A Focus on L Dwarfs with Trigonometric Parallaxes

Y. Wang¹, R. L. Smart²,³, Z. Shao⁴,⁵, H. R. A Jones⁶, F. Marocco³, A. Luo¹, A. Burgasser⁶, J. Zhong⁴, and B. Du¹

¹National Astronomical Observatories of China, CAS, 20A Datun Road Chaoyang District, Beijing, People’s Republic of China; yfwang@bao.ac.cn
²Istituto Nazionale di Astrofisica, Osservatorio Astrofisico di Torino, Strada Osservatorio 20, 10025 Pino Torinese, Italy
³School of Physics, Astronomy and Mathematics, University of Hertfordshire, College Lane, Hatfield AL10 9AB, UK
⁴Shanghai Astronomical Observatory, CAS, 80 Nandan Road, Shanghai 200030, People’s Republic of China
⁵Key Lab for Astrophysics, Shanghai 200234, People’s Republic of China
⁶Center for Astrophysics and Space Science, University of California San Diego, La Jolla, CA 92093, USA

Received 2017 July 3; accepted 2018 February 1; published 2018 May 14

Abstract

We report new parallax measurements for 10 L- and early T-type dwarfs, five of which have no previous published values, using observations over 3 years at the robotic Liverpool Telescope. The resulting parallaxes and proper motions have median errors of 2 mas and 1.5 mas/year, respectively. Their space motions indicate they are all Galactic disk members. We combined this sample with other objects with astrometry from the Liverpool Telescope and with the published literature astrometry to construct a sample of 260 L- and early T type dwarfs with measured parallaxes, designated the Astrometry Sample. We study the kinematics of the Astrometry Sample, and derived a solar motion of \((U, V, W)_0 = (7.9 \pm 1.7, 13.2 \pm 1.2, 7.2 \pm 1.0) \text{ km s}^{-1}\), with respect to the local standard of rest, in agreement with the recent literature. We derive a kinematic age of 1.5–1.7 Gyr for the Astrometry Sample assuming the age increases monotonically with the total velocity for a given disk sample. This kinematic age is less than half of the literature values for which used the same methods and similar but different low-mass dwarf samples. We believe this difference arises for two reasons: (1) the sample is mainly composed of mid to late L dwarfs, which are expected to be relatively young, and (2) the requirement that objects have a measured parallax biases the sample to the brighter examples, which tend to be younger.

Key words: parallaxes – proper motions – (stars:) brown dwarfs

Online material: tar.gz files

1. Introduction

Objects classified as L and T spectral types are predominately brown dwarfs or substellar objects with masses that cover the range from the most massive planets to the least massive stars. Since the discovery of the first examples (Becklin & Zuckerman 1988; Nakajima et al. 1995), there have been over 2000 that have been identified primarily in the large optical and near-infrared (NIR) sky surveys (e.g., Kirkpatrick et al. 2000; Knapp et al. 2004; Pinfield et al. 2008), and more recently in the mid-infrared sky surveys (Kirkpatrick et al. 2011). They are an important component of the Galaxy that can be used to study the atmospheres of hot Jupiter-like planets (e.g., Faherty et al. 2013), to explore the low-mass end of the initial mass function (e.g., Kirkpatrick et al. 2012; Burningham et al. 2013; Marocco et al. 2015), and, given their long life time and ubiquity, they will be excellent for studying the evolution of our Galaxy and its components (e.g., Burgasser 2009).

Distance is a critical parameter in understanding these objects. A distance is required to derive the absolute magnitude, and hence, the energy output. A model-independent parallax can be used to constrain radius or temperature, and aid in the exploration of relations between other parameters such as mass, surface gravity, age, and metallicity. To precisely measure a parallax, observational sequences covering several years on stable imaging systems are required, and less than 250 of the currently known L and T dwarfs have measured parallaxes. In this paper, we report new parallaxes of 10 L and early T dwarfs, then combine them with all published parallaxes of L0 to T2 dwarfs, and examine a number of relations e.g., SpT-absolute magnitude diagrams and space motions.

This paper is divided into five sections. First, in Section 2, we report the parallax measurements for our 10 targets and use their parameters to indicate the Galactic population to which they pertain. In Section 3, we study the spectral type and absolute magnitude relations. In Section 4, we study the kinematic signature of the Astrometry Sample. Finally, we provide a summary in Section 5.

