NEAR-INFRARED PHOTOMETRY OF Y DWARFS: LOW AMMONIA ABUNDANCE AND THE ONSET OF WATER CLOUDS

S. K. Leggett\(^1\), Caroline V. Morley\(^2\), M. S. Marley\(^3\), and D. Saumon\(^4\)

\(^1\) Gemini Observatory, Northern Operations Center, 670 N. A‘ohoku Place, Hilo, HI 96720, USA; sleggett@gemini.edu
\(^2\) Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA
\(^3\) NASA Ames Research Center, Mail Stop 245-3, Moffett Field, CA 94035, USA
\(^4\) Los Alamos National Laboratory, P.O. Box 1663, MS F663, Los Alamos, NM 87545, USA

Received 2014 September 12; accepted 2014 November 7; published 2015 January 14

ABSTRACT

We present new near-infrared photometry for seven late-type T dwarfs and nine Y-type dwarfs, and lower limit magnitudes for a tenth Y dwarf, obtained at Gemini Observatory. We also present a reanalysis of \(H\)-band imaging data from the Keck Observatory Archive, for an 11th Y dwarf. These data are combined with earlier MKO-system photometry, \textit{Spitzer} and \textit{WISE} mid-infrared photometry, and available trigonometric parallaxes, to create a sample of late-type brown dwarfs that includes 10 T9–T9.5 dwarfs or dwarf systems, and 16 Y dwarfs. We compare the data to our models, which include updated \(H\) and \(NH_3\) opacity, as well as low-temperature condensate clouds. The models qualitatively reproduce the trends seen in the observed colors; however, there are discrepancies of around a factor of two in flux for the Y0–Y1 dwarfs, with \(T_{\text{eff}} \approx 350–400\) K. At \(T_{\text{eff}} \sim 400\) K, the problems could be addressed by significantly reducing the \(NH_3\) absorption, for example by halving the abundance of \(NH_3\) possibly by vertical mixing. At \(T_{\text{eff}} \sim 350\) K, the discrepancy may be resolved by incorporating thick water clouds. The onset of these clouds might occur over a narrow range in \(T_{\text{eff}}\), as indicated by the observed small change in 5 \(\mu m\) flux over a large change in \(J - W2\) color. Of the known Y dwarfs, the reddest in \(J - W2\) are WISEP J182831.08 + 265037.8 and WISE J085510.83−071442.5. We interpret the former as a pair of identical 300–350 K dwarfs, and the latter as a 250 K dwarf. If these objects are \(\sim 3\) Gyr old, their masses are \(\sim 10\) and \(\sim 5\) Jupiter-masses, respectively.

\textit{Key words:} brown dwarfs – stars: atmospheres

1. INTRODUCTION

In 1995 the first definitive detection of an exoplanet orbiting a main-sequence star was announced (Mayor & Queloz 1995). In the same year, and in fact in the same edition of \textit{Nature}, the first definitive detection of a brown dwarf (an object with insufficient mass for stable hydrogen-burning) was also announced (Nakajima et al. 1995). The detection of exoplanets continued at a rapid rate. However, it was not until 1999 that more brown dwarfs were found, in the early data releases of the Sloan and Two Micron All Sky Survey (2MASS) sky surveys (Burgasser et al. 1999; Strauss et al. 1999). The first exoplanet and brown dwarf discoveries were of relatively warm and massive sources. The exoplanets were of the “hot Jupiter” class, Jupiter-mass objects close to their star. The brown dwarfs were what are now known as mid-T class objects, with effective temperatures \((T_{\text{eff}}) \approx 1000\) K, and mass \(\approx 50\) Jupiter-masses. Exoplanets that are much less massive and further from their host stars are now known, for example the planetary system around Kepler 11, with six planets at 0.1–0.5 AU, and masses as low as two Earth-masses (Lissauer et al. 2011). Similarly, cooler and lower mass brown dwarfs are now known (Cushing et al. 2011). The two populations have a significant degree of overlap, and brown dwarfs can show many observational similarities to directly imaged exoplanets (Liu et al. 2013). There is active debate on how the formation mechanisms differ and relate to each other (e.g., Beichman et al. 2014 and references therein).

This paper continues our series of papers where we present new observations of brown dwarfs, and compare these data to state-of-the-art models calculated by members of the group. The known brown dwarf population has been extended to intrinsically fainter sources by sky surveys, most recently the \textit{Wide-field Infrared Survey Explorer} (\textit{WISE}; Wright et al. 2010). The models have become increasingly advanced using new pressure- (or collision-)induced \(H_2\) absorption and \(NH_3\) opacity (Saumon et al. 2012), and incorporating low-temperature condensate cloud decks (Morley et al. 2012, 2014). Our earlier papers include the verification of the reddening caused by silicate, sulfide, and chloride clouds in L-, T-, and Y-type dwarf atmospheres (Stephens et al. 2009; Leggett et al. 2013). Here we present new near-infrared photometry, and compare our data set to models which include water clouds (Morley et al. 2014).

2. OBSERVATIONS

In this paper we present new near-infrared photometry for seven late-type T dwarfs and nine Y-type dwarfs, obtained using the Gemini Observatory’s Near-Infrared Imager (NIRI; Hodapp et al. 2003) and FLAMINGOS-2 (Eikenberry et al. 2004). For a 10th Y dwarf, we present a reanalysis of \(H\)-band imaging data taken with the Keck Observatory’s NIRC2 near-infrared imager. We start this section with the presentation of new upper-limit fluxes (lower-limit magnitudes) for an 11th Y dwarf.

2.1. \(zYJ\) Limits for WD 0806−66B Using \textit{GMOS-South} and \textit{GSAOI}

We observed WD 0806−66B, a very late-type brown dwarf companion to a white dwarf, at Gemini South using the Gemini Multi-Object Spectrograph (GMOS; Hook et al. 2004) and the Gemini South Adaptive Optics Imager (GSAOI; McGregor et al. 2004; Carrasco et al. 2012). The primary, WD 0806−66, is also referenced in the literature as L 97-3, LTT 3059, NLTT 19008,
and Gl 3483. While to our knowledge the label “WD” has never been used for an object that is not a white dwarf, this brown dwarf companion has been mainly referred to in the literature as WD 0806−66B, and we adopt that label here.

The brown dwarf was discovered in a search for common proper motion companions using *Spitzer* 4.5 μm images (Luhman et al. 2011). Follow-up *Spitzer* 3.6 μm imaging confirmed the source to be one of the coldest brown dwarfs known, with $T_{\text{eff}} \approx 350$ K (Luhman et al. 2012). Given the constraints on age imposed by the white dwarf, the mass of WD 0806−66B is $< 13 M_{\text{Jup}}$ (Rodriguez et al. 2011).

Deeper 1 μm imaging using the F110W filter and the Wide Field Camera 3 (WFC3) on the Hubble Space Telescope (HST) has now provided the first detection of the source in the near-infrared (Luhman et al. 2014b). Luhman et al. find $m_{\text{110W}} = 25.70 \pm 0.05$, and use observed spectra for T9 to Y0.5 dwarfs, as well as model-generated spectra, to estimate $m_{\text{110W}} - J \sim 0.7$. We have confirmed and further constrained $m_{\text{110W}} - J$ using observed spectroscopy of the same three brown dwarfs used by Luhman et al. (UGPS J072227.51−054503.2 [UGPS 0722, T9], WISE J014807.25−720258.7 [W0148, T9.5], WISE J154151.65−225024.9 [W1541, Y0.5]), and adding data for the resolved T9 and Y0 system WISEPC J121756.91+162640.2A (Luhman et al. 2011). Follow-up Spitzer as WD 0806−66B are similar to the Y0.5 W1541 (Section 4), hence we adopt $J = 25.00 \pm 0.10$ for the source.

