PARALLAXES AND PROPER MOTIONS OF ULTRACOOL BROWN DWARFS OF SPECTRAL TYPES Y AND LATE T

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ABSTRACT

We present astrometric measurements of 11 nearby ultracool brown dwarfs of spectral types Y and late-T, based on imaging observations from a variety of space-based and ground-based telescopes. These measurements have been used to estimate relative parallaxes and proper motions via maximum likelihood fitting of geometric model curves. To compensate for the modest statistical significance (\(\lesssim 7\)) of our parallax measurements we have employed a novel Bayesian procedure for distance estimation which makes use of an a priori distribution of tangential velocities, \(V_{\text{tan}}\), assumed similar to that implied by previous observations of T dwarfs. Our estimated distances are therefore somewhat dependent on that assumption. Nevertheless, the results have yielded distances for five of our eight Y dwarfs and all three T dwarfs. Estimated distances in all cases are \(\gtrsim 3\) pc. In addition, we have obtained significant estimates of \(V_{\text{tan}}\) for two of the Y dwarfs; both are \(<100\) km s\(^{-1}\), consistent with membership in the thin disk population. Comparison of absolute magnitudes with model predictions as a function of color shows that the Y dwarfs are significantly redder in \(J - H\) than predicted by a cloud-free model.

Key words: astrometry – brown dwarfs – stars: low-mass

Online-only material: color figures

1. INTRODUCTION

Determining accurate distances to brown dwarfs is important for a number of reasons. First, distance is a vital quantity in establishing not only the space density of these objects, but also the luminosity function which can then be used to test models of star formation at the lowest masses. Second, distances allow the spectra of brown dwarfs to be placed on an absolute flux scale to provide more quantitative checks of test models of star formation at the lowest masses. Third, distances for the nearest objects allow us to directly visualize the relative neighborhood, allowing us to construct a more complete view of our own solar neighborhood, allowing us to directly visualize the relative importance of brown dwarfs in the Galactic context. Sometimes, distance determinations produce results wholly unanticipated. For example, the \(J\)-band overluminosity of the T4.5 dwarf 2MASS J05591914-1404488 (Figure 2 of Dahn et al. 2002) was unexpected despite its location near the \(J\)-band bump at the L/T transition (e.g., Looper et al. 2008), a feature thought to be associated with decreasing cloudiness (Marley et al. 2010). It has been suggested, however, that the overluminosity is due to the presence of an unresolved binary (Burgasser et al. 2002; Dupuy & Liu 2012). Similarly unexpected was the recent determination that young, field L dwarfs are often significantly underluminous for their spectral types at near-infrared magnitudes (Faherty et al. 2012).

Some of the earliest parallax determinations for brown dwarfs were by Dahn et al. (2002), Tinney et al. (2003), Vrba et al. (2004), once surveys such as the Two Micron All-Sky Survey (2MASS; Skrutskie et al. 2006), the Sloan Digital Sky Survey (SDSS; York et al. 2000), and the Deep Near-infrared Survey of the southern sky (Epchtein et al. 1997) began to identify L and T dwarfs in large numbers. More recently, parallax programs by groups such as Marocco et al. (2010) and Dupuy & Liu (2012) have pushed astrometry measurements to the latest T spectral subclasses. With the discovery of Y dwarfs from \textit{WISE} (Cushing et al. 2011; Kirkpatrick et al. 2012) we are now pushing these measurements to even colder temperatures (Beichman et al. 2012). In this paper, we present distance and/or proper motion measurements for an additional eight Y dwarfs, along with three nearby late-T dwarfs, and present the first tangential velocity measurements for Y dwarfs.

2. OBSERVATIONS

Our set of objects includes all known Y dwarfs for which we have imaging data at a sufficient number of epochs for parallax and proper motion estimation. The exception is \textit{WISE} 1828+2650, presented separately by Beichman et al. (2012). In addition, we have included three late T dwarfs from an investigation of the low-mass end of the substellar mass function within 8 pc of the Sun (Kirkpatrick et al. 2011). The complete sample is listed in the observing log shown in Table 1. Each of these objects has been observed at two or three epochs by the \textit{Wide-field Infrared Survey Explorer} (\textit{WISE}; Wright et al. 2010) and at least four more epochs of imaging observations by the IRAC instrument (Fazio et al. 2004) on the \textit{Spitzer Space Telescope} (\textit{Spitzer}; Werner et al. 2004), the WFC3 instrument (Straughn et al. 2011) of the \textit{Hubble Space Telescope} (\textit{HST}), and various ground-based observatories. The observatories and instruments used are listed in the footnote of Table 1, and further details are given by Kirkpatrick et al. (2011, 2012).

