A SEARCH FOR HIGH PROPER MOTION T DWARFS WITH Pan-STARRS1 + 2MASS + WISE

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ABSTRACT

We have searched ≈8200 deg2 for high proper motion (∼0′.5–2′ year−1) T dwarfs by combining first-epoch data from the Pan-STARRS1 (PS1) 3σ Survey, the Two Micron All Sky Survey (2MASS) All-Sky Point Source Catalog, and the WISE Preliminary Data Release. We identified two high proper motion objects with the very red (W1 – W2) colors characteristic of T dwarfs, one being the known T7.5 dwarf GJ 570D. Near-IR spectroscopy of the other object (PSO J043.5395+02.3995) reveals a spectral type of T8, leading to a photometric distance of 7.2 ± 0.7 pc. The 2′.56 year−1 proper motion of PSO J043.5+02 is the second highest among field T dwarfs, corresponding to a tangential velocity of 87 ± 8 km s−1. According to the Besançon galaxy model, this velocity indicates that its galactic membership is probably in the thin disk, with the thick disk an unlikely possibility. Such membership is in accord with the near-IR spectrum, which points to a surface gravity (age) and metallicity typical of the field population. We combine 2MASS, Sloan Digital Sky Survey, WISE, and PS1 astrometry to derive a preliminary parallax of 171 ± 10 mas (5.8±2.0−1.2 pc), the first such measurement using PS1 data. The proximity and brightness of PSO J043.5+02 will facilitate future characterization of its atmosphere, variability, multiplicity, distance, and kinematics. The modest number of candidates from our search suggests that the immediate (∼10 pc) solar neighborhood does not contain a large reservoir of undiscovered T dwarfs earlier than about T8.

Key words: brown dwarfs – proper motions – solar neighborhood – surveys

Online-only material: color figures

1. INTRODUCTION

The Pan-STARRS1 (PS1) survey (Kaiser et al. 2010) represents the first of a new generation of multi-epoch digital sky surveys. In an effort to identify nearby T dwarfs and rare ultracool dwarfs of interest, we are conducting a proper motion search that combines the first epoch of PS1 data with the Two Micron All Sky Survey (2MASS) with initial results from PS1 commissioning data in Deacon et al. (2011). In this Letter, we present the discovery of a very high proper motion late-T dwarf, PSO J043.5395+02.3995 (hereinafter PSO J043.5+02). This object has independently been identified by Scholz et al. (2011) in a search for bright, very red objects in the WISE Preliminary Data Release with proper motions of ∼0′.3 year−1. They estimated a spectral type of T8–T10 based on the (W1 – W2) color, a photometric distance of 5.5±2.0−1.6 pc, and possible thick disk membership. Our near-IR spectroscopy gives a spectral type of T8, a photometric distance of 7.2 ± 0.7 pc, and probable thin disk membership.

2. MINING Pan-STARRS1, 2MASS, AND WISE

The PS1 survey is obtaining multi-epoch imaging in five optical bands (gP1, rP1, iP1, zP1, yP1) with a 1.8 m wide-field telescope on Haleakala, Maui. Images are processed nightly through the Image Processing Pipeline (IPP; Magnier 2006, 2007; Magnier et al. 2008). Photometry is on the AB magnitude scale, and the first generation of astrometry is tied to 2MASS, with limiting uncertainties of ∼70 mas. Although the PS1 filter system (Stubbs et al. 2010) is very similar to the Sloan Digital Sky Survey (SDSS; Fukugita et al. 1996), there are differences. Most notable are the facts that the zP1 filter is cutoff at 840 nm unlike the long-pass zSDSS filter, and SDSS has no corresponding yP1 band (λC = 990 nm, Δλ = 70 nm), which exploits the excellent red sensitivity of the PS1 detectors.8

We use data from the 3σ Survey, the most time intensive of the several PS1 surveys. This survey covers the 3σ steradians north of declination −30°, with each filter observed for a total of six epochs over three years, and with two exposures at each epoch spaced ∼30 minutes apart to identify solar system objects. We used the the IPP software known as Desktop Virtual Observatory (DVO; Magnier 2006) to manage the large number of PS1 detections and enable large-area cross-correlations (∼1010 objects). We ingested 2MASS into the DVO database to mine the two data sets. At the time we did this (2011 February), PS1 had not yet completed its first sweep of the sky. Since the filters for the 3σ Survey are observed weeks to months apart to optimize sky brightness conditions and parallax factors, we maximized our search area by focusing on the yP1 data alone,
rather than employing multi-color criteria covering a smaller patchwork on the sky.

