the survey as well as the use of the Y filter, covering 0.97 to 1.07 μm. This filter is designed to allow such objects to be distinguished from main-sequence stars and high-z quasars (Leggett et al. 2005). The UKIDSS $ZYJHK$ system is described by Hewett et al. (2006) and simulations of the projected results of the LAS concerning ultracool dwarfs described by Deacon & Hambly (2006).

In this paper, we describe early systematic efforts to probe the ultracool dwarf population observed by the LAS EDR, covering $\sim 27\,\mathrm{deg}^2$ on the sky in all four filters $YJHK$ (c.f. $4000\,\mathrm{deg}^2$ for the complete LAS, to be observed over a seven year duration). We present our successful search methodologies in Sect. 2 and detail results from imaging and spectroscopic follow-up at the AAT, TNG and Subaru in Sect. 3, before summarising in Sect. 4.

2. Catalogue search methodology

The limiting magnitudes of the LAS are $Y = 20.3$, $J = 19.5$, $H = 18.6$ and $K = 18.2$, defined on the Vega system for a S/N = 5 point source detection in a 2″ diameter aperture; Dye et al. (2006). The precise α, δ coverage of the 27^2degs of the EDR is also described by Dye et al. (2006) and is contained within the Sloan Digital Sky Survey (SDSS) DR4 release. We have performed three different source searches involving cross-correlation of the LAS EDR with SDSS DR4. The first search

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Table 1. Five SDSS dropout T dwarf candidates and a confirmed L dwarf followed up by methane imaging and/or spectroscopy. The first five objects listed are from the seven T dwarf candidates obtained in the YJH search, where two have detected methane one of which is confirmed spectroscopically, and three are methane non detections. The Last object listed is the spectroscopically confirmed L dwarf from the first $YJHK$ search. Uncertainties on YJH magnitudes are taken from the LAS EDR merged catalogue, as are $Y-J$ and $J-H$ colours. The penultimate column gives the CH_4s – CH_4l index from AAT/IRIS2 imaging, where applicable.

Name (RA dec)	Y	J	H	$Y-J$	$J-H$	CH_4	comment
ULAS J145243.59+065542.9	19.77 ± 0.14	18.66 ± 0.08	18.45 ± 0.15	1.11	0.21	-0.17 ± 0.13	T4.5 (Subaru spectroscopy)
ULAS J130150.35+002314.8	20.31 ± 0.18	19.24 ± 0.13	18.92 ± 0.20	1.07	0.32	-0.23 ± 0.15	CH_4 detection
ULAS J130519.86+001402.9	20.61 ± 0.23	19.39 ± 0.15	19.28 ± 0.27	1.23	0.11	$+0.19 \pm 0.14$	CH_4 non-detection
ULAS J130153.49+002044.9	20.74 ± 0.26	19.38 ± 0.15	18.91 ± 0.20	1.36	0.47	$+0.17 \pm 0.13$	CH_4 non-detection
ULAS J152347.60+052849.4	19.61 ± 0.11	18.68 ± 0.08	18.38 ± 0.10	0.93	0.30	-	field (Subaru spectroscopy)
ULAS J153108.89+060111.1	16.83 ± 0.01	15.81 ± 0.01	15.07 ± 0.01	1.02	0.74	-	L0 (TNG spectroscopy)

is designed to seek L dwarfs, with LAS K-band detections, and the second to detect T dwarfs without K-band detections, in an H-band limited search (see Fig. 1). The third search is designed to find blue late T dwarf-like objects with YJ-only detections.

The first search was designed to yield L and early T candidates, and used the following criteria: $Y-J$ in the range 0.9 to 1.7, $J-H$ in the range 0.5 to 1.5 and $H-K$ in the range 0.0 to 1.3. All objects were required to be $YJHK$ detections with pStar > 0.9 and mergedClass = -1 [1]. These colour constraints produced 114 candidates which were inspected on UKIDSS images. None were found to be cross-talk artifacts and all were within the SDSS DR4 footprint. SDSS DR4 cross-correlation was performed with a 1.2″ radius search for nearby matches, followed by a 0.3′ radius search for possible high proper motion counterparts, at some separation from the UKIDSS coordinates.