3. ASTROMETRY MEASUREMENT PROCEDURE

Astrometric information was extracted from the observed images at the various epochs using the standard maximum likelihood technique in which a point-spread function (PSF) is fit
### Table 1
Observing Log and Relative Astrometry Measurements

| Object               | Sp  | R.A. (nom) (°) | Decl. (nom) (°) | Instrument | Band | Date     | Elongation (°) | $\Delta \cos \delta$ (°) | $\Delta$ (°) |
|----------------------|-----|---------------|----------------|------------|------|----------|---------------|------------------------|-------------|
| WISE J035000.32−565830.2 | Y1  | 57.301375     | −56.975006     | WISE       | W2   | 2010 Jul 9 | −89.9         | −0.153 (0.232)         | −0.062 (0.208) |
|                     |     |               |                |            |      |          |               |                        |             |
| WISE J035934.06−540154.6 | Y0  | 59.892083     | −54.031703     | WISE       | W2   | 2010 Jan 13 | 93.4          | −0.203 (0.298)         | −0.200 (0.316) |
|                     |     |               |                |            |      |          |               |                        |             |
| WISEP J041022.71+150248.5 | Y0  | 62.594667     | 15.046819      | WISE       | W2   | 2010 Jul 18 | −89.2         | −0.273 (0.278)         | −0.867 (0.287) |
|                     |     |               |                |            |      |          |               |                        |             |
| WISE J173835.53+273259.0 | Y0  | 235.465250    | −22.840358     | FIRE       | 2    | 2010 Aug 29 | 89.2          | 0.945 (0.168)          | −1.083 (0.193) |
|                     |     |               |                |            |      |          |               |                        |             |
| WISE J053516.80−750024.9 | Y0  | 83.820042     | −75.007019     | WISE       | W2   | 2010 Mar 31 | −89.5         | −0.361 (0.284)         | 0.458 (0.317)  |
|                     |     |               |                |            |      |          |               |                        |             |
| WISEPC J140518.40+553421.5 | Y0p?| 211.326667    | 55.572628      | WISE       | W2   | 2010 May 13 | 90.8          | 0.206 (0.532)          | −0.209 (0.708) |
|                     |     |               |                |            |      |          |               |                        |             |
| WISE J154151.65−225024.9 | Y0.5| 235.465250    | −22.840358     | FIRE       | 2    | 2010 Aug 29 | 89.2          | 0.945 (0.168)          | −1.083 (0.193) |
|                     |     |               |                |            |      |          |               |                        |             |
| WISE J173835.53+273259.0 | Y0  | 264.648083    | 27.549758      | MIRI       | 2    | 2010 Jun 14 | 106.9         | −0.154 (0.271)         | 0.046 (0.266)  |
|                     |     |               |                |            |      |          |               |                        |             |
| WISE J205628.90+145953.3 | Y0  | 314.120417    | 14.998147      | WISE       | W2   | 2010 May 31 | −90.6         | 0.027 (0.172)          | 0.042 (0.167)  |
|                     |     |               |                |            |      |          |               |                        |             |
| WISEPA J025409.45+022359.1 | T8  | 43.539375     | 2.399750       | WISE       | W2   | 2010 Jul 18 | 94.9          | 0.052 (0.085)          | −0.745 (0.119) |
|                     |     |               |                |            |      |          |               |                        |             |
| WISE J035000.32−565830.2 | Y1  | 57.301375     | −56.975006     | WISE       | W2   | 2010 Jul 9 | −89.9         | −0.153 (0.232)         | −0.062 (0.208) |
|                     |     |               |                |            |      |          |               |                        |             |
| WISE J035934.06−540154.6 | Y0  | 59.892083     | −54.031703     | WISE       | W2   | 2010 Jan 13 | 93.4          | −0.203 (0.298)         | −0.200 (0.316) |
|                     |     |               |                |            |      |          |               |                        |             |
| WISE J173835.53+273259.0 | Y0  | 235.465250    | −22.840358     | FIRE       | 2    | 2010 Aug 29 | 89.2          | 0.945 (0.168)          | −1.083 (0.193) |
|                     |     |               |                |            |      |          |               |                        |             |
| WISE J154151.65−225024.9 | Y0.5| 235.465250    | −22.840358     | FIRE       | 2    | 2010 Aug 29 | 89.2          | 0.945 (0.168)          | −1.083 (0.193) |
|                     |     |               |                |            |      |          |               |                        |             |
| WISE J173835.53+273259.0 | Y0  | 264.648083    | 27.549758      | MIRI       | 2    | 2010 Jun 14 | 106.9         | −0.154 (0.271)         | 0.046 (0.266)  |
|                     |     |               |                |            |      |          |               |                        |             |
| WISE J205628.90+145953.3 | Y0  | 314.120417    | 14.998147      | WISE       | W2   | 2010 May 31 | −90.6         | 0.027 (0.172)          | 0.042 (0.167)  |
|                     |     |               |                |            |      |          |               |                        |             |
the latter. In order to incorporate the reference stars (or set of reference stars) in the vicinity of the object. For most objects is based on relative positions using a reference star (or set of distortion and plate scale and rotation errors, our astrometry number for which was 14. Since the co-added images were presented here were made using co-added images rather than by Cutri et al. (2003), except that the source extraction results from the more sensitive images with close reference stars, we used a hybrid scheme in which the bright stars were treated as secondary references, bootstrapped to the close reference stars using the images in which they were in common.

