Infrared Parallaxes of Young Field Brown Dwarfs and Connections to Directly Imaged Gas-Giant Exoplanets

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We have measured high-precision infrared parallaxes with the Canada-France-Hawaii Telescope for a large sample of candidate young (≈10–100 Myr) and intermediate-age (≈100–600 Myr) ultracool dwarfs, with spectral types ranging from M8 to T2.5. These objects are compelling benchmarks for substellar evolution and ultracool atmospheres at lower surface gravities (i.e., masses) than most of the field population. We find that the absolute magnitudes of our young sample can be systematically offset from ordinary (older) field dwarfs, with the young late-M objects being brighter and the young/dusty mid-L (L3–L6.5) objects being fainter, especially at J band. Thus, we conclude the “underluminosity” of the young planetary-mass companions HR 8799b and 2MASS J1207−39b compared to field dwarfs is also manifested in young free-floating brown dwarfs, though the effect is not as extreme. At the same time, some young objects over the full spectral type range of our sample are similar to field objects, and thus a simple correspondence between youth and magnitude offset relative to the field population appears to be lacking. Comparing the kinematics of our sample to nearby stellar associations and moving groups, we identify several new moving group members, including the first free-floating L dwarf in the AB Dor moving group, 2MASS J0355+11. Altogether, the effects of surface gravity (age) and dust content on the magnitudes and colors of substellar objects appear to be degenerate.

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1 Introduction

Direct detections of young exoplanets are now strengthening the link between the exoplanet and brown dwarf populations, enriching our understanding of both classes of objects. At the same time, recent exoplanet discoveries display puzzling spectrophotometric properties, with exceptionally red colors, peculiar near-IR spectra, and fainter absolute magnitudes compared to field brown dwarfs (e.g., Marois et al. 2008, Bowler et al. 2010, Barman et al. 2011). Brown dwarfs have long been considered valuable laboratories for discerning the physical properties of gas-giant planets, which are much more difficult to study directly. And yet the first examples of directly imaged planets, such as those around the young A star HR 8799 and the binary companion 2MASS J1207−39b, appear to be discrepant with field brown dwarfs. And thus we are faced with the conundrum of how to integrate both classes of objects into a common understanding of substellar evolution.

One promising approach is to identify robust free-floating analogs to gas-giant planets in the solar neighborhood. The initial mass function in the young star-forming clusters appear to go down to a several Jupiter masses (e.g., Caballero et al. 2007, Lodieu et al. 2008), and thus such low mass objects should be found in the field after departing their birth sites. At fixed effective temperature, young (≈10–100 Myr) field brown dwarfs will have larger radii and lower masses than older field objects. The combination of these two factors means a reduction in surface gravity by a factor of ≈10. Some possible examples of young planet analogs are the rare late-M and L-type field dwarfs with very red, dusty photospheres and/or signs of low surface gravity in their optical and near-IR spectra. While these objects have been studied spectroscopically, parallax measurements have been lacking, representing a key information gap in characterizing these objects.

2 Observations

Since 2007 we have been conducting a high-precision parallax program at the 3.6-meter Canada-France-Hawaii Telescope (CFHT) using the facility wide-field IR camera WIRCam (Puget et al. 2004). CFHT offers a nearly ideal platform for parallaxes, given its combination of large aperture, excellent seeing, and queue scheduling, though to our knowledge it had not been used for parallaxes prior to our effort. As described in Dupuy & Liu (2012), our measurements are as good as have ever been achieved in the near-IR, producing parallaxes with typical uncertainties of 1.3 mas and as good as 0.7 mas, but for objects ≈2–3 mags fainter than have been measured by previous work.

This combination of faint limiting infrared magnitudes and high precision is relevant for studying young field...
brown dwarfs. Since such objects are a small minority population, their typical distances will be larger than ordinary (older) field object. Furthermore, the stellar members of even the nearest young moving groups can extended to distances of \( \approx 60 \) pc (e.g. Torres et al. 2008). This is quite far compared to previous brown dwarf parallax programs. For instance, among \( \geq \)L4 dwarfs (corresponding to the stellar/substellar boundary in the field), no objects had high precision parallaxes (\( \leq 3\% \) uncertainties) beyond 13 pc prior to our CFHT effort.

