Parallaxes of Five L Dwarfs with a Robotic Telescope

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ABSTRACT. We report the parallax and proper motion of five L dwarfs obtained with observations from the robotic Liverpool Telescope. Our derived proper motions are consistent with published values and have considerably smaller errors. Based on our spectral type versus absolute magnitude diagram, we do not find any evidence for binaries among our sample—or, at least no comparable mass binaries. Their space velocities locate them within the thin disk, and based on the model comparisons, they have solar-like abundances. For all five objects, we derived effective temperature, luminosity, radius, gravity, and mass from an evolutionary model (CBA00) and our measured parallax; moreover, we derived their effective temperature by integrating observed optical and near-infrared spectra and model spectra (BSH06 or BT-Dusty) at longer wavelengths to obtain bolometric flux using the classical Stefan-Boltzmann law. Generally, the three temperatures for one object derived using two different methods with three models are consistent, although at lower temperature (e.g., for L4) the differences among the three temperatures are slightly larger than those at higher temperature (e.g., for L1).

Online material: color figures

1. INTRODUCTION

L-type dwarfs are ultracool objects, cooler than M dwarfs. Most L dwarfs are expected to be brown dwarfs, i.e., have insufficient mass to achieve the central temperatures and pressures necessary for sustained hydrogen burning. Brown dwarfs have physical properties intermediate between the least massive stars and the most massive planets and are thus a useful bridge between studies of stars and planets (Burgasser 2011). However, the lack of a unique age-mass-spectral type relationship leads to distance being a critical parameter in understanding brown dwarfs. A distance is required to derive an absolute magnitude and, hence, energy output. Parallax is a model-independent parameter that can be used to constrain radius or temperature, thus allowing modeling to explore relations between other parameters, such as mass, surface gravity, age, and metallicity, more freely. Considering that distances are so valuable, it is a sign of the difficulty in obtaining them that, out of more than 900 known L dwarfs (www.dwarfarchives.org, hereafter, Dwarf-Archive), less than 90 have measured parallaxes and, when this program started, there were less than 20.

Here we discuss the determination of parallax and proper motion for five L dwarfs using the robotic Liverpool Telescope12 (hereafter, LT; Steele et al. 2004). In general, the observations required for parallax determinations are quite simple and routine. The important characteristics for observations in a parallax program are stability in the instrumental setup and repeatability in the observational procedure. The rigorous scheduling criteria, efficient use of time, flexibility in scheduling, and observational consistency in robotic observations make them very attractive for parallax programs. This program was envisioned to see if

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the LT could become an exemplary parallax machine for future parallaxes of bright brown dwarfs and nearby red dwarfs. The number of brown dwarfs is increasing with continued discoveries from wide-field Sky Survey programs, e.g., the Sloan Digital Sky Survey (SDSS; Chiu et al. 2006), the Visible and Infrared Survey Telescope for Astronomy (VISTA) Hemisphere Survey (VHS; Lodieu et al. 2012), the Canada-France Brown Dwarf Survey (CFBDS; Delorme et al. 2008), the United Kingdom Infrared Telescope (UKIRT) Infrared Deep Sky Survey (UKIDSS; Burningham et al. 2010), and the Wide-field Infrared Survey Explorer (WISE; Kirkpatrick et al. 2011) All-Sky Survey. Many of these are observable with the LT.

This paper is divided into seven sections. In § 2, we describe the observations and data reduction procedures. In § 3, we report the main astrometric results. In § 4, we study the binarity, Galactic membership, metallicity, and gravity properties using spectral type–absolute magnitude, $U$–$V$ velocity, and color–absolute magnitude with model tracks diagrams. In § 5, we present the bolometric flux, luminosity, and effective temperature of our targets obtained by combining our measured parallaxes with the optical/infrared spectra and evolutionary/atmospheric models. In § 6, we comment on individual objects, and, in § 7, we summarize our findings and briefly describe our future work plan.

2. OBSERVATIONS AND REDUCTION PROCEDURES

The LT is a totally robotic telescope located at the Observatorio del Roque de Los Muchachos on the Canary island of La Palma in Spain and operated by the Liverpool John Moores University in the United Kingdom. It is an Alt-Az telescope with Ritchey-Chretien Cassegrain optics with a primary mirror of 2.0 m. In 2004, when this parallax program started, there were two instruments that were suitable for a brown dwarf parallax program: SupIRCam and RATCam. SupIRCam is an infrared-sensitive 256 $\times$ 256 pixel HgCdTe array with a pixel scale of 0.413 $''$ pixel$^{-1}$ and a field of view of 1.7 $'$. RATCam is an optically sensitive 2048 $\times$ 2048 pixel CCD camera with a pixel scale of 0.1395 $''$ pixel$^{-1}$ and a field of view of 4.6 $'$. The SDSS z filter (hereafter simply z) corresponds to the brightest optical magnitude for L dwarfs. The larger field, smaller pixel scale, and similar required exposure times for typical L dwarfs of the RATCam instrument in the z-band filter, compared to the SupIRCam in the J filter, led to RATCam being the preferred choice for our program.

