Discovery of a very cool brown dwarf amongst the ten nearest stars to the Solar System.

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Brown dwarfs[1] are bodies with masses in the range between those of giant planets and the lightest stars. Some are isolated[2,3], while others orbit normal stars[4] or exist in star clusters[5,6,7]. Since 1995, more than 100 methane brown dwarfs, or T dwarfs, have been found with spectra similar to that of the planet Jupiter and effective temperatures in the range 500-1300 K. The detection of even cooler bodies will open up a new arena for atmospheric physics and help to determine the formation rate of stars and brown dwarfs in our Galaxy as a function of both mass and of time. Here we report the discovery in the UKIDSS Galactic Plane Survey of a brown dwarf, UGPSJ0722-05, that is not only far less luminous and significantly cooler than previously known objects but also the nearest to the Solar System. The measured distance is 2.9±0.4 pc, from which we deduce an effective temperature in the range 400-500 K. The Gemini/NIRI near infrared spectrum displays deeper water vapour and methane absorption bands than the coolest known T dwarfs, and an unidentified absorption feature at 1.275 μm. Time will tell whether this object is regarded as a T10 dwarf or the first example of a new spectral type.

Brown dwarfs are commonly described as failed stars, owing to their lower mass (0.012-0.075 M_{sun}) and consequent inability to generate significant amounts of energy by nuclear fusion reactions. They are approximately Jupiter-sized bodies substantially supported by electron degeneracy pressure rather than thermal pressure. The majority are believed to form in the same manner as stars via the gravitational contraction and fragmentation of large clouds of molecular gas in interstellar space, though the planet formation process is thought also to create some objects of brown dwarf mass. The first verified brown dwarfs were discovered in 1995[2,3] and several hundred have since been detected as isolated objects in the local field[4,5], in young stellar clusters[6,7] and as binary companions to other objects.

The space density of brown dwarfs is not yet known. Searches in young clusters[8,9,10] suggest that the ratio of brown dwarfs to stars is ~1:3 but fewer are found in the local field[11,12,13]. The effective temperatures of the coolest known type of brown dwarfs, the methane dwarfs or T dwarfs, are in the range T_{eff} ~500-1400 K. Even cooler objects are expected to exist because brown dwarfs continuously cool over time. Objects with masses amongst the smallest that the star formation process creates (~10 M_{Jup}[7,9]) and ages similar to the older stars in the Galaxy (6-10 Gyr) are expected to be as cool as T_{eff} ~260 K. Searches for very cool brown dwarfs are motivated by the opportunity to investigate an unexplored temperature range in atmospheric physics and to investigate the mass distribution and formation history of brown dwarfs via measurement of their distribution as a function of temperature[14,15]. Infrared spectra of the cooler T dwarfs somewhat resemble that of the planet Jupiter. The study of brown dwarf atmospheres has relevance to the numerous gas giant planets known to exist in relatively close orbits around nearby stars, most of which cannot be observed directly.

Over the past five years, the UKIRT Infrared Deep Sky Survey (UKIDSS)[16] has been mapping a significant fraction of the northern sky with the aim of detecting rare objects such as the coolest T dwarfs and perhaps cooler objects, which might require a new spectral type if they exhibit new spectral features[17]. The UKIDSS Large Area Survey has discovered several brown dwarfs cooler than the coolest object previously known (2MASS0415 a T8 dwarf with T_{eff} ~760 K). Most of these have been classified as T8.5 or T9 dwarfs, on the basis that the broad water vapour and methane absorption bands in their near-infrared spectra are slightly deeper than those of T0-T8 dwarfs. The slight differences in the spectra belie a large drop in effective temperature from 700 K to 500-600 K for the coolest objects[18,19].

Here we report the discovery by the UKIDSS Galactic Plane Survey (GPS)[20] of UGPS J072227.51-054031.2 (hereafter UGPS 0722-05) – an even cooler and less

luminous brown dwarf. The candidate was initially identified as the only good candidate late-T dwarf amongst the 604 million sources in Data Release 6 of the GPS using the colour selection (J-H)<0.2 mag and (H-K)<0.1 mag, and various data quality restrictions[20,21]. (See the Methods section for details of the restrictions applied to the three GPS near-infrared imaging passbands, denoted J, H and K.)

