DISCOVERY OF A T DWARF BINARY WITH THE LARGEST KNOWN J-BAND FLUX REVERSAL∗
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ABSTRACT
We present Keck laser guide star observations of two T2.5 dwarfs – 2MASS J11061197+2754225 & 2MASS J14044941–3159329 – using NIC2 on Keck-II and find 2MASS J14044941–3159329 to be a 0′.13 binary. This system has a secondary that is 0.45 mags brighter than the primary in J-band but 0.49 mags fainter in H-band and 1.13 mags fainter in Ks-band. We use this relative photometry along with near-infrared synthetic modeling performed on the integrated light spectrum to derive component types of T1 for the primary and T5 for the secondary. Optical spectroscopy of this system obtained with Magellan/LDSS-3 is also presented. This is the fourth L/T transition binary to show a flux reversal in the 1–1.2 μm regime and this one has the largest flux reversal. Unless the secondary is itself an unresolved binary, the J-band magnitude difference between the secondary and primary shows that the J-band “bump” is indeed a real feature and not an artifact caused by unresolved binarity.

Subject headings: binaries: general, close – stars: individual (2MASS J11061197+2754225, 2MASS J14044941–3159329) – stars: low-mass, brown dwarfs – techniques: high angular resolution

1. INTRODUCTION
As brown dwarfs cool and pass through the L/T spectral class boundary, their spectral morphologies transition from red near-infrared (NIR) colors of the L dwarf class, caused by condensate dust in their photospheres, to blue near-infrared colors of the T dwarf class, where their photospheres are relatively clear of dust. This transition is rapid as implied by the nearly flat effective temperature scale around 1400 K for NIR L7–T5 dwarfs (Golimowski et al. 2004; Kirkpatrick 2005, bottom panel of Figure 7). Within this transition, a remarkable brightening in J-band (∆MJ ∼ 1) from spectral types ∼T1–T5, known as the J-band “bump” (Dahn et al. 2002; Tinney et al. 2003; Vrba et al. 2004), has been noted.

Two withstanding mechanisms to explain this brightening have been suggested – (1) The “patchy clouds” model – proposed by Burgasser et al. (2002) (see also Ackerman & Marley 2001), suggesting that the breakup of clouds in the atmosphere allows hot flux from inner layers to emerge (analogous to the 5 μm hot spots of Jupiter), and (2) The “sudden downpour” model – proposed by Knapp et al. (2004), suggesting that the dust clouds suddenly condense out due to an increase in sedimentation efficiency.

Recent studies of brown dwarf binaries have revealed that a fraction of the amplitude in this bump can be explained by systems appearing overluminous due to binarity (i.e., “crypto-binarity”; Burgasser et al. 2006b; Liu et al. 2006; Burrows et al. 2006); however, some part of this brightening is intrinsic to the atmospheres as they cool. This was revealed by HST/NFPC2 imaging of 2MASS J17281150+3948593AB (hereafter 2MASS 1728AB), the first 1–1.2 μm flux reversal binary, which has a T dwarf secondary brighter in z-band but fainter in i-band than the mid-to-late type L dwarf primary (Gizis et al. 2003). No J-band resolved photometry for this system has been published. Two later discoveries of 1–1.2 μm flux reversal binaries – SDSS J102109.69–030420.1 (hereafter SDSS 1021; HST/NICMOS, Burgasser et al. 2006) and SDSS J153417.05+161546.1 (hereafter SDSS 1534; Keck LGS AO/NIRC2, Liu et al. 2006) – provided additional information on the flux reversals. Both systems were found to have a secondary brighter in J-band but fainter in H-band (see Table 1).

L dwarf/T dwarf binaries such as those listed above provide crucial information on the L/T transition, as the components of these systems are likely coeval, with common ages and compositions. In an effort to identify additional systems, we have performed high angular resolution imaging of two T2.5 dwarfs – 2MASS J11061197+2754225 (hereafter 2MASS 1106) and 2MASS J14044941–3159329 (hereafter 2MASS 1404). These objects were identified in a near-infrared proper motion survey (Looper et al. 2007; Kirkpatrick et al., in prep) based on multi-epoch data from the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006). Both systems are in the field, unassociated with any higher mass stars within a radius of 10 arcminutes. 2MASS 1404 was discovered to be a fourth resolved L/T binary (Looper et al. 2007; Kirkpatrick et al., in prep) based on multi-epoch data from the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006).

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transition system showing this 1–1.2 μm flux reversal. These observations were made using the Keck II sodium laser guide star adaptive optics system. We describe these observations and optical spectroscopy of 2MASS 1404 in §2, discuss the results of this imaging and implications for the J-band “bump” in §3, and give our conclusions in §4.