The procedure is based on the following measurement model for the observed separation between the brown dwarf and reference star:

\[
\alpha_t - \alpha_t^{\text{ref}} = \alpha_t^{\text{BD}} - \left( \alpha_t^{\text{cat}} + \Delta \alpha_t^{\text{cat}} \right) + \nu_t - \nu_t^{\text{ref}} \tag{1}
\]

\[
\delta_t - \delta_t^{\text{ref}} = \delta_t^{\text{BD}} - \left( \delta_t^{\text{cat}} + \Delta \delta_t^{\text{cat}} \right) + \nu_t' - \nu_t^{\text{ref}}, \tag{2}
\]

where \(\alpha_t, \delta_t\) and \(\alpha_t^{\text{ref}}, \delta_t^{\text{ref}}\) represent the extracted positions of the brown dwarf and ith reference star, respectively, estimated from the image at epoch \(t\) based on the nominal position calibration of that image; \(\alpha_t^{\text{cat}}, \delta_t^{\text{cat}}\) represent the catalog position of the reference star, and \(\Delta \alpha_t^{\text{cat}}, \Delta \delta_t^{\text{cat}}\) represent errors in the catalog position; \(\nu_t, \nu_t'\) represent the estimation errors for the brown dwarf, and \(\nu_t^{\text{ref}}, \nu_t'^{\text{ref}}\) represent the estimation errors for the reference star. These estimation errors include the effects of random measurement noise on the source extraction as well as the residual effects of focal-plane distortion in the position differences. We assume that they can all be described by zero-mean Gaussian random processes.

If we further assume that the \(\Delta \alpha_t^{\text{cat}}, \Delta \delta_t^{\text{cat}}\) are described a priori by zero-mean Gaussian random processes with standard deviations substantially larger than the extraction uncertainties of the reference stars, then an optimal estimate of the brown