UGPS 0722-05 is relatively bright and has similar near-infrared colours to known T8.5 and T9 dwarfs[13] (see Table 1). Near-infrared spectra in the wavelength range 1.1 to 2.5 μm were obtained at the Gemini North Telescope on 2010 February 10, 11 and 14 (see Figure 1). While the spectrum appears broadly similar to that of a T9 dwarf, a ratio plot comparing UGPS 0722-05 with the average of three T9 dwarfs shows that the broad molecular absorption bands on either side of the flux peaks at 1.28 μm and 1.59 μm and on the long wavelength side of the 1.07 μm peak are between 10% and 30% deeper. The values of the spectral indices "W_J", "CH_4-J", "NH_3-H" and "CH_4-H", which are used for typing the coolest T dwarfs[18,22,13], are smaller than those of T9 dwarfs by amounts similar to the differences between T8 and T9 dwarfs. The near-infrared spectrum therefore suggests a spectral type of T10. There is also a narrow absorption feature at 1.275 (see Figure 2). A feature has been seen at a similar wavelength in Jupiter and (weakly) in a T8.5 dwarf and a T9 dwarf[18]. We have examined a synthetic spectrum generated from a new, as yet unpublished, high temperature NH_3 line list but there is no sign of a corresponding feature. It remains unidentified at present.

The relative brightness of UGPS 0722-05 indicated that it must be nearby, in interstellar terms. Our preliminary parallax is 340±40 mas (see Supplementary Information) corresponding to distance, d=2.9±0.4 pc. This leads to absolute J band magnitude, M_J=19.2±0.3, which means that the near infrared luminosity is more than a factor of two lower than that of the least luminous T9 dwarf and a factor of three lower than that

of the average T9 dwarf[23]. The parallax data were taken with the UKIRT Wide Field Camera, combined with the original UKIRT/UKIDSS detection in November 2006 and a faint detection in 2MASS[23] images taken in October 1998. (UGPS 0722-05 is not included in the 2MASS Point Source Catalogue). This result is consistent with the spectral type vs. absolute magnitude relation for late T dwarfs[13,23,25], an extrapolation of which suggests that T10 dwarfs should be significantly fainter than T9 dwarfs in the near-infrared, by just the amount that is observed (see Figure 3).

The preliminary distance measurement indicates that UGPS 0722-05 is the closest brown dwarf, closer than the brown dwarf binary ε Indi Bab[25], which orbits the star ε Indi A at d=3.626±0.009 pc. The current distance estimate of 2.9 pc places it amongst the ten closest systems to the sun. Neither the Gemini acquisition image nor a proper motion search reveals any indication of a companion object.

The effective temperature (T_{eff}) of UGPS 0722-05 cannot be reliably estimated with existing model atmospheres, so we instead fall back on the formal definition of this quantity ($L=4\pi R^2\sigma T_{eff}^4$) and use the estimated total luminosity and a model radius (the range of possible radii is taken from the SM2008[27] models). The total luminosity is not yet well constrained so for the purpose of a first calculation we assume that the spectral energy distribution is the same as that of a T9 dwarf. The average values of M_J and luminosity for the three T9 dwarfs[18,22,28] with measured parallaxes[23] are M_J =17.89 and $L=(8.5\pm2.9)\times10^{-7}$ Lsun. Scaling these by the observed M_J for UGPS 0722-05 leads to $L\approx2.6\times10^{-7}$ Lsun. The SM2008 models suggest that a brown dwarf with this luminosity would have a radius in the range 0.09 to 0.12 Rsun and an age between 0.1 and 10 Gyr (see Supplementary Information).

The larger radius would imply $T_{eff}\approx$ 380 K and the smaller radius implies $T_{eff}\approx$ 430 K. Both figures have uncertainties of ~9% derived from the uncertainty in the luminosity

of T9 dwarfs and the uncertainty in the parallax. We note that the SM2008 predictions extrapolated below the 500 K limit of their model atmosphere grid but the radii are similar to those of more luminous brown dwarfs and giant planets.

However, the above temperature calculations are not complete because the spectral energy distribution of brown dwarfs shifts to longer wavelengths with decreasing effective temperature[19] and the flux emitted in the near-infrared declines as a fraction of the total luminosity. The luminosity and temperature of UGPS 0722-05 are therefore expected to be higher than the above estimates. The SM2008 models, combined with the preferred temperature range of $500 < T_{eff} < 600$ K for the coolest previously known T8.5 and T9 dwarfs[19,24], indicate that the luminosity is underestimated by up to a factor, f = 2 (see Supplementary Information). Doubling the luminosity raises our effective temperature estimates by a factor of $2^{1/4}$, to $T_{eff} \approx 450$ K and $T_{eff} \approx 520$ K. However, a temperature as high as 500 K would imply a smaller luminosity correction factor: $f \leq 4/3$. We therefore conclude that the effective temperature of UGPS 0722-05 is in the range 400 to 500 K. The SM2008 evolutionary models indicate that the mass is between 5 and 30 M_{Jup}

