Fire Spectroscopy of Five Late-Type T Dwarfs Discovered with the Wide-Field Infrared Survey Explorer

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FIRE SPECTROSCOPY OF FIVE LATE-TYPE T DWARFS DISCOVERED WITH THE WIDE-FIELD INFRARED SURVEY EXPLORER

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ABSTRACT

We present the discovery of five late-type T dwarfs identified with the Wide-field Infrared Survey Explorer (WISE). Low-resolution near-infrared spectroscopy obtained with the Magellan Folded-port InfraRed Echellette (FIRE) reveal strong H$_2$O and CH$_4$ absorption in all five sources, and spectral indices and comparison to spectral templates indicate classifications ranging from T5.5 to T8.5. The spectrum of the latest-type source, WISE J1812+2721, is an excellent match to that of the T8.5 companion brown dwarf Wolf 940B. WISE-based spectrophotometric distance estimates place these T dwarfs at 12-13 pc from the Sun, assuming they are single. Preliminary fits of the spectral data to the atmosphere models of Saumon & Marley indicate effective temperatures ranging from 600 K to 930 K, both cloudy and cloud-free atmospheres, and a broad range of ages and masses. In particular, two sources show evidence of both low surface gravity and cloudy atmospheres, tentatively supporting a trend noted in other young brown dwarfs and exoplanets. In contrast, the high proper motion T dwarf WISE J2018–7423 exhibits a suppressed $K$-band peak and blue spectrophotometric $J$ – $K$ colors indicative of an old, massive brown dwarf; however, it lacks the broadened $Y$-band peak seen in metal-poor counterparts. These results illustrate the broad diversity of low-temperature brown dwarfs that will be uncovered with WISE.

Subject headings: stars: fundamental parameters — stars: individual (WISEPC J161705.75+180714.0, WISEPC J201824.98–742326.1, WISEPC J235941.07–733504.8) — stars: low mass, brown dwarfs

1. INTRODUCTION

The discovery in 1995 of a faint companion to the nearby M dwarf Gliese 229 galvanized the field of brown dwarf observational astrophysics. Its near-infrared spectrum exhibits strong H$_2$O and CH$_4$ absorption, unambiguous indicators of a low-temperature, substellar atmosphere (Nakajima et al. 1993; Orenheimer et al. 1995). These features now define the T dwarf spectral class (Burgasser et al. 2006b), the coldest known brown dwarfs with effective temperatures extending down to $T_{\text{eff}} \approx 500$ K (e.g., Burningham et al. 2008).

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Lucas et al. 2010). Over 200 T dwarfs have been uncovered in the past 15 years, identified primarily in wide-field, near-infrared imaging surveys such as the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006), e.g., Burgasser et al. 2002; Looper et al. 2007, the Sloan Digital Sky Survey (SDSS; York et al. 2000), e.g., Geballe et al. 2002; Chin et al. 2006, the United Kingdom Infrared Telescope Deep Sky Survey (UKIDSS; Lawrence et al. 2007), e.g., Lodieu et al. 2007; Burningham et al. 2010) and the Canada-France Brown Dwarf Survey (CFBDS; Delorme et al. 2008b) and Revé et al. 2010).

Efforts are now underway to identify even colder brown dwarfs, sources whose atmospheres are anticipated to bridge the temperature gap between the known population and the Jovian planets ($T_{\text{eff}} \lesssim 125$ K). This is the realm in which directly detectable young extrasolar planets are now being found and investigated (e.g., Kalas et al. 2008; Marois et al. 2008; Janson et al. 2010; Bowler et al. 2010; Currie et al. 2010). Theoretical models of substellar atmospheres predict several interesting chemical transitions at these temperatures, including the emergence of NH$_3$ as a prominent absorber at near-infrared wavelengths; the condensation of H$_2$O and formation of thick ice clouds; and the condensation of alkali salts, depleting brown dwarf atmospheres of spectrally prominent K I and Na I gases (Lodders 1999; Lodders & Fegley 2002).
WISE Photometry

2.1. WISE Photometry

Candidate late-type T dwarfs were selected from the WISE coadd source working database, as described in detail in Mainzer et al. (2011) and J. D. Kirkpatrick et al. (in prep.). In brief, sources were selected to have $W1 - W2 \geq 2$, $W2 - W3 < 2.5$ (to exclude extragalactic sources; see Wright et al. 2010), a $W2$ signal-to-noise ratio $\geq 10$, and a point spread function consistent with an unresolved point source. These sources were then compared to optical and near-infrared imaging survey data from the Digitized Sky Survey (DSS), SDSS and 2MASS to exclude optical counterparts and other contaminants. The five new T dwarfs presented here represent only a subset of the full candidate pool currently under investigation. Their designations and measured photometry (excluding $W4$) are listed in Table 1. Figure 1 displays DSS, 2MASS and WISE images of the fields around each target.

2.2. Additional Survey Photometry and Astrometry

All of the WISE targets were cross-matched to the 2MASS, SDSS and USIDSS catalogs. One source, WISE J2359−7335, had a counterpart in the 2MASS Point Source and 6x catalog with a $J$ magnitude in the latter of 16.17±0.04. WISE J2018−7423 and WISE J2313−8037 had faint counterparts in the 2MASS Reject Catalog, with $J = 17.11\pm0.21$ and 16.97±0.24 mag, respectively (detection grades of "D" and "E"), located $\sim7''$ from their WISE positions. We confirmed these counterparts were associated using our J-band FIRE acquisition images (see Section 3.2.1). WISE J1617+1807 has a nearby counterpart in the SDSS Data Release 7 catalog located $\sim7''$ from its WISE position, but this match appears spurious based on the source’s blue optical colors ($i = 21.91\pm0.16$, $i - z < -0.6$). No common proper motion companions were found within 5'' of any of the WISE sources in SIMBAD or in the US Naval Observatory CCD Astrograph Catalog (UCAC3; Zacharias et al. 2010).

