THE COOLEST ISOLATED BROWN DWARF CANDIDATE MEMBER OF TWA

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ABSTRACT

We present two new late-type brown dwarf candidate members of the TW Hydrae association (TWA): 2MASS J12074836-3900043 and 2MASS J12474428-3816464, which were found as part of the BANYAN all-sky survey (BASS) for brown dwarf members of nearby young associations. We obtained near-infrared (NIR) spectroscopy for both objects (NIR spectral types are respectively L1 and M9), as well as optical spectroscopy for J1207-3900 (optical spectral type is L0y), and show that both display clear signs of low gravity, and thus youth. We use the BANYAN II Bayesian inference tool to show that both objects are candidate members to TWA with a very low probability of being field contaminants, although the kinematics of J1247-3816 seem slightly at odds with that of other TWA members. J1207-3900 is currently the latest-type and the only isolated L-type candidate member of TWA. Measuring the distance and radial velocity of both objects is still required to claim them as bona fide members. Such late-type objects are predicted to have masses down to 11–15M_\text{Jup} at the age of TWA, which makes them compelling targets to study atmospheric properties in a regime similar to that of currently known imaged extrasolar planets.

Key words: brown dwarfs – proper motions – stars: kinematics and dynamics

Online-only material: color figures

1. INTRODUCTION

The known population of brown dwarfs (BDs) has significantly increased in the last decades due to all-sky near-infrared (NIR) surveys such as the Two Micron All Sky Survey (2MASS) and WISE (Skrutskie et al. 2006; Wright et al. 2010). The accumulation of a large number of BDs allowed for a better understanding of the underlying physics in their atmospheres, which went along with the development of increasingly more realistic atmosphere models (Baraffe et al. 2003; Saumon & Chabrier 2006; Allard et al. 2013) and empirical spectral classification schemes (Kirkpatrick et al. 1991; Cushing et al. 2005; Burgasser et al. 2006; Cruz et al. 2009; Allers & Liu 2013). These tools in turn allowed the identification of peculiar BDs, most of which are now recognized as having atypical metallicity or surface gravity.

Low surface gravity BDs are thought to be younger than several hundred million years since they have not yet reached their equilibrium radii (Burrows et al. 2001). The youngest and latest-type of these objects are believed to have cool, low-pressure atmospheres similar to those of currently known imaged gaseous giant exoplanets, but only a few of those are known in the solar neighborhood (e.g., 2MASS J03552337+1133437; Faherty et al. 2013; PSO J318.5338-22.8603; Liu et al. 2013b; CFBDsIR 2149-0403; Delorme et al. 2012). Hence, atmosphere models for such physical conditions are still subject to poor empirical constraints (e.g., the behavior of dust in these low-pressure environments). While the luminosity, equivalent width of atomic lines, and shape of the continuum can be used to identify young BDs, there is no evidence yet that those can be used to narrowly constrain ages (Allers & Liu 2013). Therefore, assembling an age-calibrated sample identified by kinematics could potentially help in addressing this in an empirical way. Given their relative proximity, nearby, young associations (NYAs) such as TW Hydrae (TWA; Zuckerman & Song 2004) are perfect test benches for such empirical calibrations. The search for late-type objects in NYAs has been the subject of many efforts (Zuckerman & Song 2004; Looper et al. 2007; Torres et al. 2008; Malo et al. 2013); however, their late-type (>M5) population is poorly constrained. To address this further, Gagné et al. (2014; called G2014 hereafter) developed Bayesian Analysis for Nearby Young AssociationNs II (BANYAN II), a tool based on Malo et al. (2013) that uses naive Bayesian inference to identify late-type candidate members to such NYAs from their sky position, proper motion and photometry. Using this new tool, our team has initiated the BANYAN all-sky survey (BASS) that generated hundreds of >M5 candidate members of NYAs from the 2MASS and WISE surveys, using both catalogues as a baseline for a proper motion measurement. The current status of this project is described in more detail in Gagné et al. (2013).