UGPS 0722-05 is significantly cooler and intrinsically fainter than the coolest T dwarfs previously known. It is usual for the range of sub-types to run from 0 to 9 so it is therefore quite possible that UGPS 0722-05 will come to be seen as the first example of a new spectral type. (The letter Y has been suggested for this but it can cause confusion with white dwarfs in conversation). The fairly strong 1.275 μm feature might perhaps form the basis of such a classification. Gross changes in spectra are not expected in cooler objects at 1-2.5 μm, given the similarity of T dwarf spectra to that of Jupiter, so some may prefer to call all such objects T dwarfs. In that case a scheme to distinguish the coolest T dwarfs should be devised based on the near-infrared to mid-IR flux ratio or on spectral features detected at wavelengths > 2.5 μm.

UKIDSS has so far surveyed ~2500 deg^2 in the 7th Data Release. The existence of this object in such a small fraction of the sky (~6%) suggests that even closer brown dwarfs will be found in future, either by UKIDSS or by new wide field facilities such as the NASA WISE satellite and the VISTA telescope. Any such bodies would very likely be as cool or cooler because most warmer bodies would have been detected previously by 2MASS. It is a virtual certainty that cooler bodies will be found at greater distances because volume scales with the cube of distance and the new facilities mentioned above all have the sensitivity to make such discoveries.

'Methods'.

UKIDSS GPS images are taken in three filters denoted J, H and K. These are centred at wavelengths of 1.25, 1.65 and 2.20 μm respectively. Data quality restrictions for the candidate selection from the source catalogue were: pstar>0.9, ppErrbits<256, ellipticity<0.3, jmhPntErr<0.3 mag, hmk_1PntErr<0.3 mag, separation<0.3 arcsec between the J and H and the J and K coordinates. A further constraint was to limit the search to Galactic longitudes l>60° and l<358°. This spatial constraint and the data quality restrictions were designed to select against blended stellar pairs with inaccurate photometry, which are a frequent occurrence in the most crowded regions of the Galactic Plane. The selection also removed normal stars and image defects. Only six candidates remained after this procedure. Of these, four were immediately revealed as blended stellar pairs or defective data by inspection of the images and one (a candidate white dwarf) was ruled out by its detection in visible light in the POSS USNO-B1.0 archive. The Gemini North J, H and K spectra were obtained with total on source integration times of 16, 60 and 30 minutes respectively. The spectral resolution was R≈500. They were reduced with the IRAF software package using standard techniques.

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'**Supplementary Information** accompanies the paper on **www.nature.com/nature**.'

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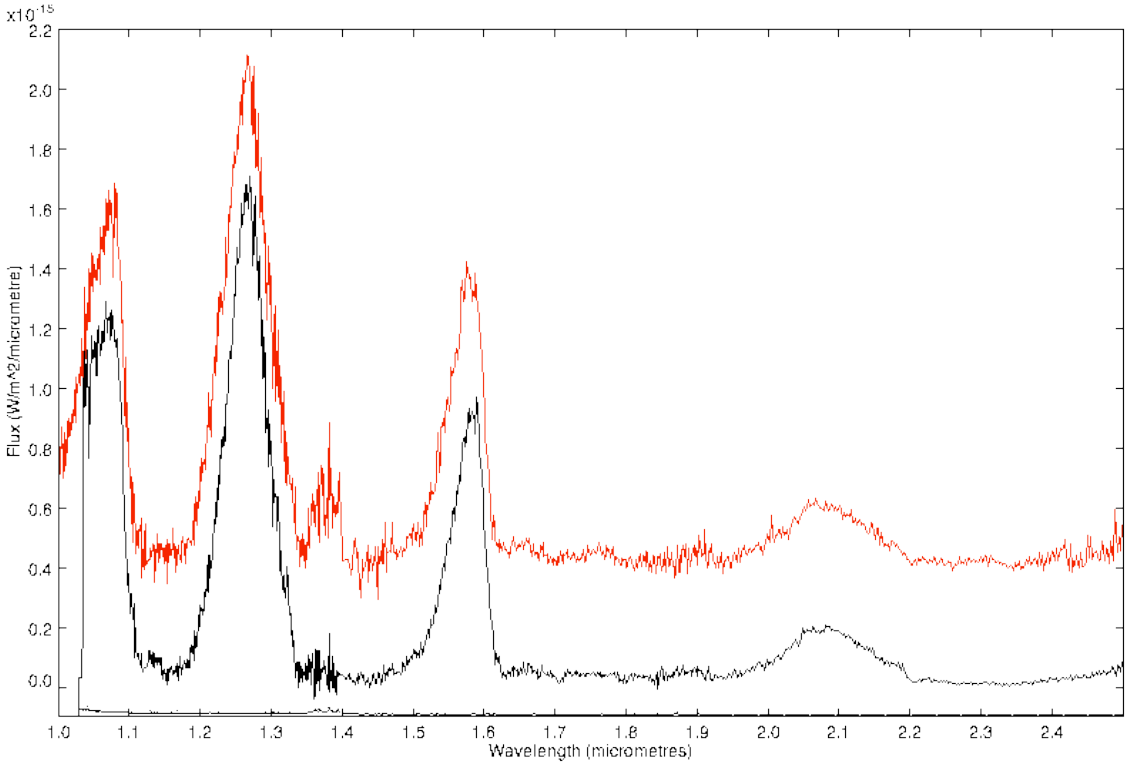
Table 1 - Details of UGPS 0722-05