This process produced 88 nearby counterparts of which 30 conformed to the additional constraints of $z-J>2$ and $i-z>$ 1.5, corresponding to an M8 dwarf or later. All SDSS (AB) magnitudes are point-spread-function fitted magnitudes, and for this sample of 30, one-sigma errors on z are <0.3 and on i, <0.35. The $z-J$ colour for these candidates ranges up to 3, corresponding approximately to the L/T boundary (Knapp et al. 2004). Six additional candidates were also revealed by the 0.3′ search for high proper motion counterparts, with DR4 catalogue iz magnitudes conforming to the same ultracool criteria as before. Also, 3 LAS sources contained in the DR4 footprint had no catalogue counterpart. Two of the SDSS images of these candidates may show a very faint detection at z, although one might be a pair of hot pixels. An examination of SDSS z-band uncertainties for neighboring objects shows that a typical one-sigma error on $z \sim 0.4$ is reached at $z \sim 21.5$. If this is taken as an approximate limit for a real z-band detection, then the three dropouts here have $z-J \gtrsim 3$, 2.8 and 2.3 respectively, corresponding to expected spectral types of T0, L6 and L0. In summary, there are 39 ultracool dwarf candidates identified by this search.

[1] see `http://surveys.roe.ac.uk/wsa/` pStar is the probability of the detection being a point source (a value between 0 and 1). mergedClass is a Class flag from all available measurements: 1 galaxy, 0 noise, −1 stellar, −2 probable stellar, −3 probable galaxy, 9 saturated.

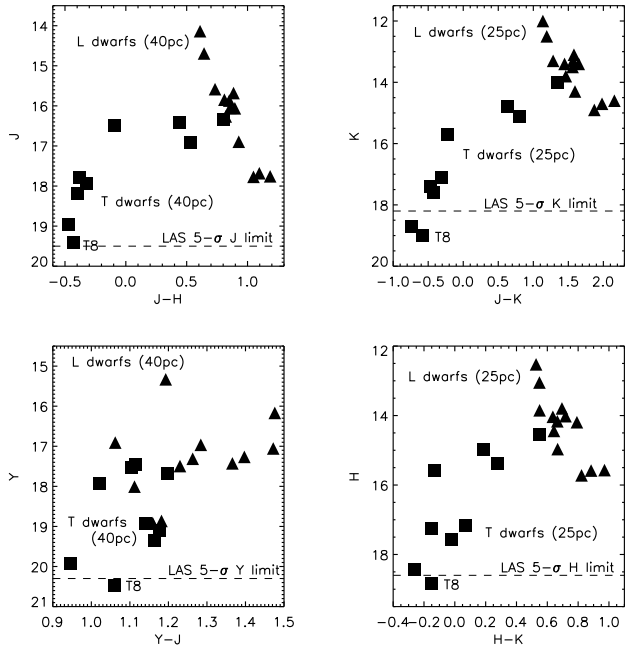

Fig. 1. Example illustrations of the UKIDSS LAS sensitivity to ultracool dwarfs, compared to empirical colour data derived from Hewett et al. (2006) for L1 – T8 dwarfs (triangles and squares for L and T types respectively) with known parallaxes and absolute magnitude, and shifted to the distances indicated. The horizontal lines near the bottom of the plots indicate the LAS sensitivity limits. At K, late T dwarfs at 25 pc would be missed. In order to be sensitive to these, more numerous, distant T dwarfs, we thus chose to require K-band non-detections in our T dwarf search. While this approach could potentially miss some nearer (<17pc), brighter objects, we do not expect a significant number in the 27 deg^2 of the EDR. We thus chose to aim for the more numerous distant population. It can be seen that our search will be H-band limited. Searches for YJ-only detections can thus potentially probe similar objects at much greater distances (m−M = 3 is shown).