2. OBSERVATIONS

2.1. High Resolution Imaging: Keck II 10.0-m/NIRC II LGS AO

We used the Keck II 10.0-m Telescope Sodium Laser Guide Star Adaptive Optics (LGS AO) system (Wizinowich et al. 2006; van Dam et al. 2006) on 2006 Jun 03 UT to observe 2MASS 1106 & 2MASS 1404. Observations were taken using the NIRC2 narrow camera and the Mauna Kea Observatories (MKO) filter set (Tokunaga et al. 2002): $K_s$-band (2.15 μm) for 2MASS 1106 and $J$ (1.25 μm), $H$ (1.635 μm), & $K_s$-bands for 2MASS 1404. The field of view was 10″2 with a 0″00994 pixel scale. Nearby (<60") and bright (R < 19 mag) stars were selected from the USNO-B1.0 catalog (Monet et al. 2003) to provide for tip-tilt (TT) sensing. For 2MASS 1106, the TT star (USNO-B1.0 1179-0233699) had a brightness of $R = 15.2$ mag and a separation of $\sim$52″. For 2MASS 1404, the TT star (USNO-B1.0 0580-0365843) had a brightness of $R = 16.3$ mag and a separation of $\sim$29″. Conditions were clear and photometric with good seeing at the start of the night (0″7 at K-band) with slight degradation afterwards.

For 2MASS 1106, we dithered by a few arcseconds between positions to obtain a set of eight images with an integration time of 60 sec for each position, for a total of six images for each of the three filters. Integration times per position were 90 sec, 60 sec, and 60 sec for a total integration time of 540 sec, 360 sec, and 360 sec in the J, H, and $K_s$ filters, respectively. The full widths at half maximum (FWHM) in the $K_s$ filter were 0″068 and 0″065 for 2MASS 1106 and 2MASS 1404, respectively.

We employed standard reduction techniques. Flats were created from differenced lights-on and lights-off images of the telescope dome interior. A super-sky frame was created from the median of the individual science frames and was subsequently subtracted from each frame. The background subtracted images were shifted so that the target landed on the same position and were then stacked to form the final mosaic.

In the mosaic of 2MASS 1106 (see Figure 1), the target is not elongated and no other objects, companions or background sources, are seen. On the other hand, we have resolved 2MASS 1404 into two components, shown in Figure 2. Based on the large proper motion of this system ($\mu = 0″.35$ yr$^{-1}$) and the elapsed 5.3 yrs between the first 2MASS observation of this field (2001 Feb 04 UT) and our observation with Keck II (2006 Jun 03 UT), we should be able to see both components separated in the 2MASS image, which has a plate scale of $\sim$1″, if they were not physically associated. Because we do not see an object on the 2001 2MASS image that is positionally coincident with the double seen in our 2006 Keck image, we conclude that this is a physical binary unresolved in 2MASS images. Using the $K_s$-band final mosaic, which has the smallest FWHM, we find a separation, $\rho$, of $0″1336 \pm 0″0006$ and a position angle, $\phi$, of $311.8^\circ \pm 0.7^\circ$.

We performed an image subtraction technique in all three bands to obtain final flux ratios for the 2MASS 1404AB system. To do this, we computed the centroid for the component to be subtracted and placed this component at the center of a 257×257 pixel subimage. This subimage was copied, rotated 180 degrees, and then subtracted from the original, non-rotated subimage. The quality of the subtraction was checked both visually and by examination of the radial profile of the unsubtracted component. In many cases, small offsets had to be applied by hand to obtain optimal subtraction. Aperture photometry was performed on the unsubtracted objects and used to obtain the flux ratio difference of the components.

Errors in the rotation-subtraction technique were estimated by creating fake binaries from (presumably) single objects observed with NIRC2 in LGS AO mode and having similar image qualities as 2MASS 1404AB. The fake binaries were created at 25 different separations and position angles. The same rotation-subtraction technique was performed on these binaries as was done for 2MASS 1404AB. The magnitude of each component was taken to be the average of the 25 separate measurements and the error was the standard deviation of the measurements.

The final errors in the photometry for 2MASS 1404AB are the square root of the sum of squares for the following eight terms: the errors in the single PSF photometry (both A and B), the standard deviation of the binary PSF photometry (both A and B), the difference between the single and binary PSF photometry (both A and B), and the errors in 2MASS 1404AB photometry (both A and B). The final flux ratios for 2MASS 1404AB are shown in Table 2.

2.2. Red Optical Spectroscopy: Magellan 6.5-m/LDSS3

Red optical spectroscopy (~6000–10500 Å) of 2MASS 1404AB was obtained on 2006 May 08 (UT) with LDSS-3 (upgraded from LDSS-2, Allington-Smith et al. 1994) on the 6.5-m Magellan Clay Telescope. Conditions were clear with good seeing (~0″6 at R-band). The VPH-red grism (660 lines/mm) and the OG590 longpass filter were used with a 0″75 (4 pixels) slit, resulting in $R = \lambda/\Delta \lambda \approx 1800$. The slit was rotated to the parallactic angle to minimize slit losses. Dispersions across the chip was 1.2 A/pixel. We obtained two exposures of 1500 s each, for a total integration time of 50 minutes at an average airmass of 1.01. The flux standard star LTT 7987 (Hamuy et al. 1994) was observed the previous night (2006 May 07 UT) using an identical set-up. Calibration exposures were taken using the HeNeAr arc lamp and the flat-field quartz lamp. The G2 V star HD 127526 was observed immediately prior to 2MASS 1404AB to use as a correction for telluric absorption.