R.A. (J2000, epoch 2010.14)	07 22 27.29
Dec (J2000, epoch 2010.14)	-05 40 30.0
J mag[a]	16.52 ± 0.01
(J-H) colour[a]	-0.38 ± 0.03
(H-K) colour[a]	-0.18 ± 0.08
W_J index	0.2074 ± 0.0012
H_2O-J index	0.0339 ± 0.0017
CH_4-J index	0.1358 ± 0.0019
NH_3-H index	0.4917 ± 0.0021
H_2O-H index	0.1218 ± 0.0017
CH_4-H index	0.0643 ± 0.0013
CH_4-K index	0.0959 ± 0.0022
K / J index	0.12615 ± 0.00033
Parallax (mas)	340 ± 40

Proper motion (milliarcsec/yr)	929 ± 8
Direction (degrees east of north)	291.8 ± 0.2

[a] Photometry and colours are Vega magnitudes on the UKIRT Wide Field Camera MKO system.


x10^-15
Flux (W/m^2/micrometre)
Wavelength (micrometres)

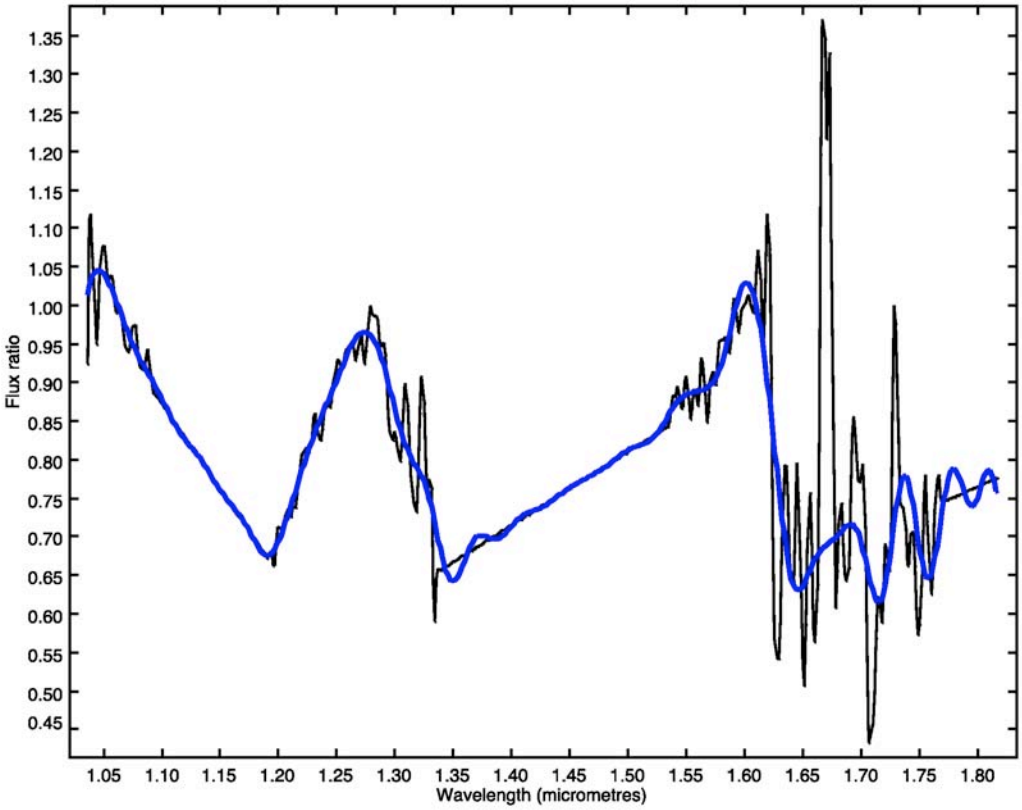

Flux ratio
Wavelength (micrometres)

