FOUR NEW T DWARFS IDENTIFIED IN Pan-STARRS 1 COMMISSIONING DATA

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ABSTRACT

A complete well-defined sample of ultracool dwarfs is one of the key science programs of the Pan-STARRS 1 optical survey telescope (PS1). Here we combine PS1 commissioning data with the Two Micron All Sky Survey (2MASS) to conduct a proper motion search (0.1–2.0 yr−1) for nearby T dwarfs, using optical+near-IR colors to select objects for spectroscopic follow-up. The addition of sensitive far-red optical imaging from PS1 enables discovery of nearby ultracool dwarfs that cannot be identified from 2MASS data alone. We have searched 3700 deg2 of PS1 y-band (0.95–1.03 μm) data to y ≈ 19.5 mag (AB) and J ≈ 16.5 mag (Vega) and discovered four previously unknown bright T dwarfs. Three of the objects (with spectral types T1.5, T2, and T3.5) have photometric distances within 25 pc and were missed by previous 2MASS searches due to more restrictive color selection criteria. The fourth object (spectral type T4.5) is more distant than 25 pc and is only a single-band detection in 2MASS. We also examine the potential for completing the census of nearby ultracool objects with the PS1 3σ survey.

Key words: brown dwarfs – stars: low-mass – surveys

Online-only material: color figures, machine-readable and VO tables

1. INTRODUCTION

The Panoramic Survey Telescope And Rapid Response System (Pan-STARRS; Kaiser et al. 2002) is a pioneering wide-field, multi-filter, multi-epoch astronomical survey program. The project is planned to consist of four two-meter class telescopes operating from the Hawaiian Islands. The first of these, the Pan-STARRS 1 telescope (PS1), has recently began full science operations on 2010 May 15 on Haleakalā on Maui and is operated by the Pan-STARRS 1 Science Consortium. The largest of the PS1 surveys is the 3σ Survey which is planned to cover the entire sky visible from Hawaii (37 steradians in area, δ > −30°) in five filters (g, r, i, z, and y) with pairs of observations in each filter being taken at six different epochs. This will allow the survey to serve a range of science goals by both stacking individual exposures for deep images and using multiple epochs to identify moving or variable objects. So far the data available have been used to search for Trans-Neptunian objects (Wang et al. 2010) and supernovae (e.g., Botticella et al. 2010). One of the key science areas where PS1 aims to contribute is the study of the local low luminosity population. The unique combination of a wide field, multiple epochs in the y band and the survey strategy is designed to allow parallax measurements of faint local ultracool dwarfs. This could yield a volume-limited sample of the coolest substellar objects unhindered by presumptive color selection.

Most substellar objects are cool enough that they lie beyond the M spectral type in the standard Morgan–Keenan classification system. These objects fall either into the L spectral class (Kirkpatrick et al. 1999) or the cooler still T dwarf class (Burgasser et al. 2006). T dwarfs show deep, wide molecular absorption bands caused by water and methane in their near-infrared spectrum (1–2.5 μm). Combined with their cool temperature these bands cause T dwarfs to have redder optical and bluer infrared colors than earlier L-type objects. The absorption bands cause a double-peaked spectral shape in the 1–1.3 μm region (the y and J bands) while a change in shape and suppression of the spectrum in the H and K bands due to water and methane absorption and collision-induced absorption from H2 molecules is also seen (Burgasser et al. 2006). The spectra also show significant absorption lines from potassium. The fluxes in the methane and water near-infrared absorption bands are used in the standard T dwarf spectral classification scheme of Burgasser et al. (2006) which supersedes the previous classification schemes of Burgasser et al. (2002) and Geballe et al. (2002).

Searches for ultracool dwarfs in wide-field surveys often rely on color selection. Studies based on the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006; work by Burgasser et al. 2004, and references therein) use infrared color cuts to exclude earlier type objects that, while excellent for discovering mid-to-late T dwarfs, can exclude redder earlier T-type objects. While the near-infrared proper motion survey of Kirkpatrick et al. (2010) (which utilizes overlap regions in the 2MASS survey) has more relaxed color selection criteria, it covers less than 10% of the sky. The Sloan Digital Sky Survey (SDSS; York et al. 2000) studies by Chiu et al. (2006) and references therein use red optical i − z colors to select targets. This choice allows them to detect objects across the L/T boundary, but are insensitive to later type objects due to their reliance on optical photometry. The UK Infrared Telescope (UKIRT) Deep Sky Survey (UKIDSS; Lawrence et al. 2007) has been exploited for late T dwarfs by Goldman et al. (2010) and Burningham et al. (2010) and references therein. These studies have pushed the boundaries of...
the coolest T dwarfs but exclude the earlier T dwarfs by color selection.