2.1. Targets

The target list was selected from the literature with the following criteria: visible to the LT, a z-band magnitude brighter than 18 mag, no published trigonometric parallax in 2004, and those objects with the smallest photometric distance were preferred. Here we report on the five that have enough observations spread over 2004/2005, 2008/2009, and 2011/2012 to provide reliable parallaxes. In Table 1, we list the five objects with their z and estimated $z$, Two Micron All Sky Survey (2MASS) $JHK$- (Skrutskie et al. 2006) and WISE $W1$- (Wright et al. 2010) band magnitudes, and optical and near-infrared spectral types.

2.2. Observational Procedure

The five targets were observed between 2004 August and 2012 July using RATCam with the z-band filter. In order to minimize the effect of differential color refraction, we observe when the targets are within 30 minutes of the meridian. The observations were primarily made during twilight hours, since this is when the objects have maximum parallax factors in right ascension. Observed this way, the data are primarily located on the ends of the major semiaxis of their parallax ellipse. During each observation we take three exposures of 160 s to allow for robust removal of cosmic rays and to diminish the random errors. One exposure of this length nominally provides a signal-to-noise ratio of more than 50 on these targets.

Differential color refraction (DCR; Monet et al. 1992; Stone 2002) is the small varying displacement of objects with different colors in a field that results from the variation of the atmosphere’s refractive index with wavelength. It is strongest in the blue bands and gradually gets very small in the infrared. The targets in this parallax program are redder than the anonymous reference objects, so this displacement is systematically different from the average of those reference objects. We request that all our observations are made within 30 minutes of the meridian so the variation in air mass, and hence

| Short Name | Discovery Name | $z_{\text{SDSS}}$ | $z_{\text{eq}}$ | $J_{\text{MASS}}$ | $H_{\text{MASS}}$ | $K_{\text{MASS}}$ | $W1$ | $S_p T_{\text{opt}}$ References | $S_p S_{\text{TNIR}}$ References |
|------------|----------------|-----------------|----------------|-----------------|-----------------|-----------------|------|----------------------|----------------------|
| 2M0141+1804 | 2MASSW J0141032+180450 | 16.34 | 16.34 | 13.88 | 13.03 | 12.49 | 12.16 | L1 | (1) | L4.5 (4) |
| 2M1717+6526 | SDSS J171714.10+652622.2 | 17.79 | 17.67 | 14.95 | 13.84 | 13.18 | 12.53 | L4 | (2) | — |
| 2M1807+5015 | 2MASSI J1807159+501531 | — | 15.43 | 12.93 | 12.13 | 11.60 | 11.25 | L1.5 | (3) | L1 (4) |
| 2M2238+4353 | 2MASSI J2238074+435317 | — | 16.42 | 13.84 | 13.05 | 12.52 | 12.20 | L1.5 | (3) | — |
| 2M2242+2542 | 2MASS W22425317+2542573 | 17.49 | 17.42 | 14.81 | 13.74 | 13.05 | 12.51 | L3 | (1) | L (4) |

REFERENCES.—(1) Cruz et al. 2007; (2) Hawley et al. 2002; (3) Cruz et al. 2003; (4) Wilson et al. 2003; (5) Zhang et al. 2010.
differential movement, is minimized. In the Torino Observatory Parallax Program (hereafter, TOPP; Smart et al. 1999), we found the effect was very small in the I band, and it will be smaller for the z band, though L dwarfs are redder than the TOPP targets. In the work by Dahn et al. (2002), they do not include DCR terms as they found they changed the z-band parallax of L and T objects by only 0.3 mas. In Albert et al. (2011), they also found the DCR in the z band for relative astrometry of brown dwarfs was small enough to neglect. Following these results, and in light of our observational criteria, we have not included DCR terms in this analysis. For future work, we will carry out a number of experiments to measure the DCR in the LT z-band system and review this decision.