| Object          | Sp  | R.A. (nom) (°) | Decl. (nom) (°) | Instrument | Band | Date     | Elongation (°) | \(\Delta \cos \delta\) (°) | \(\Delta \delta\) (°) |
|-----------------|-----|---------------|----------------|------------|------|----------|----------------|--------------------------|------------------|
| WISEPA J174124.26+255319.5 T9 | 265.351083 | 25.888750 | T6 | 226.708208 | 70.460000 | 2010 Aug 29 | −113.7 | 1.839 (0.144) | −0.514 (0.181) |
| WISEPC J150649.97+702736.0 | 2010 Sep 17 | −132.2 | 2.164 (0.110) | −0.536 (0.064) |
| WISE | 2011 Jan 27 | 95.1 | 2.349 (0.193) | −0.306 (0.231) |
| WISE | 2011 Mar 2 | 60.8 | 2.868 (0.068) | −0.411 (0.126) |
| WISE | 2012 Mar 7 | 55.0 | 5.504 (0.049) | −0.162 (0.067) |
| WISE | 2010 May 20 | 9.0 | −0.476 (0.082) | 0.086 (0.059) |
| WISE | 2010 Nov 18 | −89.0 | −0.488 (0.119) | 0.069 (0.220) |
| WISE | 2010 Dec 22 | −123.5 | −0.573 (0.069) | −0.005 (0.065) |
| WISE | 2011 Apr 23 | 114.0 | −0.707 (0.077) | 0.990 (0.136) |
| WISE | 2012 Jan 23 | −155.8 | −2.192 (0.307) | 1.377 (0.292) |
| WISE | 2012 May 25 | 82.4 | −2.278 (0.148) | 2.130 (0.115) |
| WISEPA J174124.26+255319.5 T9 | 2000 Apr 11 | −117.8 | −0.069 (0.138) | 0.188 (0.104) |
| 2MASS | 2004 Sep 16 | 90.1 | 2.320 (0.087) | 8.248 (0.104) |
| WISE | 2010 Mar 15 | −90.7 | 0.114 (0.261) | 0.125 (0.099) |
| PAIRITEL | 2010 Apr 9 | −115.4 | −0.194 (0.082) | 0.109 (0.109) |
| FanMt | 2010 Apr 10 | −116.4 | −0.136 (0.038) | 0.231 (0.058) |
| FanMt | 2010 Apr 10 | −116.4 | −0.103 (0.100) | 0.240 (0.064) |
| WISE | 2010 Sep 18 | 96.4 | −0.582 (0.132) | −0.596 (0.184) |
| Spitzer | 2010 Sep 18 | 88.6 | −0.679 (0.143) | −0.334 (0.179) |
| Spitzer | 2011 May 20 | −155.1 | −0.463 (0.184) | −1.317 (0.200) |
| Spitzer | 2011 Nov 20 | 26.3 | −1.265 (0.052) | −2.312 (0.059) |
| Spitzer | 2012 May 8 | −144.2 | −1.132 (0.088) | −2.977 (0.073) |
dwarf position can be obtained from

\[ \delta_{i}^{\text{BD}} = \delta_i + \frac{1}{N_i} \sum_{i \in \mathcal{E}(i)} \left( \alpha_{i}^{\text{cat}} - \alpha_{i}^{\text{ref}} \right), \]

(4)

where \( \mathcal{R}(t) \) is the set of detected reference stars in the image at epoch \( t \), and \( N_i \) is the number of stars in the set.

The resulting estimates are included in Table 1 in the form of offsets from the nominal position of the brown dwarf at each epoch, and the set of reference stars used is given in Table 2. After having obtained \( \delta_{i}^{\text{BD}} \) and \( \delta_{i}^{\text{BD}} \), the individual reference star catalog errors can then be estimated using

\[ \Delta \alpha_{i}^{\text{cat}} = -\Delta \alpha_{i}^{\text{cat}} + \frac{1}{N_i} \sum_{i \in \mathcal{E}(i)} \left( \alpha_{i}^{\text{BD}} + \alpha_{i}^{\text{ref}} - \alpha_{i} \right), \]

(5)

\[ \Delta \delta_{i}^{\text{cat}} = -\Delta \delta_{i}^{\text{cat}} + \frac{1}{N_i} \sum_{i \in \mathcal{E}(i)} \left( \delta_{i}^{\text{BD}} + \delta_{i}^{\text{ref}} - \delta_{i} \right), \]

(6)

where \( \mathcal{E}(i) \) is the set of all epochs for which the \( i \)th reference star is detected in the corresponding image, and \( N_i \) is the number of epochs in the set.

These values can be applied as corrections to the catalog positions of the reference stars, enabling a corresponding time series of estimated brown dwarf positions to be obtained separately for each individual reference star via Equations (1) and (2). The scatter in these estimates then provides a check on the assumptions regarding systematic effects such as focal-plane distortion and possible small proper motions of the reference stars themselves. We have included the effect of this scatter in the final quoted error bars in Table 1.