Our search method is described in detail by Deacon et al. (2011). In brief, we identified proper motion candidates by matching PS1 \( \gamma_P \) detections with 2MASS \( J \)-band detections, excluding galactic latitudes of \( |b| < 10^\circ \) and allowing PS1–2MASS separations of \( \leq 28'' \). The PS1 data were taken from 2009 June to 2011 January, during commissioning and the first year of operations; as 2MASS was in operation from 1997 to 2001, our search has a mean time baseline of 11 years, leading to a maximum proper motion of \( \approx 2.7 \) year\(^{-1} \). We used generous PS1–2MASS color cuts to remove M dwarfs and some instrument artifacts. False associations, whereby matches between PS1 and 2MASS detections in fact are two distinct stationary objects, were then screened using USNO-B (Monet et al. 2003) and SuperCOSMOS (Hambly et al. 2001), to depths of \( R < 20.5 \) and \( I < 19 \) mag. (A separate check of objects with \( I = 16–19 \) mag counterparts found no strong T dwarf candidates.)

Our search reaches magnitudes of \( J \approx 16.6 \) mag and \( \gamma_P \approx 19.6 \) mag, with 2MASS setting the search depth for T dwarfs (e.g., Figure 10 of Dupuy & Liu 2009). Given our limiting magnitudes, our culling process is inevitably incomplete. Indeed, the number of candidates increases at larger proper motions as expected due to the remaining mispairs.

Our core PS1+2MASS search program focuses on objects with \( \leq 0.8 \) year\(^{-1} \), where the false alarm rate is tractable. However, the release of the WISE Preliminary Data Release (Wright et al. 2010) in 2011 May opened the door to mining higher proper motions, by adding unique color information and an epoch of astrometry from the first half of 2010. We cross-matched our 21,070 high proper motion candidates against the WISE data at the PS1 position and excluded objects with a WISE source at the 2MASS position, returning 8140 matches. For the 131 objects with \( W1 - W2 > 0.7 \) mag, corresponding to spectral type T0 and later, we screened the sample visually to excise image artifacts (using data from all the input surveys) and remaining faint mispairs (using the DSS \( R \)-band images, as bright early-T dwarfs might have counterparts on the \( I \)-band plates). For the remaining 58 objects, the separations between the PS1 and WISE positions showed the expected bi-modal distribution of small separations (true matches) and large separations (false matches), with a minimum around \( 4'' \). Thus, we required the two positions to agree within \( 4'' \), leaving 49 objects.

The final sample is illustrated in Figure 1. Two objects stand out as being very red in \( W1 - W2 \) and having proper motions. (Objects with proper motions of \( < 0.5 \) year\(^{-1} \) will be discussed in a future paper.) One is the T7.5 dwarf GJ 570D (Burgasser et al. 2000). The other, PSO J043.5395+02.3995 (WISEP J025409.45+022359.1; Figure 2), was previously unknown at the time.\(^9\) We identified a 2MASS-only counterpart in the latest SDSS data release (DR8; Alam et al. 2011). This object’s absence in earlier releases explains why it was not found in past SDSS searches. Similarly, its faint \( J \)-band magnitude excluded it from previous 2MASS searches.