The GMOS observations were executed via program GS-2011B-Q-53 on UT 2011 December 5, 30, and 31, and 2012 January 19, 20, and 21. Forty-five 720 s exposures at $z$ were obtained for a total on-source time of 9 hr. Conditions were photometric with seeing around 0′′.8. Landolt (1992) and Smith et al. (2002) photometric standards were used for calibration each night, as is routine practice at Gemini. The data were reduced in the usual way using IRAF routines, paying particular attention to fringe correction.

The GSAOI observations were executed via program GS-2013B-Q-15. Z-band observations were obtained on UT 2013 December 17 and 18, and $J$ band on UT 2013 December 18 and 2014 January 15, 16, and 19. The total on-source time was 94 minutes at $Z$ and 91 minutes at $J$, consisting of 120 s exposures at $Z$ and 60 s at $J$. Photometric but poorer natural seeing conditions prevailed, and the adaptive optics corrected images had FHWM of 0′″3–0′″4. Stacking the images was difficult as there are relatively few point sources, and the FHWM of the stacked image was degraded further to ~0′″5. The T9 brown dwarf UGPS 0722 and other sources near this T9 (in the 85′′ by 85′′ GSAOI field of view), were imaged on 2014 January 19, and used to determine zeropoints at $Z$ and $J$ and to investigate whether the GSAOI photometric system is equivalent to the Mauna Kea photometric system (MKO; Tokunaga & Vacca 2005). We also investigated the linearity behavior. We found that no linearity correction needed to be applied, and that the GSAOI $Z$ and $J$ filters correspond directly to the MKO $Y$ and $J$. We derived identical zeropoints, within the uncertainties, for both bright and faint read modes and for each of the four detectors. The zeropoints were measured to be 26.71 at GSAOI-Z (equivalent to MKO-Y) and 26.40 at $J$, where zeropoint is defined as the magnitude of an object that produces one count (or data number) per second.

Figure 1 shows our Gemini images with the location of the source indicated. We used the 4.5 μm image to derive coordinates for WD 0806−66B of 8°07′15″195′′−66°18′51″25′′ at epoch 2009 August 24. The proper motion of the system (as determined from the white dwarf) is 0′″3403 yr−1 in right ascension and −0′″2896 yr−1 in declination, and the trigonometric parallax is 52.17 ± 1.67 mas (Subsavage et al. 2009). WD 0806−66B is not detected in our data, implying $z_{AB} > 26.2$, $Y > 23.5$ and $J > 23.9$, where these values correspond to the 3σ limits in the stacked $z$, $Y$, and $J$ images.

Our $z$ and $Y$ data extend the limits found by Luhman et al. (2014b), using archived Very Large Telescope data, to fainter magnitudes. Note that our models imply that $z - J$ turns to the blue for $M_{J} > 18$, or T8 and later types. For early-type Y dwarfs $z - J - 3$ as opposed to $z - J - 4$ for late-type T dwarfs. Detection in the $z$ band of such cool objects, however, remains challenging, as $J$ is intrinsically faint. Our $J$ limit is consistent with the $J = 25.00 \pm 0.10$ implied by the $m_{\text{110W}} = 25.70 \pm 0.05$ measured by Luhman et al. Using the archived *Spitzer* data we determine $[3.6] = 19.28 \pm 0.10$ and $[4.5] = 16.78 \pm 0.05$ (slightly different from the values derived by Luhman et al. 2012). The *WISE* All-sky source catalog gives $W2 (4.6 \mu m) = 17.68 \pm 0.41$, $W3 (12 \mu m) = 12.54 \pm 0.16$ and $W4 (22 \mu m) = 10.18 \pm 0.53$; however, the W3 and W4 fluxes are much too bright, likely due to the bright infrared cirrus coincident with the source that can be seen in the *WISE* images.

The near-infrared magnitude limits determined here are given in Table 1. No near-infrared spectrum is available for this brown dwarf, and so a spectral type cannot be derived. For plotting purposes we assign a nominal spectral type of Y1, based on its similarity to Y0.5–Y1 dwarfs in the color–color diagrams shown later. We compare the near- to mid-infrared colors of WD 0806−66B to model calculations in Section 6.

### 2.2. NIRI Photometry

NIRI was used on Gemini North to obtain YJHK photometry, or a subset thereof, for eight T8–Y0.5 dwarfs via programs GN-2013A-Q-63 and GN-2013B-Q-27. The photometry is on the MKO system; however, there is some variation in the $Y$ filter bandpass between the cameras used on Mauna Kea, and $Y_{\text{NIRI}} - Y_{\text{MKO}} = 0.17 \pm 0.03$ (Liu et al. 2012). Exposure times of 30 s or 60 s were used, with a five- or nine-position telescope dither pattern. The data were reduced in the standard way using routines supplied in the IRAF Gemini package. UKIRT Faint Standards were used for calibration, taking the $Y$ data from the UKIRT online catalog and the $JHK$ data from Leggett et al. (2006). All data were taken on photometric nights with typical near-infrared seeing of 0′″8.

Table 1 gives the results, where we have applied the correction above to the $Y$ data to get it on the standard MKO system. The date of observation is also listed. Note that the $H$-band measurement for W1541 is a repeat of the measurement we published in Leggett et al. (2013), and is significantly brighter—here we

---

5 We investigated trends with spectral type for $m_{\text{110W}} - Y$ but found more scatter, perhaps due to the fact that spectral type is based on the shape of the J-band flux peak, and $Y - J$ is sensitive to gravity, metallicity, and cloud properties (Section 7). Burgasser et al. (2006) give NICMOS F110W magnitudes for a sample of T dwarfs, and those data imply $m_{\text{110W}} - J = 1.1 \pm 0.1$. However, the instrument handbooks show that the system throughput of the NICMOS + F110W filter is significantly different from the WFC3 + F110W filter.

6 <http://www.jach.hawaii.edu/UKIRT/astronomy/calib/photcal/fs/ZYMKO_wfcam.dat>
### Table 1