The roughly ten-year baseline between the 2MASS and WISE detections of WISE J2018−7423, WISE J2313−8037 and WISE J2359−7335 allows proper motion measurements for these sources. Astrometry from the two catalogs are listed in Table 2 and the computed proper motions incorporate uncertainties in the 2MASS and WISE positions but do not account for parallactic motion. We note that an error in the astrometric calibration pipeline of the WISE working database (now corrected) leads to an occasional large offset (of order 1'') in declination coordinate. As such, these proper motions should be considered preliminary until the WISE Final Release catalog astrometry is available. Nevertheless, the relatively large angular motions of these sources, as high as 0''91±0''03 yr$^{-1}$ for WISE J2018−7423, are typical for nearby field dwarfs.
WISE T Dwarfs

Fig. 1.—Finderchart images of the five WISE T dwarfs, showing 2′×2′ fields oriented with North up and East toward the left. DSS I, 2MASS JH and WISE W1W2W3 images are centered on the WISE coordinates for each source (red circle). The rightmost image shows a false color composite of the three WISE images, with blue, green and red represented by W1, W2 and W3, respectively.

TABLE 1
PHOTOMETRIC DATA FOR WISE BROWN DWARF DISCOVERIES

<table>
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<tr>
<td>WISEPC J161705.75+180714.0</td>
<td>18.71±0.04</td>
<td>17.66±0.08</td>
<td>18.23±0.08</td>
<td>...</td>
<td>16.89±0.16</td>
<td>14.03±0.06</td>
<td>12.48±0.48</td>
<td>4.20±0.10</td>
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<td>18.83±0.16</td>
<td>...</td>
<td>17.32±0.21</td>
<td>14.15±0.05</td>
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<td>&gt;16.6a</td>
<td>16.55±0.10</td>
<td>13.76±0.03</td>
<td>&gt;12.3</td>
<td>&gt;2.7</td>
<td>2.80 ± 0.05</td>
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<td>&gt;16.4a</td>
<td>16.29±0.07</td>
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<td>2.52 ± 0.06</td>
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<td>11.63±0.20</td>
<td>2.65±0.19</td>
<td>1.86 ± 0.07</td>
</tr>
</tbody>
</table>

a Photometry from the 2MASS Reject Table (WISE J2018−7423 and WISE J2313−8037) and 6x Catalogs (WISE J2359−7335; Skrutskie et al. 2006).

3.1.1. SOAR/SpartanIRC

JH-band photometry of WISE J1617+1807 were obtained on 2010 March 21 (UT) in clear conditions with the Spartan Infrared Camera (SpartanIRC; Loh et al. 2004) on the 4.1m SOAR telescope. The source was observed at an airmass of 1.53 with five 60-s exposures in each filter, dithered in 40′′ offsets. Imaging data were reduced using custom routines that perform flat-fielding and sky-subtraction, the latter from a sky frame created from a median stack of the dither image sequence. A 2′×2′ mosaic was created by stacking the reduced images to a common center and averaging. Aperture photometry was measured for all sources in the mosaic, and photometric calibration was done on the 2MASS system using three bright stars in the field-of-view, with a zero-point uncertainty estimated from the standard deviation of photometric offsets for these three stars. Measurements are listed in Table 1.

3.1.2. Fan Mountain/FanCam

Y-band photometry of WISE J1617+1807 was obtained on 2010 April 1 (UT) in photometric conditions with the FanCam near-infrared imager mounted on the 0.8 m Fan Mountain telescope (Kanneganti et al. 2009). Imaging data were obtained and reduced as described in...
Table 2

Proper Motions for WISE T Dwarfs Detected in 2MASS

<table>
<thead>
<tr>
<th>Source</th>
<th>Astrometry</th>
<th>WISE</th>
<th>∆t (yr)</th>
<th>µ α cos δ (mas yr⁻¹)</th>
<th>µ δ (mas yr⁻¹)</th>
<th>V_∞(y) (km s⁻¹)</th>
</tr>
</thead>
</table>

a Based on the spectrophotometric distance estimates listed in Table 5.

Mainzer et al. (2011), with 15 exposures of 60 s and 80 exposures of 30 s obtained in a 15′′ dither pattern, for a total exposure time of 55 minutes. Aperture photometry on the mosaiced frame was measured using standard IRAF routines, with an instrumental zeropoint derived by estimating Y-band magnitudes of neighboring stars from their 2MASS J and K_s photometry and the transformation of Hamuy et al. (2006). We found Y = 18.71±0.04 for WISE J1617+1807, implying Y − W2 = 4.68±0.07, about 0.7 mag bluer than WISE J0458+6434 (Mainzer et al. 2011).

3.1.3. Palomar/WIRC

JH-band photometry of WISE J1812+2721 were obtained on 2010 Aug 30 (UT) using the Wide-Field Infrared Camera (WIRC; Wilson et al. 2003) mounted on the 200-inch Hale Telescope at Palomar Observatory. WIRC has a pixel scale of 0.′′2487 pixel⁻¹ and a total field of view of 8.7′×8.7′. Conditions were clear during the observations, but with high humidity and poor seeing (~2.5′′ at J). For each filter, a series of 15 exposures of 60 s each were obtained, dithering by 50-100′′. Targets were observed over an airmass range of 1.09–1.13.