At the time of our search, about 8200 deg\(^2\) had \( \gamma_P \) data and were in the WISE Preliminary Data Release, with about 7800 deg\(^2\) of the area also having \( \gamma_P \) data. (This includes the 74\% fill factor for individual PS1 exposures due to gaps between CCDs, masked pixels around bright stars, and bad regions of the detectors.) To check our completeness, we examined the known T dwarfs from Dwarfarchives. Out of the 16 objects that are present in WISE, bright enough to be in 2MASS, and residing within the area imaged by PS1, we retrieved 12 of them, with the rest being culled during the filtering process described above, e.g., by being too close to a USNO-B source. Thus, our estimated completeness is 75\%. The other high proper motion object found by Scholz et al. (2011), the T9–T10 dwarf WISEP J1741+2533, was not selected as its sky position did not have \( \gamma_P \) imaging when we did our data mining.

3. SPECTROSCOPY

We obtained low-resolution \( (R \approx 100) \) spectra of PSO J043.5+02 on 2011 June 25 and July 21 UT from NASA’s Infrared Telescope Facility located on Mauna Kea, HI. The two spectra agree well, but the July one had a higher signal-to-noise ratio (S/N) so we use it here. Conditions were photometric with average seeing. We used the near-IR spectrograph SpeX (Rayner et al. 1998) in prism mode with the 0.8’ slit, obtaining 0.8–2.5 \( \mu m \) spectra in a single order. The total on-source integration time was 16 minutes. We observed the A0V star HD 18571 contemporaneously with PSO J043.5+02 for telluric calibration. All spectra were reduced using version 3.4 of the SpeXtool software package (Vacca et al. 2003; Cushing et al. 2004).

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\(^{9}\) The PS1 name used here is based on the computed position at epoch 2010.0.
The spectrum shows the strong H$_2$O and CH$_4$ absorption characteristic of late-T dwarfs (Figure 3). We classified PSO J043.5+02 using the five spectral indices from Burgasser et al. (2006b), with spectral types assigned using the polynomial fits from Burgasser (2007). Excluding the saturated CH$_4$-K index, the average spectral type from the indices was T8.0 with an rms of 0.14 subclasses. We also computed the WJ and NH$_3$-H indices of Warren et al. (2007) and Delorme et al. (2008), respectively, and found values similar to known T8 dwarfs (e.g., Burningham et al. 2010).

In addition, we visually classified PSO J043.5+02 by comparing with SpeX prism spectra of late-T dwarf spectral standards. Following the prescription of Burgasser et al. (2006b), the depth of the H$_2$O and CH$_4$ absorption bands were examined, normalizing the spectra of PSO J043.5+02 and the standards at their J-, H-, and K-band peaks. The agreement with the T8 standard 2MASS J0415$-$0935 is excellent, with PSO J043.5+02 showing stronger absorption than the T7.5 dwarf GJ 570D. The T8.5 objects from Delorme et al. (2008) and Burningham et al. (2008) have deeper H$_2$O absorption and narrower J- and H-band continua than PSO J043.5+02. Thus, the indices and visual typing both give a spectral type of T8.

We fit the solar metallicity BT-Settl-2010 model atmospheres (Allard et al. 2010) to our spectrum. The models span $T_{\text{eff}} = 500$–1500 K ($\Delta T_{\text{eff}} = 100$ K) and log($g$) = 4.0–5.5 (cgs; $\Delta \log(g) = 0.5$). We first flux-calibrated our spectrum to the weighted average of the 2MASS J- and H-band photometry (which is only S/N $\approx$ 5–6 in each filter). Following Bowler et al. (2009) and Cushing et al. (2008), we used a Monte Carlo approach to fit the 0.8–2.4 $\mu$m data, excluding the 1.60–1.65 $\mu$m region because of the known incompleteness of the methane line list. For each Monte Carlo trial, we changed the flux calibration and spectrum assuming normal distributions for the photometric and spectroscopic uncertainties, respectively. We then fit the model atmospheres to each artificial spectrum and repeated the process 10$^3$ times.

The best-fitting model has $T_{\text{eff}} = 800$ K and log($g$) = 4.0 (Figure 3), comparable to atmosphere fitting results for other comparably late-type objects (e.g., Saumon et al. 2007; Leggett et al. 2007; Liu et al. 2011). The broadband photometry agrees well with the model, except for W2 where the model is a factor of 2.92 $\pm$ 0.35 fainter. The mid-IR colors of late-T dwarfs show significant scatter with spectral type (Figure 3), due to non-equilibrium CO/CH$_4$ chemistry, metallicity, and surface gravity effects (e.g., Leggett et al. 2010), which are not fully incorporated into current models. This empirical scatter also explains the spectral type of T8–T10 inferred by Scholz et al. (2011) based on the mid-IR colors, compared to the actual type of T8.