2.3. Reduction Procedures

The bias subtraction, trimming of the overscan regions, dark subtraction, and flat fielding are carried out via the standard LT pipeline (Steele et al. 2004). However, images in the z band display prominent fringes caused by thin-film interference (see Appendix A in Berta et al. 2008). Fringes have a small effect on the photometry and astrometry for bright objects but can have a significant impact for faint objects when their fluxes are comparable to the intensity of the fringes. Since our targets are relatively faint, we must investigate the impact of fringes.

To examine the intensity and evolution of the fringes, we divide the images into three subsamples: (1) 2004/2005, (2) 2008/2009, and (3) 2011/2012 images. Each subsample contains several hundreds of frames. For each frame in each subsample we pick out an empty area (of 100 × 100 pixels) that is seriously fringed but without any or with very few objects. We calculate the rms of the counts and average the values within each subsample. We find the count variations before and after defringing are 11.2 and 9.5, 6.8 and 6.8, 6.6 and 7.5, respectively, for the three subsets, a difference that we consider significant.

The standard LT pipeline constructed biannual fringe maps, and our first attempt was to use the most appropriate for each night. However, fringes are dependent on the sky conditions at the time of observation and vary during the course of a night. The ideal case would be to make a fringe map for each image, but this is not feasible. In addition, we usually only have a few images in any given night so even a per night fringe map is not possible. Our second attempt was to construct fringe maps following the recipe in Andrei et al. (2011) for subsets of 20–30 frames while attempting to keep nights and periods covered intact. Using the fringe maps constructed by ourselves usually gave similar parallax results to those using the LT fringe map, except in the case of the fainter targets. This is probably due to the fact that sometimes, to have sufficient frames to construct a fringe map, we had to include a relatively long time span but with few frames compared to the LT fringe maps. The results presented here used the LT fringe maps, which also produced more robust parallax solutions.

2.4. Centroid Precision

Since our targets are faint and our data are impacted by fringes that we cannot remove completely, it is critical to have appropriate centroiding software to determine position, which is the fundamental data for a parallax determination. We tried several different methods: (1) a two-dimensional Gaussian fit to the point-spread function, as used in the TOPP; (2) the widely used SExtractor routine, which is designed for large scale galaxy surveys and also works well on moderately crowded star fields (http://www.astromatic.net/software/sextractor); and (3) the maximum likelihood barycenter, as implemented in the imcore software of the Cambridge Astronomy Survey Unit (CASU; http://casu.ast.cam.ac.uk/surveys-projects/software-release).

We tested all the centroiding procedures by comparing object positions from 57 frames of the 2M1807 + 5015 field. The centroiding was also tested with different defringing procedures. We found that for brighter objects we get similar results, but CASU Imcore centroids work significantly better for the fainter ones, giving smaller errors. If we do not defringe, the median $\sigma_x$, $\sigma_y$ for the $(x, y)$-coordinates are 25, 28 mas for all objects and 13, 14 mas for objects brighter than $z = 17$ mag. Applying the fringe map provided by LT pipeline, we find that the precision improves to 21, 21 mas and 11, 11 mas, respectively. In Figure 1 we present the standard deviations of the object coordinates in the 2M1807 + 5015 sequence defringed with the LT biannual fringe maps and centroided with the CASU routines.
Based on our experience in other parallax programs we expected to achieve a lower floor than 11, 11 mas for the centroiding precision. We note that the RATCam CCD has electronic gates aligned with the x-axis and physical gates aligned with the y-axis. The precision from electronic gates is better than from the physical gates. The reason for this higher noise is probably because nominally x is orientated in the direction of right ascension and y is oriented in the direction of declination but due to flexibility problems with the RATCam coolant pipes, it was not possible to always keep the same alignment. A procedure of “cardinal pointing” is adopted that aligns the rotator to one of the four cardinal positions: 0°, 90°, 180° and 270°. A third of our observations have the rotator aligned to 0°, that is with north at the top, east to the left. The other images are evenly distributed between the other cardinal points, except during the first year of observation when there are also nonstandard positions at a number of different angles. Since the astrometric distortion is partially a function of the focal plane variations, this physical rotation of the focal plane impacts negatively on the expected precision. The new infrared-optical camera on the LT does not have this constraint.