Here, we present two of the potential latest-type and lowest-mass objects that were identified as candidate members to TWA from this all-sky survey: 2MASS J12474428-3816464 (M9; J1247-3816 hereafter) and 2MASS J12074836-3900043 (L1; J1207-3900 hereafter), with NIR spectral types M9 and L1, respectively. We present NIR SpeX spectroscopy for the two objects, as well as optical MAGE spectroscopy for J1207-3900 in Section 3.1. In Section 3.2, we show evidence that both have low surface gravity, and we use the

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BANYAN II tool in Section 3.3 to show that both objects are likely members of TWA with a small probability of being young field contaminants, but that J1247-3816 seems to display slightly discrepant kinematics.

2. SPECTROSCOPY

2.1. NIR Spectroscopy

We have obtained SpeX (Rayner et al. 2003) NIR spectroscopy for J1207-3900 and J1247-3816 at the IRTF telescope on 2013 May 10. Observations were obtained under a typical seeing of 0.6 arcsec. We used the prism disperser with the 0.8′′ slit for both objects, yielding a resolution R ~ 95 over 0.8 to 2.5 μm. Four exposures of 200 s for J1207-3900 and 180 s for J1247-3816 were sufficient to reach a signal-to-noise ratio (S/N) per resolution element of ~240 for both objects. We have subsequently obtained an R ~ 750 spectrum for J1207-3900 in the cross-dispersed mode with the 0.8′′ slit on 2013 May 14 to measure the equivalent width of several atomic lines and better constrain its low gravity using the approach of Allers & Liu (2013; see Section 3.2). Ten exposures of 200 s yielded an S/N per resolution element of ~65. Individual exposures were reduced by subtracting dithered sequences along the slit, extracting both traces and correcting for telluric absorption with A0-type standards, using the SpeXtool IDL package (Cushing et al. 2004; Vacca et al. 2003). The NIR spectra for both objects are displayed in Figure 1.

2.2. Optical Spectroscopy

In addition to the NIR spectroscopy described in the previous section, we have obtained optical spectroscopy for J1207-3900 on 2013 May 14 with MagE at the Magellan telescope to compare it with standard optical templates of low-gravity BDs (Cruz et al. 2009). We used the 0.7′′ slit and 2800 s of exposure to obtain an R ~ 5800 spectrum in the 5500–10300 Å range with an S/N per resolution element of ~16. Individual exposures were reduced in a similar manner than described in the previous section by using the MASE IDL package (Bochanski et al. 2009). The optical spectrum of J1207-3900 is presented in Figure 2.

3. RESULTS AND DISCUSSION

3.1. Spectral Classification

We used the method of K. Cruz et al. (in preparation) to median-combine all NIR spectra from Allers & Liu (2013) by spectral type to create individual NIR spectroscopic templates for intermediate-gravity (INT-G) objects in the M8–L3 range, as well as very low gravity (VL-G) objects in the M6–L4 range. We used objects that were classified as having a normal surface gravity, as well as medium-resolution spectra from the SpeX Prism library to build field NIR templates in the M5–L9 range. We then assigned spectral types to both objects by visually comparing their spectra band-by-band with those composite spectroscopic templates (see Figure 1). We find that the M9 VL-G template is clearly the best match to J1247-3816 and that the L1 INT-G and L1 VL-G templates are equally good matches to J1207-3900. We have visually assigned uncertainties of ±0.5 and ±1 subtypes, respectively. If we restrict our comparison to field NIR standards only, we also find that M9 and L1 spectral types are the best matches; however, we would have assigned larger uncertainties to them. We also directly compared the spectra of the two candidates to the latest currently known TWA members and candidates (TWA 28, M8.5 member; TWA 26, M9 member; and TWA 29, M9.5 candidate; see Mamajek & Looper 2007) to confirm our results.