LDSS-3 data were reduced in the IRAF environment.

6 Located on the summit of Mauna Kea, Hawaii.

7 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities.
Raw science images were first trimmed, bias-subtracted and then divided by the normalized, median-combined and bias-subtracted set of flat field frames. Spectra were optimally extracted using the APALL task, with the extraction of HD 127526 used as a dispersion template for 2MASS 1404AB. Wavelength solutions were determined from the arc lamp spectra; solutions were accurate to ~0.1 pixels, or ~0.12 Å. Flux calibration was determined using the tasks STANDARD and SENSFUNC with observations of LTT 7987, adequate over the spectral range 6000–10000 Å. Corrections to telluric O$_2$ (6860–6960 Å B-band, 7580–7700 Å A-band) and H$_2$O (7150–7300 and 9270–9675 Å) absorption bands were computed using the G dwarf spectrum.

The optical spectrum is shown in Figure 3, along with the L8 optical standard 2MASS J1632291+190441 (hereafter 2MASS 1632, Kirkpatrick et al., 1999) and the T2 optical standard SDSS J125453.90–01224.74 (hereafter SDSS 1254, Burgasser et al., 2003B) for comparison. The spectra are shown on a log flux scale and have been smoothed to R=1000 to match the resolution of 2MASS 1632 observed with Keck/LRIS. Overall, the continuum of 2MASS 1404AB is intermediate between the L8 and T2 standards, consistent with an optical spectral type of T0. The inset box in this same figure shows the Cs I lines and FeH/CrH bands between 8400 and 9100 Å. The spectra shown in this insert have been divided through by a 4th-order polynomial fit to the continuum in order to highlight the strength of these features. The Cs I lines are of comparable strength in 2MASS 1404AB as in SDSS 1254, while the FeH/CrH band in 2MASS 1404AB is intermediate between the L8 and T2 standards. We therefore adopt an optical spectral type of T0 ± 1 for the 2MASS 1404AB system.

3. ANALYSIS

3.1. Component Spectral Types of 2MASS 1404AB

Since the relative J- and H-band photometry is on the MKO photometric system and the relative K-band photometry is on the 2MASS photometric system, we need to convert the K-band photometry onto the same system. To do this, we examined a set of 25 T dwarfs, described below, and computed the relative K-band photometry is on the 2MASS photometric system, we therefore adopt an optical spectral type of T0.

1. Convert $J_{AB}$ (2MASS) to $J_{AB}$ (MKO) using the (MKO–2MASS) color term computed from the spectrum of 2MASS 1404AB (Looper et al., 2007). $J_{AB}$ (MKO–2MASS) = −0.17; $J_{AB}$ (MKO) = 15.41 ± 0.07.

2. Decompose the system: $J_A = J_{AB} + 2.5 \log(1 + 10^{0.4 \times \Delta J})$; $\sigma^2_J = \sigma^2_{J_{AB}} + \frac{\sigma^2_{\Delta J}}{(10^{0.4 \times \Delta J} - 1)^2}$, where $\Delta J = J_A - J_B$. $J_A$ (MKO) = 16.46 ± 0.12.

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3. Similarly, $J_B = J_{AB} + 2.5 \log(1 + 10^{0.4 \times \Delta J})$; $\sigma^2_J = \sigma^2_{J_{AB}} + \frac{\sigma^2_{\Delta J}}{(10^{0.4 \times \Delta J} - 1)^2}$, where $\Delta J = J_A - J_B$. $J_B$ (MKO) = 15.93 ± 0.09.

In the same manner, this procedure was carried out to determine the MKO H-band and K-band component photometry (see Table 4).

To estimate NIR spectral types for the AB components, we compared the integrated light spectrum to a suite of synthetic IRTF/SpeX spectra constructed in the same manner as Burgasser, submitted. The constituents for these synthetic spectra are the 25 L6–T2 dwarfs, used for the primaries, and the 38 T3–T8 dwarfs, used for the secondaries, as listed in Burgasser, submitted. The constituents, which are drawn from Burgasser et al. (2004, 2005, 2006); Chi et al. (2005); Cruz et al. (2004); Liebert & Burgasser (2005); Looper et al. (2007); Reid et al. (2006); Siegler et al. (2007). In cases where more than one spectrum for an object was available, we used the highest SNR spectrum available. This resulted in 1000 synthetic spectra. To estimate the goodness of fit between the data (2MASS 1404AB) and the model, we first interpolated the flux of the model onto the wavelength scale of the data and normalized each to their peak flux over the 1.2–3.0 μm window. We then calculated the chi-square values ($\chi^2$) between the data and each model over the wavelength ranges 0.95–1.35 μm, 1.45–1.8 μm, and 2.0–2.35 μm to avoid low SNR regions of the spectra. In addition, we calculated $\chi^2$ for a range of multiplicative scale factors (0.5 to 1.5) of the data, in steps of 0.01, to eliminate the normalization bias, selecting the normalization that yielded $\chi^2_{\text{min}}$.