Figure 1. *(upper panel)* Near-infrared spectrum of UGPS 0722-05, taken with the Near InfraRed Imager and Spectrometer (NIRI) on Gemini North (black line). The separate J, H and K band spectra were normalised and joined using the UKIDSS fluxes. The error spectrum is also shown at the bottom (offset by -1x10^{-16} W/m^{2}/µm for clarity.) Overplotted in orange is a suitably scaled spectrum of the T9 dwarf ULAS 1335+11[17] (offset by 4x10^{-16} W/m^{2}/µm for clarity) which appears very similar at first sight. *(lower panel)* A lightly smoothed ratio spectrum (black line) showing the 1.05 to 1.8 µm region of the UGPS 0722-05 spectrum divided by the average of three T9 dwarf spectra and normalised to unity at 1.279 µm. The blue curve shows a high order polynomial fit to the black line (the noise feature at 1.67 µm was excluded from the fit). This plot shows clearly that the broad molecular absorption bands in UGPS 0722-05 are deeper on either side of the flux peaks near 1.27 and 1.59 µm, and on the long wavelength side of the 1.07 µm peak. Straight lines interpolate across noisy regions where there is little flux.

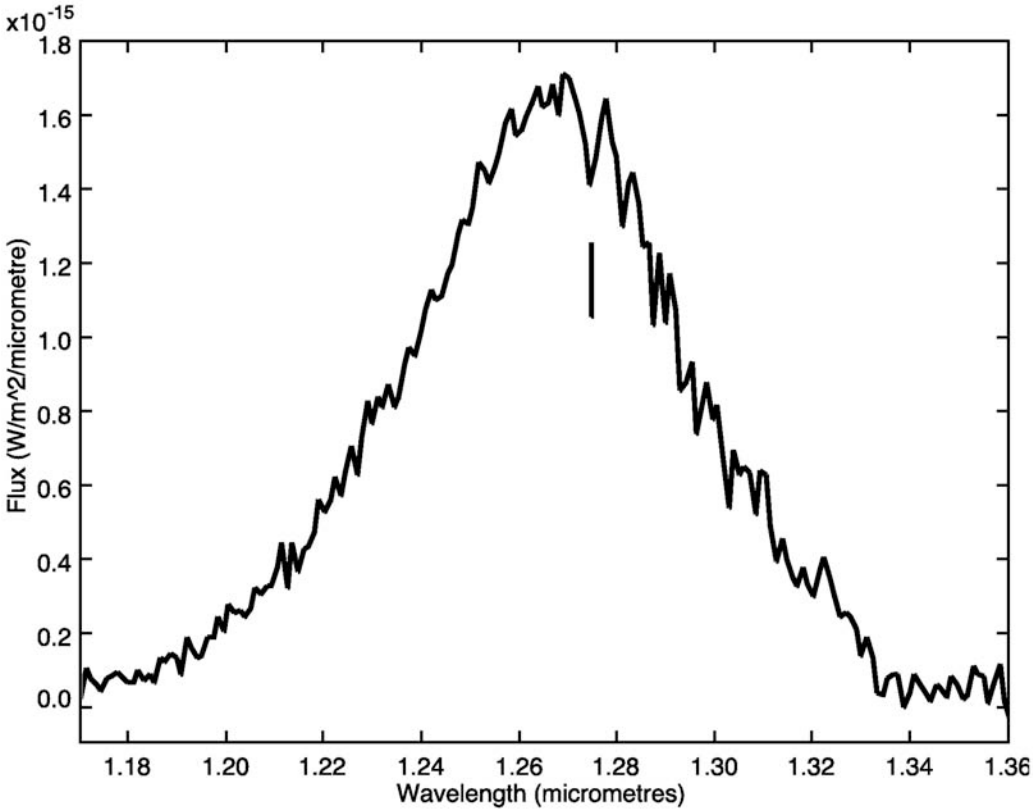


Figure 2. Expanded view of the Gemini/NIRI J band spectrum of UGPS 0722-05. The unidentified absorption features at 1.275 μm is marked with a vertical line.