**4. PHYSICAL PROPERTIES OF PSO J043.5+02**

Based on an unweighted fit to 19 objects from L5–T10 with parallaxes and WISE data, we derive a third-order polynomial
for the W 2 band absolute magnitude $M(W 2) = \sum a_i (Sp T)^i$, where $a_i = \{-1.075, 1.580, -0.06780, 0.001060\}$ and $Sp T = 15$ for L5, = 20 for T0, etc. The rms scatter about the fit is only 0.18 mag. This gives a photometric distance of 7.2 ± 0.7 pc.\textsuperscript{10}

The 2.56 year\textsuperscript{-1} proper motion of PSO J043.5+02 is exceptional. Among field T dwarfs, the only object with a larger value is the T7.5 dwarf 2MASS J1114−26 (3/05 year\textsuperscript{-1}; Tinney et al. 2005), which Leggett et al. (2007) characterize as slightly metal-poor ($[\text{M/H}] \approx -0.3$ dex). Our photometric distance of 7.2 ± 0.7 pc leads to a tangential velocity of 87 ± 8 km s\textsuperscript{-1}. Following Dupuy et al. (2009), we assess the galactic memb

\textsuperscript{10} Another distance estimate comes from the “spectroscopic parallax” method of Bowler et al. (2009), whereby the model atmosphere fitting produces a distance of (12.1 ± 0.7) pc at R = 0.25 dex. The Lyon/Cond evolutionary models (Baraffe et al. 2003) predict a radius of 0.10–0.08 R\textsubscript{\odot} for an effective temperature of 800 K and ages of 1–10 Gyr, resulting in a tangential velocity of 10–12 pc. Liu et al. (2011) show that such distances for late-T dwarfs range from ≈1–2 times the parallactic distance.

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### Notes

\textsuperscript{a} The SDSS, PS1, and WISE astrometry has been tied to common system, using 2MASS as the absolute reference (Section 4).

\textsuperscript{b} Average of multi-epoch photometry.

\textsuperscript{c} Broadband photometry was synthesized from our flux-calibrated spectrum, with errors derived from the 2MASS J- and H-band photometry and the spectrum’s uncertainties. The errors in the synthesized colors are smaller than for the magnitudes, because the colors incorporate only the spectrum’s uncertainties. Note that the synthesized (J − H) 2MASS color (−0.044 ± 0.002 mag) is consistent with the T8 spectral type, but different than the 0.7 ± 0.3 mag from the 2MASS catalog, likely due to underestimated errors in the 2MASS photometry.
The model provides \( V_{\text{tan}} \) distributions for thin disk, thick disk, and halo stars. We compute the membership probabilities for PSO J043.5+02 from the fraction of its nearest neighbors that belong to each model population. For \( V_{\text{tan}} = 87 \text{ km s}^{-1} \), we find membership probabilities in the thin/thick disk of 0.87/0.13, with <0.01 probability of belonging to the halo. Thus, even though the \( V_{\text{tan}} \) of PSO J043.5+02 is large, it is merely on the cusp of thin/thick disk membership, because of the many more thin disk stars (a divide of 0.973/0.026/0.002 between thin disk/thick disk/halo members in this model). Thin disk membership is preferred, even accounting for the measurement uncertainty; at the \( \pm 1\sigma \) limits of \( V_{\text{tan}} \) (79 and 95 km s\(^{-1}\)), the thin/thick disk probabilities are 0.90/0.10 and 0.77/0.23, respectively.\(^{11}\)

The near-IR spectrum indicates a metallicity comparable to other field objects (Figure 3). PSO J043.5+02 is very similar to the T8 dwarf 2MASS J0415−09, which is inferred to have [Fe/H] = 0.0−0.3 and \( \log(g) = 5.0−5.4 \) (Saumon et al. 2007). A solar metallicity is also signalled by the \( Y \) measurements, only three objects have \( Y < 0.01 \). The \( g \) value, consistent with a (negligible) correction from relative to absolute magnitude, is inferred to be 15.93, 15.65, and 16.47 mag (HD 3651B, 2MASS J1114−26, and GJ 570D, respectively) and the T8 dwarf 2MASS J0415−09 is inferred to have a relatively high surface gravity \( \log(g) \approx 5.0−5.5 \) based on its large \( K/J \) value, consistent with an old (\( \gtrsim \)Gyr) age.