The imaging data were reduced using a suite of IRAF and FORTRAN programs provided by T. Jarrett. These routines first linearize and dark subtract the images, then create a sky frame and flat field images for each dither set which are subtracted from and divided into (respectively) each science image. At this stage, WIRC images still contain a significant bias that is not removed by the flat field. Comparison of 2MASS and WIRC photometric differences across the array shows that this flux bias has a level of ∼10% and the pattern is roughly the same for all filters. Using these 2MASS-WIRC differences for many fields, we created a flux bias correction image that was applied to each of the “reduced” images. Finally, we determined an astrometric calibration for the images using 2MASS stars in the field, and the images were mosaiced together. This final mosaic was photometrically calibrated using 2MASS stars, and magnitudes computed using aperture photometry. Measurements are listed in Table 1.

3.2. Spectroscopy

3.2.1. Magellan/LDSS-3

Optical spectroscopy of WISE J2359−7335 was obtained on 2005 December 2 (UT) in clear conditions using the Low Dispersion Survey Spectrograph (LDSS-3; Allington-Smith et al. 1999) mounted on the Magellan 6.5m Clay Telescope (see Table 3 for a complete observing log). Data were obtained using the VPH-red grism (660 lines/mm) and the 0′′75 (4-pixel) wide longslit, aligned along the parallactic angle, providing 6050–10500 Å spectroscopy with λ/Δλ ≈ 1800. The OG590 longpass filter was used to eliminate second order light shortward of 6000 Å. Two exposures of 1800 s each were obtained over an airmass range of 1.62–1.81. This was followed by observation of the nearby G2 V star HD 10991 (V = 9.38) for telluric absorption correction. HeNeAr arc lamp and flat-field quartz lamp exposures reflected off of the Clay secondary flat field screen were obtained for dispersion and pixel response calibration. The data were reduced using the IRAF onedspec package, as described in Burgasser et al. (2007).

Figure 2 displays a portion of the WISE J2359−7335 LDSS-3 spectra spanning 8000–10000 Å, compared to equivalent data15 for the T6 dwarf 2MASS J12255432−2739466 (hereafter 2MASS J1225−2739: Burgasser et al. 1999, 2003a). Both spectra are logarithmically scaled to highlight absorption features within their steep red optical slopes. Absorption from Cs I (8521 and 8943 Å) and H_2O (9250 Å bandhead) are visible. The pseudoequivalent widths of the Cs I lines were measured to be 4.9±2.1 Å and 8.9±2.5 Å, respectively, the latter consistent with measurements for mid-type T dwarfs (Burgasser et al. 2003a).

3.2.2. AAT/IRIS2

Near-infrared spectroscopy of WISE J2359−7335 was obtained on 2006 May 15 and 2006 June 11 (UT) with the Infrared Imager and Spectrograph (IRIS2; Hamuy et al. 2004) mounted on the 3.9m Anglo-Australian Telescope (AAT). Conditions on both nights were clear but humid with poor seeing (1′′5–2′′). Spectra in the J-band (1.47–1.81 μm) were obtained in May using the 1′′ wide slit, Sapphire-240 transmission grating and J_t filter, at an airmass of 1.49. Spectra in the H-band (1.47–1.81 μm) were obtained in both May and June using the 1′′ wide slit, SAPPHIRE-316 transmission grating and H_t filter, at airmasses of 1.60 and 1.52, respectively. Average resolution of these spectral modes is λ/Δλ = 2100. Individual exposures of 150 s were obtained in ABBA dither patterns nodding along the slit, for a total exposures of 600 s at J and 1200 s at H. The G0 V star HIP 118079 was observed on both nights immediately after the WISE target for telluric absorption and flux calibration. Exposures of Quartz halogen and Xe lamps reflected off of the AAT flat-field screen were also obtained at the beginning of these observations.

15 These data were obtained with the Low-Resolution Imaging Spectrometer (LRIS; Oke et al. 1993)
TABLE 3  
SPECTROSCOPIC OBSERVATIONS

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<thead>
<tr>
<th>Source</th>
<th>Instrument</th>
<th>UT Date</th>
<th>Integration (s)</th>
<th>Airmass</th>
<th>Calibrator Star</th>
<th>Conditions/Seeing</th>
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<tr>
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<td>Magellan/FIRE</td>
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<td>BD+29 3523</td>
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<td>Magellan/FIRE</td>
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<td>1045</td>
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<td>BD+30 3488</td>
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<td>Magellan/FIRE</td>
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<td>1.53-1.55</td>
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<td>clear, 0&quot;4</td>
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<td>1.61</td>
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<td>HD 10991</td>
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<td>Wolf 940B</td>
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<td>1045</td>
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<td>HD 208368</td>
<td>clear, 1&quot;5-2&quot;</td>
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</table>

* For $J$ and $H_s$ observations, respectively.

...of each night for pixel response correction and high-order dispersion calibration of the wavelength scale. The latter calibration was then updated using the telluric OH emission in the science frames. Data were reduced following the procedures described in Tinney et al. (2005).

Figure 3 displays the resulting spectra, smoothed to $\lambda/\Delta\lambda = 500$. The data have relatively low signal-to-noise ($\sim$5 at the 1.27 $\mu$m peak; $\sim$10 at the 1.58 $\mu$m peak), but are nevertheless sufficient to resolve the strong near-infrared H$_2$O and CH$_4$ bands characteristic of mid- to late-type T dwarf spectra.