We have subsequently compared the MAGE optical spectrum to several field and young M8 to L5 optical templates (Stauffer et al. 2003; Reid & Gizis 2005; Burgasser & McElwain 2006; Reid et al. 2008) to find that the best match are LHS 2924 (a field M9), KPNO-Tau 4 (a young M9.5 BD in the Taurus star forming region; 1–10 Myr; Briceño et al. 2002) and 2MASS 0141-4633 (a young L0V candidate member of the 10–40 Myr Tucana-Horologium association; Kirkpatrick et al. 2006, G2014). The continuum redder of 8500 Å matches 2MASS 0141-4633 better, however J1207-3900 clearly shows a VO band at 7450 Å which is deeper than that of 2MASS 0141-4633, and similar to that of KPNO-Tau 4. This is consistent with J1207-3900 having a similar spectral type to 2MASS 0141-4633 while being slightly younger. We thus assign it an optical classification of L0V (see Figure 2).

3.2. Signs of Low Gravity

We used the NIR gravity classification scheme described in Allers & Liu (2013; based on the gravity-sensitive equivalent widths of the K1, Na1, and continuum features) to analyze the NIR spectra presented here and find that, based on a comparison to other objects of the same spectral type, both objects are clearly VL-G objects (see Figure 3), as expected from the visual comparison with low gravity dwarfs. The MAGE spectrum of J1207-3900 was subsequently used in deriving various gravity-dependent indices described in Cruz et al. (2009; e.g., K-a, K-b, Na-a, Na-b), which also point toward low surface gravity. We used the IRSA dust extinction tool (2007) to verify that both objects are not significantly reddened by interstellar dust along the line of sight, which could potentially mimic some signatures of low gravity. We find that J1207-3900 and J1247-3816 respectively lie in regions of the sky where the E(B − V) extinction is low at 0.0687 ± 0.0035 mag and 0.0492 ± 0.0014 mag, using a 5 arcmin search radius (Schlafly & Finkbeiner 2011).

3.3. TWA Membership

We have applied the BANYAN II tool described in G2014 to assess the probability that both objects considered here are members of NYAs. We used their sky position, proper motion, spectral types, as well as 2MASS and WISE photometry as input observables in this analysis, which are then compared to the spatial and kinematic models of each hypothesis considered (TWA, β Pictoris, Tucana-Horologium, Columba, Carina, Argus, AB Doradus, and the field) using a naive Bayesian classifier. The spatial and kinematic models are built by fitting the spatial XYZ and U/V/W distribution of known bona fide members or synthetic objects from the Besançon Galactic model (A. C. Robin et al., in preparation; Robin et al. 2012) with three-dimensional ellipsoids that are free to rotate along any axes. Following our conclusion that both systems are low gravity dwarfs, we have
assumed conservatively that they are younger than 1 Gyr in the construction of the field hypothesis. Using this tool, we find that J1207-3900 and J1247-3816 are both candidate members of TWA with Bayesian probabilities of 99.6% and 29.4%, respectively. In an ideal case where quantities input in BANYAN II are strictly independent, the Bayesian probability should represent the best estimate of the probability that a given star be a member of a given NYA, taking into account all available evidence (i.e., data input in the Bayesian inference tool). However, as described in G2014, the Bayesian probabilities determined this way are biased when quantities fed to BANYAN II (which consists of a naive Bayesian classifier) are not strictly independent, which is generally the case in our analysis. A Monte Carlo analysis was thus performed to estimate the unbiased probability
that a given object is a field contaminant based on its Bayesian probability. Here, we applied this analysis and found very low field contamination probabilities of 0.004% and 0.002%, respectively (meaning that our present Bayesian probabilities are conservative estimates). In Table 1 we show the radial velocities \( v_r \) and distances \( d_\ast \) predicted by BANYAN II, according to the hypotheses that they are actual members of TW A or the field. These estimates were shown by G2014 to be accurate to 8% and 1.6 km s\(^{-1}\), respectively, when membership is confirmed.