2. Parallax Measurements

The parallax measurements in this paper were made as part of the program described in (Wang et al. 2014, hereafter WJS14); here, we briefly summarize the observations and data reduction procedures, and the reader is referred to the aforementioned paper.
Table 1
Target List/LT Sample with their SDSS $z_{AB}$ Magnitude, NIR Spectral Type, and Published Astrometry Information.
The Five Objects Below the Solid Line are from WJS14

| 2MASS Designation | Short Name | $z_{AB}$ (mag) | SpT$_{NIR}$ | Binary sep. ($^{\prime}$) | $v_{r}$ (km s$^{-1}$) | Literature $\pi$, $\mu_{\alpha}$cos$\delta$, $\mu_{\delta}$ (mas, mas/yr, mas/yr) |
|--------------------|------------|---------------|-------------|---------------------|----------------|--------------------------------------------------|
| J04234858-0414035  | 2M0423-0414 | 17.29         | T0          | 0.61$^{1}$           | 28.0 ± 2.0$^{9}$ | 73.3 ± 1.4, −325.3 ± 1.0, 93.1 ± 0.9$^{10}$ |
| J07171620+5705430  | 2M0717+5705 | 17.23         | L3          | ...                 | −16.3 ± 0.2$^{2}$ | −7.179 ± 17.87, 67.17 ± 15.1$^{13}$ |
| J07584037+3247245  | 2M0758+3247 | 17.96         | T2          | ...                 | ...             | −204.23 ± 18.01, −316.21 ± 12.42$^{8}$ |
| J08578459+5708514  | 2M0857+5708 | 17.74         | L8          | ...                 | ...             | −413.61 ± 20.52, −353.43 ± 16.85$^{8}$ |
| J10170754+1308398  | 2M1017+1308 | 16.74         | L2          | 0.10$^{2}$          | ...             | 30.0 ± 1.6, 44.1 ± 0.7, −114.3 ± 0.6$^{7}$ |
| J11040127+1959217  | 2M1104+1959 | 17.21         | L5          | ...                 | ...             | 74.8 ± 14.7, 138.7 ± 20.3$^{9}$ |
| J12392727+5515371  | 2M1239+5515 | 17.52         | L6          | 0.21$^{3}$          | 42.4 ± 1.7, 125.2 ± 1.1, 0.04 ± 1.1$^{17}$ |
| J13004255+1912354  | 2M1300+1912 | 15.14         | L1          | ...                 | −17.6 ± 0.2$^{6}$ | 70.4 ± 2.5, −793.0 ± 10.0, −1231.0 ± 10.0$^{10}$ |
| J15150083+4847416  | 2M1515+4847 | 16.74         | L5          | ...                 | −30.0 ± 0.1$^{4}$ | ... −949.9 ± 21.3, 1471.5 ± 21.4$^{9}$ |
| J20282035+0052265  | 2M2028+0052 | 16.98         | L2          | 0.05$^{4}$          | ...             | 33.25 ± 1.32, 96.50 ± 0.93, −6.05 ± 2.0$^{11}$ |

Note. All magnitudes are measured SDSS DR10 $z_{AB}$ magnitudes except the three objects in italics, which are estimated from their $I$ and $K$ magnitudes. The SpT$_{NIR}$ is estimated in this work following the Kirkpatrick et al. (2010) method using SpX-Prism spectra. The Binary sep. indicates the angular separation in arcsecond for known binary systems. The last column lists literature absolute parallax and proper motions when available. The five objects below the line are from WJS14.

References: $^{1}$ Burgasser et al. 2006a; $^{2}$ Bouy et al. 2003; $^{3}$ Gizis et al. 2003; $^{4}$ Pope et al. 2013; $^{5}$ Prato et al. 2015; $^{6}$ Blake et al. 2010; $^{7}$ Dupuy & Liu 2012; $^{8}$ Casewell et al. 2008; $^{9}$ Jameson et al. 2008; $^{10}$ Faherty et al. 2016; $^{11}$ Weinberger et al. 2016; $^{12}$ Wang et al. 2014.

for more details. The observations were made on the 2 m robotic Liverpool Telescope$^{7}$ (LT). The LT, an Alt-Az mounted telescope with Ritchey-Chrétien Cassegrain optics, is a totally robotic telescope located at the Observatorio del Roque de Los Muchachos on the Canary island of La Palma, Spain, and operated by the Liverpool John Moores University in the United Kingdom. We used the SDSS-$z$ band filter (hereafter simply $z_{AB}$; York et al. 2000) and the RATCam CCD which is an optically sensitive 2048 × 2048 pixel CCD camera with a pixel scale of 0.1395 arcsecond/pixel providing a total field of view of 4.6 arcmin.