3.2.3. Magellan/FIRE

Near-infrared spectroscopy of the WISE candidates and the T8.5 dwarf companion brown dwarf Wolf 940B (Burningham et al. 2009) was obtained on three separate runs during 2010 April 7, 2010 September 19-20, and 2010 December 24 (UT). All targets were observed with FIRE in its low-resolution, prism-dispersed mode, which delivers 0.85–2.45 $\mu$m continuous spectroscopy in a single order. Each source was initially acquired using FIRE’s $J$-band acquisition camera, then placed into a 0"6 slit aligned to the parallactic angle (rotator angle 89.5°). This prism/slit combination provides a variable resolution of $\lambda/\Delta\lambda = 250–350$ across the near-infrared band. A series of AB or ABBA dither exposure sequences were obtained with integrations ranging from 60 s to...
120 s per exposure (plus 10.6 s read time), the latter being the maximum permitted to avoid saturating OH telluric lines in the H-band. The spectrograph detector was read out using the 4-amplifier mode at “high gain” (1.2 counts/e−) with either Fowler-8 sampling (April and September) or Sample Up The Ramp (December) modes. Each science target observation was accompanied by an observation of a nearby A0 V calibrator star (typically with V = 10–12) at a similar airmass. Given FIRE’s high sensitivity, these calibrators were occasionally observed out of focus and/or offset from the slit to avoid saturation in FIRE’s minimum readout time (11.6 s). We also obtained exposures of a variable voltage quartz flat field lamp (set at 1.2 V and 2.2 V) and arc lamps (NeAr) reflected off of Baade’s secondary flat-field screen for pixel response and wavelength calibration. Data were measured out of focus and/or offset from the slit to avoid strong telluric absorption. Figure 5 displays the detector flux peak compared to the normalization at their respective flux peaks. Primary absorption bands from H2O and CH4 are indicated.

4. CHARACTERIZING THE T DWARFS

4.1. Spectral Classification

The T dwarfs were classified using their FIRE spectra following two methods. First, we compared the data to a suite of spectral templates drawn from the SpeX Prism Spectral Libraries, including the T dwarf standards defined in Burgasser et al. (2006b). The SpeX prism data have lower resolution than the FIRE data, λ/Δλ = 90–120; we therefore smoothed the latter to this resolution using a gaussian kernel. We quantified the agreement between normalized FIRE and template spectra using the χ² statistic, sampling over the wavelength regions 1.0–1.35 µm, 1.45–1.8 µm and 2.0–2.4 µm to avoid strong telluric absorption. Figure 3 displays the best-matching templates for each of the FIRE spectra. Note that the spectra of WISE J1812+2721 and (to a lesser extent) WISE J2313−8037 appear later than that of the T8 spectral standard 2MASS J04151954−0335066 (hereafter 2MASS J0415−0935; Burgasser et al. 2002) based on their narrower J-band flux peaks. We also computed the near-infrared classification indices H2O-J, CH4-J, H2O-H, CH4-H, CH4-K and W4 from the FIRE data using the definitions given in Burgasser et al. (2006b) and Warren et al. (2007), and the spectral type/index ranges defined in Burningham et al. (2010b) which extend to type T9. For completeness, we also measured the K/J index defined in Burgasser et al. (2006b) and the spectrophotometric J − K color on the MKC system following Cushing et al. (2005). We accounted for uncertainty in these measures through Monte Carlo simulation, sampling 1000 realizations of each spectrum varied pixel-

17 Interactive Data Language.
18 See http://www.browndwarfs.org/spexprism
19 Mauna Kea Observatory filter system; see Tokunaga et al. (2002) and Simons & Tokunaga (2002).
WISE T Dwarfs

by-pixel by random offsets drawn from a normal distribution scaled to the noise spectrum. The final index values, listed in Table 4, reflect the means and standard deviations of these measurements. The associated spectral types for each index, rounded off to the nearest half subtype, are also listed in Table 4. These types are generally in agreement with each other and with the template-comparison classification, although the noisier spectrum of WISE J1812+2721 results in greater scatter. The final classifications were taken as an average of the index and template classifications, accounting for limits in the index types. Classifications range from T5.5 for WISE J2359−7335 to T8.5: for WISE J1812+2721, where the colon indicates an uncertain classification due to noise. WISE J1617+1807, WISE J1812+2721 and WISE J2313−8037 are all classified as T8 and later.

4.2. Estimated Distances and Kinematics

To estimate the distances of these T dwarfs, we first derived a linear absolute $W_2$ magnitude/spectral type relation for T6–T8 dwarfs based on WISE photometry (Mainzer et al. 2011) and parallax measurements (Perryman et al. 1997; Tinney et al. 2003; Vrba et al. 2004) for the T6 dwarf SDSSp J162414.37+002915.6 (Strauss et al. 1999), the T7.5 dwarf Gliese 570D (Burgasser et al. 2000) and the T8 dwarf 2MASS J0415−0935. The inferred relation is

