AN INFRARED HIGH PROPER MOTION SURVEY USING THE 2MASS AND SDSS: DISCOVERY OF M, L, AND T DWARFS

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ABSTRACT

A search of the Two Micron All Sky Survey (2MASS) and Sloan Digital Sky Survey (SDSS) reveals 36 previously unknown high proper motion objects with $J < 17$ mag. Their red optical colors indicate that 27 are M dwarfs, eight are early-type L dwarfs, and one is a late-type T dwarf. The L dwarfs have $J - K_s$ colors near the extrema of known L dwarfs, indicating that previous surveys for L dwarfs using color as a selection criterion may be biased. Follow-up near-infrared spectroscopy of six dwarfs confirm that they are all late-type with spectral types ranging from M8 to T4. Spectroscopy also shows that some of the L dwarf spectra exhibit peculiar features similar to other peculiar “blue” L dwarfs, which may indicate that these dwarfs have a relatively condensate free atmosphere or may be metal poor. Photometric distance estimates indicate that 22 of the new M, L, and T dwarfs lie within 100 pc of the Sun with the newly discovered T dwarf, 2MASS J10595185+3042059, located at ~25 pc. Based on the colors and proper motions of the newly identified objects, several appear to be good subdwarf candidates. The proper motions of known ultracool dwarfs detected in our survey were also measured, including, for the first time, SDSS J085834.42+325627.6 (T1), SDSS J125011.65+392553.9 (T4), and 2MASS J15261405+2043414 (L7).

Key words: solar neighborhood – stars: distances – stars: late-type – stars: low-mass, brown dwarfs – surveys

1. INTRODUCTION

Stars that exhibit high proper motions (HPMs; $\mu > 0.4$yr$^{-1}$) are likely to be within the solar neighborhood (less than ~100 pc). Indeed, most of our nearest stellar neighbors have been identified through their proper motions using shallow optical surveys such as the Digital Sky Survey (DSS; Luyten 1979; Wroblewski & Costa 2001; Ruiz et al. 2001; Oppenheimer et al. 2001; Lepine et al. 2003; Teegarden et al. 2003; Hambly et al. 2004; Scholz et al. 2004; Pokorny et al. 2004; Subasavage et al. 2005, Deacon et al. 2005; Lodieu et al. 2005; Finch et al. 2007; Lepine 2008). However, these surveys are not sensitive to the very red ($I - J > 4$), low-mass ultracool ($T_{\text{eff}} < 2400$ K) L and T dwarfs. The L and T dwarfs are extremely faint in the optical and to date have only efficiently been identified based on their colors at red optical (0.6–1.0 $\mu$m) wavelengths in the Sloan Digital Sky Survey (SDSS; e.g., Fan et al. 2000, Legget et al. 2002, Chiu et al. 2006) and the Canada–France Brown Dwarf Survey (CFBDS; e.g., Delorme et al. 2008), and at near-infrared (NIR; 1–2.5 $\mu$m) wavelengths in the Two Micron All Sky Survey (2MASS; e.g., Kirkpatrick et al. 1999, 2000; Burgasser et al. 2002, 2003b, 2004a; Cruz et al. 2003; Timney et al. 2005; Kendall et al. 2007; Looper et al. 2007), the Deep Near Infrared Southern Sky Survey (DENIS; Phan-Bao et al. 2008; Kendall et al. 2004), and the UKIRT Infrared Deep Sky Survey (UKIDSS; e.g., Lawrence et al. 2007; Chiu et al. 2008, Pinfield et al. 2008). Because these surveys select ultracool dwarf candidates based on color alone, they may be biased against objects with unusual colors. Metchev et al. (2008) have been able to partially relax this color constraint for low-mass objects by comparing the colors of objects in the 2MASS catalog with colors of objects in the SDSS catalog. Although such surveys have proven very successful in identifying L and T dwarfs, it is likely, based on the luminosity function of stellar and substellar objects, that the census of the solar neighborhood within 25 pc remains roughly 20%–60% deficient (Henry et al. 1997, 2002; Reid et al. 2004; Cruz et al. 2007; Reid et al. 2007).