### 2.1. Target Selection

The targets were selected from the literature with the following criteria: they were at a declination visible to the LT, had a SDSS $z_{AB}$ magnitude brighter than 18, and had no published trigonometric parallax in 2004. From this list of objects, those with the smallest photometric distance were preferred. Here, we report on 10 objects that have enough observations to provide reliable parallaxes.

In Table 1, we list the 10 targets presented in this contribution and the five targets from WJS14 with their discovery designation, a short name, SDSS $z_{AB}$ magnitude, NIR spectral type (hereafter SpT$_{NIR}$), binary separations from the literature if the object if the literature is if the object is a known binary system, and any published astrometry. SpT$_{NIR}$ is the near-infrared spectral type found from NIR spectra in the SpEx-Prism spectra library$^{8}$ (Burgasser 2014) comparing standards in the 0.9–1.4 $\mu$m region (Kirkpatrick et al. 2010). The five objects below the solid line in Table 1 are from WJS14, which used the the same methodology as presented here. These five objects combined with the 10 targets with homogeneous astrometry we designate the LT Sample.

### 2.2. Observations

All observations were obtained within 30 minutes of the meridian to minimize differential color refraction (Monet et al. 1992; Stone 2002). This is the small varying positional displacement of objects due to their different colors and the variation of the atmosphere refractive index with wavelength. Observing at small hour angles minimizes the part of the refraction that varies as a function of the amount of atmosphere traversed. In each observation, we took three exposures of 160 s to allow for robust removal of cosmic rays and to minimize random errors. This combination of exposures nominally provides a signal-to-noise ($S/N$) of better than 50 on these targets.

### 2.3. Data Reduction

The bias subtraction, trimming of the over-scan regions, dark subtraction, and flat fielding are carried out via the standard LT pipeline (Steele et al. 2004). Images in the $z$ band display prominent fringes caused by thin-film interference (Berta et al. 2008). These fringes can have a significant impact on the astrometry of our targets, as the targets are relatively faint. The LT website provides binocular fringe maps that we used to remove the

---

$^{7}$ http://telescope.livjm.ac.uk/

$^{8}$ http://pono.ucsd.edu/~adam/browndwarfs/spexprism
fringes using IRAF’s \textit{rmfringe}. We derived the x and y positions using a maximum likelihood barycenter centroid as implemented in the \textit{imcore} software of the Cambridge Astronomy Survey Unit (hereafter CASU\textsuperscript{9}). We compared successive observations of the same field, and found the centroid precision is approximately 11 mas for bright objects in both x and y coordinates (WJS14).

2.4. Parallax Determination and Comparison

We derived the parallaxes and proper motions using the methods adopted in the Torino Observatory Parallax Program (Smart et al. 2003, 2007), using the x, y coordinates determined from the CASU \textit{imcore} software. The Torino pipeline selects the frames and reference stars in an unsupervised fashion with user-supplied parameters to vary the minimum number of common reference stars and the outlier rejection criteria. 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 the Sloan Digital Sky Survey (York et al. 2000) as a reference catalog except for 2M0717+5705, where we used the Two Micron Sky Survey (Skrutskie et al. 2006).

The other observations of each target are translated to the base-frame standard coordinate system using all common stars via a linear transformation. Once we have all observations in the base-frame system, we fit the observations of the target with a position offset, parallax, and proper motion in each coordinate. The best relative parallax is found from a weighted mean of the estimates in each coordinate. The correction from relative to absolute parallax is calculated using the Galaxy model of Mendez \& van Altena (1998) as described in Smart et al. (2003). We estimate the error on this correction to be around 30\% or 0.4–0.6 mas for these fields, which is negligible compared with the formal error of the parallaxes.

In Table 2, we list the parallax and proper motions of 10 L/T dwarfs. The motion and corresponding fit over the observed period for all targets are shown in the Figure 4 of the Appendix.

In the last column of Table 1, published parallax and proper motion results are shown. We found that five of our targets have literature parallaxes for which our values are all consistent to within two \sigma except for the target 2M2028+0052, which differs by three times the combined \sigma from the value in Weinberger et al. (2016). 2M2028+0052 is a known binary with almost equal mass and magnitude components (Pope et al. 2013), while both the Weinberger and the LT solutions assume it is single. The LT solution has more epochs, 17 versus 4, and a longer baseline, 3.74 versus 2.0 yr, so we expect the results presented here to be more robust.