Our ongoing CFHT program is monitoring candidate young field objects with spectral types of M6 and later that have been identified from a variety of sources, primarily candidate members of nearby young (<300 Myr) stellar associations and field objects whose optical and near-IR spectral peculiarities are thought to arise from surface gravity effects. Our sample contains three subsets:

1. **Low-gravity ultracool field objects:** We selected targets from SDSS or 2MASS-based searches for ultracool dwarfs in the solar neighborhood have been flagged as low gravity based on their optical and/or near-IR spectra (e.g., Cruz et al. 2007, Reid et al. 2008, Kirkpatrick et al. 2008, Shkolnik et al. 2009, Allers et al. 2010).

2. **Stellar association members:** Our sample includes candidate members of the TW Hya Association (TWA; 8–10 Myr), Pleiades moving group (120 Myr), Ursa Major moving group (500 Myr), and Hyades cluster (625 Myr). These candidates have been identified in the literature based on their common kinematics with the stellar members of these groups.

3. **Extremely red L dwarfs:** A small number of field L dwarfs show extremely red near-IR colors and peculiar near-IR spectra. The archetype for this genre is 2MASS J2244+20, which has an ordinary L6.5-type optical spectrum but a very unusual near-IR spectrum, distinguished by its much redder color, stronger CO, and more peaked \( H \)-band continuum shape compared to other field objects (Kirkpatrick et al. 2000, McLean et al. 2003). Kirkpatrick et al. (2008) conclude this is young field object based on its near-IR SED, as opposed to an ordinary (high gravity) object with extreme clouds. Allers & Liu (2012) scrutinize its near-IR spectrum and also conclude this object is young.

Our methods for obtaining high-precision astrometry from CFHT/WIRCam images are detailed in Dupuy & Liu (2012). Our young sample has a time baseline of \( \approx 1.5–3.0 \) years with 7–12 observing epochs per object (e.g., Figure 1). In all cases, the \( \chi^2 \) value of the fit (proper motion + parallax) is commensurate with the number of degrees of freedom in each dataset, validating the accuracy of our astrometric errors. The median parallax uncertainty for the young sample presented here is 1.4 mas (5% in the distances), with a median distance of 31 pc.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig1.png}
\caption{One of our CFHT parallax measurements, for the young L5\textsubscript{\gamma} object 2MASS J0355+11. The top and middle panels show relative astrometry in \( \delta \) and \( \alpha \), respectively, as a function of Julian year after subtracting the best-fit proper motion. (This is for display purposes only; our analysis fits for both the proper motion and parallax simultaneously.) The bottom panel shows the residuals after subtracting both the fitted parallax and proper motion, leaving a RMS scatter per epoch of 3.3 mas. After statistically accounting for the finite parallax of the background stars using a galactic population model, the resulting absolute parallax is \( 109.6 \pm 1.3 \) mas, with \( \chi^2 = 16.3 \) (11 degrees of freedom).}
\end{figure}

3 Absolute Magnitudes

Figure 2 shows the absolute magnitudes of our sample determined from CFHT parallaxes, as a function of spectral type. Many of the young field objects have \( J \)-band absolute magnitudes \( M(J) \) that are displaced from the locus of field dwarfs, but the displacement varies with spectral type. The late-M young objects tend to be brighter in \( M(J) \) than the field objects, with the early-L dwarfs being comparable, and the mid-L dwarfs being fainter. The faintest object in \( J \)-band is the primary component of the young L3.5 binary SDSS J2249+00A (Allers et al. 2010), which is about 1.5 magnitudes fainter than field objects of comparable spectral type. Therefore, the fainter \( J \)-band absolute magnitudes of the young planetary-mass companions HR 8799b and 2MASS J1207–39b compared to field dwarfs are also manifested in young free-floating brown dwarfs.