Here we outline the results of a search to identify new, bright T dwarfs in Pan-STARRS 1 commissioning data.

2. CANDIDATE SELECTION

In the run-up to full science operations (from 2009 June to 2010 March), the PS1 telescope took data in an observing mode matching the full survey strategy in order to provide information on data quality and survey efficiency. This data set has provided us with observations in the 0.95–1.03 μm y band, with some areas having additional coverage in the z band. The filter profile of the PS1 z band is different to that used by SDSS. Hence they cannot be directly compared without taking into account a color term. However like SDSS, Pan-STARRS 1 reports AB magnitudes. Faint ultracool objects discovered in wide-field surveys such as PS1 are relatively nearby, allowing us to filter distant background contaminants by requiring proper motion. PS1 y-band data are only single epoch or have a maximum time baseline of three months, but, by combining these with information from other surveys, we are able to measure proper motions. The ideal companion survey for our first epoch of Pan-STARRS 1 data is 2MASS. This provides both a second epoch with a time baseline of approximately 10 years and photometry in the near-infrared J, H, and K_s bands. Thus, these additional data allow us to refine our photometric selection as well as provide the opportunity for astrometric selection. Although 2MASS has been extensively mined for ultracool dwarfs either as a data set in its own right (Burgasser et al. 2004) or in combination with other surveys (e.g., Metchev et al. 2008), the addition of Pan-STARRS 1 photometry means we can explore faint 2MASS detections excluded by previous studies which were often limited to J = 15.8.

2.1. PS1 Colors of Ultracool Dwarfs

In order to determine appropriate color selection criteria to identify ultracool dwarfs we used the sample of late-type objects with astrometric solutions from Faherty et al. (2009) and corrected their positions to epoch 2010.0. We then searched the available PS1 data around these positions with a pairing radius of 5 arcsec. These results were combined with the published 2MASS magnitudes to produce z–y and y–J colors (Figure 1). It is clear that ultracool dwarfs have distinctive red z–y and y–J colors and hence these can be used for candidate selection. It should be noted that PS1 magnitudes are from a preliminary version of the calibration system (Magnier 2006, Magnier 2007) which uses 2MASS photometry to calculate zero points. Our internal consistency checks indicate that these are in reasonable agreement with external data sets such as SDSS (with a typical scatter due to systematic errors of 0.03 mag in the z band).

2.2. Color Cuts

We searched 3700 deg^2 of PS1 y-band commissioning data taken before 2010 March with right ascensions between 9 hr and 24 hr. Of these data, 2500 deg^2 had complementary z-band coverage (Figure 2). These coverages were calculated by summing the number of 0.1 × 0.1 deg boxes which contained PS1 detections and then applying a fill factor of 0.74 to take account of masked pixels around bright stars, chip gaps, and bad cells. Candidates were identified as having good quality point source y band detections on two or more images with the total significance of the mean of these detections >5σ and no corresponding J detection within 1 arcsec in 2MASS. The Pan-STARRS 1 survey strategy involves taking two images of the same area of sky approximately 30 minutes apart. Hence our double detection requirement will exclude transient sources such as asteroids and potential image artifacts. We then searched around the PS1 positions for objects which had a 2MASS J-band detection (not filtering on 2MASS photometry flags), no corresponding 2MASS z or y detection within 1 arcsec and with a maximum distance between the 2MASS and PS1 positions being the epoch difference between the two observations multiplied by our maximum proper motion of 2 arcsec yr^{-1}. When more than one 2MASS pair was found for a PS1 source we kept all matches which met our criteria. We selected candidates with 2.2 < y − J < 5.0 and, where objects had PS1 z-band photometry, we required that z − y > 0.6. These cuts were designed to exclude the bulk of low-mass stars (spectral type M) from the sample. As we were searching for candidate T dwarfs, we also required a blue near-infrared color of J − H < 1.0 (including quoted H-band upper limits). To reduce contamination from faint background stars in PS1 being paired with transient sources (such as uncataloged asteroids in 2MASS), all objects with a USNO (Monet et al. 2003) counterpart with R- or I-band magnitudes brighter than 20.5 and 18.5, respectively, within 6″' of either the PS1 or 2MASS positions were excluded. We undertook this step as true faint, red brown dwarfs are unlikely to have counterparts on relatively insensitive optical photographic plates. This initial
query yielded 21,990 candidates. Additionally we searched both positions for each of our objects against the SuperCOSMOS Sky Survey (Hambly et al. 2001) with the same pairing radius and removed objects with R- or I-band detections brighter than 20.5 and 18.5, respectively, and/or multiple band detections (i.e., objects with B and R detections, detections in both R epochs or R and I detections). While SuperCOSMOS and USNO use mostly the same plate material, this method provides an additional check that objects do not have clear photographic plate counterparts. After the SuperCOSMOS cross-match stage fourteen objects with counterparts in the Dwarf Archives 6 database of known brown dwarfs were removed from the sample. The USNO I-band images of the remaining 16,520 candidates were also visually inspected to ensure all objects with clear counterparts were excluded. Following this final visual inspection stage, 474 objects remained.