2.5. Galactic Population Membership

Kinematic information can be used as an indication of Galactic population membership. Eight of our 10 targets have low tangential velocities of $<25$ km s$^{-1}$, while 2M1515+4847 has $V_t = 66 \pm 2.5$ km s$^{-1}$ and 2M1300+1912 has $V_t = 91.1 \pm 2.1$ km s$^{-1}$. The galaxy model of $V_t$ shown in Figure 31 of Dupuy \& Liu (2012) implies that all these targets are thin disk, although 2M1300+1912 may be thick disk.

UVW space velocities can also be used to indicate Galaxy population. Determination of U and V requires a measurement of parallax, proper motion and radial velocity. Four of our 10 targets have radial velocity measurements, and these are given in Table 1. For the remaining targets, we calculate their U and V velocities, assuming a Gaussian distribution of radial velocities centered on zero with a \sigma = 30 km s$^{-1}$, as seen for M dwarfs radial velocity (WSJ14). Figure 1 shows the UV velocities for our 10 targets, as well as the one and two sigma disk stars' velocity ellipsoids (Oppenheimer et al. 2001; Reid et al. 2001). Targets beyond the two sigma ellipsoid with $[U^2 + (V + 35)^2]^{1/2} > 94$ km s$^{-1}$ are likely to be halo members (Oppenheimer et al. 2001). In this view, all of the targets appear to be likely thin disk members, although SDSS 1515+4847 lies near the two sigma ellipsoid and may be a thick disk object.

\begin{table}[h]
\centering
\caption{Parallax and Proper Motions for Our 10 Targets}
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
Short Name & \(N_{\text{obs}}, N_{\text{ref}}\) & \(\Delta t\) & \(\pi\) & COR & \(\mu_\alpha \cos \delta\) & \(\mu_\delta\) & \(V_t\) \\
& & (yr) & (mas) & (mas) & (mas) & (mas) & (km s\(^{-1}\)) \\
\hline
2M0423-0414 & 50, 13 & 4.33 & 66.3 \pm 3.7 & 1.5 & \(-325.6 \pm 1.8\) & \(83.1 \pm 1.5\) & \(24.0 \pm 1.3\) \\
2M0717+5705 & 48, 27 & 4.22 & 46.4 \pm 2.3 & 1.4 & \(-180.8 \pm 1.6\) & \(54.3 \pm 1.3\) & \(5.9 \pm 0.3\) \\
2M0758+3247 & 62, 16 & 4.18 & 106.9 \pm 4.6 & 1.5 & \(-230.7 \pm 1.7\) & \(-327.7 \pm 2.1\) & \(17.9 \pm 0.8\) \\
2M0857+5708 & 71, 9 & 4.15 & 98.0 \pm 2.6 & 2.0 & \(-400.0 \pm 1.7\) & \(-374.9 \pm 1.7\) & \(26.5 \pm 0.8\) \\
2M1017+1308 & 55, 5 & 4.10 & 32.3 \pm 2.8 & 2.5 & \(61.0 \pm 1.4\) & \(-116.3 \pm 1.5\) & \(19.3 \pm 1.7\) \\
2M1104+1959 & 66, 5 & 4.08 & 66.2 \pm 1.9 & 2.2 & \(55.9 \pm 0.7\) & \(126.6 \pm 0.7\) & \(9.9 \pm 0.3\) \\
2M1239+5515 & 43, 6 & 4.04 & 45.0 \pm 2.1 & 2.0 & \(131.7 \pm 2.0\) & \(-2.6 \pm 1.4\) & \(13.9 \pm 0.7\) \\
2M1300+1912 & 42, 10 & 3.48 & 76.4 \pm 1.8 & 2.0 & \(-789.0 \pm 1.1\) & \(-1237.2 \pm 1.0\) & \(91.1 \pm 2.1\) \\
2M1515+4847 & 43, 6 & 3.46 & 123.8 \pm 5.0 & 1.7 & \(-930.4 \pm 4.1\) & \(1469.3 \pm 2.2\) & \(66.8 \pm 2.5\) \\
2M2028+0052 & 54, 79 & 3.74 & 39.1 \pm 1.6 & 1.2 & \(96.9 \pm 0.8\) & \(-9.0 \pm 0.8\) & \(11.8 \pm 0.5\) \\
\hline
\end{tabular}
\end{table}