The second search was for later-type T dwarfs. The latest T dwarfs have $J-K$ <0, and if one requires a K-band detection for such objects, the LAS K-band sensitivity will

unnecessarily limit the distance and volume probed (see Fig 1). The T dwarf search was thus made requiring K-band non-detections. While this approach could potentially miss some nearer (<17pc), brighter objects, we do not expect a significant number in the 27 deg^2 of the EDR, and we thus chose to aim for the more numerous distant population. Colour criteria used were $Y-J>0.9$ and $J-H<0.5$ together with a likelihood of stellarity requirement that mergedClass $=-1$ or -2. Note that the first two searches cover adjacent but not overlapping regions in the $Y-J$, $J-H$ colour-colour diagram with the boundary at $J-H=0.5$. SDSS DR4 cross correlation was performed as for the first search, requiring either a red $z-J>2$ colour or an optical non detection. Finally, image inspection was carried out to identify cross-talk and other spurious sources. The search resulted in seven T dwarf candidates.

All seven candidates are SDSS dropouts. LAS YJH zero-points were checked in the fits image headers, to ensure that they were not significantly different to other survey zero points derived from observations made on the same night (if they were, this could indicate a problem with the pipeline calibration). None of the relevant zero points were found to be significantly different from their associated nightly averages, with values typically $Y=22.7$, $H=24.5$ and $J=24.7$. Ellipticities measured for the detected sources, and given in the LAS merged catalogue, are maximum ~ 0.3 at Y and typically ~ 0.15–0.2 at J and H, quantifying further the maximum allowed deviation from a point source. One-sigma errors on YJH are typically ~ 0.2, 0.15 and 0.2 respectively. All the candidates except one are faint in the H-band (~ 19), and thus have $J-H$ colours indicative of mid-T dwarfs. The one exception is the reddest in both $Y-J$ and $J-H$ and might be more likely a late L or early T dwarf.

Thirdly, a search for YJ-only detections has been carried out, motivated by the wish to identify late T dwarfs with blue $J-H$ and $J-K$ colours, and possibly even cooler bluer objects. The benefits of this approach are made clear when one considers the J-band depth that can be probed. For an object with $J-H=-1$, one would only reach $J=17.6$ in the EDR if an H-band detection were required. Even for $J-H=0$, one would still only reach $J=18.6$. T dwarfs have $Y-J\sim 1$ (Fig. 1) so a YJ-only search should be capable of probing for such objects to the J-band limit, resulting in a several-fold increase in search volume.

Candidates were selected to have $Y-J\geq 0.8$ and SNR >5 detections (errors on Y and $J\leq 0.2$). A constraint $J\leq 19.5$ was employed, together with mergedClass $=-1$ or -2 as above. The LAS YJ-only sample was uploaded to the DR4 foorprint tool to ensure that only sources within the footprint were considered. These sources were then cross-matched with the DR4 catalogue, and the nearest SDSS source (for each YJ-only source) returned.

YJ-only candidates were retained if this cross-matching resulted in one of three possible criteria being met: (i) The nearest SDSS object was $>2''$ from the LAS position, which would imply that the SDSS object was either a mis-match (ie the LAS source was not detected in SDSS), or that the SDSS counterpart was indicative of a possible high proper motion object (which could also be interesting). (ii) A SDSS source was found within $2''$, but it was not a significant detection. Significant detections were defined as having a signal-to-noise $>5\sigma$ in any of the *ugriz* bands. This criteria ensured that potentially interesting sources were not ruled out by the presence of an insignificant SDSS detection. (iii) A significant SDSS source was found within $2''$, with $i-z>2$ and $z-J>2.5$. Such red optical-infrared colours are indicative of very cool objects such as T dwarfs (e.g. Chiu et al. 2006).

LAS images of the retained objects were then inspected, to identify and remove cross-talk artifacts and other spurious detections such as diffraction spikes and blended sources, and SDSS images were also examined to ensure the credence of the optical constraints. The final selection of YJ-only sources from the EDR included 20 candidates, all of which were DR4 non-detections. A high fraction (80%) of these have J>19.