New YJHK MKO Photometry

| Name     | Spectral Type | Y(err)$^a$ | J(err) | H(err) | K(err)$^a$ | Date YYYYMMDD | Instrument | Discovery Reference |
|----------|---------------|------------|--------|--------|------------|----------------|------------|---------------------|
| WISE J000517.48 + 373720.5 | T9 | 18.48(0.02) | 17.59(0.02) | 17.98(0.02) | 17.99(0.02) | 2013 0717 | NIRI | M13 |
| WISE J001354.39-063448.2 | T8 | 20.56(0.04) | 19.54(0.03) | 19.98(0.04) | 20.79(0.10) | 2013 0812 | NIRI | P14a |
| WISE J033515.01 + 431045.1 | T9 | 19.95(0.03) | 19.32(0.02) | 19.87(0.04) | 20.86(0.11) | 2013 1127 | NIRI | K12 |
| WISE J035000.32−565830.2 | Y1 | 21.62(0.12) | 22.09(0.12) | 22.51(0.20) | ... | 2014 0104,0108,1008,1104 | FLAMINGOS-2 | K12 |
| WISE J035934.06−540154.6 | Y0 | 21.84(0.11) | 21.53(0.11) | 21.72(0.17) | 22.8(0.3) | 2013 1121,1122 | FLAMINGOS-2 | K12 |
| WISE J041358.14−475039.3 | T9 | 20.82(0.10) | 19.63(0.06) | 20.02(0.08) | 20.68(0.12) | 2013 1121 | FLAMINGOS-2 | K12 |
| WISE J05516.80−750024.9 | Y1 | 22.73(0.30) | 22.50(0.20) | 23.34(0.34) | ... | 2014 0105,0106,1008 | FLAMINGOS-2 | K12 |
| WISE J064723.23−623235.5$^b$ | Y1 | 23.13(0.09) | 22.94(0.10) | >23.5 | >24 | 2014 0111,0220,0222,0223 | FLAMINGOS-2 | K13 |
| WISE J071322.55−291751.9 | Y0 | 20.34(0.08) | 19.98(0.05) | 20.19(0.08) | 21.30(0.31) | 2013 0112 | NIRI | K12 |
| WISE J073444.02−715744.0 | Y0 | 21.02(0.05) | 20.05(0.05) | 20.92(0.12) | 20.96(0.15) | 2013 1127 | FLAMINGOS-2 | K12 |
| WISEPA J075108.79−763449.6 | T9 | 20.02(0.10) | 19.37(0.13) | 19.68(0.13) | 20.03(0.20) | 2013 1129 | FLAMINGOS-2 | K11 |
| WD 0806−66B$^{bc}$ | Y1 | >23.5 | >23.9 | ... | ... | 2013 1217,1218; 2014 0115,0116,0119 | GSAOI | L11 |
| WISE J081117.81−805141.3 | T9.5 | 20.17(0.07) | 19.65(0.07) | 19.99(0.14) | 20.49(0.20) | 2013 1126,1129,1206 | FLAMINGOS-2 | K12 |
| WISEPC J140518.40+553421.5 | Y0 | ... | ... | ... | ... | 21.61(0.12) | 2013 0421 | NIRI | C11 |
| WISEP J154151.65−225025.2 | Y0.5 | ... | ... | 21.07(0.07) | 21.7(0.2) | 2013 0508,0511,0805 | NIRI | C11 |
| WISEPA J161441.45+173936.7 | T9 | 19.58(0.04) | 18.90(0.02) | 19.31(0.04) | 19.74(0.07) | 2013 0404 | NIRI | K11 |
| WISE J222055.31−362817.4 | Y0 | 20.91(0.09) | 20.64(0.05) | 20.96(0.08) | 21.33(0.15) | 2014 0716 | NIRI | K12 |

Notes. Discovery references are: Cushing et al. (2011); Kirkpatrick et al. (2011, 2012, 2013); Luhman et al. (2011); Mace et al. (2013); Pinfield et al. (2014a).

$^a$ The NIRI Y magnitudes and FLAMINGOS-2 Ks have been put on the MKO Y and K system as described in the text.

$^b$ Where given, lower limit magnitudes correspond to the limit for a 3σ detection.

$^c$ For WD 0806−66B a limit of z$^{AB}$ > 26.2 was obtained using GMOS-South on 2011 1205, 1230, 1231 and 2012 0119, 0120 and 0121.
find $H = 21.07 \pm 0.07$ compared to the previous value of $H = 22.17 \pm 0.25$. The data used here were obtained in much better seeing, 0.5′′ compared to 0.7, which allowed better separation of the target from a very close star. Hence we use the results from the more recent data set only.

2.3. FLAMINGOS-2 Photometry

FLAMINGOS-2 was used on Gemini South to obtain YJHKs photometry, or a subset thereof, for eight T9–Y1 dwarfs, via programs GS-2013B-Q-15, GS-2014A-Q-50 and GS-2014B-Q-17. In order to confirm that the photometric system corresponds to MKO for the YJH filters, and to determine the transformation from Ks to K, we observed 2MASS J04151954−0935066 (T8) and UGPS 0722 (T9) on 2013 November 22 and 27, and December 25. For the science targets, exposure times of 60 s or 120 s were used for Y, 60 s for J, and 10 s or 15 s for H and Ks, with a five- or nine-position telescope dither pattern. The data were reduced in the standard way using routines supplied in the IRAF Gemini package. The instrument was inadvertently used in both bright and faint read mode, so zeropoints were derived for both modes. We derived zeropoints at $Y/J/H/Ks$ of 24.83/24.91/25.15/24.45 and 24.09/24.16/24.39/23.68 for bright and medium mode, respectively.

The FLAMINGOS-2 Ks filter profile is very similar to that of the 2MASS Ks filter. Stephens & Leggett (2004) find that $K - Ks = 0.15$ for T8 spectral types. We determine a slightly larger correction for FLAMINGOS-2, measuring $K - Ks = 0.3$ for 2MASS 0415 and $K - Ks = 0.5 \pm 0.1$ for UGPS 0722. For all targets presented here we adopt $K - Ks = 0.4 \pm 0.1$. The YJH photometry was found to be on the MKO system, as expected from the filter bandpasses.

Table I gives the results, where we have applied the correction above to the Ks data to transform it to MKO K. The date of observation is also listed. The upper flux limits quoted at H and
as Y1.5 as it is not very different from the Y1 dwarfs in this faint object is noisy. In the literature it has been labeled type of W1828 is uncertain as the near-infrared spectrum of W0855, and it has been assigned a type >Y2 in the literature based on the type assigned to W1828 (e.g., Tinney et al. 2014). Here we assign a nominal spectral type of Y2 to W0855 for plotting purposes (but see discussion in Section 4). We used NIC2 data taken on 2011 October 16 for principal investigator Beichman. The night was photometric with excellent 0.3 seeing. Thirty-three frames were obtained, each consisting of a 60 s times two-coadd exposure. A NIC2 H-band flat was also downloaded from the KOA site. The data were reduced in the standard way using IRAF routines, and stacked using offsets measured from the images. The stacked image was calibrated using 10 sources in common with a shallower image of the field obtained using NIRI on 2014 July 02, via program GN-2014A-Q-64. The NIRI image in turn was calibrated using UKIRT photometric standards; both NIC2 and NIRI use MKO H filters.

We derive $H = 22.73 \pm 0.13$ for W1828, somewhat fainter (1.6σ) than the 22.42 ± 0.14 determined by Beichman et al. (2013) from the same data set using different secondary standards, and consistent with the 22.85 ± 0.24 measured by Kirkpatrick et al. (2012) using 2010 NIC2 data. In this paper we adopt our measurement of $H = 22.73 \pm 0.13$.

3. PHOTOMETRY COMPILATION AND DISCREPANCIES BETWEEN PUBLISHED MAGNITUDES

Discrepancies between near-infrared photometry obtained at Gemini and obtained by the WISE team have been noted previously (e.g., Leggett et al. 2013). Figure 2 compares $J$ and $H$ magnitudes obtained by the two groups. Gemini data are taken from this work and Leggett et al. (2013); WISE team data are from Beichman et al. (2013, 2014), Kirkpatrick et al. (2012, 2013) and Mace et al. (2013). The sample consists of 14 T8 to Y1 dwarfs where we have data in common. It can be seen that for about one-third of the sample the two measurement sets differ by more than 2σ, with two $J$ measurements differing by 6σ−7σ. Variability in near-infrared flux has been observed for brown dwarfs. Primarily this is seen for late-L and early-T dwarfs, and has been associated with the transition from cloudy to clear atmospheres (e.g., Radigan et al. 2014). Clouds are also present in the atmospheres of late-T and Y dwarfs; however, the level of variability observed for the warmer brown dwarfs is typically ≤10%, and it seems unlikely that variability can explain the large discrepancies of up to one magnitude seen here. As the scatter is larger for $J$ than $H$, and there are generally more variations in $J$ filter bandpasses used at observatories than in $H$, we suspect the cause is unrecognized differences in photometric systems. These differences can be very large for objects with unusual energy distributions, such as T and Y dwarfs (e.g., 0.4 mag for mid-T types, Stephens & Leggett 2004). The trends with spectral type shown in Section 4 support the Gemini measurements and not the WISE team results, where the two datasets disagree. Examples include the T9 0005+43 for which Mace et al. give $J - H = 0.23 \pm 0.14$ compared to our −0.39 ± 0.03, and the T9pec (T. J. Dupuy et al. 2015, in preparation) 0146+42AB for which Kirkpatrick et al. (2012) and Beichman et al. give $J - H = -1.51 \pm 0.33$ compared to our −0.61 ± 0.14.