Another possible source for this high floor is that our observations for 2M1807 + 5015 covered several years, and there will be a small contribution from random proper and parallactic motion of the reference stars. Since we expose three times for each target in each night, the precision in using these three frames excludes this random motion contribution. There are three observations on 19 nights, so we have 19 subgroups with three frames in each. For each subgroup, we calculated their median \( \sigma_x, \sigma_y \) for all objects and for objects brighter than \( z = 17 \). In Figure 2, we plot the sigma versus epoch, the median precision for the objects brighter than \( z = 17 \) mag, improved to 3.8, 3.7 mas. As each sample comprises of only three images, we expect this to be an underestimate of the true sigma, but it is consistent with our hypothesis of the contribution from random motions. Since our parallax solutions come from the combined datasets, we must include the instrumental and reference system variations; so, considering the consistency of the final and per-epoch errors, we assume an observational precision of 11, 11 mas.

### 3. PARALLAXES AND PROPER MOTIONS

Using the \((x, y)\)-coordinates determined from the CASU image core software, we derived the parallaxes and proper motions using the methods adopted in the TOPP (Smart et al. 2003, 2007). The software selects the frames and reference stars automatically; for example, frames with less than four reference stars in common or stars with large errors or high proper motions, are dropped. A base frame is selected in the middle of the sequence with a high number of stars. This base frame is transferred to a standard coordinate system using objects in common with 2MASS. The other frames are then transferred to this system using all common stars with a linear transformation. Then, by fitting the combined observations of the target in the standard coordinate system, we find its relative parallax and proper motion. The correction from relative to absolute parallax is calculated using the Galaxy model of Mendez & van Altena (1996) as described in Smart et al. (2003). We estimate the error in this correction to be around 30% or 0.4–0.6 mas for these fields (Smart et al. 2007), which is negligible compared to the formal error of the parallaxes.

In Table 2 we list our results, and in Figure 3 we plot the solutions for the targets 2M1807 + 5015 and SD1717 + 6526, which have, respectively, the lowest and highest parallax errors. As shown in Figure 1, the centroiding deteriorates significantly as the object gets fainter. This is reflected in the correlation of derived parallax precision with apparent magnitude in Tables 1 and 2 and explains the noisier observations of SD1717 + 6526. In Table 3 we compare our proper motion results with the literature ones. Our results have smaller error bars, and are consistent with the literature ones with in one \( \sigma \).

### 4. ANALYSIS OF PROPERTIES

In this section we examine the physical characteristics of our objects using our parallax and proper motion results and taking advantage of two different brown dwarf models.
4.1. Absolute Magnitude and Spectral Type Interpretation

In Figure 4 we plot the spectral type versus absolute magnitude diagram in J, H, and K bands including our objects (large filled circles) and published objects (small filled circles and open diamonds) with measured parallaxes from Dupuy & Liu (2012). The magnitudes are 2MASS values, and the spectral types are from optical spectra unless there is only a NIR spectral type available. The black dashed lines are the polynomial fit from Dupuy & Liu (2012). They used a sixth-order polynomial fitting following the convention $M0 = 0, \ldots L0 = 10, \ldots T0 = 20$ to make a quantization for the spectral type. We refitted the same sample as Dupuy & Liu (2012), adding our five targets using the sample and method; the difference is imperceptible, though we do note our targets are systematically lower than the fitted line. Since there are only a few early to mid L dwarfs, the line may be defined by the other objects, however, we will require a larger sample to confirm or disprove this hypothesis.

We compare our five targets with the Dupuy & Liu (2012) curve to identify possible binaries. If any of our targets comprises an unresolved binary, then it will be brighter than a single object line in Figure 4. This brightening reaches a maximum for equal-mass binaries with an expected difference of 0.75 mag. Since this is not the case, we conclude none of the five targets consists of comparable mass binaries.

In Table 4, we compare the Dupuy & Liu (2012) spectrophotometric distances with our trigonometric ones, and the two distances for the five L dwarfs are generally consistent within $\sigma$, though the trigonometric distances are generally slightly smaller.

4.2. Kinematic Analysis

The velocities of nearby objects are dominated by their rotation around the Galactic center. But, they also have peculiar motions of several km s$^{-1}$. In the Galactic coordinate system, this spatial motion can be described using $U$, $V$, and $W$ velocities, with the $U$ axis oriented towards the Galactic center.
We use a check from Oppenheimer et al. (2001) to identify their membership in the different Galactic components. Objects that satisfy \( |U^2 + (V + 35)^2|^{1/2} > 94 \text{ km s}^{-1} \) are considered halo objects at the 2\( \sigma \) level. In the \( U-V \) diagram (Fig. 5), we find 2M0141 + 1804 and 2M1807 + 5015 have measured radial velocities both located within the 2\( \sigma \) circle—which means that these two targets are likely disk objects. We assume that the other three L dwarfs without measured radial velocities have velocities that follow the Gaussian distribution of the SDSS M dwarfs, as described above, and then plot their \( U \) and \( V \) projection along the straight lines, as shown in Figure 5. The dotted, dash-dotted, and dashed lines in Figure 5 describe the \( U \) and \( V \) velocities when adopting different radial velocities for the three targets. Their \( U \) and \( V \) velocities when using 1\( \sigma \) and mean radial velocities 30, 0, and 30 km s\(^{-1}\) are shown on each line. The star symbols indicate “critical radial velocities,” which locate the \( U \) and \( V \) velocities of the three targets on the 2\( \sigma \) ellipse.