$$M_{W_2} = 11.33 + 0.268 \times SpT$$

(1)
Fig. 5.— Individual FIRE spectra of the WISE T dwarfs (black lines) compared to their best-fitting SpeX spectral templates (red lines): 2MASS J04151954−0935066 (T8; Burgasser et al. 2002, 2004), 2MASS J10475385+2124234 (T6.5; Burgasser et al. 1999, 2008) and 2MASS J05160945−0445499 (T5.5; Burgasser et al. 2003b, 2008). All spectra are normalized at the 1.3 µm flux peaks, and the FIRE data have been smoothed to match the resolution of the SpeX data (λ/Δλ ≈ 120) using a gaussian kernel.
<table>
<thead>
<tr>
<th>Index</th>
<th>WISE J1617+1807</th>
<th>WISE J1812+2721</th>
<th>WISE J2018-7423</th>
<th>WISE J2313-8037</th>
<th>WISE J2359-7335</th>
<th>Wolf 940B</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O-J</td>
<td>0.020±0.004 (≥T8)</td>
<td>0.04±0.05 (T7/≥T8)</td>
<td>0.086±0.006 (T7)</td>
<td>0.044±0.008 (≥T8)</td>
<td>0.206±0.008 (T5)</td>
<td>0.026±0.012 (T6)</td>
</tr>
<tr>
<td>CH₄-J</td>
<td>0.170±0.003 (≥T8)</td>
<td>0.12±0.03 (≥T8)</td>
<td>0.198±0.004 (≥T8)</td>
<td>0.116±0.004 (≥T8)</td>
<td>0.261±0.004 (T7)</td>
<td>0.100±0.013 (T5)</td>
</tr>
<tr>
<td>H₂O-H</td>
<td>0.159±0.007 (T8)</td>
<td>0.14±0.13 (T6/≥T9)</td>
<td>0.244±0.011 (T7)</td>
<td>0.174±0.012 (T8)</td>
<td>0.343±0.011 (T5)</td>
<td>0.13±0.04 (T8)</td>
</tr>
<tr>
<td>CH₄-H</td>
<td>0.108±0.006 (≥T8)</td>
<td>0.29±0.11 (T5/T7)</td>
<td>0.231±0.010 (T7)</td>
<td>0.142±0.011 (≥T8)</td>
<td>0.315±0.008 (T6)</td>
<td>0.08±0.04 (≥T8)</td>
</tr>
<tr>
<td>CH₄-K</td>
<td>0.033±0.016 (≥T7)</td>
<td>-0.03±0.23 (N/A)</td>
<td>0.17±0.04 (T5/≥T7)</td>
<td>0.14±0.03 (T6/≥T7)</td>
<td>0.145±0.007 (T6)</td>
<td>0.00±0.12 (N/A)</td>
</tr>
<tr>
<td>W₇</td>
<td>0.275±0.003 (T8/≥T9)</td>
<td>0.22±0.04 (≥T9)</td>
<td>0.420±0.005 (≥T6)</td>
<td>0.324±0.005 (T8)</td>
<td>0.549±0.005 (≤T6)</td>
<td>0.251±0.014 (T8)</td>
</tr>
<tr>
<td>K/J</td>
<td>0.156±0.002</td>
<td>0.14±0.03</td>
<td>0.097±0.003</td>
<td>0.196±0.004</td>
<td>0.158±0.002</td>
<td>0.135±0.000</td>
</tr>
<tr>
<td>J−Kₐ</td>
<td>-0.21±0.05</td>
<td>-0.5±0.8</td>
<td>-0.5±0.10</td>
<td>-0.12±0.07</td>
<td>-0.48±0.02</td>
<td>-0.7±0.4</td>
</tr>
<tr>
<td>Template Spt</td>
<td>T8</td>
<td>≥T8</td>
<td>T6.5</td>
<td>≥T8</td>
<td>T5.5</td>
<td>≥T8</td>
</tr>
<tr>
<td>Adopted SpT</td>
<td>T8</td>
<td>T8.5</td>
<td>T7</td>
<td>T8</td>
<td>T5.5</td>
<td>T8.5</td>
</tr>
</tbody>
</table>

**Note.** — Index spectral types based on the index ranges defined in [Burningham et al. (2010b)](https://doi.org/10.1088/0004-637X/715/2/1155), which incorporates the definitions set out by [Burgasser et al. (2006)](https://doi.org/10.1086/504419) for T0-T8 dwarfs and [Burningham et al. (2008)](https://doi.org/10.1086/527446) for the W₇ index for T9 dwarfs. The final type is an average of the index types and the template classification, accounting for upper/lower limits.

ₐ Spectrophotometric colors computed from the spectral data following [Cushing et al. (2005)](https://doi.org/10.1086/428215).
where SpT(T6) = 6, SpT(T8) = 8, etc. The scatter in the fit is formally 0.03 mag; however, due to the small number of calibrators used we assume a systematic uncertainty of 0.1 mag. Distances, taking into account uncertainties in the photometry, spectral classification (0.5-1.0 subtypes) and absolute magnitude relation are listed in Table 5. All of the WISE T dwarfs in this sample are roughly 12–13 pc from the Sun (modulo 1.5–3 pc uncertainties), assuming they are single.

For WISE J2018-7423, WISE J2313-8037 and WISE J2359-7335, we combined these distances with proper motion measurements to infer tangential velocities. We find $V_{tan}$ = 56±6 km s$^{-1}$, 31±5 km s$^{-1}$ and 20±3 km s$^{-1}$ for these sources, respectively. The motions of WISE J2313-8037 and WISE J2359-7335 are consistent with the mean kinematics of nearby field T dwarfs (30±20 km s$^{-1}$; Faherty et al. 2009, while WISE J2018-7423 is a $\sim$sigma outlier. This high velocity source is discussed in further detail in Section 6.3.

5. SPECTRAL MODEL FITS

To further characterize these brown dwarfs, we compared our FIRE spectra to both cloudy and cloud-free atmosphere models from Saumon & Marley (2008). We restricted our analysis to the near-infrared spectra alone; i.e., we did not include the WISE photometry. As such, this analysis should be regarded as a preliminary reconnaissance of the atmospheric and physical properties of these dwarfs. A more comprehensive modeling effort will be presented in a forthcoming paper (M. Cushing et al. 2011, in preparation).