From the 1000 model spectra, we selected the 15 spectra with the smallest $\chi^2$ values for visual inspection. The model spectrum created from SDSS J205235.31−160929.8 (T1, hereafter SDSS 2052; Chiu et al., 2006) is the best fit for the primary and from 2MASS J23312378−4718274 (T5, hereafter 2MASS 2331; Burgasser et al., 2004) for the secondary. We also examined model combinations constructed from two earlier type (L9 and T0) and two later type (T1.5 and T2) primaries with a T5 used as the secondary. In addition, we examined model combinations constructed from a T1 as the primary and two earlier type (T4 and T4.5) and two later type (T5.5 and T6) secondaries. Since many spectra with identical spectral types were available, we used those with model spectra that minimized $\chi^2$. All fits are shown in Figure 4. The best fit is clearly the T1/T5 model, which shows an excellent match to the data of 2MASS 1404AB over all wavelengths. Deviating the spectral type of either the primary or secondary while holding the other fixed, results in a degraded goodness of fit to the data. We therefore

8 Also, see http://web.mit.edu/ajh/www/brownbdwars/spepxml/html/binar for a list of these 25 spectra, where we have estimated 2MASS J21510838−4853542 (T4) and 2MASS J05105350−4208140 (T5) from the list of T3–T8 used due to the poor signal-to-noise ratio (SNR) of their spectra.

9 Defined as $\chi^2_A = \sum_{j} \left(\frac{f_{\text{data}}(J_{AB}) - f_{\text{model}}(J_{AB})}{\sigma_{J_{AB}}}ight)^2$, where $f_{\text{data}}(J_{AB})$ is the data for 2MASS 1404AB, $f_{\text{model}}(J_{AB})$ is the synthetic model spectrum, and $\sigma_{J_{AB}}$ are the errors in the data for 2MASS 1404AB. The summation is performed over the wavebands 0.95–1.35 μm, 1.45–1.8 μm, and 2.0–2.35 μm.
fore estimate a final NIR spectral type of the primary as T1 and of the secondary as T5.

Using the MKO component photometry of 2MASS 1404AB and component spectral type estimates of T1 and T5, we compute the 2MASS component photometry (see Table 4) using the appropriate transformations from Stephens & Leggett (2004). These relations are dependent on spectral type with errors that add negligibly to the component photometric errors. From the 2MASS composite photometry, we compute NIR colors of each component and compare these to the NIR colors of published colors of near-infrared L and T dwarfs in Figure 5. In this color–color diagram, component A is seen coincident with a cluster of L7−T4 dwarfs. Component B is associated with a cluster of T4−T6 dwarfs. This color comparison yields an average spectral type estimate of ~L9 for component A and ~T5 for component B.

In Figure 6, we plot SDSS 2052 and 2MASS 2331 scaled with the relative photometry of the A & B components of 2MASS 1404AB, with the 2MASS & MKO filter transmission profiles overlaid. The 2MASS J-band filter profile extends to slightly shorter wavelengths, covering more of the CH₄ absorption band at ~1.15 µm, than does the MKO J-band profile. This explains the reduced relative 2MASS J-band photometry of the two components compared to the relative MKO J-band photometry, since the secondary (T5) has larger CH₄ absorption than does the primary (T1). The flux peaks, however, are more illuminating than the broad-band photometry. The peak at 1.25 µm of the scaled T5 is ~70% brighter than that of the scaled T1, and the 1.05 µm peak (outside the J-band filter profile) is ~40% brighter. This redistribution of flux into the 1.05 & 1.25 µm peaks is remarkably similar to that seen for SDSS 1021AB and SDSS 1534AB. SDSS 1021B is ~30% and ~25% brighter at the 1.25 µm and 1.05 µm bands than SDSS 1021A, respectively. Likewise, SDSS 1534B is ~30% and ~20% brighter at the 1.25 µm and 1.05 µm bands than SDSS 1534A. While no atmospheric models can accurately reproduce this flux redistribution, we refer the reader to Burgasser et al. (2006b) for a qualitative description of how this brightening may arise.

3.2. Construction of Color Magnitude Diagrams (CMDs)

To estimate a distance for this system, we first derived JHKₜ absolute magnitude versus spectral type relations using optically classified late-type M and L dwarfs and NIR classified T dwarfs with parallax measurements of SNR > 5 and not known to be binary (collected from van Altena et al. 1995; Perryman et al. 1997; Dahn et al. 2002; Tinney et al. 2003; Vrba et al. 2004). The coefficients of the sixth-degree polynomial fits to this unweighted data are given in Table 5 and shown graphically in Figure 7. We have used optical spectral classification for the L dwarfs because no formal L dwarf NIR spectral classification scheme has been constructed. These relations use the new NIR spectral classification scheme for T dwarfs (Burgasser et al. 2006a), superceding previous MₗHK versus spectral type (SpT) relations on the old NIR T dwarf scheme (Geballe et al. 2002; Burgasser et al. 2002).