Since the space velocities mentioned above are located within the 2\( \sigma \) circle, it is likely that these three L dwarfs are disk objects. To further quantify the possibility of the three L dwarfs without measured radial velocities being halo objects, we use the test from § 5 of Marocco et al. (2010) to see if these objects are very young. Younger stars have a small space velocity dispersion, and hence small space velocities. Objects with \( U \) between \(-20 \) and \( 50 \) km s\(^{-1}\), \( V \) between \(-30 \) and \( 0 \) km s\(^{-1}\), and \( W \) between \(-25 \) and \( 10 \) km s\(^{-1}\) will be younger than 0.5 Gyr. With the \( U, V, \) and \( W \) ranges presented in Table 5 it is unlikely that these objects are younger than 0.5 Gyr.

Thus, the inferences from \( U, V, \) and \( W \) information mean our targets are not especially young or old and suggest their ages lie between 0.5 and 10 Gyr.

### 4.3. Comparison with Model Predictions

In Figure 6, we plot our objects on color versus absolute magnitude diagrams. Model tracks from Burrows et al. (2006; hereafter, BSH06) and Allard et al. (2001; hereafter, BT-Dusty) are overplotted for comparison. The BSH06 model grids cover log \( g \) of 4.5, 5.0, and 5.5 (gravities in cgs) and effective temperatures from 700 to 2200 K, with metallicities of [Fe/H] = \(-0.5, 0, \) and \(+0.5\). The BT-Dusty model grids cover log \( g \) of 4.5, 5.0, and 5.5 and effective temperatures from 1500 to 3500 K, with metallicities of [Fe/H] = \(-0.5, 0.0, \) and \(+0.5\). The synthetic colors and absolute magnitudes are derived by convolving the model spectra with the 2MASS filter profiles (see Marocco et al. 2010). The BSH06 model grids supply the flux at the surface of the object and at 10 pc. The latter calculation assumes the radius-log \( g \cdot T_{\text{eff}} \) relation from Burrows et al. (1997). The BT-Dusty model grids only provide the flux at the surface of the object, so to calculate the absolute magnitudes, we calculate the radius associated with each model spectrum by interpolating the BT-Dusty isochrones (Baraffe et al. 2003).

From Figure 6 we can see that BSH06 and BT-Dusty can fit the colors of these L dwarfs. In principle, we could determine metallicity or gravity information from them. But, because of the known degeneracy between gravity and metallicity, our objects can be described by different combinations of the
two parameters. This prevents assignment of a single gravity or metallicity based only on this diagram. Nonetheless, our targets are consistent with a log $g$ between 5.0 and 5.5 for solar or higher metallicity. This is consistent with the thin-disk membership found in § 4.2. We note that SD1717 + 6526 shows signs of dust condensing below the atmosphere as it departs from the dusty model tracks.

We overplotted 1700 and 2000 K temperature isochrones with solar metallicity in Figure 6 to examine the temperatures of our targets. The five targets are shown as two clusters, one near the 2000 K isochrone and the other near the 1700 K isochrone. This is consistent with results in § 5.2: three of the five targets have higher temperatures, and the other two have lower temperatures—though the absolute values differ between the two models. For a certain fixed temperature (e.g., 1700 K), we find that the BSH06 $J$-$K$ model color is not as red as we expect, and the BT-Dusty $J$-$K$ model color is not as blue, especially at lower temperatures.

5. TEMPERATURES AND LUMINOSITIES

In this section, we derive effective temperature, bolometric luminosity, radius, gravity and mass using the Chabrier et al. (2000; hereafter, CBA00) dusty evolutionary model. Then, we combine observational spectra with synthetic spectra from two brown dwarf models (BSH06 or BT-Dusty) and the Stefan-Boltzmann law to estimate temperatures and luminosities.