4. ESTIMATION OF PARALLAX AND PROPER MOTION

The measurement model incorporated the effects of parallax and linear proper motion, with appropriate correction for the Earth-trailing orbit in the case of Spitzer observations. The equations used (Kirkpatrick et al. 2011) were as follows:

\[ \cos \delta_1 (\alpha_1 - \alpha_1) = \Delta \alpha + \mu_\alpha (t_i - t_1) + \pi_{\text{trig}} R_i \cdot \hat{W} \]

(7)

\[ \delta_i - \delta_1 = \Delta \delta + \mu_\delta (t_i - t_1) - \pi_{\text{trig}} R_i \cdot \hat{N}, \]

(8)

where \( t_i \) is the observation time [yr] of the \( i \)th astrometric measurement, and \( R_i \) is the vector position of the observer relative to the Sun in celestial coordinates and astronomical units. \( \hat{N} \) and \( \hat{W} \) are unit vectors pointing north and west from the position of the source. \( R_i \) is the position of the Earth for 2MASS, SDSS, WISE, and HST observations; for Spitzer observations, \( R_i \) is the position of the spacecraft. The observed positional difference on the left-hand side is in arcseconds, the parameters \( \Delta \alpha \) and \( \Delta \delta \) are in arcseconds, the proper motion \( \mu_\alpha \) and \( \mu_\delta \) are in arcseconds yr\(^{-1}\), and the parallax \( \pi_{\text{trig}} \) is in arcseconds.

Maximum likelihood estimates, based on the assumption of Gaussian measurement noise, were made of five parameters: the R.A. and decl. position offsets of the source at a specified reference time, the R.A. and decl. rates of proper motion, and the parallax. The uncertainties were derived using the standard procedure for maximum likelihood estimation (Whalen et al. 2010).

\[ \text{Table 2} \]

Reference Stars Used

| Object | Sp | R.A.(ref) | Decl.(ref) | Separation | Comment |
|--------|----|-----------|------------|------------|---------|
| WISE 0350–5658 Y1 | 57.505458 | −56.976833 | 10.4 | 2MASS |
| WISE 0359–5401 Y0 | 59.895458 | −54.033444 | 9.5 | 2MASS |
| WISE 0410+1502 Y0 | 62.600125 | 15.050856 | 44.7 | 2MASS |
| WISE 0535–7500 Y0 | 83.824208 | −75.002278 | 9.0 | 2MASS |
| WISE 1405+5534 Y0p | 211.327083 | 55.574778 | 7.8 | 2MASS |
| WISE 1541–2250 Y0.5 | 235.464417 | −22.836833 | 13.0 | 2MASS |
| WISE 1738+2732 Y0 | 264.643542 | 27.547750 | 16.2 | 2MASS |
| WISE 2056+1459 Y0 | 314.117042 | 15.000111 | 13.7 | 2MASS |
| WISE 2056+1459 Y0 | 314.118667 | 15.002556 | 17.0 | 2MASS |
| WISE 2056+1459 Y0 | 314.104174 | 15.007694 | 34.3 | 2MASS |
| WISE 2056+1459 Y0 | 314.106625 | 14.999250 | 48.1 | 2MASS |
| WISE 0254+0223 T8 | 43.540792 | 2.142833 | 47.3 | 2MASS |
| WISE 0506+7027 T6 | 226.736757 | 70.461806 | 34.5 | 2MASS |
| WISE 1741+2553 T9 | 265.355375 | 25.896583 | 31.4 | 2MASS |
| WISE 1741+2553 T9 | 265.341375 | 25.893556 | 35.9 | 2MASS |
| WISE 1741+2553 T9 | 265.332083 | 25.886311 | 64.2 | 2MASS |
| WISE 1741+2553 T9 | 265.346958 | 25.869194 | 71.7 | 2MASS |
| WISE 1741+2553 T9 | 265.339750 | 25.905861 | 71.7 | 2MASS |

Note. Columns represent the object name, spectral type, the R.A. and decl. values of the associated reference stars, their separations from the object, and a comment column indicating which of the reference stars are in the Two Micron All-Sky Survey (2MASS) point-source catalog.
Figure 1. Proper motion and parallax fits to astrometry measurements of four of the Y dwarfs. Blue symbols represent observations from the ground and Low Earth Orbit (LEO), and red symbols represent *Spitzer* observations. The blue and red curves represent the corresponding model fits, respectively. The origins for the position offsets on the vertical (motion) axes have been adjusted with respect to the values in Table 1; the Δδ and Δα cos δ values are relative to a constant position fit, so they are relative to the weighted mean of the α and δ. In addition, the Δ values are offset for clarity by different amounts for the different plots.