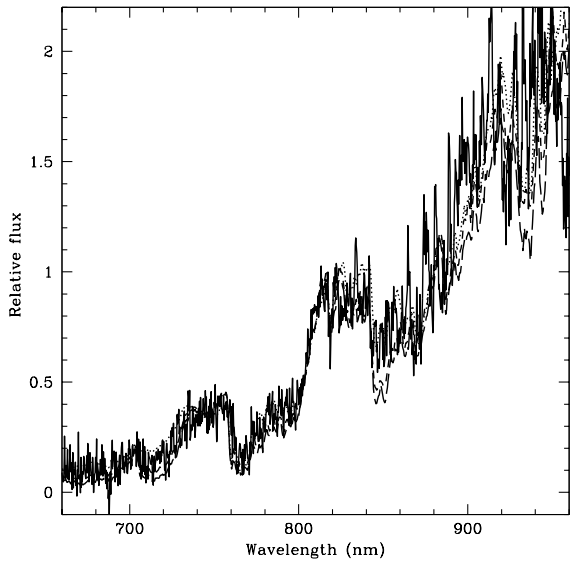

Fig. 2. The spectrum of ULAS J153108+060111, an early ~L0 dwarf found in the LAS EDR, is shown as a solid black line. Also shown for comparison are the spectra of the dL0 DENIS 0909-06 as a dotted line, the dM9.5 DENIS 1208+01 as a short dashed line, and the dM9 DENIS 1431-19 as a long dashed line. The spectrum of the dL0 Martín et al. (1999) is the closest match to the LAS spectrum, and has an estimated spectral type uncertainty of 0.5 subclasses.

3. Follow-up observations and Results

3.1. L dwarfs

In Fig. 2 we show the optical spectrum of an L0 dwarf from the sample of 39 outlined in Sect. 2. This object (see Table 1) is the reddest of the brightest two sources in the sample (with $J=15.81$), and was thus selected as suitable for followup on 4m class telescopes. Spectroscopic observations were made with the DOLORES instrument at the 3.6 m Telescopio Nazionale Galileo on 2006 March 14 with the low resolution red grism yielding a resolution of 11 Å. The detector is a Loral thinned 2048×2048 CCD with 15μm pixels and a

0.275″ pix^{-1} scale. Telluric correction and relative flux calibration was achieved using an observation of an A0 standard star made at a similar airmass to the target observation.

ULAS J153108+060111 yields both interesting photometric and astrometric measurements. Its SDSS/UKIDSS colours of $i - z = 1.95$ and $z - J = 2.44$ compare very well to expectations for an ∼L0 dwarf (Knapp et al. 2004, their Fig. 3). The close agreement between the spectral type inferred from the SDSS/UKIDSS colours and the spectroscopically derived L0 type is extremely encouraging, and suggests that future searches involving LAS/SDSS cross-correlation should yield reasonably accurate spectral type predictions for such dwarfs. In addition, the object is bright enough to be detected in the 2MASS All-Sky point source catalogue, and it can be seen that its motion over a ∼5 yr epoch difference is too small to be measured with any significance. This is exactly what would be expected given its estimated distance of 64 pc, which was derived from the calibration of Cruz et al. (2003).

Further followup of the remaining L dwarf candidates from this sample has yet to be attempted, but could be desirable in the future, particular for the fainter and therefore more distant dwarfs. If improved L dwarf model atmospheres allow the $T_{\rm eff}$ of these objects to be accurately measured, then their distances could be inferred, and constraints placed on the disk scale-height for L dwarfs.

3.2. T dwarfs

This section discusses followup observations of the sample of seven candidates identified via YJH colour cuts and K-band non detections. The most important result so far is the discovery of one certain and one very probable T dwarf via CH_4 imaging using IRIS2 at the Anglo-Australian Telescope (AAT). The certain discovery, ULAS J1452+0655 has been confirmed spectroscopically at Subaru and has a ≈ T4.5 spectral type. ULAS J1301+0023 has an almost identical CH_4 colour, and consistent YJH colours, suggesting a very similar spectral type.