5.1. Physical Parameters from an Evolutionary Model

We directly found the effective temperature and other parameters for all our targets using the CBA00 dusty evolutionary model and our derived parallax. The gravity of our targets are between log $g = 5.0$ and log $g = 5.5$ (see § 4.3). Given that these objects have higher gravity than young field dwarfs (e.g., Cruz et al. 2009), and following our findings in § 4.2, we assume our targets to be between 0.5 and 10 Gyr old. For this age range, the dusty evolutionary model CBA00 provides relations between $M_K$ and effective temperature, radius, bolometric luminosity, gravity, and mass. Combining our parallax with 2MASS magnitudes, we obtain $M_K$, and, using CBA00, we find the parameters listed in Table 6.

5.2. Temperatures and Luminosities from the Stefan-Boltzmann Law

We have obtained both optical (from Cruz et al. 2007; Hawley et al. 2002) and infrared (from K. L. Cruz et al. [2013, in preparation]; Burgasser et al. [2008a, 2010]; A. J. Burgasser [2013, in preparation]) spectra for all five targets. To calibrate the spectra in flux, we used the $z$-band magnitude (for 2M1807 + 5015 and 2M2238 + 4353 we use $z_{\text{est}}$ in Table 1) in the optical and 2MASS $J$-band photometry in the near-infrared. To calculate the bolometric flux, we combined the observational spectra with the BSH06 and the BT-Dusty models. We calibrated the flux level of the model spectra using WISE W1 magnitudes, since these are well-calibrated long
wavelength measurements and allow the spectra to join reasonably with the observed K band. To calculate an effective temperature range, following a similar method to Marocco et al. (2010), we use the classical Stefan-Boltzmann law and the relationship between $F_{\text{bol}}$, $L_{\text{bol}}$, and $T_{\text{eff}}$:

$$F_{\text{bol}} = L_{\text{bol}}/4\pi D^2, \quad L_{\text{bol}} = 4\pi\sigma R^2T_{\text{eff}}^4.$$  \hspace{1cm} (1)

Integrating the observed optical and near-infrared spectra, we obtained a preliminary flux, which, combined with our parallax, yields a luminosity. Interpolating the CBA00 luminosity-radius relationship, we derived the model-predicted radius for our targets. Having the radius and preliminary flux, we then obtained a preliminary effective temperature from equation (1). For the moment we do not consider metallicity and gravity; this is discussed below. Using this temperature, we can choose the appropriate model spectra. We then integrated the spectral energy distribution (formed by optical, near-infrared, and model spectra) to recalculate the bolometric flux, and therefore a more precise temperature. Iterating the above procedure twice, we obtain the bolometric flux, luminosity, and effective temperature listed in Table 7.

When we choose the model spectra for an object, either BSH06 or BT-Dusty model spectra, we assume the targets have solar metallicity and test two values of gravity: $\log g = 5.5$ and $\log g = 5.0$. Usually there are four models available; taking 2M1807 + 5015, for example, the preliminary temperature is between 1875 and 1985 K (see Table 7), and we choose the four synthetic spectra with closest model parameters amongst the grids available: in this case, 1900 K, $\log g = 5.5$; 1900 K, $\log g = 5.0$; 2000 K, $\log g = 5.5$; and 2000 K, $\log g = 5.0$. For each of the chosen model spectra, we then overlap with our observational spectra in order to create a full energy distribution. We then output the $F_{\text{bol}}$, $L_{\text{bol}}$, and $T_{\text{eff}}$ values. In

### TABLE 4
PHOTOMETRIC AND TRIGONOMETRIC DISTANCES OF THE FIVE L DWARFS

| Short Name      | $D_J$ (pc) | $D_H$ (pc) | $D_K$ (pc) | $\langle D_P \rangle$ (pc) | $D_\pi$ (pc) |
|-----------------|------------|------------|------------|-----------------------------|-------------|
| 2M0141+1804     | 24.2 ± 4.2 | 24.2 ± 4.2 | 22.6 ± 3.9 | 23.7 ± 4.1                  | 22.7 ± 1.1  |
| SD1717+6526     | 22.9 ± 3.4 | 22.0 ± 3.3 | 20.3 ± 3.2 | 21.7 ± 3.3                  | 17.5 ± 1.7  |
| 2M1807+5015     | 14.4 ± 2.5 | 14.9 ± 2.6 | 14.0 ± 2.4 | 14.4 ± 2.5                  | 12.9 ± 0.3  |
| 2M2238+4353     | 21.9 ± 3.8 | 22.7 ± 4.0 | 21.3 ± 3.6 | 22.0 ± 3.8                  | 18.5 ± 0.6  |
| 2M2242+2542     | 26.1 ± 3.9 | 24.8 ± 3.7 | 21.9 ± 3.4 | 24.2 ± 3.7                  | 20.9 ± 1.2  |

**NOTES.**—We calculated the spectrophotometric distances according to the $J$-, $H$-, and $K$-band spectral type (SpT)-absolute magnitude relationship of Dupuy & Liu (2012). $\langle D_P \rangle$ is the weighted mean spectrophotometric distance, and $D_\pi$ is the distances derived from our trigonometric parallax.