We have compared our results to those of BANYAN I (without using photometry as an observable; see Malo et al. 2013), as well as the convergent point analysis (CPA; see Rodriguez et al. 2013). In the case of J1207-3900, BANYAN I yields a membership probability of 99.94% for TW A and 0.06% for the field with predictions \((v_r = 9.78 \pm 2.2 \text{ km s}^{-1}, d_\ast = 54.0 \pm 5.6 \text{ pc})\) for TW A, whereas the CPA yields a 91.6% probability for TW A, 100% probability for \( \beta \) Pictoris, and 81.1% probability for Columba with respective predictions \((v_r = 6.8 \pm 0.5 \text{ km s}^{-1}, d_\ast = 69.6 \pm 6.5 \text{ pc})\). Probabilities from BANYAN I are generally higher than those from BANYAN II because prior probabilities were set to unity in their analysis, whereas prior probabilities in BANYAN II are smaller to reflect the smaller populations of NYAs compared to that of the field. Furthermore, we stress the fact that even BANYAN II probabilities as low as \( P_{\text{HL}} \sim 20\% \) for any NYA must be considered as potentially significant, since such values are often found for several known bona fide NYA members that lie \( 1\sigma \sim 2.5\sigma \) away from the spatial and kinematic locus of bona fide members (see G2014). Probabilities yielded by the CPA are determined individually for each NYA, which means that the total probability can be larger than 100%. Thus, both versions of BANYAN agree very well, but the CPA would place J1207-3900 as an ambiguous candidate amongst \( \beta \) Pictoris, TW A, and Columba. We do not consider that J1207-3900 to be a viable candidate for \( \beta \) Pictoris or Columba, since it has been shown by G2014 that such cross-contamination from those two associations to TW A are lower than 3%, even for low probability TW A candidates. The CPA tool does not consider spatial information or the magnitude of proper motion, and thus often cannot differentiate between a few NYA hypotheses without a radial velocity measurement, especially when their convergent points are close one to another on the celestial sphere, which is the case for TW A, \( \beta \) Pictoris, and Columba.

In the case of J1207-3900, BANYAN II yields a membership probability of 87.59% for TW A and 12.41% for the field, with predictions \((v_r = 7.25 \pm 2.57 \text{ km s}^{-1}, d_\ast = 55.5 \pm 5.9 \text{ pc})\) for TW A, and the CPA yields 99.5% for TW A, 98.7% for \( \beta \) Pictoris, and 96.0% for Columba, with respective predictions \((v_r = 4.0 \pm 0.1 \text{ km s}^{-1}, d_\ast = 120.7 \pm 1.2 \text{ pc})\) and \((v_r = 9.5 \pm 0.1 \text{ km s}^{-1}, d_\ast = 141.0 \pm 1.2 \text{ pc})\). We note that the relatively smaller probabilities yielded by BANYAN as well as the very large predicted distances from the CPA can both be seen as a consequence of the fact that J1207-3916 has a slightly deviant proper motion compared to TW A members at this sky position. Effectively, the most probable scenario yielded by BANYAN II places this object at a Galactic position and space velocity \((X, Y, V)\) of, respectively, 32.6 \pm 3.6 \text{ pc}, \(-51.9 \pm 5.7 \text{ pc}, 28.0 \pm 3.1 \text{ pc}\), \(-2.8 \pm 2.4 \text{ km s}^{-1}\), \(-15.4 \pm 2.3 \text{ km s}^{-1}\), and \(-0.8 \pm 2.9 \text{ km s}^{-1}\) at respectively \( 1\sigma \) and \( 2\sigma \) from the spatial and kinematic models used in BANYAN II. The CPA tool, which is purely kinematic, places J1207-3916 at a larger distance so that it ends up with kinematics closer to those of TW A (at 0.7 pc) and \( \beta \) Pictoris, and Columba.