\textsuperscript{9} http://casu.ast.cam.ac.uk/surveys-projects
Gaussian radial velocity distribution centered in 0 and 1 km s$^{-1}$ velocities distribution for each objects when assuming each of them have four targets with measured radial velocities. The six gray dashed lines indicate Oppenheimer et al. 2001 combination of the Dupuy & Liu all brown dwarfs with spectral types between L0 to T2 and ($\pm 45$, 0) km s$^{-1}$ and radii of 47 km s$^{-1}$ and 94 km s$^{-1}$ (Reid et al. 2001; Oppenheimer et al. 2001). The labeled solid dots with error bars indicate the four targets with measured radial velocities. The six gray dashed lines indicate six targets without measured radial velocity, the lines also indicate the U and V velocities distribution for each objects when assuming each of them have Gaussian radial velocity distribution centered in 0 and 1$\sigma$ of 30 km s$^{-1}$.

We can also calculate a probability of these objects being Galactic disk members. Adopting a Gaussian distribution for radial velocity, these objects have U and V velocities that trace a straight line on a U-V plot as shown in Figure 1. Integrating within the 2$\sigma$ circle, we derived the probability of them being Galactic disk members. The probability is very high, $\sim$100% for all of our targets indicating that they are Galactic disk members.

3. Study of Spectral Type versus Absolute Magnitude Diagrams

We now examine the Spectral Type versus absolute Magnitude relations (hereafter SpT-Mag) in the 2MASS and WISE magnitude systems.

3.1. The Astrometry Sample and the LT Sample

To obtain a larger, statistically significant sample, we combine all brown dwarfs with spectral types between L0 to T2 and published trigonometric parallax measurements. This sample is a combination of the Dupuy & Liu (2012) online compendium, five targets from WJS14, and the 10 targets presented in this contribution resulting in 260 objects (239 L and 21 T dwarfs), designated the Astrometry Sample. In the online table available from stacks.iop.org/PASP/130/064402/mmedia, we list the object name; position; optical and NIR spectral types; 2MASS magnitudes; object flag; WISE magnitudes; trigonometric distance; tangential velocity; radial velocity; U, V, and W space motions; and trim status in Section 5 for our Astrometry Sample. We will use the Astrometry Sample when plotting the SpT-Mag diagrams in the next subsection and in the Section 4.

The LT Sample (Table 1) is a subsample of the Astrometry Sample that contains the 10 targets with new astrometry presented here and the five targets presented in WJS14. This LT sample is considered separately because it has homogeneous photometry, spectroscopy and astrometry.

3.2. SpT-Mag Diagrams

In Figure 2, we plot the SpT-Mag diagrams in the 2MASS and WISE systems, respectively. The gray solid circles indicate the objects from Astrometry Sample, the black symbols indicate the LT Sample. The small black asterisks indicate four LT sample targets that are known binaries. The solid gray line is the relation from Dupuy & Liu (2012) using a sixth-order polynomial fit.

There are 200 objects with valid 2MASS $JHK_s$ magnitudes plotted in the left panel of Figure 2. We have labeled three under-luminous outliers in each 2MASS band. Both 2MASSWJ1207334-393254B (Allers & Liu 2013) and VHSJ125601.92-125723.9B (Gauza et al. 2015) have low surface gravity and young age. While WISEJ164715.57+563208.3 has a very red near-infrared color, it cannot be attributed to low gravity (Kirkpatrick et al. 2011).

For the plots in WISE absolute magnitudes to maximize the numbers of objects, we selected on W1 and W2 separately from W3; all objects with values were considered valid regardless of the flags and error estimates. This resulted in 151 objects in the W1 and W2 bands and 129 objects in the W3 band plotted in the right panel of Figure 2. The gray solid line shows the polynomial fit presented in Dupuy & Liu (2012).

The outliers 2MASSWJ1207334-393254B and VHSJ125601.92-125723.9B do not have valid WISE magnitudes, as they are both blended with bright stars. WISEJ164715.57+563208.3 remains an outlier in the WISE bands.