### TABLE 5
CALCULATED $U$, $V$, AND $W$ FOR OUR FIVE TARGETS

| Short Name      | $V_{\text{rad}}$ (km s$^{-1}$) | $U$ (km s$^{-1}$) | $V$ (km s$^{-1}$) | $W$ (km s$^{-1}$) |
|-----------------|-------------------------------|------------------|------------------|------------------|
| 2M0141+1804     | 24.7                          | 24.7             | 24.7             | 24.7             |
| SD1717+6526     | 30                            | -3.1             | 44.0             | 15.2             |
|                 | -30.0                         | 1.6              | -5.3             | -18.6            |
|                 | 0.0                           | -0.8             | 19.4             | -1.7             |
| M1807+5015      | -0.4                          | -3.5             | 11.7             | 4.4              |
| 2M2238+4353     | 30.0                          | -33.9            | 33.0             | -22.3            |
|                 | -30.0                         | -24.8            | -24.8            | -8.9             |
|                 | 0.0                           | -29.3            | 4.1              | -15.6            |
| 2M2242+2542     | 30.0                          | -39.4            | 26.2             | -29.8            |
|                 | -30.0                         | -39.6            | -26.4            | -1.0             |
|                 | 0.0                           | -39.5            | -0.1             | -15.4            |

**NOTES.**—We assume the three L dwarfs without measured radial velocities to have 0 and ±30 km s$^{-1}$ as radial velocities, following the SDSS M dwarfs’ distribution.
Figure 7, we show the selected best-fit model spectra overplotted with the observational ones for target 2M1807 + 5015, as an example. The smallest and largest values generated by this process enable us to find the range for each parameter given in columns (5)–(10) of Table 7. We note that the model grids available offer one or two synthetic spectra for each temperature, which correspond to different values of log \( g \). Thus we are not in a position to estimate reliable gravities for our targets.

The uncertainty in temperature is calculated via standard propagation of the errors in flux, distance, and radius. For SD1717 + 6526, 2M2238 + 4353, and 2M2242 + 2542, the flux errors in the optical or near-infrared bands were derived using the average flux errors of 2M0141 + 1804 and 2M1807 + 5015 since they are not available in their spectral file. There is no uncertainty associated with the model spectra. However, when calculating the effective temperature, we used BSH06 and BT-Dusty model grids to locate the appropriate synthetic spectra for each object, and thus find the uncertainty in the synthetic spectra flux—so that we can calculate the uncertainty on bolometric flux. To determine the error in radius we use the spread between the two values derived from the CBA00 evolutionary model (see Table 6). The final temperature errors obtained are listed in columns (7) and (10) of Table 7. We note that the uncertainties in temperatures reflected the ranges of the temperatures, which are dominated by the radius errors; Burgasser et al. (2008b) find the same conclusion with a similar approach, although they did a piecewise scaling of the model spectra using multiband photometry.

5.3. Comparison

Using two methods, we derived three temperatures for each of the five targets. A comparison of the temperatures deduced from the CBA00 dusty evolutionary models based on the observed distance and \( K \)-band magnitudes (Table 6) and the temperatures obtained by integrating the spectral energy distribution (SED) and using the Stefan-Boltzmann equation (Table 7) show that both methods are consistent for each individual object. The two effective temperatures obtained from

| Short Name   | \( M_\star \) (K) | \( T_{\text{eff}} \) (K) | Luminosity [\( \log_{10}(L/L_\odot) \)] | Radius \( (R/R_\odot) \) | Gravity [\( \log_{10} g \)] | Mass \( (M/M_\odot) \) |
|--------------|-----------------|----------------|---------------------------------|---------------------|-------------------|-----------------|
| 2M0141+1804  | 10.71           | 2225–2305      | –3.63 (–3.60)                   | 0.1000–0.1055       | 5.21–5.34         | 0.067–0.080     |
| SD1717+6526  | 11.96           | 1520–1650      | –4.41 (–4.36)                   | 0.0860–0.1040       | 5.00–5.41         | 0.040–0.070     |
| 2M1807+5015  | 11.04           | 2000–2138      | –3.82 (–3.78)                   | 0.0958–0.1036       | 5.18–5.36         | 0.058–0.077     |
| 2M2238+4353  | 11.19           | 1828–2038      | –3.95 (–3.85)                   | 0.0930–0.1030       | 5.15–5.37         | 0.053–0.075     |
| 2M2242+2542  | 11.45           | 1688–1850      | –4.14 (–4.08)                   | 0.0905–0.1032       | 5.08–5.39         | 0.048–0.073     |