Methane observations of four candidates (see Table 1) were carried out on 2006 May 15 and 2006 July 8, though on both nights seeing was not optimal. The observations employed the CH_4s (1.53 − 1.63 μm) and CH_4l (1.64 − 1.74 μm) methane filters installed in IRIS2. The IRIS2 detector is a HAWAII1 1024×1024 HgCdTe array with 18.5 μm pixels yielding an image scale of 0.4486″/pix at f/8. Observing strategies, reduction and analysis procedures followed those described by Tinney et al. (2006), and in particular the use of 2MASS photometry of background objects to obtain differential CH_4s−CH_4l photometry, which is reported in Table 1, along with the LAS merged catalogue YJH photometry and associated uncertainties. Two of the candidates were methane non-detections, and two showed significant evidence for methane (see Table 1).

Tinney et al. (2006) provide spectral type versus JHK colour versus CH_4s−CH_4l sequences for dwarf stars and brown dwarfs. Because the UKIDSS LAS adds a more sensitive Y band to its catalogue, YJH based sequences will be much more useful in interpreting its discoveries. This requires adding a Y-J versus spectral type sequence to those of Tinney et al. (2006), which we do in Figure 3 and Table 2. Plotted in Figure 3 is the synthetic Y-J photometry derived by Hewett et al. (2006) for A-T dwarfs on the UKIDSS photometric system, as a function of spectral type. Spectral type is numerically parameterised as the spectral sub-type, plus a constant dependent on the spectral type, where the constant is 0 for A, 10 for F, 20 for G, 29 for K, 35 for M, 45 for L and 54 for T. Note that the spectral types used by Hewett et al. are consistent with those used by Tinney et al. with the possible exception of the T-types. These were therefore checked against the compilation of hybridised T-types recently published by Burgasser et al. (2006), (the Tinney et al. sequences are based on these types) and where necessary the Hewett et al. types were changed to the Burgasser et al. types. A smoothed spline has been fitted through those data points to give the dwarf sequence in Table 2.

This Y-J sequence, and the J-H sequence of Tinney et al. (2006) are plotted in Fig. 4(a) and 4(b), along with the observed photometry of the ULAS T dwarf candidates with methane detections (large symbols) as well as the LAS and IRIS2 photometry of all the field objects in the background of each field. In both cases the UKIDSS Y-J and J-H colours are consistent with the relevant colour versus CH_4s−CH_4l locus for dwarf stars, and suggest a spectral type of T3±1.

Spectroscopic observations of ULAS J1452+0655 were carried out at the Subaru telescope on 2006 June 16 with the CISCO (Cooled Infrared Spectrograph and Camera for the OH-Airglow Suppressor) instrument and the JH grism. The resultant wavelength coverage is 1.1 − 1.8 μm at a dispersion of 8.6 Å/pix with a 0.55″ wide slit. The detector was a HAWAII1 array. The integration time used was 30min (300s × 6 frames) and the seeing was measured at 0.5″ in the H band. An F5 telluric standard was observed at a similar airmass for calibration.

The resultant spectrum for ULAS J1452+0655 is plotted in Fig. 5, *(solid centre line)* along with T2, T4.5 and T7 comparison spectra. Based on these spectra we assign a spectral type of T4.5. Measurement of the H_2O-H and CH_4-H indices of Burgasser et al. (2006) yield 0.439 and 0.625 (respectively), suggesting spectral types of T3.5 and T3.5-T4. These measurements, are consistent with the T3±1 derived from CH_4 photometry and the T4.5 derived from inspection of the H spectrum in Fig. 5.

We give precedence to the spectral type derived by direct comparison with the T4.5 comparison spectrum (2MASSJ0559-1404) and adopt T4.5 type for ULAS J1452+0655. The other comparison spectra in Fig. 5 certainly indicate that ULAS J1452+0655 cannot be as early as T2, nor as late as T7. Given the agreement between the direct spectroscopic comparison, and the results given by spectral indices and methane imaging, we believe that the adopted spectral type is accurate to one subclass.