The previously known objects from Dwarf Archives which survived the SuperCOSMOS cross-match are detailed in Table 1. To test the completeness of our survey, we cross-matched T dwarfs from Faherty et al. (2009) with the PS1 database searching for 5σ y double detections. In addition to our seven T dwarfs recovered, four are detected but have right ascensions earlier than 9 hr so they did not fall in to our sample. Two fell outside our color cuts, one (SDSS J151114.66+060742.9) is inferred to be a mid-L/mid-T binary by Burgasser et al. (2010) and was marginally too red in J − H, while the other (SDSS J120602.51+281328.7) was too blue in y − J by less than 0.02 mag. Additionally one object was excluded due to a noisy (σ > 0.2) y-band measurement, while three objects lay close to USNO or SuperCOSMOS detections. Additionally we extracted y-band images from the commissioning data for all T dwarfs in Faherty et al. (2009) with no y-band double detection. One object appeared in only one y-band detection. Four objects were in the footprints of multiple images but fell into masked regions such as chip gaps or poor cells. These four objects are 19% of T dwarfs which fell into the footprint of two or more PS1 commissioning images. This number is in agreement with the 26% loss or area estimated in the fill factor used to calculate our survey area.

3. FOLLOW-UP OBSERVATIONS

3.1. Imaging

We obtained follow-up imaging of candidates using WFCAM (Casali et al. 2007) on the UKIRT. As our PS1 data are separated by 10 years from 2MASS, many of our supposedly red high proper motion objects will in fact be anonymous blue PanSTARRS 1 objects paired with 2MASS transient sources such as uncataloged asteroids. Such PS1 sources will be too faint to appear in 2MASS, USNO-B or SuperCOSMOS. Additionally many of our sample are low signal-to-noise single J-band detections in 2MASS. While these could be the most scientifically interesting (due to their faint, blue infrared photometry), many are expected to be noise spikes or other image artifacts. Follow-up infrared imaging allows us to confirm that the candidates are as red in y − J as the PS1 and 2MASS photometry suggest and to improve on the signal to noise of our 2MASS infrared photometry.

Over the course of three and a half nights, a total of 195 candidates were imaged in Y, J, H, and K on the 2010 June 16–19 (Hubble Space Telescope, HST). Observations were reduced at the Cambridge Astronomical Survey Unit using the WFCAM survey pipeline (Irwin et al. 2004; Hodgkin et al. 2009). Additionally 56 objects had four band photometry in the UKIDSS Large Area Survey (Lawrence et al. 2007). As many of our candidates will in fact be spurious associations, we plotted the difference between the J-band magnitudes from 2MASS and WFCAM/UKIDSS. This produced a bimodal distribution with a division at 0.6 mag (see Figure 3). We chose this as the division between objects with good and discrepant photometry. We then selected objects which appeared to be red (i.e., yP − JM0 > 2.0). These were given further visual screening and had their photometry from the SDSS (which was not used in our initial color cuts) examined, before the four best candidates were followed up spectroscopically. These candidates are plotted on a color–color diagram in Figure 4 and images for the object are shown in Figure 5. The remaining objects which were judged not to have discrepant photometry and which we judged to be not interesting enough for spectroscopic follow-up were likely late M or L dwarfs which scattered into the T dwarf sample.