However, perhaps a comparably interesting result is the large fraction of our young targets which do not have significantly different absolute magnitudes than the field sample, despite having spectroscopic indications of low surface gravity. Almost none of our M9–L2 objects are fainter than the field sequence within the measurement uncertain-
Fig. 2  $J$-band absolute magnitudes of our young sample on the MKO system. The spectral types are all based on optical data, except for the Hyades early-T dwarf CFHT-Hy-20 (Bouvier et al. 2008) which has a near-IR type. In the upper panel, the uncertainties in the absolute magnitudes are typically smaller than the plotting symbols. The thick black line shows the fit from Dupuy & Liu (2012) for field ultracool dwarfs, and the light grey swath represents the 1σ scatter about the fit. The lower panel shows the difference of the data with respect to the polynomial fit. The integrated-light datum for the young binary SDSS J2249+00AB (Allers et al. 2010) is shown as an open circle and the resolved data for component A as a filled colored circle, with grey vertical lines connecting the two circles. (We assume the optical spectral type of component A is the same as the integrated-light type.)

Fig. 3  Infrared color-magnitude diagram on the MKO system showing our young sample compared to normal field dwarfs, with the latter from from Dupuy & Liu (2012). The young substellar companions HD 8799bcd (Marois et al. 2008) and 2MASS J1207−39b (Chauvin et al. 2005) are also plotted. In this plot, low surface gravity objects of different classifications are all represented by the red square. Candidate moving group members from the literature are labeled as “MG?” in the legend.

termixed with the field sequence in the near-IR CMD, despite their low gravity optical spectra.

4 New AB Dor Member 2MASS J0355+11

By combining our parallaxes and proper motions with radial velocity data in the literature, we can assess whether the 6-dimensional locations (space velocity and position) of our targets are consistent with any young moving groups or stellar associations. Such linkages would establish the ages of the ultracool dwarfs, by adopting the ages estimated for the stellar members, and thereby calibrate the time dependence of gravity-dependent spectral features and delineate empirical isochrones of substellar evolution. Also, such linkages would add to the low-mass census of these groups, which is known to be incomplete for optically faint members (e.g., Shkolnik et al. 2011).

We have identified several low-mass members of nearby young moving groups, some previously flagged as candidates without using parallax data and others as completely new linkages (Liu et al. 2013). One such object is
the nearby L dwarf 2MASS J0355+11, one of the reddest L dwarfs found from 2MASS by Reid et al. (2008) and optically classified as L5\(\gamma\) by Cruz et al. (2009). We measure a parallax of 109.6 ± 1.3 mas (9.10 ± 0.10 pc), making it the nearest known young brown dwarf.

Using the radial velocity from Blake et al. (2010), we associate 2MASS J0355+11 with the AB Dor moving group, given its similar space position to known members and the small \((U, V, W)\) difference with the group (Figure 4). This suggests the \(\gamma\) gravity classification for mid-L dwarfs corresponds to an age of \(\approx100\) Myr, as determined for the AB Dor moving group (Torres et al. 2008). This is older than the speculation of Cruz et al. (2009) that their lowest gravity objects (\(\gamma\)) have ages closer to \(\approx10\) Myr while the intermediate-gravity objects (\(\beta\)) are closer to \(\approx100\) Myr. In addition, this age estimate combined with the bolometric luminosity of the object indicate a mass of \(\approx25\ M_{\text{Jup}}\) based on models by Chabrier et al. (2000).

Contemporaneous with our Cool Stars 17 presentation, Faherty et al. (2012) presented a parallax of \(134 \pm 12\) mas \((7.5^{+0.6}_{-0.5}\) pc) for 2MASS J0355+11, based on infrared astrometry from the CTIO Blanco 4-m Telescope. As a result, they find that 2MASS J0355+11 is not associated with any known young moving groups, thereby concluding that its age and mass are indeterminate. The difference between their results and ours arises from the parallaxes, with their CTIO and our CFHT measurements differing by \(2\sigma\). While the statistical difference is relatively modest, the \(\approx10\times\) higher precision of our CFHT parallax enables a more robust assessment of the kinematics.

Compared to field L dwarfs, 2MASS J0355+11 is redder than the field CMD locus (Figure 3) and fainter (0.7 mag) than other L5 dwarfs (Figure 2). However, it is still \(\approx2\) magnitudes brighter than the directly imaged planets. Indeed, there are other objects in our CFHT sample that have even fainter absolute magnitudes and comparably red colors, but their kinematics do not suggest they are young – the effects of dust and age appear to be degenerate in such data. Overall, while some of the objects in our sample have atypical, or perhaps even extreme, SEDs compared to most field objects, none of them coincide in their colors and magnitudes with the exoplanets directly imaged to date.

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