(A color version of this figure is available in the online journal.)

| Table 3 | Parallax and Proper Motion Estimates |
|---------|-------------------------------------|
| Object  | Sp  | χ² | N_{df} | μ_α cos δ (″ yr⁻¹) | μ_δ (″ yr⁻¹) | π (″) | Significance (sigmas) | d (pc) | V_{tan} (km s⁻¹) |
| WISE 0350−5658 | Y1  | 14.22 | 11  | −0.125 ± 0.097 | −0.865 ± 0.076 | 0.291 ± 0.050 | 5.8 | 3.7_{-0.4}^{+0.6} | 18 ± 4 |
| WISE 0359−5405 | Y0  | 13.02 | 15  | −0.177 ± 0.053 | −0.930 ± 0.062 | 0.145 ± 0.039 | 3.7 | 5.9_{-0.8}^{+1.3} | 58 ± 10 |
| WISE 0410+1502 | Y0  | 11.53 | 9   | 0.974 ± 0.079 | −2.144 ± 0.072 | 0.233 ± 0.056 | 4.2 | 4.2_{-0.6}^{+1.2} | 50 ± 10 |
| WISE 0535−7500 | ≥Y1 | 11.80 | 7   | −0.310 ± 0.128 | 0.159 ± 0.092 | 0.250 ± 0.079 | 3.2 | 21_{-11}^{+13} |  |
| WISE 1405+5534 | Y0? | 9.16  | 9   | −2.297 ± 0.096 | 0.212 ± 0.137 | 0.133 ± 0.081 | 1.6 | 3.4 |  |
| WISE 1541−2250 | Y0.5 | 15.21 | 9   | −0.983 ± 0.111 | −0.276 ± 0.116 | −0.021 ± 0.094 | <1 | <6.0 |  |
| WISE 1738+2732 | Y0  | 15.22 | 13  | 0.348 ± 0.071 | −0.354 ± 0.055 | 0.066 ± 0.050 | 1.3 | >6.0 |  |
| WISE 2056+1459 | Y0  | 6.64  | 11  | 0.881 ± 0.057 | 0.544 ± 0.042 | 0.144 ± 0.044 | 3.3 | 7.5_{-1.8}^{+1.3} |  |
| WISE 0254+0223 | T8  | 5.67  | 11  | 2.578 ± 0.042 | 0.309 ± 0.050 | 0.185 ± 0.043 | 4.4 | 4.9_{-0.6}^{+1.0} | 62 ± 10 |
| WISE 1506+7027 | T6  | 17.44 | 11  | −1.241 ± 0.085 | 1.046 ± 0.064 | 0.310 ± 0.042 | 7.4 | 3.4_{-0.4}^{+0.7} | 27 ± 4 |
| WISE 1741+2553 | T9  | 9.90  | 19  | −0.495 ± 0.011 | −1.472 ± 0.013 | 0.176 ± 0.026 | 6.8 | 5.8_{-0.6}^{+1.1} | 45 ± 6 |

Notes. Columns represent the object name, spectral type, χ² of the parallax/proper motion fit to the estimated positions, number of digits of freedom, proper motion in R.A. and decl., the maximum likelihood estimate of parallax and its statistical significance, most probable distance (corrected for Lutz–Kelker bias), and the tangential velocity. Distance lower limits are based on a 2σ criterion. Tangential velocities are quoted only for cases with parallax significance >4, otherwise the V_{tan} estimate becomes strongly biased toward the assumed a priori mean value of 30 km s⁻¹.