To avoid possible systematic errors, we use only near-infrared photometry for the Y dwarfs that we are confident is on the MKO system, in this analysis. The exceptions are the recent J-band detections of WD 0806−66B (Luhman et al. 2014b) and W0855 (Faherty et al. 2014). We include these objects in order to populate the low-luminosity end of the sample. The WFC3 detection of WD 0806−66B is described in Section 2.1. For W0855, Faherty et al. used the FourStar imager at Las Campanas Observatory and measured $J3 = 24.8^{+0.33}_{-0.35}$, implying $J_{MKO} = 25.0^{+0.53}_{-0.35}$. We adopt the parallax given by Luhman & Esplin (2014) and assign a nominal spectral type of Y2 to this source for plotting purposes (see Section 2.4). Table 2 gives $YJHK$, or a subset thereof, for 17 Y dwarfs with MKO-system near-infrared photometry, together with spectral types and distance moduli as derived from published parallaxes.

For this paper, T and Y dwarf photometry is from this work, the UKIRT Infrared Deep Sky Survey (Lawrence et al. 2007), the AllWISE catalog (Wright et al. 2010; Mainzer et al. 2011).
Table 2
MKO Photometry of WISE Y Dwarfs

| Name            | Spectral Type | $M - m$ (err) Magnitude | Y (err) | J (err) | H (err) | K (err) | Parallax       | Photometry   | Discovery   |
|-----------------|---------------|-------------------------|---------|---------|---------|---------|----------------|-------------|-------------|
| WISE J030449.03−270508.3 | Y0            | ...                     | 20.79(0.09) | 21.02(0.16) | ...     | ...     | P14b           |             | P14b        |
| WISE J035000.32−565830.2 | Y1            | 2.32(0.37)              | 21.62(0.12) | 22.09(0.12) | 22.51(0.20) | ...     | M13            |             | this work   |
| WISE J035934.06−540154.6 | Y0            | −1.00(0.20)             | 21.84(0.11) | 21.53(0.11) | 21.72(0.17) | 22.80(0.3) | T14            |             | K12         |
| WISEP J041022.71 + 150248.5 | Y0            | 1.02(0.12)              | 19.61(0.04) | 19.44(0.03) | 20.02(0.05) | 19.91(0.07) | B14            |             | Leg13       |
| WISE J053516.80−750024.9 | Y1            | −0.65(0.41)             | 22.73(0.30) | 22.50(0.20) | 23.34(0.34) | T14     | M13            |             | this work   |
| WISE J064723.23−623235.5 | Y1            | 0.09(0.18)              | 23.13(0.09) | 22.94(0.10) | >23.5    | >24     | K13,T14        |             | K13         |
| WISE J071322.55−291751.9 | Y0            | 0.18(0.08)              | 19.34(0.08) | 19.98(0.05) | 20.19(0.08) | 21.30(0.31) | T14            |             | this work   |
| WISE J073444.02−715744.0 | Y0            | −0.66(0.19)             | 21.02(0.05) | 20.05(0.05) | 20.92(0.12) | 20.96(0.15) | T14            |             | K12         |
| WD 0806−66B      | Y1            | −1.41(0.07)             | >23.5    | 25.0(0.10)  | ...     | ...     | S09            | Luh14b      | Luh11       |
| WISE J085510.83−071442.5 | Y2            | 3.29(0.15)              | ...     | 25.0(0.15)  | ...     | ...     | L&E            | F14         | Luh14a      |
| WISEPC J121756.91+162640.2B | Y0         | −0.02(0.35)             | 20.26(0.03) | 20.08(0.03) | 20.51(0.06) | 21.10(0.12) | D13            |             | Liu12       |
| WISEPC J140518.40+553421.5 | Y0         | 0.55(0.50)              | 21.24(0.10) | 21.06(0.06) | 21.41(0.08) | 21.61(0.12) | D13            |             | Leg13, this work |
| WISE J154151.65−225025.2 | Y0.5         | 1.22(0.06)              | 21.46(0.13) | 21.12(0.06) | 21.07(0.07) | 21.70(0.2)  | T14            |             | C11         |
| WISE J173835.52 + 273258.9 | Y0         | 0.54(0.17)              | 19.86(0.07) | 20.05(0.09) | 20.45(0.09) | 20.58(0.10) | B14            |             | C11         |
| WISE J182831.08 + 265037.8 | Y1.5         | 0.13(0.14)              | 23.03(0.17) | 23.48(0.23) | 22.73(0.13) | 23.48(0.36) | B14            |             | Leg13, this work |
| WISEPC J205628.90 + 145953.3 | Y0         | 0.73(0.13)              | 19.77(0.05) | 19.45(0.04) | 19.96(0.04) | 20.01(0.06) | B14            |             | C11         |
| WISE J222055.31−362817.4 | Y0         | −0.30(0.09)             | 20.91(0.09) | 20.64(0.05) | 20.96(0.08) | 21.33(0.15) | T14            |             | Leg13       |

Notes. References are: Beichman et al. (2014); Cushing et al. (2011); Dupuy & Kraus (2013); Faherty et al. (2014); Kirkpatrick et al. (2011, 2012, 2013); Leggett et al. (2013); Liu et al. (2012); Luhman et al. (2011); Luhman (2014a); Luhman & Esplin (2014); Luhman et al. (2014b); Marsh et al. (2013); Pinfield et al. (2014b); Subasavage et al. (2009); Tinney et al. (2014); Wright et al. (2014).

a Spectral sub-type is uncertain for WD 0806−66B, WISE J085510.83−071442.5 and WISE J182831.08 + 265037.8, which have very noisy or no near-infrared spectra.

b The J magnitude for WD 0806−66B has been derived from the F110W detection by Luhman et al. (2014b) as described in Section 2.1. The J magnitude for WISE J085510.83−071442.5 is the FourStar measurement published by Faherty et al. (2014).
Figure 3. Trends in absolute magnitude as a function of spectral type. Note the varied y-axis ranges. All magnitudes are Vega based. The YJHK are on the MKO system, [3.6] on the Spitzer IRAC system and W2 (4.6 μm) on the WISE system. Photometry and parallax sources are given in the text. New observations presented here are identified by red symbols.

4. OBSERVED TRENDS WITH SPECTRAL TYPE

Figure 3 shows absolute 1–5 μm magnitudes as a function of spectral type, and Figure 4 shows 0.9–12.0 μm colors as a function of type, for a sample of late-T and Y dwarfs. New data presented here are indicated by red symbols. Color sequences are better defined, as is the intrinsic scatter in the sequences, when the new data are included. The new data enable a more meaningful comparison with the models (Section 6).