6 http://dwarfarchives.org/
Table 1
Previously Known Objects Found in PS1 Commissioning Data

| Name              | SpT | z   | σz | y   | σy | J   | σJ | H   | σH | KS  | σK | Reference |
|-------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----------|
| SDSS J115553.86+055957.5 | L7.5 | −   | −   | 18.00 | 0.02 | 15.66 | 0.08 | 14.07 | 0.08 | 14.12 | 0.07 | a         |
| SDSSp J120358.19+001550.3 | L3   | −   | −   | 16.25 | 0.02 | 14.01 | 0.02 | 13.06 | 0.02 | 12.48 | 0.02 | b         |
| SDSS J125011.65+392553.9  | T4   | −   | −   | 19.17 | 0.12 | 16.54 | 0.11 | 16.18 | 0.18 | 16.06 | 0.25 | c         |
| SDSSp J125852.68+374711.9  | T2.5 | 20.61 | 0.08 | 19.75 | 0.09 | 16.94 | 0.18 | 16.26 | 0.24 | 15.35 | 0.14 | c         |
| SDSS J140231.75+014830.3 | T4   | 21.09 | 0.11 | 19.16 | 0.04 | 16.46 | 0.09 | 16.14 | 0.17 | 16.1   | 0.0   | c         |
| SDSS J140321.75+04830.3 | T1   | 18.37 | 0.02 | 18.15 | 0.04 | 15.45 | 0.06 | 14.65 | 0.07 | 14.18 | 0.07 | e         |
| Gliese 570D | T8   | 19.93 | 0.06 | 19.06 | 0.05 | 15.32 | 0.05 | 15.27 | 0.09 | 15.24 | 0.16 | f         |
| SDSS J154508.93+355527.3 | L7.5 | −   | −   | 20.38 | 0.09 | 19.71 | 0.13 | 16.83 | 0.17 | 16.0   | 0.19 | c         |
| 2MASSI J1553022+153236 | T7   | 20.20 | 0.16 | 18.65 | 0.07 | 15.82 | 0.07 | 15.94 | 0.16 | 15.51  | 0.18 | g         |
| SDSS J162255.27+115924.1  | T6   | 20.09 | 0.09 | 19.12 | 0.18 | 16.88 | 0.18 | 16.15 | 0.22 | 15.55  | 0.2   | c         |
| SDSSp J162414.37+002915.6  | T6   | 19.77 | 0.06 | 18.21 | 0.03 | 15.49 | 0.05 | 15.50 | 0.10 | 15.52  | 0.0   | h         |
| SDSS J162838.77+230821.1 | T6   | −   | −   | 19.40 | 0.08 | 16.46 | 0.10 | 16.11 | 0.15 | 15.87  | 0.24 | c         |
| SDSS J214046.55+011259.7 | L3   | −   | −   | 18.35 | 0.07 | 15.89 | 0.08 | 15.31 | 0.09 | 14.42  | 0.08 | e         |

Notes. Citation key: (a) Knapp et al. 2004; (b) Fan et al. 2000; (c) Chiu et al. 2006; (d) Leggett et al. 2000; (e) Hawley et al. 2002; (f) Burgasser et al. 2000a; (g) Burgasser et al. 2002; (h) Strauss et al. 1999.