Using these new MₗHK−SpT relations, we estimate distances for component A, assuming a T1 spectral type, of ~25.8, ~22.6, & ~20.2 pc, respectively, yielding a mean distance of ~23 pc. We can now place 2MASS 1404AB and its components on a color–magnitude diagram (see Figure 7). Likewise, SDSS 1021AB and SDSS 1534AB are also shown, and these have been converted onto the 2MASS photometric system using the spectral type estimates of their components, their component MKO photometry, and the appropriate transformations from Stephens & Leggett (2004). The parallax measurement for SDSS 1021AB (Tinney et al. 2003) is used to place it on the diagram. Since SDSS 1534AB lacks a parallax measurement, we use the MₗHK−SpT relations for component SDSS 1534A (dₑₚₓ ≈ 41 pc) to place SDSS 1534AB on the diagram.

Of note, only two other T dwarfs in the J-band “bump,” SDSS J175032.96+175903.9 (T3.5; hereafter SDSS 1750) & 2MASS J05591914−1404488 (T4.5; hereafter 2MASS 0559), lie above the J-band fit, by ~0.3 & ~0.9 mag, respectively. Neither object has been resolved in high-resolution images (Burgasser et al. 2006b, 2003). Indeed, neither show any signs of unusual metallicity or gravity effects in their spectra. These objects could still be binaries with very small separations and/or imaged at an unpropitious place in their orbits, as was originally the case with Kelu-1 (Liu & Leggett 2003; Gelino et al. 2006). However, Osorio et al. (2007) have monitored 2MASS 0559 over a period of 4.37 years with radial velocity measurements and have ruled out companions more massive than 10 Mₖₑₚₓ in orbits of ~1 yr and companions more massive than 2 Mₖₑₚₓ in orbits less than a few days.

In order to eliminate the J-band “bump,” SDSS 1750 would have to be an unresolved binary, 2MASS 0559 would have to be an unresolved triple (since ∆J > 0.75 mags) with the above restrictions on the orbital periods of its components, and 2MASS 1404AB would also have to be a triple system instead of a binary. The small observed frequency of brown dwarf triple systems (3 ^+4^−1%) – not considering selection effects; Burgasser et al. 2007b) suggests this is highly unlikely. Hence, the amplitude of the J-band “bump” is probably at least ~0.5 mag as illustrated by the components of 2MASS 1404AB and likely as high as ~1 mag in light of the recent null result of radial velocity companions to 2MASS 0559 by Osorio et al. (2007). A parallax measurement and resolved spectroscopy of this system are needed to accurately place the components on a color magnitude diagram. Radial velocity monitoring of the 2MASS 1404AB system can resolve if this brightening is intrinsic to the atmospheres as they cool or if higher-order multiplicity is responsible for this peculiar flux reversal at 1−1.2 µm.

3.3. Physical Parameters of 2MASS 1404AB

To estimate the physical parameters of 2MASS 1404AB (see Table 2), we first rederived MKO K-band bolometric corrections (BCₖ) versus spectral type and T eff versus spectral type relations, using M9–T8 data from Golimowski et al. (2004) and references there-in, excluding known binaries. In both relations, we classify L dwarfs on the Kirkpatrick et al. (1999) optical clas-
sification scheme, and T dwarfs on the [Burgasser et al. (2006a) NIR classification scheme. Our choice of optical L dwarf spectral classification for these fits is further strengthened because the far-ultraviolet spectrum of mid-to-late type L dwarfs is less influenced by cloud opacities than the [Geballe et al. (2002) 1.5 μm H2O index (Knapp et al. 2004)]. The coefficients to the fourth-degree weighted BC\(_K\) polynomial fit and to the sixth-degree unweighted \(T_{\text{eff}}\) polynomial fit are given in Table 5 and shown graphically in Figure 8. The RMS (87 K) in this fit compared to that of [Golimowski et al. (2004)] (124 K) is less because of the elimination of objects found in this fit compared to that of Golimowski et al. (2004) for the primary and secondary, respectively, assuming an age of 3 Gyr. We also find BC\(_K\) values of 2.91 ± 0.16 & 2.34 ± 0.16 for the primary and secondary, respectively. In both cases, the error is the RMS in the fit and does not include the error in spectral typing.

To determine \(M_{\text{bol}}\), for each component, we used the BC\(_K\) corrections, a distance estimate of d≈23 pc, and the MKO component photometry (see Table 4). This yielded \(M_{\text{bol}} = 15.96 ± 0.19\) mag & 16.59 ± 0.25 mag for the primary and secondary, respectively. The ratio of bolometric luminosities, L\(_{\text{bol},A}/L_{\text{bol},B}\), is 1.79 ± 0.52, with the primary having the higher luminosity. We use the mass-luminosity relation \(L_{\text{bol}} \propto M^{2.64}\) [Burrows et al. 2001], which assumes solar metallicities, and the ratio of bolometric luminosities to find the mass-ratio: q ≡ \(M_A/M_B = 0.80 ± 0.09\). This mass ratio is typical for known brown dwarf binaries, which tend to peak at q≈1 (73% of observed binaries have q ≥ 0.8, although, observational bias would favor high-q ratios; [Burgasser et al. 2006]). Using the age-luminosity relation from [Burrows et al. 2001], we find a total mass for the system of 50, 70, & 80 \(M_{\text{Jup}}\), corresponding to ages of 0.5, 1.0, & 5.0 Gyr, typical for local disk dwarfs [Reid & Hawley 2000]. This corresponds to individual masses of ~28 & 22 \(M_{\text{Jup}}\); ~39 & 31 \(M_{\text{Jup}}\); and ~44 & 36 \(M_{\text{Jup}}\) for these respective ages.