Currently the Y dwarf spectral classification is defined by the width of the J-band flux peak in the (often noisy) near-infrared
Figure 4. Trends in color as a function of type. Data sources are given in the text. All magnitudes are Vega based. New observations presented here are identified by red symbols.

Trends in color as a function of type. Data sources are given in the text. All magnitudes are Vega based. New observations presented here are identified by red symbols.

Figure 4. Trends in color as a function of type. Data sources are given in the text. All magnitudes are Vega based. New observations presented here are identified by red symbols.

Figure 4. Trends in color as a function of type. Data sources are given in the text. All magnitudes are Vega based. New observations presented here are identified by red symbols.

In the current classification scheme, $T_{\text{eff}}$ across the T/Y boundary drops sharply—from 750 K at T8, to 600 K at T8.5, to 500 K at T9, to 400 K at Y0 (e.g., Saumon et al. 2007; Smart et al. 2010; Leggett et al. 2012, 2013). The atmospheres are also changing dramatically, from being reasonably clear for mid-T types, to cloudy for late-T and early-Y with sulfide and chloride condensates, to cloudy with water ice for later Y types (Morley et al. 2012, 2014).

Outliers are identified in Figures 3 and 4. In the case of WISE J035000.32−565830.2 (W0350) and WISEP J140518.40+553421.4 (W1405), the brightness and color trends would be improved if their classifications were shifted 0.5 subclass later: W0350 to Y1.5 and W1405 to Y0.5. However, for W0350 the absolute magnitude-color relations shown later suggest that the absolute magnitudes are also too faint, in other words the distance is too small and measured parallax too large. For one source, WISE J053516.80−750024.9 (W0535), both the near- and mid-infrared absolute magnitudes appear too bright, implying that the distance is too large (parallax too small) or the source is multiple.
Figure 5. Opacity cross sections multiplied by equilibrium gas volume mixing ratio, calculated for three layers of a $T_{\text{eff}} = 400$ K, log $g = 4.48$, brown dwarf atmosphere. The top panel shows the layer from which the $Y$-band flux emerges, the middle panel the $5 \mu$m flux, and the bottom panel the $10 \mu$m flux. See text for discussion.

W0855 is extremely red in $J - W2$, and is intrinsically fainter than any known Y dwarf, by $\sim 4$ magnitudes at $J$ and $\sim 2$ magnitudes at $W2$ (neglecting W0350 whose parallax we suspect is erroneous). More Y dwarfs with good quality near-infrared spectra are required to establish the classification scheme beyond Y1 types. A simple extrapolation of the $MW2$ as a function of type diagram suggests a spectral type for W0855 of around Y4.

Other sources appear to have unusual spectral energy distributions. SDSS J141624.08 + 134826.7 (S1416B) WISE J033515.01 + 431045.1 (W0335) and WISE J014656.66 + 243410.0AB (W0146) appear to be unusually faint in the $K$ band and blue in $J - K$ and $H - K$. S1416B is a known low-metallicity high-gravity T dwarf (e.g., Burningham et al. 2010). Similarly, Beichman et al. (2014) show that W0335 has quite a large tangential velocity, and their model interpretation suggests a relatively high gravity and an age around 8 Gyr. WISE J182831.08 + 265037.7 (W1828) appears unusually bright in the mid-infrared, and has been widely discussed in the literature (e.g., Beichman et al. 2013); we return to this object later in Section 7.4.

We also see an indication of populations with unusual $Y - J$ colors. ULAS J232600.40 + 020139.2 (U2326), WISE J041358.14-475039.3 (W0413) and WISE J073444.02-715744.0 (W0734) appear to be red in $Y - J$, and WISEP J173835.53 + 273258.9 (W1738) and W0350 appear blue in this color. We discuss $Y - J$ colors in Section 7.3.

5. DESCRIPTION OF THE MODELS

In this analysis we use spectra and colors generated from model atmospheres with a variety of cloud cover. We include cloud-free models from Saumon et al. (2012) and models with homogeneous layers of chloride and sulfide clouds from Morley et al. (2014). The magnitudes generated from the published models and used in this paper can be obtained at http://www.ucolick.org/~cmorley/cmorley/Models.html.

We also see an indication of populations with unusual $Y - J$ colors. ULAS J232600.40 + 020139.2 (U2326), WISE J041358.14-475039.3 (W0413) and WISE J073444.02-715744.0 (W0734) appear to be red in $Y - J$, and WISEP J173835.53 + 273258.9 (W1738) and W0350 appear blue in this color. We discuss $Y - J$ colors in Section 7.3.

6. DESCRIPTION OF THE MODELS

In this analysis we use spectra and colors generated from model atmospheres with a variety of cloud cover. We include cloud-free models from Saumon et al. (2012) and models with homogeneous layers of chloride and sulfide clouds from Morley et al. (2014). The magnitudes generated from the published models and used in this paper can be obtained at http://www.ucolick.org/~cmorley/cmorley/Models.html.
Figure 6 shows synthetic 0.8–20 µm spectra for a log $g = 4.48$ brown dwarf at 10 pc, with different cloud cover parameters and $T_{\text{eff}} = 400$ K, 300 K and 250 K. These temperatures and gravity correspond to an approximately 10 Jupiter-mass object aged 3 to 10 Gyr. Far-red, near- and mid-infrared filter bandpasses are also shown in Figure 6. The water ice condensates scatter at wavelengths $\sim 1$ µm, and absorb at $\sim 5$ µm (Morley et al. 2014, their Figure 2). Figure 6 shows that when the water cloud extent and depth is increased, the $z$ and W2 fluxes are decreased, and the flux is redistributed to $K$, [3.6] and W3. At $T_{\text{eff}} = 400$ K the flux at $Y$ and $J$ also decreases with increasing water clouds. At $T_{\text{eff}} = 300$ K and 250 K very little flux emerges in the near-infrared, independent of the cloud parameters.

We compare the cloud-free and cloudy models to the observations in the next section.

6. COMPARING DATA TO MODELS

Figures 7 and 8 are near- and mid-infrared color–magnitude diagrams. Figure 9 shows near-infrared colors against $J - W2$. In Figure 8, the kink in the thick water cloud model sequence at $M_{W2} \approx 16$ is due to the combination of changing opacity and pressure-temperature structure between 325 and 300 K, as water condenses into ice.

The model trends are in reasonable agreement with the data, for example Figure 7 shows that the models reproduce the redward turn in $J - H$ at $M_J \approx 21$ or $T_{\text{eff}} \approx 400$ K. There are problematical discrepancies, however, such as the divergence between models and data in $J - K$, for $M_J > 21$. Variations in gravity cannot account for the discrepancies: increasing gravity improves the match for $J - H$ but makes it worse for $J - K$, for example. Note that all models are for solar metallicity, and it is likely that the sample contains brown dwarfs with a range of metallicity. This is one area that the models still need to address.