Table 2
Objects with Discrepant Photometry Between 2MASS and UKIRT/UKIDSS

| R.A. (2MASS) Decl. (2MASS) | J2MASS | σJ2MASS | R.A. (PS1) Decl. (PS1) | Jy1 | σJy | YMKO | σYMKO | JMKO | σJMKO |
|-----------------------------|--------|---------|------------------------|-----|-----|------|-------|-----|--------|
| 11:35:49.89 +04:33:18.3    | 16.56  | 0.15    | 11:35:49.06 +04:33:27.4 | 19.28 | 0.12 | 18.40 | 0.03 | 17.81 | 0.04   |
| 11:38:34.63 +04:41:04.7    | 16.42  | 0.15    | 11:38:33.81 +04:41:16.0 | 20.01 | 0.12 | 19.27 | 0.06 | 18.72 | 0.07   |
| 11:39:32.50 +00:49:05.6    | 16.50  | 0.14    | 11:39:33.10 +00:49:16.0 | 20.14 | 0.14 | 19.86 | 0.14 | 19.00 | 0.12   |
| 11:43:01.81 +10:53:41.3    | 16.47  | 0.15    | 11:43:01.90 +10:53:38.8 | 20.32 | 0.14 | 19.67 | 0.10 | 19.01 | 0.10   |
| 11:48:05.09 +09:28:08.8    | 16.63  | 0.16    | 11:48:05.19 +09:28:01.1 | 20.04 | 0.12 | 19.66 | 0.07 | 19.05 | 0.09   |
| 11:55:30.23 +03:29:30.9    | 16.42  | 0.15    | 11:55:49.18 +03:29:34.9 | 19.97 | 0.12 | 18.99 | 0.05 | 18.47 | 0.06   |
| 11:56:10.24 +05:14:04.9    | 16.53  | 0.13    | 11:56:10.40 +05:14:10.6 | 19.45 | 0.08 | 18.59 | 0.04 | 18.06 | 0.04   |
| 12:01:10.66 −00:09:05.4    | 16.82  | 0.15    | 12:01:10.46 −00:09:14.9 | 19.72 | 0.09 | 18.97 | 0.07 | 18.36 | 0.11   |
| 12:02:09.47 −00:19:03.8    | 17.01  | 0.15    | 12:02:10.13 −00:18:54.3 | 19.57 | 0.19 | 18.73 | 0.06 | 18.14 | 0.06   |

Notes. For these purposes we define discrepant as objects whose J-band photometry differs by more than 0.6 mag between the two measurements. All coordinates are J2000.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

3.2. Spectroscopy

We obtained low-resolution ($R \approx 75–120$) spectra of objects selected by their WFCAM and PS1 photometry from...
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Figure 5. Images for our four candidate objects centered on the PS1 position. The offsets in the position of the 2MASS detection are due to proper motion. The black streaks on the images are gaps between the chips of the PS1 camera. Note PSO J201.0320+19.1072 was spectroscopically confirmed before our UKIRT observing run and hence has no UKIRT photometry.

Table 3
Spectroscopic Follow-up Using SpeX on IRTF

| Object              | UT date     | Airmass | Slit (arcsec) | $T_{\text{int}}$ (s) | Resolution |
|---------------------|-------------|---------|---------------|----------------------|------------|
| PSO J201.0320+19.1072 | 2010 May 17 | 1.06    | 0.8 \times 15 | 1200                 | 75         |
| PSO J226.2599−28.8959 | 2010 Jul 15 | 1.72    | 0.8 \times 15 | 960                  | 75         |
| PSO J246.4222+15.4698 | 2010 Jun 19 | 1.77    | 0.5 \times 15 | 1440                 | 120        |
| PSO J247.3273+03.5932 | 2010 Jun 19 | 1.50    | 0.5 \times 15 | 720                  | 120        |

atmospheric dispersion. Each target was nodded along the slit in an ABBA pattern, with individual exposure times of 120–150 s, while the telescope was guided using the off-axis optical guider. For flux and telluric calibration, we observed A0 V stars contemporaneously with the science targets and at comparable airmass and sky location. All spectra were reduced using version 3.4 of the SpeXtool software package (Cushing et al. 2004; Vacca et al. 2003). A summary of the observations is provided in Table 3.

3.3. Infrared Spectral Types

Figure 6 presents our near-IR spectra, showing the strong water and methane absorption bands that are the hallmarks of the T spectral class. We assigned spectral types by measuring the five flux indices defined by Burgasser et al. (2006) and then applying the polynomial relations of Burgasser (2007). We also visually determined spectral types by comparing with IRTF/Spex prism spectra of the T dwarfs spectral standards chosen by Burgasser et al. (2006). For each object, the depth of the H$_2$O and CH$_4$ absorption bands were examined, normalizing the spectra of the objects and the standards to their peak fluxes in the J, H, and K bands individually. The types from the flux indices agreed well with those from visual examination. For PSO J226.2599−28.8959, the two results disagreed by 1 subclass, therefore we took the average to assign the final spectral type (Table 4).

Figure 6. Spectra for our objects spectral types derived from the classification system of Burgasser et al. (2006).