Finally, this allows determination of the orbital parameters of this system. At an estimated distance of ~23 pc and with an apparent separation of 0′′134, the projected physical separation is \(r ≈ 3.1\) AU. Statistically, the true semi-major axis can then be estimated as a = 1.26 × \(r ≈ 3.9\) AU [Fischer & Marcy 1992]. This implies an orbital period of roughly 28–35 yr, assuming a total system mass of 50–80 \(M_{\text{Jup}}\).

4. CONCLUSIONS

We have presented high resolution imaging of two T2.5 dwarfs – 2MASS 1106 and 2MASS 1404 – and solved the latter into a 0′′13 binary. 2MASS 1404AB is an intriguing binary as its presumably cooler secondary is brighter in J-band than the primary by 2MASS \(\Delta J = 0.45\) mags but fainter in both 2MASS H- (by 0.49 mags) and 2MASS K\(_S\)-bands (by 1.13 mags). This secondary brightening in J-band is much more pronounced than that seen in the other two known flux reversal binaries with resolved J-band photometry – SDSS 1021 (2MASS \(\Delta J = −0.05\), MKO \(\Delta J = 0.04\)) and SDSS 1534 (2MASS \(\Delta J = 0.03\), MKO \(\Delta J = 0.17\)). [Osorio et al. 2007] have found no companions in their radial velocity monitoring of the T4.5 dwarf 2MASS 0559, which lies ~0.9 mag above the 2MASS \(M_J\) versus spectral type relation we derive. This result in conjunction with ours suggests that a brightening of at least ~0.5 mag and likely as high as ~1 mag in the J-band “bump” is real and intrinsic to the atmospheres of these objects as they cool across early-to-mid type T classes.

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Facilities Used: Keck II/LGS AO NIRC2 & Magellan/LDSS-3.

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Fig. 1.— Keck LGS AO image of 2MASS 1106 in K$_s$ band. North and East are indicated by an arrow. The image is $\sim$0",8 on a side, with no other sources besides the target detected in the full-sized ($\sim$13".5) field-of-view. The FWHM is 0",068.

Fig. 2.— Keck LGS AO images of 2MASS 1404AB in J, H, and K$_s$ bands. North and East are indicated by an arrow and is the same for all images. Note that the B component is brighter in J-band than the A component but is fainter in both H- and K$_s$-bands. Each subimage is $\sim$0",8 on a side, and the separation of the binary is $0".1336 \pm 0".0006$ with a position angle of $311.8^\circ \pm 0.7^\circ$. No other sources besides components A & B were detected in the full-sized ($\sim$14") field-of-view. The FWHM is 0",065 in K$_s$-band.

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Fig. 3.— Red optical spectrum of 2MASS 1404AB (obtained with LDSS-3/Magellan; opt SpT T0 ± 1) in comparison to 2MASS 1632 (L8 optical standard; Kirkpatrick et al. 1999) and SDSS 1254 (T2 optical standard; Burgasser et al. 2003b) normalized and shown on a log flux scale. The insert shows the region between 8400–9100 Å, where the spectra have been divided by a 4th-order polynomial fit to the continua. 2MASS 1404AB and SDSS 1254 have been smoothed down to approximately the same resolution as 2MASS 1632 (R ≈ 1000). Major atomic and molecular features are labeled, and the spectra are separated along the vertical axis for clarity. 2MASS 1404AB appears to be intermediate in type between the L8 and T2 optical standards.

### TABLE 1

| Designation  | $J^{2MASS}$ | $\Delta J^{2MASS}_A-B$ | $\Delta J^{MKO}_A-B$ | SpT AB$^d$ | SpT A$^d$ | SpT B$^d$ | Ref$^e$ |
|--------------|-------------|------------------------|----------------------|------------|----------|----------|--------|
| SDSS 1021AB  | 16.25 ± 0.09| 0.05                   | 0.04                 | T3         | T1       | T5       | 1      |
| SDSS 1544AB  | 16.75 ± 0.13| 0.03                   | 0.17                 | T3.5       | T1.5     | T5.5     | 2      |
| 2MASS 1404AB | 15.56 ± 0.09| 0.45                   | 0.53                 | T2.5       | T1       | T5       | 3      |