We followed a fitting prescription similar to that described in Burgasser et al. (2010b), built upon contemporary work by Cushing et al. (2008) and Bowler et al. (2009). We used solar metallicity models with non-equilibrium chemistry (eddy diffusion parameter $\kappa_{zz} = 10^4$ cm s$^{-2}$, Griffith & Yelle 1994; Saumon et al. 2006; Hubeny & Burrows 2005), and considered both cloud-free and cloudy models, the latter with condensate sedimentation parameter $f_{sed} = 2$ (Ackerman & Marley 2001). Atmospheric parameters $T_{eff} = 500$–1000 K (50 K steps) and log $g$ = 4.0–5.5 cgs (0.5 dex steps) were sampled, with corresponding physical parameters (mass, age and radius) determined using the appropriate evolutionary tracks from Saumon & Marley (2008). The FIRE spectra were scaled to the apparent J-band magnitude of each source, and both models and data were smoothed to a common resolution of $\lambda/\Delta \lambda = 300$ and sampled at 4 pixels per resolution element to match FIRE’s projected slit width. Spectra were compared in the 1.0–1.35 $\mu$m, 1.45–1.8 $\mu$m and 1.95–2.3 $\mu$m regions, using the $\chi^2$ statistic to assess both the goodness-of-fit and the relative scaling factor $C \equiv (R/d)^2$, where $R$ is the radius of the brown dwarf and $d$ its distance from the Sun. We further constrained our fits by requiring that the model-inferred distance be within 3$\sigma$ of the estimated distance based on W2 photometry (Section 4.2). Note that this constraint is only weakly sensitive to unresolved multiplicity since both distances are based on photometric scaling. Means and uncertainties in the atmospheric parameters were determined using the F-distribution probability distribution function (F-PDF) as a weighting factor (Equations 1–4 in Burgasser et al. 2010b). Sampling uncertainties of 25 K and 0.25 dex were also imposed on the inferred $T_{eff}$ and log $g$ values, which were propagated into the estimated physical parameters.

Figures 6-11 show the best-fitting models for each of the WISE spectra and for Wolf 940B, as well as the F-PDF weighted distributions of $T_{eff}$, log $g$ and $f_{sed}$ parameters. Table 5 summarizes the inferred atmospheric and physical parameters. Overall, the models provide reasonable fits to the spectral data, with the exception of known discrepancies in the core of the 1.6–1.7 $\mu$m band, the strength of the 1.25 $\mu$m K I lines (for the warmer T dwarfs), and the detailed shape of the 1.05 $\mu$m Y-band peak. Fits to WISE J2359-7335 are particularly poor, likely due to the best fitting models residing at the end of our parameter range. For Wolf 940B, the best-fitting models poorly reproduce the brightness of the observed K-band peak. Examining the inferred parameters in detail, we find that $T_{eff}$ is track well with spectral type and are consistent with the spectral type/$T_{eff}$ scales of Golimowski et al. (2004); Stephens et al. (2009) and Marocco et al. (2010). This correlation may be an artifact of the imposed distance constraints, which are tied to the $M_{W2}$/spectral type relation defined above. However, our inferred parameters for Wolf 940B, which are constrained by the parallactic distance of the system (Harrington & Dahn 1980), are consistent with the broadband spectral fitting results of Leggett et al. (2010). We infer similar $T_{eff}$s for the WISE targets when the distance constraint is removed. Surprisingly, a range of cloud parameters are indicated, with both WISE J1617+1807 and WISE J2313–8037 exhibiting evidence for the presence of photospheric cloud opacity. We discuss some of these secondary parameters in further detail below.

6. DISCUSSION OF INDIVIDUAL SOURCES

6.1. The T8.5: Dwarf WISE J1812+2721

The latest-type source in this sample is WISE J1812+2721, tentatively classified T8.5: based on spectral comparison to 2MASS J0415-0935 in Figure 5 and spectral indices. It also has the reddest J-band peak. Examining the inferred parameters in detail, we find that $T_{eff}$ is track well with spectral type and are consistent with the spectral type/$T_{eff}$ scales of Golimowski et al. (2004); Stephens et al. (2009) and Marocco et al. (2010). This correlation may be an artifact of the imposed distance constraints, which are tied to the $M_{W2}$/spectral type relation defined above. However, our inferred parameters for Wolf 940B, which are constrained by the parallactic distance of the system (Harrington & Dahn 1980), are consistent with the broadband spectral fitting results of Leggett et al. (2010). We infer similar $T_{eff}$s for the WISE targets when the distance constraint is removed. Surprisingly, a range of cloud parameters are indicated, with both WISE J1617+1807 and WISE J2313–8037 exhibiting evidence for the presence of photospheric cloud opacity. We discuss some of these secondary parameters in further detail below.

6.2. WISE J1617+1807 and WISE J2313–8037: Young and Cloudy Field T Dwarfs?

WISE J1617+1807 and WISE J2313–8037 exhibit relatively red $J$ – $K$ spectrophotometric colors and large $K/J$ ratios for their spectral types, and our spectral model fits suggest cool ($T_{eff} = 600$ K), low surface gravity (log $g = 4.0$ cgs), and cloudy atmospheres. The inferred surface gravities are driven largely by the rela-
Fig. 6.—(Top panel) Best-fitting spectral model (red line) to FIRE data for WISE J1617+1807 (black line). Both spectra are smoothed to the average resolution of the FIRE prism mode ($\lambda/\Delta\lambda \approx 300$). The data are shown in $f_\nu$ units scaled to the apparent $J$-band magnitude of WISE J1617+1807, and the model scaled to minimize $\chi^2$ (the reduced $\chi^2$ is listed). Model parameters in the form $T_{\text{eff}}/\log g/f_{\text{sed}}/\log \kappa_{zz}$ are listed, with units as given in the text. We also list the inferred distance-to-radius ratio for this model based on the optimal scaling. Spectral regions over which the fits were made are indicated by the grey bars at top. (Bottom panels) From left to right, distributions of $T_{\text{eff}}$, $\log g$ and $f_{\text{sed}}$ based on an F-test PDF factor weighting of each model fit relative to the best-fitting model (see Burgasser et al. 2010b).