The consistency of our data with the published data in the SpT-Mag diagrams is a confirmation that our parallax measurements are reasonable. In the SpT-Mag diagram, the unresolved binaries stand out as over-luminous objects, up to 0.75 magnitudes for equal mass binaries. There are four of our 10 targets located above the fitting line in both panels of Figure 2 that are the known binaries 2M0423-0414 (Burgasser et al. 2006b), 2M1017+1308 (Bouy et al. 2003), 2M1239+5515 (Gizis et al. 2003), and 2M2028+0052 (Pope et al. 2013) with separations listed in Table 1.

4. Kinematic Analysis

In our Astrometry Sample we have 260 objects consisting of 239 L and 21 T dwarfs. There are 22 known binary systems in our sample, each of which we treat as just one tracer for our kinematical analysis, hence we have 238 tracers for consideration.
These tracers are distributed within \( \sim 100 \text{ pc} \) in distance with a median value of 21 pc and represent the very close solar neighborhood. In this sample, 70 objects have radial velocity \((v_r)\) measurements: 41 from Blake et al. (2010) with uncertainties usually less than 0.2 km s\(^{-1}\) and 29 are gathered from various sources (Basri et al. 2000; Reiners & Basri 2009; Seifahrt et al. 2010; Burgasser et al. 2015; Prato et al. 2015) with typical uncertainties of \( \sim 2 \text{ km s}^{-1} \).

### 4.1. Galactic Motions

The majority of the dwarfs in our sample do not have radial velocities. However, we can estimate two out of the three UVW velocities by determining which motion is most dependent on the unknown radial motion from the target location and calculating the other two velocities assuming a radial velocity of zero (Lépine et al. 2013). We tested this procedure with simulations and comparing the global parameters of the subsample with known radial velocities and found no evidence for biases. Together with the 70 objects with measured radial velocities, we find 200, 182 and 164 measurements of \( U, V, \) and \( W \) velocities, respectively. The distributions of these three velocity components are shown as histograms in Figure 3.

### 4.2. Velocity Distributions

We first examine the velocity distribution properties in the Galactic reference frame, i.e., the average values and the dispersions of all \( U, V, \) and \( W \) components. To exclude high-velocity objects, we use 3\( \sigma \) clipping in all of the \( U, V, \) and \( W \) distributions. If an object is rejected from one of these velocity components, it will also not be used in the other two components. An iterative process was employed to produce a clean final sample yielding 21 outliers and 217 tracers. The trimmed tracer numbers \((n_t)\) for \( U, V, \) and \( W \) components are 181, 167, and 145. Their average velocities \((\bar{v})\) and dispersions \((\sigma)\) are listed in Table 3. In Figure 3, we see the trimmed sample dwarfs are well matched to Gaussian distributions. A Kolmogorov–Smirnov test of the
Figure 3. Distributions of $U$, $V$, and $W$ velocity components with their best fitted Gaussian curves (dotted-dashed lines). The solid gray histograms are for the whole sample, and those within the black solid lines are for the trimmed sample.

distributions indicates the untrimmed data is not Gaussian at the 95% level, while the trimmed samples are, from which we conclude the cleaning process is required.

Our velocity data are all heliocentric, so the average value of the sample reflects the anti-motion of the solar system relative to these dwarfs. Using our dwarfs for reference, we find $(U, V, W) = (7.9 \pm 1.7, 13.2 \pm 1.2, 7.2 \pm 1.0) \text{ km s}^{-1}$. These average values agree within $2\sigma$ of recent literature results for the solar motion, e.g., Schönrich et al. (2010) re-examine the HIPPARCOS data and conclude that $(U, V, W) = (11.10^{+0.69}_{-0.75}, 12.24^{+0.47}_{-0.37}, 7.25^{+0.37}_{-0.36}) \text{ km s}^{-1}$, with additional systematic uncertainties $\sim (1, 2, 0.5) \text{ km s}^{-1}$, and Huang et al. (2015) derive $(U, V, W) = (7.01 \pm 0.20, 10.13 \pm 0.12, 4.95 \pm 0.09) \text{ km s}^{-1}$, based on radial velocities from the LAMOST results (Luo et al. 2015). These agreements, especially in the Galactic rotation direction ($V$), indicate that our dwarf sample is not much different from the motion of the local standard of rest.