4. DISCUSSION

4.1. Photometric Distances

We calculated photometric distance estimates for our objects based on spectral type versus absolute magnitude relations. For PSO J247.3273+03.5932, PSO J246.4222+15.4698, and

PSO (Pan-STARRS Object) is the standard IAU designation for objects detected in Pan-STARRS.
PSO J226.2599—28.8959 we used our UKIRT photometry and the relations of Liu et al. (2006). This paper quotes both a bright relation which includes suspected and confirmed binaries and a faint relation which excludes these. The disagreement between these relations is most pronounced in the mid-Ts at approximately 1 mag. As the binarity of our sample of four objects is unknown, we use an average of the bright and faint relations to estimate the intrinsic brightness of our objects. For PSO J201.0320+19.1072 we used 2MASS photometry and the relations of Liu et al. (2006) converted into the 2MASS system using the relations of Stephens & Leggett (2004). The distance estimates for each filter were then averaged to produce the values shown in Table 5.\textsuperscript{9} Three of our objects PSO J201.0320+19.1072, PSO J247.3273+03.5932, and PSO J226.2599—28.8959 have distance estimates within 25 pc with PSO J246.4222+15.4698 lying further away at 31.3 pc.

4.2. Our Objects in Other Surveys

Our four objects are relatively bright and thus could have been detected by previous work such as studies of the 2MASS survey (Burgasser et al. 2004, and references therein), the SDSS (York et al. 2000; Chiu et al. 2006, and references therein), and the UKIDSS (Lawrence et al. 2007; Deacon et al. 2009; Goldman et al. 2010; Burningham et al. 2010, and references therein). The Burgasser 2MASS searches used two different $H - K_s$ cuts and made photometric selections from 2MASS data products before the final calibration. For comparison we use the final bluer cut $H - K_s < 0.0$ and photometry from the final 2MASS catalog.

PSO J201.0320+19.1072. The UKIDSS observation for this object is from Data Release 7 while the most recent publications (Goldman et al. 2010; Burningham et al. 2010) only include data up to Data Release 4. It is too red in $H - K_s$ (0.06) for the 2MASS T dwarfs surveys. However, it should appear in Chiu et al. (2006) due to its red SDSS colors. We are unsure as to why it does not appear in this study as its observation date of 2005 May is later than most objects in Chiu et al.’s catalog, but one object appears from 2005 June.

PSO J226.2599—28.8959. This object falls outside the UKIDSS and SDSS survey areas and is too red ($H - K_s = 0.30$) to be detected by 2MASS searches for T dwarfs.

PSO J246.4222+15.4698. This is similarly not in UKIDSS and is too faint in $J$ (16.77) to fall into the 2MASS studies’ selection sample. It appears in the SDSS database that would have been searched by Chiu et al. (2006), but has a high error on the $z$ magnitude, which could have lead to it falling outside their sample.

PSO J247.3273+03.5932. This object is not in UKIDSS or SDSS and is too red in $H - K_s$ (0.39) to appear in the 2MASS T dwarf samples.

\textsuperscript{9} Note the PS1 positions quoted here and in other tables are derived from our astrometric solutions and calculated for an epoch of 2010.0.

Figure 7. Our four new T dwarfs plotted against discoveries from Burgasser et al. (1999, 2000a, 2000b, 2003, 2004). Three of our objects appear redder than the bulk of T dwarfs discovered in these 2MASS searches. The colors of the Burgasser et al. objects spread beyond their color selection criteria ($J - H < 0.3, H - K_s < 0.0$). This is due to their selection being made before the final 2MASS calibration and some objects having colors from the final calibration which take them outside the initial selection.

(A color version of this figure is available in the online journal.)

Three of our objects appear redder than the final color cuts of the Burgasser searches for T dwarfs. Figure 7 shows how our objects compare to the discovered in these earlier studies.

4.3. Prospects for Future Pan-STARRS 1 Ultracool Dwarf Searches

To characterize the parameter space covered by the Pan-STARRS 1 3$\sigma$ survey and to compare with other leading wide-field surveys for ultracool dwarfs we calculated the expected volume each survey would cover for different spectral types. For the UKIDSS survey we averaged the bright and faint spectral type–absolute magnitude relations of Liu et al. (2006) and assumed a $J$-band completeness limit of 18.8 (Burningham et al. 2010). In the case of 2MASS most searches to date have only gone to the nominal completeness limit of $J = 15.8$, so this was used along with the absolute magnitude relations of Liu et al. (2006) transformed into the 2MASS filter system using the relations from Stephens & Leggett (2004). Searches for T dwarfs based on 2MASS are less complete than this estimate as these objects are blue and the 2MASS $H$ and $K_s$ bands are shallower than the $J$ band. Conversely 2MASS will be deeper in $H$ and $K_s$ for the reddest L dwarfs. For PS1 we also used the Liu et al. (2006) and Stephens & Leggett (2004) relations and added an empirical spectral type versus $y - J$ relation derived from the data in Figure 1. For our $y$-band limit we used 19.5 (see Figure 2) and assume a future PS1 only search.\textsuperscript{10} The results can be seen in Figure 8. It is clear that in absolute volume terms PS1 is competitive with UKIDSS until about T4 and will perform