For the $T_{\text{eff}} \lesssim 450$ K models, we find that increasing the cloud cover fraction (from 50% to 80%) and decreasing the sedimentation efficiency (from $f_{\text{sed}} = 5$ to $f_{\text{sed}} = 3$) greatly improves the agreement with most of the observed colors. To explore the validity of this change, we compare the observed near-infrared spectrum of the Y0 dwarf W1217B (Leggett et al. 2014) to $T_{\text{eff}} = 400$ K log $g = 4.48$ synthetic spectra in
Figure 7. Absolute $J$ magnitude as a function of near-infrared colors for T8 and later type dwarfs. Not shown are WD 0806$-$66B with $M_J = 23.6$, $z_{AB} - J > 1.2$, and $Y - J > -1.5$, and WISE J085510.83$-$18142.5 with $M_J \approx 28.3$ (see Section 1). WISE J035000.32$-$565830.2 appears unusually faint in $M_J$ and the parallax should be confirmed. Model sequences (Saumon et al. 2012; Morley et al. 2012, 2014) are shown for $\log g = 4.48$: blue lines are cloud-free, green lines have thin sulfide and salt cloud decks with $f_{\text{sed}} = 5$ over the entire surface, red lines have thin water cloud decks with $f_{\text{sed}} = 5$ over half the surface, and violet lines have thick water cloud decks with $f_{\text{sed}} = 3$ over 80% of the surface. The dashed line is for $\log g = 5.0$ and dotted for $\log g = 4.0$. The right axis of the top panel shows $T_{\text{eff}}$ values for the $\log g = 4.48$ water cloud models.

Figure 10. Here the observed flux has been scaled to 10 pc using the trigonometric parallax measured by Dupuy & Kraus (2013), and the model fluxes are scaled to 10 pc adopting a brown dwarf radius of 0.1054 $R/\astrosun$ based on the evolutionary models of Saumon & Marley (2008). Spectra for other Y0 dwarfs with trigonometric parallaxes are very similar in brightness, but have less complete wavelength coverage. We find that the 1.0–1.3 $\mu$m spectrum in fact supports very thin to no cloud, and not the thick cloud model.

The large photometric discrepancies ($\sim 1$ mag) at $T_{\text{eff}} \approx 400$ K (spectral type Y0, $M_J \approx 20, M_{W2} \approx 15$) consist of the models being too blue in $J - H$, $J - K$, and $W2 - W3$, and too red in $[3.6] - W2$. Adding more extensive and thicker water clouds appears to address the problems in $J - H$, $J - K$, and $W2 - W3$ by reducing the flux at $J$, and increasing the flux at $K$ and W3. However, the spectral comparison shows that the apparent improvement is misleading—in fact the $J$ flux becomes much too weak if the extent and thickness of the water clouds are increased. Instead, the near-infrared spectral comparison shown in Figure 10 and the photometric comparisons shown in Figures 7–9 indicate that the patchy cloud model fluxes for Y0 dwarfs are too low, by about a factor of two or a magnitude, at $Y, H, K, [3.6]$ and W3. For later Y-types with $T_{\text{eff}} \approx 300$ K, additional discrepancies seem to arise.
Figure 8. Absolute W2 magnitude as a function of various colors for T7 and later type dwarfs. For WD 0806–66B the W2 magnitude is uncertain ($\delta M = 0.4$) and we have replaced it with the Spitzer 4.48 \(\mu\)m magnitude transformed to W2 by adding 0.1 magnitude (Leggett et al. 2013). See note regarding WISE J035000.32–565830.2 in the caption to Figure 7. Sequences are as in Figure 7.

We discuss possible solutions to these problems in the next section.

7. DISCUSSION

7.1. Y0 Dwarfs, $T_{\text{eff}} \approx 400$ K

As noted above, for Y0 dwarfs with $T_{\text{eff}} \approx 400$ K, we have found that our state-of-the-art models generate fluxes that are about a factor of two too low at $Y$, $H$, $K$, $[3.6]$, and $W3$ (filter profiles are shown in Figure 6). For the $Y$, $H$, and $W3$ bandpasses (the $\sim1.05$, 1.6, and 12.0 \(\mu\)m spectral regions) Figure 5 shows that the dominant opacity source is NH$_3$. Figure 5 also includes cross sections for an arbitrary reduction in NH$_3$ abundance of a factor of two. In that case the dominant opacity in the $Y$ band and in the blue wing of the $H$ band (1.5–1.6 \(\mu\)m) becomes pressure-induced H$_2$. The result would be that the pronounced double absorption feature at 1.03 \(\mu\)m goes away, and the flux in the $Y$ and $H$ bands significantly increases, all of which is in agreement with the observations (see Figure 10). Note that the dominant opacity in the $J$ band is already H$_2$, and the agreement between the cloud-free or thin-cloud models and the data are good for $J$ (Figure 10).

For most of the $W3$ band (8–17 \(\mu\)m) the dominant opacity is NH$_3$ and remains so even if the abundance is halved. However, the absorption would be dramatically weakened—note that Figure 5 is plotted on a log scale. In this band, weakening the NH$_3$ absorption could mimic the gain caused by the redistribution of flux due to increasing cloud cover (Figure 6). With ammonia absorption significantly reduced, the remaining problems would be too little flux in the $K$ and $[3.6]$ bands.

For higher $T_{\text{eff}}$ models than considered here, convective mixing leads to more N$_2$ and less NH$_3$ in the spectrum-forming part of the atmosphere (e.g., at $T_{\text{eff}} \approx 600$ K, Leggett et al. 2009). However, Morley et al. (2014, their Figure 16) show that preliminary models that include vertical mixing do not resolve the discrepancies for 400 K brown dwarfs—the introduction of disequilibrium chemistry has a large impact on the $H – K$
color in particular, and makes the disagreement between models and data worse. These atmospheres are extremely complex, with low-lying chloride and sulfide clouds, high water clouds and possibly multiple convective zones (Morley et al. 2014, their Figure 4). Including vertical mixing in this context in a consistent fashion is challenging. The next stage in model generation will likely require an inversion approach, where a retrieval algorithm iterates both the pressure-temperature profile and the abundances to find the best match to the data (Line et al. 2014).

7.2. Y1 Dwarfs, \(T_{\text{eff}} \approx 350\) K

For brown dwarfs with \(M_J \gtrsim 22\) and \(T_{\text{eff}} \approx 350\) K, additional issues with the models appear. The discrepancy at \(J-H\) and \(J-K\) increases by around 0.5 magnitudes (Figure 7). In the mid-infrared it appears that \(M_{W2}\) increases more slowly with \(J-W2\) than calculated (Figure 8). These could point to a significant reduction of the 1 \(\mu\)m flux, of about a factor of two, so that \(J-H\), \(J-K\), and \(J-W2\) become much redder.

At \(T_{\text{eff}} \approx 350\) K thick water clouds may be required to reproduce the data, as Figure 10 shows that such clouds cause a drop in the 1 \(\mu\)m flux of about the required size. Also the thick water cloud sequences in Figure 8 show interesting trends at \(300 \lesssim T_{\text{eff}} K \lesssim 350\) which are similar to those observed. The thick water cloud model has a shoulder in the trend of increasing \(M_{W2}\) with increasing \(J-W2\), followed by a sharp drop in \(M_{W2}\). This flattening of the decrease in \(M_{W2}\) followed by a dramatic drop could explain both the brightness of W1828 and the faintness of W0855, in W2 (5 \(\mu\)m; see Section 7.4).

Figure 11 reproduces the \(J-W2: M_{W2}\) diagram. A simple solution to the apparent brightness of W1828 is that it is an equal-mass binary (see discussion in Section 7.4). Making this assumption, we have fit a polynomial to the observed \(J-W2: M_{W2}\) data, weighted by the inverse of the square of the uncertainty in the absolute magnitude, excluding known binaries. We find that the fifth-order polynomial

\[
M_{W2} = 8.93387 + 4.37546 * x - 1.80318 * x^2 \\
+ 0.376357 * x^3 - 0.0359539 * x^4 + 0.00126562 * x^5
\]
Figure 10. Observed (smoothed) near-infrared spectrum for the Y0 WISEPC J121756.91 + 162640.2B (Leggett et al. 2014) is shown as a black line. The flux has been scaled to what would be observed were the dwarf at a distance of 10 pc. The region of poor atmospheric transmission, 1.80–1.94 μm, is noisy. The blue, red, and violet lines are synthetic spectra for a $T_{\text{eff}} = 400$ K, log $g = 4.48$ brown dwarf at 10 pc, with different cloud cover parameters as in Figure 7.