The velocity dispersions of our sample are $(\sigma_U, \sigma_V, \sigma_W) = (23.0 \pm 1.3, 15.8 \pm 0.9, 12.2 \pm 0.7) \text{ km s}^{-1}$. We compare our values with other velocity dispersions that focus on late M, L, and T dwarfs, e.g., $(30.2, 16.5, 15.8) \text{ km s}^{-1}$ from Zapatero Osorio et al. (2007), $(22, 28, 17) \text{ km s}^{-1}$ from Faherty et al. (2009), $(25, 23, 20) \text{ km s}^{-1}$ from Schmidt et al. (2010) and $(33.8, 28.0, 16.3) \text{ km s}^{-1}$ from Seifahrt et al. (2010). Our results are consistent but systematically smaller than these literature values. These differences might be due to small sample sizes, incomplete outlier exclusion or, as we require there to be a parallax determination, our sample will be biased to brighter, hence younger examples.

4.3. Kinematical Age Estimation

Because there are various heating processes in the dynamic evolution of the disk, it was found that there is a monotonic increase of the velocity dispersion with the mean age of a given stellar population (Wielen 1977).

We use two methods to find ages from this empirical relation. First, we employ the velocity-dependent diffusion relationship of Wielen (1977), Equation (13) for age <3 Gyr:

$$\tilde{\sigma}_v(\tau) = (\sigma_0^3 + 1.5\gamma_v\tau)^{1/3},$$

(1)

where $\tau$ is the statistical age measured in Gyr, $\sigma_0 = 10 \text{ km s}^{-1}$, $\gamma_v = 1.4 \times 10^4 (\text{km s}^{-1})^3 \text{Gyr}^{-1}$, and $\tilde{\sigma}_v$ is the total velocity dispersion measured by $W$-weighted velocity dispersion of all three components. The dispersion results, together with the number of dwarfs with $W$-velocity ($n_W$), are listed in Table 3. For $\tilde{\sigma}_v = 32.0 \pm 0.7 \text{ km s}^{-1}$, we obtain the age of our sample as 1.5 ± 0.1 Gyr.

Second, we follow the development in Binney & Tremaine (2008) via the power-law relation

$$\sigma_v(\tau) = \sigma_0 \left(10 \text{ Gyr} + \tau_1\right)^{\beta},$$

(2)
where \( \sigma_v \) is the unweighted total velocity dispersion, and we used all six best-fit parameter sets of \( v_{10}, \tau_1 \) and \( \beta \) in Table 2 of Aumer & Binney (2009) to provide an average age in \( \tau \). With \( \sigma_v = 30.5 \pm 1.7 \text{ km s}^{-1} \), we find \( \tau = 1.7 \pm 0.3 \text{ Gyr} \). The results of both of the above methods are consistent. This timescale is roughly eight times longer than the orbital period of the Galactic rotation at the solar position, so our sample dwarfs should be kinematically mixed with the disk, which is also expressed by the velocity dispersion ratios.

In Table 4, we list age estimations from the literature that use the same methods as here, but with different samples. The estimated kinematic ages for nearby low-mass stars and brown dwarfs have a large spread; however, our sample is found to be significantly younger. We note that our kinematic age estimation is directly related to the total velocity dispersion. Velocity dispersion can be affected by the sample size, sample population, and peculiar objects with large velocity etc. In Table 4, each sample—late M dwarfs, small samples, color
selected objects—have characteristics that could produce larger velocity dispersions. Our sample is significantly larger than those in Table 4, and the outlier rejection is crucial to remove contamination by thick disk or halo objects. With this in mind, we review the 21 rejected outliers.

Comparing the $J-K_s$ colors of the selected and rejected samples, we find that the median value of the 21 outliers is 0.2 mag bluer than that of the normal dwarfs, although both outliers and the normal dwarf sample have large dispersions in $J-K_s$ color. This finding is consistent with the result of Burgasser et al. (2015) that unusually blue L-dwarfs have a large velocity dispersion. Because our goal is to have a tracer sample and not a volume-complete sample, we believe a rejection of 10% should not form a significant bias, hence we are confident of our rejection criteria.

Figure 8 of Burgasser (2004) shows that the median age of late M and very early-L dwarfs, where you still have main-sequence objects, is ~4 Gyr, while mid- to late-Ls have a median age below 2 Gyr and T dwarfs have a median age of ~5 Gyr. As our sample is predominantly mid- to late L dwarfs, an age of about ~2 Gyr is therefore not unexpected. We note that Dupuy & Liu (2017) found a young median age of 1.3 Gyr for a sample that is very similar to ours, but using a very different approach that exploits their dynamical masses with luminosities to compare to models. Our selection criteria that required the targets to have a measured parallax, which combined with the normal procedures in building parallax target lists, means that our sample will be biased to brighter candidates, which tend to be younger.