For a spectral type of T4.5 we adopt an absolute magnitude of M_J=14.1 (Knapp et al. 2004) yielding a distance of 83pc for ULASJ1452+0655. This is the first demonstration that the UKIDSS LAS will deliver its stated potential to find Tdwarfs out to beyond 50pc. The second methane detection, ULASJ1301+0023, has a fainter apparent magnitude. If it has a similar spectral type, as seems likely, it lies at

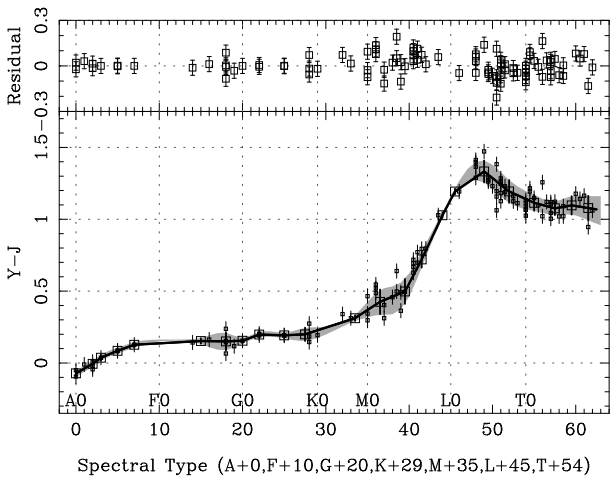

Fig. 3. Y-J (UKIDSS) as a function of A-T spectral type, following Tinney et al. (2006). Y-J synthetic photometry and spectral types from Hewett et al. (2006), supplemented by T-dwarf types from Burgasser et al. (2006). These data have been binned by spectral type *(large squares)*, which have themselves been fitted with a cubic-spline interpolating function *(solid line)*. The shaded region shows the 1-σ rms scatter about the binning. These Tracks are summarised in Table 2.

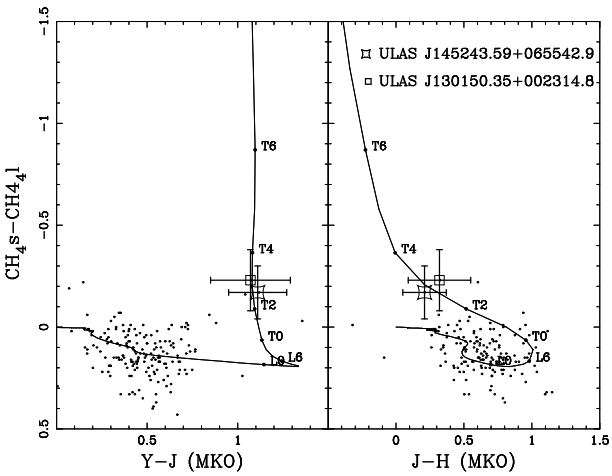

Fig. 4. IRIS2 CH4 and ULAS photometry for ULAS J145243.59+065542.9 and ULAS J130150.35+002314.8 and the objects in the same IRIS2 field as these targets (small points). The solid line is the dwarf locus in Y-J and J-H versus CH4 from Table 2 and Tinney et al. (2006).

a greater distance. ULASJ1452+0655 is potentially therefore one of the most distant spectroscopically confirmed Tdwarfs yet found, standing comparison with other distant T dwarfs; the T6 SOri 70 at a distance of at least 75-100pc and possibly as distant as 400pc (Zapatero Osorio et al. 2002); the T6 NTTDF1205-0744 at 90pc (Cuby et al. 1999); the T3 IfA0230-Z1 at 45pc (Liu et al.(2002). Finally, we note that based on the IMF of Chabrier (2002, 2003) which reproduces presently observed counts (Chabrier2005), we expect 0.001BD/pc^3, and 5–6 T dwarfs in the LAS EDR, assuming a depth of J=19. This is reasonably consistent with the discovery of two T dwarfs from a sample of seven candidates in which only 5 have had follow-up observations sufficient to confirm or deny their T-dwarf status. Followup of the two additional candidates will be attempted in the future.

3.3. YJ-only search

The colour space probed by the YJ-only search will naturally select some faint (J >19) late M dwarfs (cf Table 2), some early L dwarfs, and the majority of early-mid T dwarfs, as well as the sought after late T and even cooler dwarfs. It is thus important to place further constraints on spectral type via photometric followup observations, before spectroscopy on 8m class telescopes can be attempted. Optical z-band measurements can be used to rule out late M and early L dwarfs, and the latest T and cooler candidates can be confidently identified by obtaining deeper J- and H-band imaging to accurately measure the $J-H$ colour, as well as performing methane imaging (in the manner reported here). The sample of 20 YJ-only objects from the EDR are to be followed up with both optical and near infrared photometry in this way, so as to identify the most promising candidates for spectroscopy.