The presence of clouds has recently been suggested in similar model fits to the T8 dwarf Ross 458C, a widely-separated companion to a nearby M dwarf binary system which has an independent age constraint of 150–800 Myr (Burgasser et al. 2010b; Goldman et al. 2010; Scholz 2010a). The similarity in the inferred properties of Ross 458C, WISE J1617+1807 and WISE J2313−8037—low temperature, low surface gravity and cloudy atmospheres—appears indicative of a trend toward cloudier atmospheres in younger brown dwarfs. Indeed, such a trend has previously been
WISE J1812+2721

$650/4.5/NC/4$

$\chi^2_r = 0.06$

d/R = 19.3 pc/R_Jup

Fig. 7.— Same as Figure 6 for WISE J1812+2721.

TABLE 5
RESULTS FROM MODEL FITS TO T DWARF FIRE SPECTRA.

<table>
<thead>
<tr>
<th>Source</th>
<th>SpT</th>
<th>$T_{eff}$ (K)</th>
<th>$\log g$ (cm s$^{-2}$)</th>
<th>Cloudy?</th>
<th>Mass (M$_{Jup}$)</th>
<th>Age (Gyr)</th>
<th>Model Fit Distance (pc)</th>
<th>Photometric Distance (pc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WISE J1617+1807</td>
<td>T8</td>
<td>600$^{+30}_{-30}$</td>
<td>4.0$^{+0.3}_{-0.3}$</td>
<td>Yes</td>
<td>7±3</td>
<td>0.2±0.3</td>
<td>13.1±0.6</td>
<td>13.0±1.5</td>
</tr>
<tr>
<td>WISE J1812+2721</td>
<td>T8.5</td>
<td>620$^{+30}_{-30}$</td>
<td>4.3$^{+0.3}_{-0.3}$</td>
<td>No</td>
<td>13±7</td>
<td>0.9±1.3</td>
<td>19±3</td>
<td>13±3</td>
</tr>
<tr>
<td>WISE J2018-7423</td>
<td>T7</td>
<td>710$^{+50}_{-50}$</td>
<td>5.4$^{+0.3}_{-0.3}$</td>
<td>Yes?</td>
<td>50±9</td>
<td>10±4</td>
<td>12.2±2.3</td>
<td>13.1±1.4</td>
</tr>
<tr>
<td>WISE J2313-8037</td>
<td>T8</td>
<td>600$^{+30}_{-30}$</td>
<td>4.0$^{+0.3}_{-0.3}$</td>
<td>Yes</td>
<td>7±3</td>
<td>0.3±0.4</td>
<td>9.3±0.4</td>
<td>11.7±1.6</td>
</tr>
<tr>
<td>WISE J2359-7335</td>
<td>T5.5</td>
<td>930$^{+30}_{-30}$</td>
<td>5.1$^{+0.4}_{-0.4}$</td>
<td>No</td>
<td>38±18</td>
<td>4±4</td>
<td>17±3</td>
<td>12.5±1.7</td>
</tr>
<tr>
<td>Wolf 940B</td>
<td>T8.5</td>
<td>560$^{+30}_{-30}$</td>
<td>5.0$^{+0.3}_{-0.3}$</td>
<td>Yes?</td>
<td>30±10</td>
<td>7±4</td>
<td>11.5±1.6</td>
<td>12.5±0.7$^a$</td>
</tr>
</tbody>
</table>

$^a$ Parallax distance measurement for the Wolf 940A primary [Harrington & Dahn, 1980].
Fig. 8.— Same as Figure [for WISE J2018−7423.
proposed to explain the spectra of young L dwarfs (e.g., Metchev & Hillenbrand 2006; Stephens et al. 2009) and in contemporary studies of directly-detected exoplanets (e.g., Bowler et al. 2010b; Currie et al. 2011; Madhusudhan et al. 2011). While compelling, evidence for these trends are not yet conclusive. Our model fits for the WISE T dwarfs indicate relatively young ages (∼200–300 Myr) and low masses (∼7 M\textsubscript{Jup}), values that are somewhat suspect for a pair of isolated field objects (although we cannot rule out membership in a nearby young association such as AB Doradus or Tucana Horologium; Zuckerman et al. 2001, 2004). The fits are also constrained by fairly uncertain spectrophotometric distance estimates. Moreover, we have not considered metallicity variations in this study which are also known to modulate the $K$-band peaks of both L and T dwarf spectra (Burgasser et al. 2006a; Burgasser 2007; Liu et al. 2007; Looper et al. 2008). We therefore regard the increased role of clouds in shaping young T dwarf spectra as a suggestive trend, and defer further analysis to more comprehensive, broad-band spectral modeling (M. Cushing, in prep.).