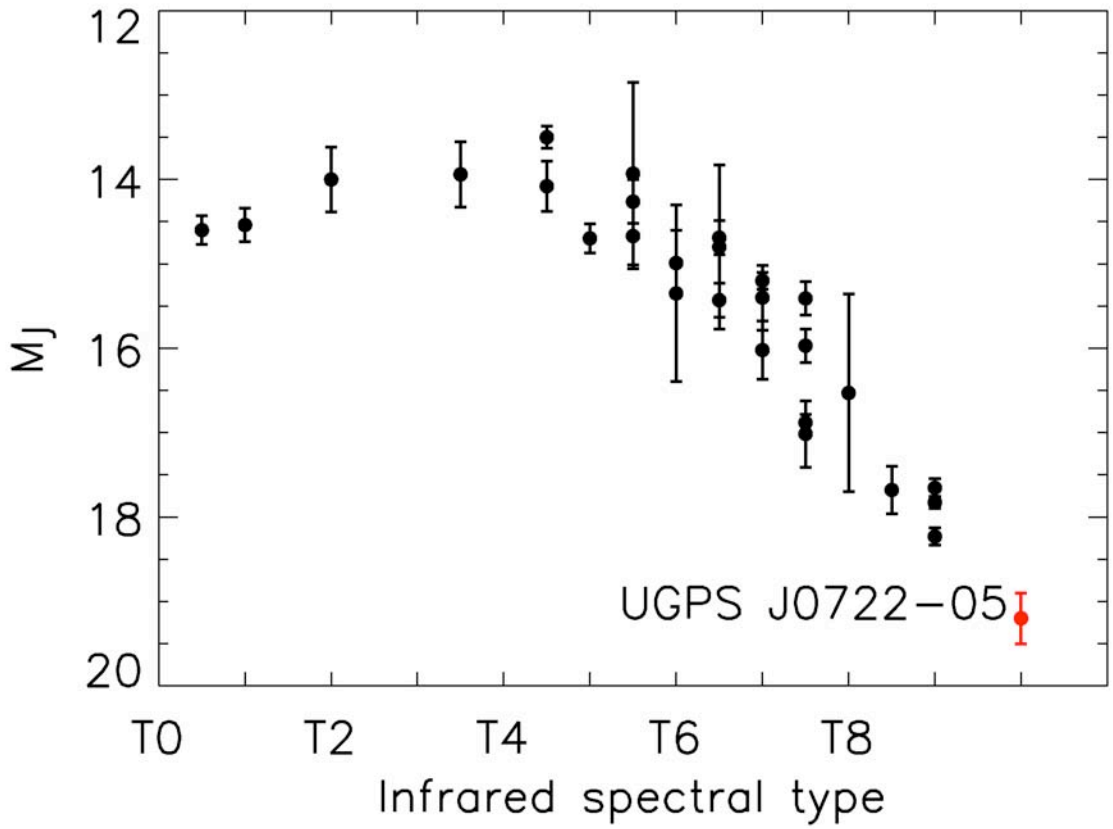


Figure 3. The absolute J magnitude vs. spectral type relation for T dwarfs. This plot was constructed using data from a paper on UKIRT parallax measurements[23]. The trend from T6.5 to T9 appears to be linear. This plot that suggests that classification of UGPS 0722-05 as a T10 or Y0 dwarf would fit the trend.

Supplementary Information

Astrometric Observations

UGPS 0722-05 has been observed in the near-infrared J passband at the epochs listed in Table S1. The 3.7 year baseline between the initial UKIDSS observation in 2006 and the first recovery of it with the NIRI instrument on Gemini allowed an approximate proper-motion to be generated, which in turn allowed the identification of UGPS 0722-05 with a previously uncatalogued source in the 2MASS Atlas image acquired with the 2MASS South telescope in 1998 (see Figure S1).

Detailed astrometric analysis has been performed using the UKIDSS data (the NIRI data, while taken in better seeing, has poor astrometric quality), with a sample of 8 reference stars near UGPS 0722-05 and following the procedures used for near-infrared astrometry of T dwarfs (Tinney et al. 2003). The reference stars range in brightness from 1.9 mag brighter than the target, to 0.2 mag fainter (with most lying within ±0.2 magnitudes of UGPS0722-05). The root-mean-square (rms) scatter of the residuals about the astrometric solution of each epoch onto the master frame (2006 Nov 28), range from 4.4mas to 6.8mas. Analysis of this scatter as a function of the brightness of the reference stars indicates that the rms about the astrometric solution for reference stars within ±0.2 magnitudes of UGPS0722-05 is 6.2mas, and we adopt this as our estimate for the precision of each individual observation of UGPS0722-05.