Schneider et al. (2012) point out that the Lower Centaurus Crux complex is a possible source of contamination for TW A; however, it is located at \( \sim 120 \text{ pc} \) (farther than typical TW A members at \( \sim 50 \text{ pc}\)). Most probable distances derived from BANYAN II for both the TW A and field hypotheses place J1207-3900 and J1207-3816 at distances of \( \sim 60 \text{ pc} \) either for TW A or the field hypothesis, which is not compatible with them being at such a large distance. We conclude that J1207-3900 should be considered as the first isolated L dwarf candidate.
Figure 3. Spectral indices as defined by Allers & Liu (2013) for J1207-3900 and J1247-3816 (red dots), compared to known TW A members (blue dots), the field sequence (thick, black line), and its scatter (beige shaded region). The dotted line represents the delimitation between intermediate (INT-G) gravity and very low gravity (VL-G) regimes. Both candidates have spectral indices consistent with TW A members. Spectral types were offset by small (0.15) random subtypes so that vertical error bars can be distinguished. All indices displayed here for J1207-3900 and J1247-3816 were measured using the SpeX prism spectra, except for the FeH index which was measured with the cross-dispersed spectrum. The spectra of known TW A members in this figure are those of TW A 22 A (M5) and TW A 34 (M6) obtained respectively from Bonnefoy et al. (2009) and J. Gagné et al. (in preparation), as well as TW A 27 A (M8), TW A 26 (M9), TW A 28 (M8), and TW A 29 (M9) obtained from Allers & Liu (2013).

We have compared these same distance estimates yielded by BANYAN II as well as 2MASS and WISE NIR photometry to the AMES-COND isochrones (Baraffe et al. 2003) in combination with CIFIST2011 BT-SETTL atmosphere models (Allard et al. 2013; Rajpurohit et al. 2013) in a likelihood analysis, while assuming the age of TW A (8–12 Myr), to estimate the masses of both components. We find that J1207-3900 is thus a candidate 11–13 $M_{\text{Jup}}$ BD and J1247-3816 is a candidate 14–15 $M_{\text{Jup}}$ BD.

Both new candidates presented here bring the opportunity of extending the population of TW A members redward in a color–magnitude diagram, up into the L dwarf regime. In Figure 4, we show an NIR color–magnitude diagram comparing current TW A members in the literature to field stars and new TW A candidates. In the cases where a trigonometric distance is not available (e.g., for both candidates presented here), we used BANYAN II to produce a statistical distance estimate corresponding to the kinematics of TW A and used it to compute a statistical absolute magnitude. It can be seen that the TW A sequence is shifted toward redder colors (for late-type objects) and brighter absolute magnitudes (for early-type objects) compared to the field sequence, which is consistent with current evidence on the atmospheric properties of young systems (Faherty et al. 2012; Liu et al. 2013a), whereas the membership of J1247-3816 is more ambiguous: its kinematics would tend to place it farther away than TW A while its luminosity would place it no farther than ~60 pc. This object could be a contaminant to TW A from a young association not included in BANYAN II.
Figure 4. Color–magnitude sequence for all known primary TWA members and field stars from the CNS3 catalog (Gliese & Jahreiß 1991) and Trent Dupuy’s Database of Ultracool Parallaxes (black dots; Dupuy & Liu 2012). We used parallax measurements for TWA candidates when they were available (pink down-side triangles; van Leeuwen 2007; Teixeira et al. 2008; Weinberger et al. 2013; Ducourant et al. 2014), or otherwise statistical predictions from BANYAN II (purple circles). J1247-3816 (left-pointing blue triangle) also rely on distance predictions from BANYAN II, and appear as an extension of the TWA sequence into the L dwarfs regime. (A color version of this figure is available in the online journal.)

J1207-3900 and J1247-3816 are similarly redder toward the field dwarf sequence, and extend the TWA sequence.

4. CONCLUDING REMARKS

The two new candidates to TWA presented here were discovered as part of BASS, an all-sky survey for late-type low-mass stars and BDs in NYAs based on the 2MASS and WISE catalogs. This survey has already identified other young objects such as 2MASS J01033563-5515561 ABb (see Delorme et al. 2013). Several hundreds of >M5 candidates identified in the same way are currently being followed and results will be published in an upcoming paper (see Gagné et al. 2013 for more information).

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