6.3. WISEPC J201824.98–742326.1: An Old Blue T Dwarf?

WISE J2018–7423 exhibits an opposing spectral peculiarity: a suppressed $K$-band peak resulting in an unusually blue spectrophotometric near-infrared color ($J−K=−0.54±0.10$) and small $K/J$ index ($0.097±0.003$) for its spectral type. Previously identified blue T dwarfs, such as 2MASS J09373487+2931409 ($J−K=−1.10±0.07$; $K/J=0.08$; Burgasser et al. 2002; 2006a; Knapp et al. 2004) and SDSS J141624.08+134826.7B (hereafter SDSS J1416+1348B, $J−K=−1.58±0.17$; $K/J=0.037±0.004$; Burningham et al. 2010a; Burgasser et al. 2010a; Scholz 2010b), have similarly suppressed $K$-band peaks from strong collision-induced H\textsubscript{2} absorption, at-
Fig. 10.— Same as Figure 6 for WISE J2359–7335.

tributed to a high surface gravity and/or subsolar metallicity. Our spectral model fits support a high surface gravity for this source, indicating log $g \sim 5.4$ cgs, age $\tau \gtrsim 6$ Gyr and mass $M \sim 50$ $M_{\text{Jup}}$; the estimated $V_{\text{ion}} = 56 \pm 6$ km s$^{-1}$ of this object supports a relatively old age. However, our fits cannot test whether this source is metal-poor.

Fortunately, metallicity effects can be separately discerned in the 1.05 $\mu$m $Y$-band peak, which is broadened in both the theoretical and observed spectra of metal-poor T dwarfs (Burgasser et al. 2006a, 2010a). In Figure 13 we compare the spectrum of WISE J2018–7423 to those of two equivalently-classified T dwarf companions to stars with independent age and metallicity constraints: the young, metal-rich T6.5 G 204-39B (a.k.a. SDSS J175805.46+463311.9; Knapp et al. 2004; Faherty et al. 2010) and the old, metal-poor T7 SDSS J1416+1348B. G 204-39A is an M3 star which exhibits weak signatures of H$\alpha$ and X-ray activity consistent with $\tau = 0.5–1.5$ Gyr, and optical spectral indicators (i.e., ratio of TiO/CaH) suggesting a slightly supersolar metallicity. SDSS J1416+1348A is an unusually blue L dwarf, and spectral model fits to both primary and secondary indicate an older ($\tau > 3$ Gyr) and possibly metal-poor system (e.g., Bowler et al. 2010a; Burgasser et al. 2010a,b; Cushing et al. 2010. As Figure 13 shows, the spectra of all three sources are roughly equivalent in the 1.2–1.8 $\mu$m region, but vary in $K$-band peak brightness, with WISE J2018–7423 being the intermediate source. More importantly, WISE J2018–7423 does not have the broadened 1.05 $\mu$m peak seen in the spectrum of SDSS J1416+1348B. This comparison suggests that WISE J2018–7423 is a roughly solar-metallicity field brown dwarf that is both older and more massive than the average local population.

7. SUMMARY
We have identified five new late-type T dwarfs with WISE, confirmed through low-resolution, near-infrared spectroscopy with the Magellan FIRE spectrograph. The spectra indicate classifications ranging from T5.5 to T8.5, with the latest-type source, WISE J1812+2721, found to be an excellent match to the T8.5 companion brown dwarf Wolf 940B. Estimated distances are roughly 12–13 pc, assuming single sources. Preliminary spectral model fits indicate $T_{\text{eff}}$ as low as 600 K, with a broad range of surface gravities, masses, ages and cloud properties. In particular, WISE J1617+1807 and WISE J2313−8037 show indications of being young, low-mass and cloudy based on the relative strengths of their $JHK$ flux peaks, characteristics similar to the 150–800 Myr T8 companion Ross 458C; while the relatively blue and high proper motion T dwarf WISE J2018−7423 may be a solar-metallicity, older and more massive brown dwarf. Validation of the atmospheric and physical properties of these objects requires more comprehensive broad-band modeling with improved treatment of molecular opacities and the role of clouds. Nevertheless, it is clear from these early results that WISE will produce an extensive and diverse sample of cool brown dwarfs that can be used to improve our physical understanding of low-temperature, substellar atmospheres (J. D. Kirkpatrick et al. 2011, in preparation).

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Fig. 12.— Comparison of FIRE spectra for WISE J1812+2721 (black line) and Wolf 940B (red line), both smoothed to a resolution of $\lambda/\Delta\lambda = 150$ and normalized at 1.27 $\mu$m.

Fig. 13.— Comparison of the near-infrared spectra of WISE J2018−7423 (black line; FIRE data) and the T dwarf companions G 204-39B (red line; SpeX data from Burgasser et al. 2006a), and SDSS J1416+1348B (blue line; SpeX data from Burgasser et al. 2010b). All three spectra are normalized at their 1.27 $\mu$m spectral peaks.

REFERENCES


National Aeronautics and Space Administration. This publication also makes use of data products from NEOWISE, which is a project of the Jet Propulsion Laboratory/California Institute of Technology, funded by the Planetary Science Division of the National Aeronautics and Space Administration. This publication makes use of data from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center, and funded by the National Aeronautics and Space Administration and the National Science Foundation. 2MASS data were obtained from 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. The Digitized Sky Surveys were produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. The Second Palomar Observatory Sky Survey (POSS-II) was made by the California Institute of Technology with funds from the National Science Foundation, the National Geographic Society, the Sloan Foundation, the Samuel Oschin Foundation, and the Eastman Kodak Corporation. The Oschin Schmidt Telescope is operated by the California Institute of Technology and Palomar Observatory. This research has also made use of the SIMBAD database, operated at CDS, Strasbourg, France; the M, L, and T dwarf compendium housed at DwarfArchives.org and maintained by Chris Gellino, Davy Kirkpatrick, and Adam Burgasser; and the SpeX Prism Spectral Libraries, maintained by Adam Burgasser at http://www.browndwarfs.org/spexprism.

Facilities: Anglo-Australian Telescope (IRIS2), Fan Mountain (FANCAM), Magellan: Baade (FIRE), Magellan: Clay (LDSS-3), Palomar: Hale (WIRC), SOAR (SpartanIRC)
WISE T Dwarfs