The parallaxes that we present are, strictly speaking, relative parallaxes since no correction has been made for the small parallaxes and proper motions of the reference stars, most of which are relatively nearby. However, the expected correction for such effects is only ~2 mas (Dupon & Liu 2012) which is at least an order of magnitude smaller than our typical astrometric uncertainties listed in Table 3, so in this error regime the distinction between relative and absolute parallaxes is unimportant.

1971) using the positional uncertainties quoted in Table 3. The resulting estimates of proper motion and parallax and their associated uncertainties are given in Table 3, and the model fits with respect to the astrometry measurements are presented in Figures 1–3. The chi-squared values, χ², for the parameter fits in Table 3 are, for the most part, close to the number of degrees of freedom, N_{df}, indicating reasonably good modeling of position uncertainties. Formally, the probability of exceeding χ² given N_{df} has a median value 0.29.
In order to check to what extent our parallax and proper motion estimates may have been affected by systematic effects of focal-plane distortion not properly modeled by the statistical assumptions of the previous section, we have compared the rms residuals of the above fits (obtained using multiple reference stars) with those obtained using a single reference star for each brown dwarf, and found that there was no significant difference. This suggests that whatever residual focal-plane distortion errors exist, they are smaller than the random errors of source extraction.

We have converted our maximum likelihood estimates of parallax into most probable estimates of distance taking into account both the parallax measurements themselves and prior information. The latter includes an assumption that our objects are spatially distributed in a statistically uniform manner.

\[ P(\pi) \propto \pi^{-4}; \text{the singularity at zero would then lead to difficulties in estimating the a posteriori most probable } \pi. \]

Even though the zero parallax can be excluded on physical grounds, there is still a bias toward small values such that for \( S/N < 4 \), maximum likelihood parallax estimates become insignificant (Lutz & Kelker 1973). Fortunately there is additional prior information to alleviate this problem; small parallaxes (i.e., large distances) can be excluded if they are inconsistent with the observed proper motion based on an assumed velocity dispersion of the objects being studied (Thorstensen 2003).

With these considerations in mind, our estimates of distance, \( d \), are based on the following assumptions:

1. Our maximum likelihood parallax values, \( \pi_{\text{ML}} \), are distributed as Gaussians with standard deviation \( \sigma_\pi \).
2. Our objects are distributed spatially in a statistically uniform way, so that the a priori probability density distribution of \( d \) is proportional to \( d^2 \).
3. The distribution of tangential velocities of Y dwarfs in the solar neighborhood can be described by a Gaussian random process with mean and standard deviation \( \bar{V} \) and \( \sigma_V \), respectively; we assume the values \( \bar{V} = 30 \text{ km s}^{-1} \) and \( \sigma_V = 20 \text{ km s}^{-1} \) respectively, representative of previous observations of T dwarfs (Faherty et al. 2009).

We then obtain the most probable distance, \( \hat{d} \), by maximizing the conditional probability density \( P(d|\pi_{\text{ML}}, \mu_{\text{ML}}) \), which from Bayes’ rule can be expressed by

\[
P(d|\pi_{\text{ML}}, \mu_{\text{ML}}) \propto d^2 \exp \left( - \frac{1}{2} \left( \frac{\mu_{\text{ML}} - \frac{\bar{V}}{d}}{\sigma_V^2} \right)^2 \right) \times \exp \left( - \frac{1}{2} \left( \frac{\pi_{\text{ML}} - \frac{1}{d}}{\sigma_\pi^2} \right)^2 \right),
\]

where \( \mu_{\text{ML}} \) represents the magnitude of our maximum likelihood estimate of proper motion. Our distance estimates are presented in Column 9 of Table 3. The error bars correspond to the 0.159 and 0.841 points of the cumulative distribution with respect to \( P(d|\pi_{\text{ML}}, \mu_{\text{ML}}) \).