$^a$ There is one other (possible) J-band flux reversal binary not tabulated here: 2MASS 1728AB because it has been observed at z-band not at J-band (see §1).$^b$ Relative 2MASS photometry calculated in this paper.$^c$ Relative MKO photometry from References.$^d$ NIR spectral types on Burgasser et al. (2006c) scheme.$^e$ References – (1) Burgasser et al. (2006b), (2) Liu et al. (2000), (3) this paper.
Fig. 4.— Comparison of the T2.5 integrated light spectrum of 2MASS 1404AB (black; Looper et al. 2007) with the best synthetic spectral fits (red; see §3.1). The T1 and T5 combination provides the best fit across all wavelengths to the spectrum of 2MASS 1404AB.
Fig. 5.— Near-infrared color-color plot of 74 known NIR L7-T7 dwarfs with $\sigma_{J-H}$ & $\sigma_{H-K_s} < 0.3$ mags and spectral types with uncertainties $\leq 1$ subtype. L dwarfs are shown in red with spectral types represented by numbers $-7 = L7, 8 = L8$, etc. T dwarfs are shown in blue with spectral types represented by numbers $-10 = T0, 15 = T5$, etc. The resolved colors of 2MASS 1404AB are shown as stars with associated error bars.

### TABLE 2

Properties of the 2MASS 1404AB System

| Property                           | Value               |
|------------------------------------|---------------------|
| MKO J (mags)                       | 15.41 ± 0.07        |
| MKO H (mags)                       | 15.02 ± 0.08        |
| MKO K (mags)                       | 14.55 ± 0.10        |
| MKO $\Delta$ J (mags)             | 0.53 ± 0.16         |
| MKO $\Delta$ H (mags)             | -0.48 ± 0.11        |
| MKO $\Delta$ K (mags)             | -1.20 ± 0.21        |
| 2MASS J (mags)                     | 15.58 ± 0.07        |
| 2MASS H (mags)                     | 14.96 ± 0.08        |
| 2MASS K$_s$ (mags)                 | 14.54 ± 0.10        |
| 2MASS $\Delta$ J (mags)           | 0.45 ± 0.15         |
| 2MASS $\Delta$ H (mags)           | -0.49 ± 0.13        |
| 2MASS $\Delta$ K$_s$ (mags)       | -1.13 ± 0.22        |
| Composite Optical SpT              | T0                  |
| Composite NIR SpT                  | T2.5$^b$            |
| $\mu$ (" yr$^{-1}$)               | 0.35 ± 0.03$^a$     |
| $\theta$ (deg)                    | 275.3 ± 0.2$^b$     |
| $\rho$ (mas)                      | 133.6 ± 0.6         |
| $\phi$ (deg)                      | 311.8 ± 0.7         |
| $\log (L_A/L_B)^b$                | 0.25 ± 0.13         |
| $q \equiv M_B/M_A$                 | 0.80 ± 0.09         |
| $M_{tot}$ (M$_{Jup}$) for 0.5, 1.0 & 5.0 Gyr | 50, 70 & 80        |
| Est. distance (pc)                 | ~23                 |
| Est. projected separation (AU)     | ~3.1                |
| Est. actual separation (AU)        | ~3.9                |
| Orbital Period (yr)                | 28 – 35             |

$^a$ Measurements are from Looper et al. (2007).

$^{b}$ $L_{bol,\odot} = 100(M_{bol,\odot} - M_{bol})/5$, where $M_{bol,\odot} = +4.76$. 
Fig. 6.— Left: SDSS J205235.31−160929.8 (T1; Chiu et al. 2006), shown in green, and 2MASS J23312378−4718274 (T5; Burgasser et al. 2004), shown in blue, scaled by the MKO magnitudes of the A & B components of 2MASS 1404AB. The 2MASS JHKs (solid lines) and MKO JHK (dotted lines) transmission plus atmospheric profiles are overlaid.

### Table 3

| Quantity        | L6  | L7  | L8  | L9  | T0  | T1  | T2  | AVG  |
|-----------------|-----|-----|-----|-----|-----|-----|-----|------|
| 2MASS $K_s$ − MKO $K$ | 0.03 ± 0.01 | 0.02 ± 0.01 | 0.01 ± 0.01 | 0.01 | −0.01 ± 0.02 | −0.03 ± 0.02 | −0.01 ± 0.04 |
| Number of Objects\(^a\) | 4   | 1   | 2   | 2   | 1   | 7   | 8   | 25   |

\(^a\) The number of objects available per spectral type class, where a class also includes a half subtype - i.e., L6.0 & L6.5. Note that the T2 spectral class only includes T2.0 objects and no T2.5 objects.
Fig. 7.— $M_{JHK}$ vs SpT of optical L dwarfs (on Kirkpatrick et al. 1999 scheme) and NIR T dwarfs (on Burgasser et al. 2006a scheme) with parallax measurements of SNR > 5 (solid points). The (unweighted) sixth-degree polynomial fits defined in §3.2 are shown as solid lines. Late type M dwarfs were also included in these fits to prevent an artificial downturn at L0. Known binaries are encircled and were not included in the fit, with the exception of ε Ind Bab (blue), where the spectrally classified components have been used. Top: A clear brightening in $M_J$ is seen from $\sim$T1–T5, known as the J-band “bump.” The three known J-band flux reversal binaries – SDSS 1021AB, SDSS 1534AB, & 2MASS 1404AB – and their A+B components are shown as orange, purple, and red, respectively. 2MASS 1404AB & SDSS 1534AB are indicated by squares, not circles, since no parallax measurement has been made for either of these sources. No H- & $K_s$-band resolved photometry is available for SDSS 1021AB.