A search for high proper motion stars at red optical and NIR wavelengths could (1) potentially identify brown dwarfs in the solar neighborhood via their large proper motions, and (2) remove any potential color bias inherent in most of the surveys conducted to date. Two surveys covering up to a few hundred square degrees have been successful in identifying ultracool dwarfs via proper motion in the NIR (Artigau et al. 2006; Looper et al. 2008). In this paper, we present a large area survey (~8000 deg$^2$) to search for faint, high proper motion stars in the near infrared using the 2MASS and SDSS catalogs.

2. TARGET SELECTION

The 2MASS point source catalog (PSC; Skrutskie et al. 2006) between 0.6 and 6.6 $\mu$m declination was compared to the SDSS catalog (York et al. 2000; Pier et al. 2003) within this same range to search for high proper motion (HPM) objects. Before comparing the 2MASS and SDSS databases, we performed several cuts on the 2MASS PSC in order to limit the number of candidate HPM objects. (1) The object must be detected in all three filters ($J$, $H$, and $K_s$). (2) The $J$-band magnitude must be brighter than 17th magnitude. (3) The distance between the source and its nearest neighbor in the PSC must be greater than 5$''$9 (a few pixels) to prevent confusion (prox $> 5''9$). (4) The contamination and confusion flags must be “0” in all three bands to prevent known artifacts or bright nearby objects from giving false positives (cc_flg = 000). (5) The extended source contamination flag must be “0” to indicate the object does not fall within the elliptical boundary of a known extended source (gal_contam = 0). (6) The minor planet flag must be “0” to identify known minor planets (mp_flg = 0). (7) The object cannot be identified with a known object within 5$''$ from either the USNO-A2.0 or Tycho 2 catalogs ($\alpha = 0$).

The filtered 2MASS PSC was then compared with the SDSS catalog in order to identify 2MASS point sources that did not
A current list of all known L and T dwarfs is compiled at DwarfArchives.org. No. 1, 2009 INFRARED HIGH PROPER MOTION SURVEY USING 2MASS AND SDSS 305

were in the 2MASS PSC but had no point sources observed not included in the SDSS catalog and thus resulted in false motions between the SDSS and 2MASS data. These stars were not cataloged by the SDSS. Of these objects, 1307 were visually revealed that 1826 objects were cataloged by the 2MASS but stars and white dwarfs with motions between 0

DwarfArchives.org.

The comparison between the 2MASS and SDSS surveys revealed that 1826 objects were cataloged by the 2MASS but not cataloged by the SDSS. Of these objects, 1307 were visually identified as stars in the SDSS images with no detected proper motions between the SDSS and 2MASS data. These stars were not included in the SDSS catalog and thus resulted in false positives. The other 519 objects are candidate HPM objects that were in the 2MASS PSC but had no point sources observed within 2′35 in the SDSS data. Three hundred and fifty-seven of the 519 were identified through SIMBAD as known HPM stars and white dwarfs with motions between 0′2 and 3′9 yr⁻¹, 98 were identified as known asteroids that the 2MASS minor planet flag did not register (Lowell Observatory’s asteroid plot program ASTPLOT was used; Granvik et al. 2003), 15 were identified through SIMBAD and the Dwarf Archives as known L and T dwarfs (see Table 1). Thirteen objects (Table 2) could not be correlated with any known SDSS objects or asteroids and

Notes.
a Indicates this is the first time that this type of measurement for this object has been published.
b The proper motion (PM) of the object as observed between the 2MASS and SDSS data. Uncertainties are at about the 10 percent level.
c The Position Angle (P.A.) of the motion. Uncertainties are generally about 1°.
d The J-band photometry from 2MASS. Uncertainties are less than 0.1 mag.
e The spectral types of the L dwarfs are based on red optical spectroscopy and are on the Kirkpatrick et al. (1999) system. The spectral types of the T dwarfs are based on near-infrared spectroscopy and are on the Burgasser et al. (2006) system. The spectral type for 2MASS J16262034+3925190 is tentative (Burgasser et al. 2007a).
f References for discovery, spectral type identification, proper motion, and position angle measurements if applicable.