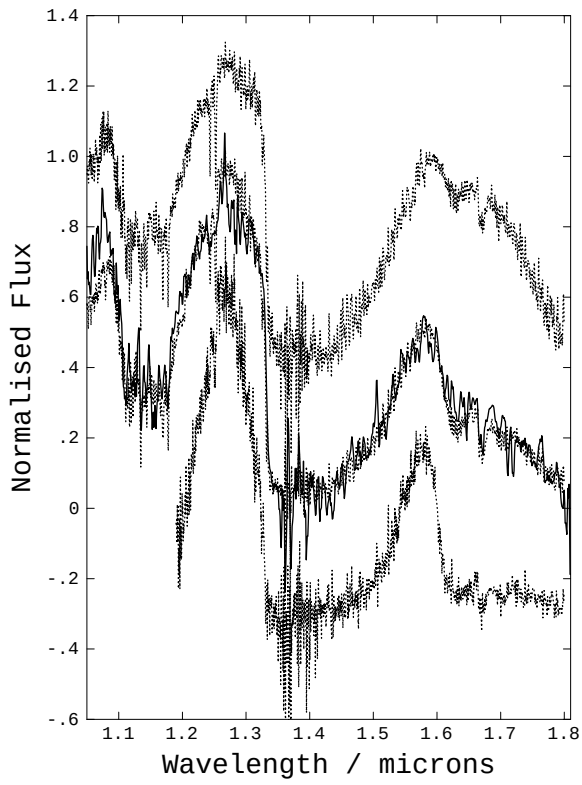

Fig. 5. Subaru/CISCO spectrum of ULAS J 1452+0655 (solid line, centre). Over-plotted on this (dotted line) is the T4.5 spectrum of 2MASSJ0559−1404 from Cushing et al. (2005). Also shown are the T2 spectrum of SDSS 1254−0122 from Cushing et al. (2005) and the T7 spectrum of 2MASS 0348−6022 from Burgasser et al. (2006), shifted by +0.3 and −0.3 continuum units respectively.

Table 2. Y-J (UKIDSS) Dwarf Sequence based on Burgasser et al. (2006) spectral types.

SpT	Y-J(UKIDSS)
A0	-0.072
A5	0.085
F0	0.157
F5	0.153
G0	0.155
G5	0.193
K0	0.212
K3	0.268
M0	0.371
M2	0.428
M4	0.467
M6	0.657
M8	0.910
L0	1.144
L2	1.305
L4	1.333
L6	1.243
L8	1.157
T0	1.133
T2	1.093
T4	1.081
T6	1.096
T8	1.070

4. Conclusions

- We have spectroscopically confirmed a new L0 dwarf in the UKIDSS Large Area Survey Early Data Release using LAS and SDSS photometry. The spectral type inferred from the UKIDSS/SDSS photometry is in good agreement with the spectroscopic observations.
- We have also spectroscopically confirmed a T4.5 dwarf in the EDR, ULAS J 1452+0655, as well as another object ULAS J 1301+0023, which likely has a similar spectral type (estimated from our methane imaging). The discovery of two T dwarfs from 27^2degs of UKIDSS is in reasonable agreement with expectations of the surface density of T dwarfs on the sky.
- We have used our knowledge of LAS sensitivities and late T dwarf colours to identified a sample of objects that should probe the LAS for late T dwarfs (and potentially even cooler objects) down to the J-band limit. By selecting sources that are undetected in both the H- and K-bands, this search probes a significantly larger volume than comparable searches limited by H-band sensitivity.
- Our findings, from this small area of sky, show that the UKIDSS LAS is already performing up to expectation, and shows excellent promise for the future in fulfilling one of its main science drivers of finding unprecedentedly large numbers of brown dwarfs.

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