Figure 11. Black line is fifth-order polynomial weighted fit to the $J - W2$, $M_{\text{W2}}$ data points, excluding known binaries. The fit is not scientifically significant, and is intended only as an indication of observed trends, with the assumption that W1828 is an equal-mass binary. W0350 is included in the fit; however, the parallax for this object appears to be erroneous. While admittedly arbitrary, we note that a very similar trend can be obtained by shifting the thick water cloud model sequence in $J - W2$ and $M_{\text{W2}}$ (Figure 8, violet line).

The function is useful, however, as a reference for future observations and theoretical modeling. The function does show reproduces the trend seen in the observed data with W1828 as an equal-mass binary (Figure 11). The polynomial fit is not scientifically significant and we have not derived any measures of quality of fit. We would expect the sample to have a range in metallicity, gravity, and cloud properties that would result in scatter in the $J - W2:M_{\text{W2}}$ diagram (see Section 7.3).
similarity to the thick water cloud model sequence in Figure 8, which gives some support to its validity. If that model sequence is shifted to fainter J and brighter W2 magnitudes, say J + 1 and W2 + 0.3, then there would be a shoulder at \( M_{W2} \approx 15.5 \), followed by rapidly increasing W2 for J − W2 ≳ 9, as seen in Figure 11.

Water ice scatters at J and absorbs at W2, and so these colors likely constrain the ice particle size and composition, as well as cloud cover. Clearly this is a very interesting and challenging parameter space for atmospheric modeling. An inversion approach may also be necessary to improve the models at these temperatures. Note that for \( T_{\text{eff}} < 300 \) K vertical transport no longer affects the NH3 abundance because it is far more abundant than H2 down to deep levels in the atmosphere.

7.3. Intrinsic Scatter

There is a large range, of about one magnitude, in the observed Y − J and J − K colors for \( T_{\text{eff}} \approx 400 \) K (Figures 7 and 9). The models in this temperature range show that Y, J, and K are sensitive to the details of the cloud structure (Figures 6 and 10). Also, we have shown that the NH3 absorption is likely to be much lower than calculated, implying that pressure-induced H2 becomes an important opacity source at 1.55 \( \mu \)m and dominant at 1.05, 1.25, and 2.05 \( \mu \)m (Figure 5). These wavelength regions coincide with the \( YJHK \) filter bandpasses, which were designed to avoid the Earth’s H2O absorption bands. The observed near-infrared colors will become a function of the H2 absorption, which in turn is dependent on metallicity and gravity (Saumon et al. 2012). The spread in the near-infrared colors for spectral types around Y0 therefore likely reflects a range of metallicity, gravity, and cloud properties.

7.4. WISEP J182831.08 + 265037.8 and WISE J085510.83 − 071442.5

Of the known Y dwarfs, the reddest in J − W2 are W1828 (Y1.5) and W0855 (nominally Y2). These are likely to be the coolest of the known Y dwarfs.

W1828 appears unusually bright in the mid-infrared, and has been widely discussed in the literature (Beichman et al. 2013 and references therein). The WISE atlas image does not show any obvious infrared cirrus coincident with the source, which might lead to a mid-infrared excess. This work and other recent publications have produced more photometry and parallaxes for comparable objects, and we can explore the nature of W1828 further.

We have calculated the colors of a binary system composed of W0647 (Y1) and W0855. However, a simple composite of these two sources put at the same distance does not produce a binary that is sufficiently red in J − W2. This is because W0855 is intrinsically faint and does not contribute enough to the mid-infrared total flux. Instead, as mentioned in Section 7.2, we suggest that W1828 is a simple pair of identical brown dwarfs. Each component would have \( M_J \approx 24.4 \) and \( M_{W2} \approx 15.2 \). Such a source has colors consistent with the trends seen in Figures 7–9. Binaries are not uncommon in brown dwarf spectral types. Also, Burgasser et al. (2007) find that very low mass multiple systems tend to be closely separated and are more frequently in near-equal mass configurations.

The binary explanation of W1828 would imply that it consists of a pair of 300 ≲ \( T_{\text{eff}} \) K ≲ 350 brown dwarfs. For W0855, our models together with the observed J- and W2-band luminosity imply that it is a ~250 K dwarf. If W1828 and W0855 are, say, 3 Gyr old (being in the solar neighborhood), evolutionary models show that their masses are ~10 and ~5 Jupiter-masses, respectively (Saumon & Marley 2008).

8. CONCLUSION

We have found that current state-of-the-art models can qualitatively reproduce the trends seen in the observed colors of the latest-type T dwarfs and known Y dwarfs. However, significant discrepancies exist. For brown dwarfs with \( T_{\text{eff}} \approx 400 \) K, corresponding to spectral type ~Y0, the model fluxes are a factor of two low at \( Y, H, K, [3.6] \), and W3. For \( T_{\text{eff}} \approx 350 \) K, corresponding to spectral type ~Y1, it appears that a reduction in the J-band flux of about a factor of two is needed, while the W2 flux remains approximately constant.

The problems at \( Y, H, \) and W3 (or ~1.05, 1.6, and 12.0 \( \mu \)m) may be addressed by significantly reducing the NH3 absorption, for example by halving the abundance of NH3. This could be explained by mixing of N2 and NH3, as is seen in T dwarfs, but incorporating mixing in a realistic way in an atmosphere with chloride, sulfide, and water condensates is challenging. Once the NH3 absorption is reduced, pressure-induced H2 becomes the dominant opacity source in the near-infrared filter bandpasses, making those colors sensitive to gravity and metallicity variations, and probably explaining the scatter seen in the near-infrared colors of Y0 dwarfs.

While the cloud layers are thin to non-existent for the 400 K brown dwarfs, as \( T_{\text{eff}} \) decreases to 350 K thick and extensive water clouds appear to form, based on the observed reduction in the J-band flux. The onset of these clouds might occur over a narrow range of \( T_{\text{eff}} \), as indicated by the observed small change in 5 \( \mu \)m flux over a large change in J − W2 color.

Diagnosis of cloud cover for Y dwarfs, however, will remain uncertain until the models, which are already complex, can be further improved to the point of reproducing the near- and mid-infrared observations. The expectation had been that the atmospheres of the cold brown dwarfs would be simpler because most elements are condensed out and the chemistry is reduced to CH4, H2O, and NH3, but this was clearly rather optimistic.

D.S. is supported by NASA Origins NNH12AT89I. Based on observations obtained at the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the Science and Technology Facilities Council (United Kingdom), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), Ministério da Ciência, Tecnologia e Inovação (Brazil) and Ministerio de Ciencia, Tecnología e Innovación Productiva (Argentina). S.K.L.’s research is supported by Gemini Observatory. This publication makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration. This research has made use of the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This research has made use of the Keck Observatory Archive (KOA), which is operated by the W. M. Keck Observatory and the NASA
Exoplanet Science Institute (NExScI), under contract with the National Aeronautics and Space Administration.