| Property                  | 2MASS 1404A  | 2MASS 1404B  |
|---------------------------|-------------|-------------|
| MKO J (mags)              | 16.46 ± 0.12| 15.93 ± 0.09|
| MKO H (mags)              | 15.56 ± 0.09| 16.04 ± 0.10|
| MKO K (mags)              | 14.86 ± 0.11| 16.06 ± 0.19|
| 2MASS J (mags)            | 16.65 ± 0.12| 16.20 ± 0.09|
| 2MASS H (mags)            | 15.51 ± 0.09| 16.00 ± 0.10|
| 2MASS K$_s$ (mags)        | 14.83 ± 0.11| 15.96 ± 0.19|
| MKO J–H (mags)            | 0.90 ± 0.15  | −0.11 ± 0.13 |
| MKO H–K (mags)            | 0.70 ± 0.14  | −0.02 ± 0.21 |
| MKO J–K (mags)            | 1.60 ± 0.16  | −0.13 ± 0.21 |
| 2MASS J–H (mags)          | 1.14 ± 0.15  | 0.20 ± 0.13  |
| 2MASS H–K$_s$ (mags)      | 0.68 ± 0.14  | 0.04 ± 0.21  |
| 2MASS J–K$_s$ (mags)      | 1.82 ± 0.16  | 0.24 ± 0.21  |
| Est. NIR SpT$^a$          | T1          | T5          |
| Est. $T_{\text{eff}}$ (K)$^b$ | 1390 ± 90   | 1180 ± 90   |
| $M_{bol}$ (mags)          | 15.96 ± 0.19| 16.59 ± 0.25|

$^a$ Component NIR spectral types are derived in §3.1. $^b$ Based on the $T_{\text{eff}}$ vs SpT relation defined in Table 5, using the component spectral types listed and assuming an age of 3 Gyr.
Fig. 8.— Polynomial fits (solid lines) to M9–T8 objects with BC$_K$ measurements and T$_{\text{eff}}$ estimates (from Golimowski et al. 2004 and references therein), excluding known binaries. The relations are fourth- and sixth-degree polynomial fits for BC$_K$ and T$_{\text{eff}}$, respectively, with the coefficients listed in Table 5. The plotted values used in the T$_{\text{eff}}$ relation are for an age of 3 Gyr, and the error bars represent an age range of 0.1 – 10 Gyr (younger ages are cooler and older ages are hotter). The BC$_K$–SpT relation is weighted by the errors while the T$_{\text{eff}}$–SpT relation is unweighted. The large outlier seen in the BC$_K$ plot and included in the fit is the T6 dwarf 2MASSI J0937347+293142, which is thought to be unusually blue due to high surface gravity/low-metallicity. Shown for comparison are the polynomial fits (dashed lines) from Golimowski et al. (2004).

**Table 5**

| R                | c0              | c1               | c2                | c3               | c4               | c5               | c6               | RMS  |
|------------------|------------------|------------------|-------------------|------------------|------------------|------------------|------------------|------|
| M$_J$ (mag)      | 11.817           | 1.255e-1         | 3.690e-2          | 1.663e-2         | -3.915e-3        | 2.595e-4         | -5.462e-6        | 0.29 |
| M$_H$ (mag)      | 11.010           | 1.125e-1         | 3.032e-2          | 1.261e-2         | -2.970e-3        | 1.987e-4         | -4.218e-6        | 0.29 |
| M$_K$ (mag)      | 10.521           | 7.369e-2         | 2.565e-2          | 1.299e-2         | -2.864e-3        | 1.911e-4         | -4.104e-6        | 0.33 |
| BC$_K$ (mag)     | 3.221            | 2.371e-2         | 6.428e-3          | 1.631e-3         | 5.579e-5         | · · · · · ·       | · · · · · ·       | 0.16 |
| T$_{\text{eff}}$ (K) | 2319.920         | -108.094         | 1.950             | -3.101           | 6.414e-1         | -4.255e-2        | 9.084e-4         | 87   |

*Polynomial fits to optical L dwarfs (classified on Kirkpatrick et al. [1999] scheme) and NIR T dwarfs (classified on Burgasser et al. [2006a] scheme) with parallax measurements and not known to be binary (see §3.2 & §3.3 for a full description). Each function is defined as $R = \sum_{i=0}^{6} c_i \times (\text{SpT})^i$ and is valid for spectral types L0 to T8, where 0 = L0, 10 = T0, etc. These fits are shown graphically in Figures 7 & 8. Photometry is on the 2MASS system. Photometry is on the MKO system. Data are from Golimowski et al. (2004) and references therein.