5. Conclusion

In this paper, we report new parallax measurements for 10 L- and early T-type dwarfs using the robotic LT telescope; of these, five had no previous distance determinations. We used the same method as WJS14 adopted for five L dwarfs using the LT SDSS $z_{AB}$ band data. We study their motions, and conclude that they are probably members of the Galactic disk.

The location of our 10 targets in the SpT-Mag diagrams have shown the reliability of our trigonometric parallax measurements. In the 2MASS and WISE absolute magnitude versus spectral type diagrams, we find four LT targets are over-luminous, which are the known binaries 2M0423-0414, 2M1017+1308, 2M1239+5515, and 2M2028+0052.

We combined our sample with the literature L and T dwarfs, compiling a list of 260 objects with measured parallaxes, proper motions, radial velocities (for 70 objects), as well as 2MASS and WISE magnitudes, which are listed in the online table. We study the velocity distribution and the kinematic age of this sample. We derive the solar motion $(U, V, W)_0 = (7.9 \pm 1.7, 13.2 \pm 1.2, 7.2 \pm 1.0) \text{ km s}^{-1}$, which is consistent with the recent literature. The velocity dispersion of our sample is $(\sigma_U, \sigma_V, \sigma_W) = (23.0 \pm 1.3, 15.8 \pm 0.9, 12.2 \pm 0.7) \text{ km s}^{-1}$. The kinematical age of our sample is 1.5–1.7 Gyr, significantly younger than other estimates for the ages of other samples of late M and L dwarfs with the same methods as ours. We believe that this arises because our sample is dominated by mid to late L dwarfs, and, biased to intrinsically brighter, therefore younger, examples. We note that our kinematical age is is consistent with that found in Dupuy & Liu (2017) using different procedures and data.

We thank the referee, Dr Sandy Leggett, for insightful and useful comments on the original submission of this paper. We thank Leigh Smith from the University of Hertfordshire for his help in analyzing the image data; Zhenghong Tang, Yong Yu, and Zhaoxiang Qi from Shanghai Astronomical Observatory for their helpful discussion on the centroiding precision; and Yihan Song from National Astronomical Observatories of China for his helpful discussion on the proper motion transformation. This work is partially funded by IPERCOOL No. 247593 International Research Staff Exchange Scheme and PARSEC No. 236735 International Fellowship within the Marie Curie 7th European Community Framework Programme. R.L.S.’s research was supported by a visiting professorship from the Leverhulme Trust (VP1-2015-063). Y.W. and A.L. acknowledge NSFC grant No. 11233004. Z.S. acknowledges NSFC grant No. 11390373. H.R. acknowledges support from the UK’s Science and Technology Facilities Council (grant No. ST/M001008/1). J.Z. acknowledges NSFC grant No.11503066 and the Shanghai Natural Science Foundation (14ZR144900). This research has benefited from the M, L, and T dwarf compendium housed at Dwarfarchive.org and maintained by Chris Gelino, Davy Kirkpatrick, and Adam Burgasser. This research has benefited from the SpX-Prism Spectral Libraries, maintained by Adam Burgasser at http://www.browndwarfs.org/spexprism. The Liverpool Telescope is operated on the island of La Palma by Liverpool John Moores University in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias with financial support from the UK Science and Technology Facilities Council.

References

Allers, K. N., & Liu, M. C. 2013, ApJ, 772, 79
Aumer, M., & Binney, J. J. 2009, MNRAS, 397, 1286
Basri, G., Mohanty, S., Allard, F., et al. 2000, ApJ, 538, 363

Table 4

| Ref. | Sample | Method | Age (Gyr) |
|------|--------|--------|-----------|
| R1   | 63 M7-M9.5 $d < 20$pc dwarfs | 1 | 3.1       |
| R2   | 43 L dwarfs | 1 | ~5.1      |
| R3   | 16 normal colour late L dwarfs | 1, 2 | 3.4 ~ 3.8 |
| R3   | 28 unusually blue L dwarfs | 1, 2 | 5.5 ~ 6.5 |

Note. Column 1: References: R1: Reiners & Basri (2009), R2: Seifahrt et al. (2010), R3: Burgasser et al. (2015). Column 2: Samples. Column 3: Method 1 from Wielen (1977) and Method 2 from Binney & Tremaine (2008). Column 4: Kinematic ages from different samples.