REFERENCES

Beichman, C., Gelino, C. R., Kirkpatrick, J. D., et al. 2013, ApJ, 764, 101
Beichman, C., Gelino, C. R., Kirkpatrick, J. D., et al. 2014, ApJ, 783, 68
Burgasser, A. J., Kirkpatrick, J. D., Brown, M. E., et al. 1999, ApJL, 522, L65
Burgasser, A. J., Kirkpatrick, J. D., Cruz, K. L., et al. 2006, ApJS, 166, 385
Burgasser, A. J., Reid, I. N., Siegler, N., et al. 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson, AZ: Univ. Arizona Press), 427
Burningham, B., Cardoso, C. V., Smith, L., et al. 2013, MNRAS, 433, 457
Burningham, B., Pinfield, D. J., Lucas, P. W., et al. 2010, MNRAS, 406, 1885
Carrasco, E. R., Edwards, M. L., McGregor, P. J., et al. 2012, Proc. SPIE, 8447, 84470N
Chiu, K., Fan, X., Leggett, S. K., et al. 2006, AJ, 131, 2722
Cushing, M. C., Kirkpatrick, J. D., Gelino, C. R., et al. 2011, ApJ, 743, 50
Dupuy, T. J., & Kraus, A. L. 2013, Sci, 341, 1492
Eikenberry, S., Elston, R., Raines, S. N., et al. 2004, Proc. SPIE, 5492, 1196
ESA 1997, The Hipparcos and Tycho Catalogues (ESA SP-1200; Noordwijk: ESA)
Faherty, J. K., Tinney, C. G., Skemer, A., & Monson, A. J. 2014, ApJL, 793, L16
Hodapp, K. W., Jensen, J. B., Irwin, E. M., et al. 2003, PASP, 115, 1388
Hook, I., Jørgensen, I., Allington-Smith, J. R., et al. 2004, PASP, 116, 425
Kirkpatrick, J. D., Cushing, M. C., Gelino, C. R., et al. 2011, ApJS, 197, 19
Kirkpatrick, J. D., Cushing, M. C., Gelino, C. R., et al. 2013, ApJ, 776, 128
Kirkpatrick, J. D., Gelino, C. R., Cushing, M. C., et al. 2012, ApJ, 753, 156
Knapp, G. R., Leggett, S. K., Fan, X., et al. 2004, AJ, 127, 3553
Landolt, A. U. 1992, AJ, 104, 340
Lawrence, A., Warren, S. J., Almaini, O., et al. 2007, MNRAS, 379, 1599
Leggett, S. K., Burningham, B., Saumon, D., et al. 2010, ApJ, 710, 1627
Leggett, S. K., Currie, M. J., Varricatt, H. P., et al. 2006, MNRAS, 373, 781
Leggett, S. K., Cushing, M. C., Saumon, D., et al. 2009, ApJ, 695, 1517
Leggett, S. K., Liu, M. C., Dupuy, T. J., et al. 2014, ApJ, 780, 62
Leggett, S. K., Morley, C. V., Marley, M. S., et al. 2013, ApJ, 763, 130
Leggett, S. K., Saumon, D., Marley, M. S., et al. 2007, ApJ, 655, 1079
Leggett, S. K., Saumon, D., Marley, M. S., et al. 2012, ApJ, 748, 74
Line, M. R., Fortney, J., Marley, M. S., & Sorahana, S. 2014, ApJ, 793, 33
Lissauer, J. L., Fabrycky, D. C., Ford, E. B., et al. 2011, Natur, 470, 53
Liu, M. C., Delorme, P., Dupuy, T. J., et al. 2011, ApJ, 740, 108
Liu, M. C., Dupuy, T. J., Bowler, B. P., Leggett, S. K., & Best, W. M. J. 2012, ApJ, 758, 57
Liu, M. C., Magzier, E. A., Deacon, N. R., et al. 2013, ApJL, 777, L20
Lucas, P. W., Tinney, C. G., Burningham, B., et al. 2010, MNRAS, 408, L56
Luhman, K. L. 2014, ApJL, 786, L18
Luhman, K. L., Burgasser, A. J., & Bochanski, J. J. 2011, ApJL, 730, L9
Luhman, K. L., Burgasser, A. J., Labbé, I., et al. 2012, ApJ, 744, 135
Luhman, K. L., & Esplin, T. L. 2014, ApJ, 796, 6
Luhman, K. L., Morley, C. V., Burgasser, A. J., Esplin, T. L., & Bochanski, J. J. 2014, ApJ, 794, 16
Mace, G. N., Kirkpatrick, J. D., Cushing, M. C., et al. 2013, ApJS, 205, 6
Mainzer, A., Bauer, J., Grav, T., et al. 2011, ApJ, 731, 53
Manjavacas, E., Goldbaum, B., Reffert, S., & Henning, T. 2013, A&A, 560, 52
Marsh, K. A., Wright, E. L., Kirkpatrick, J. D., et al. 2013, ApJ, 762, 119
Mayor, M., & Queloz, D. 1995, Natur, 378, 355
McGregor, P., Hart, J., Stevanovic, D., et al. 2004, Proc. SPIE, 5492, 1033
Morley, C. V., Fortney, J. J., Marley, M. S., et al. 2012, ApJ, 756, 172
Morley, C. V., Marley, M. S., Fortney, J. J., et al. 2014, ApJ, 787, 78
Nakajima, T., Oppenheimer, B. R., Kulkarni, S. R., et al. 1995, Natur, 378, 463
Patten, B. M., Stauffer, J. R., Burrows, A., et al. 2006, ApJ, 651, 502
Pinfield, D. J., Gomes, J., Day-Jones, A. C., et al. 2014a, MNRAS, 437, 1009
Pinfield, D. J., Gromadzki, M., Leggett, S. K., et al. 2014b, MNRAS, 444, 1931
Radigan, J., Jayawardhana, R., Lafreniere, D., Dupuy, T., Liu, M. C., & Scholz, A. 2013, ApJ, 778, 36
Radigan, J., Lafreniere, D., Jayawardhana, R., & Artigau, E. 2014, ApJ, 793, 75
Rodriguez, D. R., Zuckerman, B., Melis, C., & Song, I. 2011, ApJL, 732, L29
Saumon, D., & Marley, M. S. 2008, ApJ, 689, 1327
Saumon, D., Marley, M. S., Abel, M., Frommhold, L., & Freedman, R. S. 2012, ApJ, 750, 74
Saumon, D., Marley, M. S., Leggett, S. K., et al. 2007, ApJ, 656, 1136
Smart, R. L., Jones, H. R. A., Lattanzio, M. G., et al. 2010, A&A, 511, 30
Smith, J. A., Tucker, D. L., Kent, S., et al. 2002, ApJ, 123, 2121
Stephens, D. S., & Leggett, S. K. 2004, PASP, 116, 9
Stephens, D. S., Leggett, S. K., Cushing, M. C., et al. 2009, ApJ, 702, 154
Strauss, M., Fan, X., Gunn, J. E., et al. 1999, ApJL, 522, L61
Subasavage, J. P., Jao, W.-C., Henry, T. J., et al. 2009, AJ, 137, 4547
Tinney, C. G., Faherty, J. K., Kirkpatrick, J. D., et al. 2014, ApJ, 796, 39
Tokunaga, A. T., & Vacca, W. D. 2005, PASP, 117, 421
Vrba, F. J., Henden, A. A., Luginbuhl, C. B., et al. 2004, AJ, 127, 2948
Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140, 1868
Wright, E. L., Mainzer, A., Kirkpatrick, J. D., et al. 2014, AJ, 148, 82