An astrometric solution for UGPS0722-05 using the UKIDSS data alone results in the solution shown in Table S2 (where the parallax is based on the right ascension solution alone, as the declination solution has little or no weight for an equatorial object). While this solution clearly shows that UGPS0722-05 is nearby, the non-optimal sampling of its proper motion results in a large degeneracy impacting on the parallax solution.

Fortunately, the 2MASS datum helps significantly here. Even though the observation has low signal-to-noise, and is much shallower than the UKIDSS data we can nevertheless define an astrometric transformation between this image and the UKIDSS data with residuals about the transforming stars of 60mas. Because in this image UGPS0722-05 is so faint, we have used a variety of tests to estimate our ability to reliably centroid its image, and on this basis we estimate a position accuracy for this epoch of 100mas. While this is much poorer than the precision for other epochs, the eight year baseline between the 2MASS and UKIDSS images taken at similar times of year significantly constrain the proper motion and improve the astrometric solution. We therefore adopt 340±40mas as our best estimate of the distance to this brown dwarf.

Note to editor: This solution will rapidly and significantly improve over the next month (i.e. as the paper is being refereed) as UGPS0722-05 approaches, and then recedes from, its maximum parallax factor.

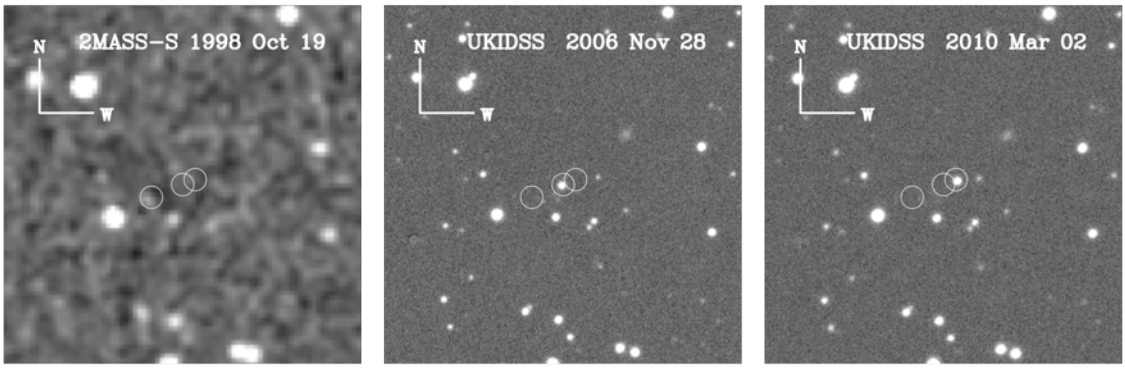


Figure S1 – UKIDSS discovery epoch image (centre), and 2MASS (left) and UKIRT (right) recovery images of UGPS 0722-05 in the J passband, showing its proper motion of 0.930”/yr over a 12 year period. The circles indcate the object at each epoch. Each image is 80” on a side.

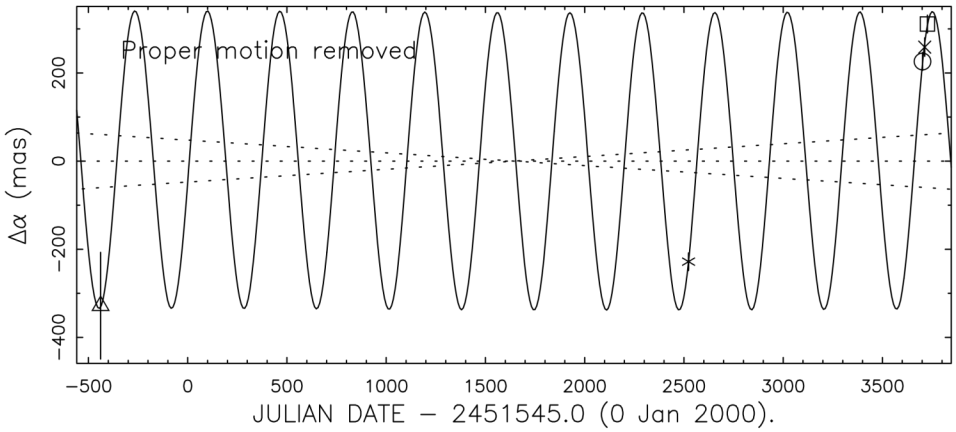


Figure S2 – Right ascension astrometric fit (solid line) for UGPS0722-05 using UKIDSS and 2MASS data (triangle, asterisk, circle, cross and square in the chronological order listed in Table S1) with the fitted proper motion removed (the resultant proper motion uncertainties are indicated by the dotted lines).