\textsuperscript{10} Magnier et al. (2008) and Beaumont & Magnier (2010) outline how PS1 can be used for $y$-band parallax only studies of the local brown dwarf population.
### Table 5

Photometry and Astrometry for Our Four T Dwarfs

| Name                        | SpT  | $\mu_\alpha$ cos(δ) | $\mu_\delta$ | $z$       | $y$        | $Y$        | $J$        | $H$        | $K/K_s$    | $d_{phot}$ | Source       |
|-----------------------------|------|----------------------|--------------|-----------|-----------|-----------|-----------|-----------|-----------|------------|--------------|
| PSO J201.0320+19.1072       | T3.5 | -0.10                | -0.09        | ...       | 19.00 ± 0.04 | 18.37 ± 0.17 | 15.77 ± 0.07 | 15.47 ± 0.12 | 15.41 ± 0.16 | 20 ± 4 pc  | PS1/2MASS    |
| PSO J226.2599−28.8959       | T1.5 | 0.10                 | -0.44        | 19.45 ± 0.06 | 18.04 ± 0.04 | 16.95 ± 0.03 | 15.86 ± 0.02 | 15.29 ± 0.02 | 14.9 ± 0.02 | 21 ± 4 pc  | SDSS         |
| PSO J246.4222+15.4698       | T4.5 | -0.24                | -0.24        | ...       | 19.7 ± 0.10  | 2010.132   | 16.77 ± 0.15 | 16.48 U     | 17.17 U    | 34 ± 7 pc  | UKIRT        |
| PSO J247.3273+03.5932       | T2   | 0.24                 | -0.16        | 19.11 ± 0.04 | 17.65 ± 0.02 | 16.19 ± 0.02 | 15.10 ± 0.01 | 14.53 ± 0.01 | 14.28 ± 0.02 | 15 ± 3 pc  | PS1/2MASS    |

**Notes.** Values with errors marked U are 2MASS 95% confidence upper limits. Proper motions are in arcseconds per year. Photometric distances are calculated using the relations of Liu et al. (2006) (for MKO) and Liu et al. (2006) and Stephens & Leggett (2004) (for 2MASS) with errors estimated using the typical rms scatter quoted for the absolute magnitude relations (0.4 mag). UKIRT photometry is in the MKO system. Note PSO J201.0320+19.1072 was confirmed spectroscopically prior to our UKIRT run and thus has no MKO photometry. The two objects with SDSS photometry have only their $z$-band magnitudes listed. As previously stated the SDSS and PS1 $z$ bands have different filter profiles, hence the two are not directly comparable. All other bands for both were fainter than 23rd magnitude. Our astrometry errors have two contributions: a systematic floor of 80 mas from the 2MASS reference frame and shot noise of 100–200 mas for these faint detections (Magnier et al. 2008). With a baseline of roughly 10 years, our proper motion accuracy is approximately 20–30 mas yr$^{-1}$. The positions in the object designations are derived from our astrometric solutions and calculated to an epoch of 2010.0.
better than 2MASS across the full range of spectral types plotted. Furthermore, UKIDSS is a deeper, narrower survey, so objects discovered in PS1 will be brighter and easier to follow up. This is well demonstrated by the lower panel of Figure 8 which shows that Pan-STARRS 1 will provide a reliably complete survey of the solar neighborhood into the mid-T regime.

5. CONCLUSIONS

We have identified the first new T dwarfs from the Pan-STARRS 1 3σ survey. This survey will likely lead to the most complete sample of brown dwarfs in the solar neighborhood. Of our four discoveries, three were bright enough to be detected by previous surveys, but were excluded due to the restrictive color selection. This shows that Pan-STARRS 1 based surveys will be able to loosen color selection criteria, detect substellar extrema missed by work in the field so far and provide the most complete survey to date of brown dwarfs in the solar neighborhood.

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