PS1 3\( \pi \) Survey \( \xi_{\pi} \) and \( \gamma_{\pi} \) imaging are scheduled to maximize the parallax factor between epochs, with the goal of deriving parallaxes over the entire survey. Given the proximity of PSO J043.5+02, a preliminary result is possible even with only a five-month PS1 baseline (three epochs from 2010.65 to 2011.06, with two exposures per epoch), by adding astrometry from 2MASS (2000.73), SDSS (2008.72), and WISE (2010.08). Altogether, these data span a 10 year baseline. For WISE, there are known \( \sim 0.5 \) systematic errors in the Preliminary Release Source Catalog, so we constructed our own astrometric catalog for 1 deg\(^2\) around PSO J043.5+02 from the Preliminary Single Exposure (L1b) Working Database, which we found to be unaffected by such problems. We cross-matched individual WISE detections and used the weighted average and standard error for positions and uncertainties. For 2MASS and SDSS, we assumed relative positional uncertainties of 100 mas and 70 mas, respectively, based on our experience with matching these catalogs to high-precision (\( \lesssim 10 \) mas) relative astrometry from our parallax program on the Canada–France–Hawaii Telescope (Dupuy 2010). We then combined all nine astrometric data points (2MASS, SDSS, WISE, and \( 6 \times \) PS1), allowing for small shifts and a full linear transformation. We used a Markov Chain Monte Carlo method to determine the posterior distributions of the proper motion and parallax. The best solution had \( \chi^2 = 9.9 \) (13 degrees of freedom), validating our astrometric errors, a parallax of 171 ± 45 mas (Figure 4), and a proper motion of \( \mu = 2\′′.559 \pm 0.011 \) year\(^{-1}\) and \( \pi = 84.82 \pm 0.25 \). This includes a (negligible) correction from relative to absolute parallax of 1.34 ± 0.15 mas computed using the Besançon model as described in Dupuy (2010).

5. DISCUSSION

For the median \( V_{\text{tan}} \) of 30 km s\(^{-1}\) of ultracool dwarfs within 20 pc (Faherty et al. 2009), our proper motion range of 0.5−2.7 \( \text{year}^{-1} \) corresponds to distances of 12 pc and 2 pc. (Objects with higher tangential velocities of course can be selected at even larger distances.) This approximate kinematic limit is well matched to the \( J \approx 16.5 \) mag limit for our search: the three T7.5 dwarfs with 2MASS photometry and parallaxes have \( M_J = 15.93, 15.65, \) and 16.47 mag (HD 3651B, 2MASS J1217−03, and GJ 570D, respectively) and the T8
dwarf 2MASS J0415−09 has $M_J = 16.90$ mag, meaning our search has a limiting distance of $\approx 12$ pc for T dwarfs (9 pc for the 2MASS full-sky completeness of $J = 15.8$). The limiting distance drops precipitously for later types: the T10 dwarf UGPS J0722−05 (Lucas et al. 2010) at 4 pc has $J = 16.49 \pm 0.13$ mag, right at the nominal 2MASS limit.

The modest number of candidates from our search suggests that the immediate (~10 pc) solar neighborhood does not contain a large reservoir of undiscovered T dwarfs down to $\approx 10$ pc for T8 dwarfs (9 pc for the 2MASS full-sky completeness of $J = 16.8$). The limiting distance drops precipitously for later types: the T10 dwarf UGPS J0722−05 (Lucas et al. 2010) at 4 pc has $J = 16.49 \pm 0.13$ mag, right at the nominal 2MASS limit.

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