5. DISCUSSION

As is evident from Table 1, our observations represent a mixed bag in terms of telescopes (and hence spatial resolution) and time sampling since they were not specifically designed for astrometry, but rather for follow-up photometry of brown dwarfs detected by WISE. The quality of the observations was quite varied, and not always with sufficient pixel subsampling for the estimation of the high-quality PSFs necessary for astrometry. In the case of Spitzer, for example, each observation consisted of a set of only five dithered images.
and this is achieved by WISE, albeit with large position errors (typically ~0.1–0.3). These elongation angles are critical for an object on the ecliptic and less important at high ecliptic latitudes. For the parallax measurements described here, the worst example of poor sampling was WISE 1541–2250 for which all of the non-WISE observations were in one quadrant of solar elongation angle (see Column 8 of Table 1), so it is not surprising that the observations did not yield a significant parallax measurement. The previous measurement, corresponding to an elongation angle of 3 pc, has enabled the estimation of absolute magnitudes. These indicate that luminosities plummet at the T/Y boundary (Kirkpatrick et al. 2012) as illustrated by Figures 4 and 5, which represent updated versions of the absolute magnitude versus spectral-type plots from the latter work. The steep decrease may at least partially account for the apparent scatter in absolute magnitudes of objects of the same spectral type, since in the Y0 regime an error of half a spectral type apparently corresponds to more than a magnitude difference in luminosity. More data will be required to make a definitive statement, however.

The absolute magnitudes also provide valuable guidance for models in the ultra-cool regime. To this end we have compared our observational results with model-based and empirical predictions using plots of absolute magnitude as a function of color, as shown in Figure 6. The $M_J$ versus $J−H$ plot in the upper panel shows that the Y dwarfs continue the trend set by the L and T dwarfs based on the parallax observations of Dupuy & Liu (2012). A key feature is the turnover in the blueward progression of the color at $M_J \sim 16$, at considerably redder $J−H$ than predicted by cloud-free models (Saumon & Marley 2008) as illustrated by the solid curve. Such behavior is also apparent in the color–magnitude diagrams for cloud-free models presented by Leggett et al. (2010). The dotted/dashed curves in Figure 6 represent models incorporating the effect of clouds containing various amounts of Cr, MnS, Na$_2$S, ZnS, and KCl condensates (Morley et al. 2012), as indicated by the sedimentation efficiency parameter, $f_{\text{sed}}$. Lower values correspond to optically thicker clouds. It is apparent that these models can account at least partly for the relative redness of some of the $J−H$ colors, but they predict a blueward hook for temperatures below
Figure 4. Absolute $H$ magnitude as a function of spectral type. This is a revised version of the corresponding figure in Kirkpatrick et al. (2012) and includes the objects from the present paper and the new parallax estimate for WISE 1828+2650 (Beichman et al. 2012). The blue curve represents the relation used by Kirkpatrick et al. (2012), which appears still to be an accurate representation of the absolute magnitude vs. spectral type trend despite the fact that our results have been revised since the Kirkpatrick et al. paper was published. (A color version of this figure is available in the online journal.)

Figure 5. Absolute $W_2$ magnitude as a function of spectral type. As with Figure 4 it is taken from Kirkpatrick et al. (2012) except for the inclusion of the objects from the present paper. It also includes WISE 1639−6847 (Tinney et al. 2012). (A color version of this figure is available in the online journal.)

Figure 6. Absolute magnitude as a function of color. Large filled circles with error bars represent the objects from this paper, plus WISE 1828+2650 (Beichman et al. 2012). Also included are the L and T dwarfs from Dupuy & Liu (2012), represented by open circles and small filled circles, respectively. For comparison, model curves are overplotted. The solid curve represents a cloud-free model from Saumon & Marley (2008), assuming $g = 1000$ m s$^{-2}$, $K(z) = 0$. The numbers along this line represent the assumed values of effective temperature [K]. Also plotted (dashed/dotted lines) are four cloudy models from Morley et al. (2012) with the same assumed $g$ and $K(z)$, and with various values of the sedimentation efficiency parameter $f_{sed}$, as indicated. 400 K, which does not appear to be matched by the observations. Perhaps some of the scatter in $J−H$ colors in Figure 6 might be explained in terms of a patchy cloud model; it is also possible that the inclusion of water clouds might improve consistency with the observations.

Figure 6 does show reasonable consistency between observations and models based on IRAC colors, i.e., $M_{[3.6]}$ and $M_{[4.5]}$ as a function of the $[3.6]−[4.5]$ color. The only major discrepancy is that WISE 1828+2650, whose effective temperature is believed to be $\sim 300$ K, falls at a location more indicative of 500 K on these plots.
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