Table S1 – Log of observations.

Date	Facility	Seeing (“)	Scale (“/pix)
1998 Oct 19	2MASS-S	2.46	1.00
2006 Nov 28	UKIRT/WFCAM	0.82	0.2013
2010 Feb 10,11,14	Gemini North/NIRI	0.46, 0.40, 0.82	0.116
2010 Feb 19	UKIRT/WFCAM	0.80	0.2013
2010 Mar 02	UKIRT/WFCAM	1.00	0.2013
2010 Mar 16	UKIRT/WFCAM	0.82	0.2013

Table S2 - Astrometric solution for UGPS0722-05.

Solution	Span (Epochs)	μ (mas/yr)	θ (°)	π (mas)
UKIDSS	2006.93-2010.24 (4)	946±9	291.5±0.2	302±96
UKIDSS+2MASS	1998.80-2010.24 (5)	929±8	291.8±0.2	341±40

Discussion of the temperature, age, mass and surface gravity implied by model atmospheres

The correction factors to the luminosities and effective temperatures inferred from assumption that UGPS 0722-05 has the same spectral energy distribution as a T8.5 or T9 dwarf are calculated as follows. At T_{eff}=600 K only 40% of the total flux is emitted at wavelengths λ<3 μm. This figure declines linearly with effective temperature to 30% at 500 K[19]. An extrapolation suggests that the fraction may be as low as 20% at 400 K. The total luminosity obtained by scaling from the near-infrared flux would then have to be doubled (i.e. f=2), relative to a 600 K template spectrum. Since the preferred temperature range is 500< T_{eff}<600 K for the coolest previously known T8.5 and T9 dwarfs[19,24] we therefore assume that we have not underestimated the total luminosity by more than a factor of two. At 500 K, the factor is f=4/3, relative to the 600 K template spectrum. Given that the range is actually 500< T_{eff}<600 K for the coolest T8.5 and T9 dwarfs this implies f ≤ 4/3 at 500 K.

Leggett et al. (2010) discuss the temperatures, metallicities and surface gravity (and hence mass and age) of a sample of very late-type T dwarfs. The parameters are constrained using models by Saumon & Marley (2008) to interpret observed trends in infrared colours and brightness. UGPS0722-05 has (H-K) = -0.18±0.08 and M_H=19.56. In the top panel of Figure 9 of Leggett et al. it would lie at the bottom of the plot under Wolf 940B, indicating that the dwarf has slightly lower gravity or higher metallicity than the T8.5 to T9 dwarfs Wolf 940B, ULAS J003402.77-005206.7 and ULAS J133553.45+113005.2, but is significantly cooler. As also suggested by the luminosity arguments in the text, UGPS0722-05 appears to be cooler than 500K, the lower limit of the SM2008 model atmospheres. The similarity otherwise to the three T8.5 to T9 dwarfs implies that UGPS0722-05 has solar or slightly enhanced over solar metallicity, and a surface gravity given by log g = 3.75 to 5.0. This range in gravity corresponds to a mass of 5 M_Jup to 30 M_Jup (Saumon & Marley 2008). Assuming that 400 <= T_eff K <= 500, this range in gravity also implies a range in age of 0.1 Gyr to 10 Gyr (Saumon & Marley 2008). A lower gravity and younger age is in principle permissible if the object also has a lower metallicity to compensate for the redward shift in the (H-K) colour that would be produced by the low gravity. Similarly an age >10 Gyr only permissable if the dwarf is extremely metal-rich, to compensate for the effect of the high gravity. The small tangential velocity of the dwarf (~13 km/s) also indicates that the dwarf is not a very old object.

The high temperature ammonia line list

For ammonia we used the new high temperature line list of Yurchenko et al.(2010). This line list was generated using the same methodology developed earlier for room temperature study of NH_3 (Yurchenko et al. 2009) but both used an improved representation of the potential energy surface and considered a greatly extended range of both energy levels and transitions. The line list contains over one billion transitions.

For this study transitions involving rotationally excited states up to $J = 23$ were explicitly used to generate synthetic spectra.

We note that the spectrum of UGPS 0722-05 shows a hint of a weak absorption feature at 1.514 μm, which is the same wavelength as the strongest feature in the 1.4-1.6 μm region in the synthetic ammonia spectrum, when binned to a similar resolution. Confirmation of such possible associations will require spectroscopy at higher spectral resolution.

References

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