**Notes.**—The range of values shown are found by assuming an age range between 0.5 and 10 Gyr.

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**Table 6**

**Temperature, Luminosity, Radius, Gravity, and Mass Derived from CBA00 Model**
integrating the SED (combined with the BSH06 and BT-Dusty models) are very close for each of the individual targets. The three temperatures for SD1717 + 6526 are consistent, but the temperature derived from the CBA00 dusty evolutionary model is lower than that derived by integrating the SED. As discussed in § 4.3, the discrepancy arises because dusty models are not applicable at lower temperatures (see Allard et al. 2001, 2003).

6. COMMENTS ON INDIVIDUAL TARGETS

2M0141 + 1804.—Our results on temperature are consistent with Sengupta & Marley (2010), who estimate a temperature of 1850 ± 250 K using equations (3) and (4) of Stephens et al. (2009). The large error of 250 K is due to the difference in optical and IR spectral types, and the authors used both values when calculating the temperature. Our results have a smaller range in temperature because we have the optical and near-infrared spectra, which allow us to get a relatively precise luminosity, and hence effective temperature. The radial velocity is 24.7 km s^{-1}, as reported by Blake et al. (2010). Our proper motions are within one sigma of those in Casewell et al. (2008), though ours are significantly more precise.

2M1807 + 5015.—This object is the brightest of our five targets. Sengupta & Marley (2010) reported a $T_{\text{eff}} = 2100 ± 100$ K, and Witte et al. (2011) derived $T_{\text{eff}} = 1900$ K, $\log g = 5.5$, and [Fe/H] = 0.0 through Drift-Phoenix model fitting. Our results are more consistent with the lower value. Seifahrt et al. (2010) reported a radial velocity of $-0.4$ km s^{-1} and very low values for the $U, V$, and $W$ velocity components, which is consistent with our results.

2M2283 + 4353.—Bernat et al. (2010) reported it is a binary candidate with a mass ratio of 0.57–0.84, assuming an age between 1 and 5 Gyr. However, we do not see any binary signature in our parallax determination residuals. Also, the position in Figure 4 does not indicate binarity; although, unless the mass ratio is larger than about 0.6, we would not expect to see any significant brightening.

2M2242 + 2542.—Bouy et al. (2003) observed this object using the Hubble Space Telescope in a search for binaries and concluded it was a single object, which is consistent with our conclusions. Gizis et al. (2003) and Cruz et al. (2007)
derived photometric distances of $\sim$30 and $\sim$27 pc, respectively. We find a trigonometric distance of $\sim$21 pc, which is consistent with the photometric distance from Table 4.

7. SUMMARY AND FUTURE WORK

We report the parallaxes and proper motions of five L dwarfs using a robotic telescope. Our trigonometric distances are very close to the photometric ones. Our proper motions are consistent with the literature but have smaller errors. Examinations of the objects’ spectral type versus absolute magnitude, U versus V velocity, and color versus absolute magnitude overplotted with model tracks diagrams indicate that the five L dwarfs are single thin-disk objects with solar metallicity. For all five objects, effective temperature, luminosity and bolometric flux, radius, gravity, and mass are derived from the CBA00 model. We also derived the effective temperature through integrating their SEDs and combining their observational spectra with synthetic spectra (BSH06 or BT-Dusty). For each individual target, the two methods give consistent temperatures. The larger difference in temperatures for SD1717 + 6526 (an L4) show that the dusty models are not applicable at lower temperature.

This work is the first parallax determination using a ground-based robotic telescope. Parallax determinations have stringent observational requirements, which are efficiently satisfied by robotic scheduling. The requirement for long term stability and repeatability is also well met by robotic procedures. The RATCam camera is scheduled to be completely decommissioned in 2013 and be replaced by the infrared-optical (IO) camera, though RATCam and the IO (with only a z-band filter) are both working currently. Once the IO is fully commissioned and with the lessons learnt from this program, we plan to launch a more ambitious program to observe the nearby and rapidly expanding sample of interesting L and T dwarfs that are available for the Liverpool Telescope.

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