References. (1) Kirkpatrick et al. 2000; (2) Dahn et al. 2002; (3) Knapp et al. 2004; (4) Chiu et al. 2006; (5) Burgasser et al. 2002; (6) Burgasser et al. 2006; (7) Vrba et al. 2004; (8) Burgasser et al. 2004a; (9) Gizis et al. 2000; (10) Schmidt et al. 2007; (11) Burgasser et al. 2008; (12) Kirkpatrick et al. 1999; (13) Jameson et al. 2008; (14) Wilson et al. 2003; (15) Cruz et al. 2007; (16) Burgasser et al. 2007a; (17) Reid et al. in preparation.

have a SDSS source within 2′35. This HPM survey covered area from the SDSS using data releases one to five: DR1 (~2099 deg²; Abazajian et al. 2003), DR2 (~1225 deg²; Abazajian et al. 2004), DR3 (~1958 deg²; Abazajian et al. 2005), DR4 (~1388 deg²; Adelman-McCarthy et al. 2006), and DR5 (~1330 deg²; Adelman-McCarthy et al. 2007). In all about 8000 deg² of sky were covered by the SDSS between DR1 and DR5.

The main belt asteroid population at these faint magnitudes is probably close to complete, though near-Earth objects (NEOs) are not. As seen in Figure 1, there is no obvious clustering of unidentified objects near the ecliptic as would be expected if most were unknown asteroids. The likely source for each of these unidentified objects is given in Table 2. In addition to comparing the 2MASS and SDSS catalogs we used the Lowell asteroid ephemeris service to determined that the hundreds of 2MASS sources that Burgasser et al. (2003a, 2003b, 2004a) did not detect in their follow-up imaging observations of candidate T dwarfs were indeed asteroids with a few objects being obvious 2MASS artifacts.

The remaining 36 objects in our sample were found to have proper motions between about 0′2 and 1′0 yr⁻¹ but were not in SIMBAD (within 60″ of the predicted position) or the Dwarf Archives as of 2008 May 1. These 36 objects are thus identified as new HPM objects. Their proper motions (PM), position angles (P.A.), and 2MASS J, H, K_s and SDSS r′, i′, and z′ photometry are given in Table 3. We discuss these 36 HPM objects in more detail in the following sections.

3 A current list of all known L and T dwarfs is compiled at DwarfArchives.org.

| Name | PM a (yr⁻¹) | P.A. b (deg) | J c (mag) | i – J (mag) | Spec.d | Type |
|------|-------------|--------------|-----------|-------------|-------|------|
| 2MASS J14213145+1827407 | 0.79 | 257 | 13.23 | 4.2 | L0 | 9, 10, 17 |
| 2MASS J14392836+1929149 | 1.34 | 288 | 12.76 | 4.4 | L1 | 2, 12 |
| 2MASS J13040255+1912354 | 1.48 | 213 | 12.72 | 4.5 | L1 | 9, 10, 11 |
| 2MASS J15065441+1321060 | 1.14 | 269 | 13.37 | 4.6 | L3 | 9, 13 |
| 2MASS J16154416+3559005 | 0.53 | 184 | 14.54 | 4.6 | L3 | 1, 13 |
| 2MASS J16262034+3925190 | 1.79 | 279 | 14.44 | 3.5 | sdL4 | 8, 16 |
| 2MASS J13285503+2114486 | 0.50 | 150 | 16.20 | 5.2 | L5 | 2, 12 |
| 2MASS J15150083+4847416 | 0.50 | 150 | 16.20 | 5.2 | L6 | 13, 14, 15 |
| 2MASS J15261405+2043414 | 0.43 | 216 | 15.59 | 5.0 | L7 | 1 |
| 2MASS J16351968+2115521 | 0.62 | 241 | 15.10 | 5.5 | L7,5 | 1, 2, 3 |
| SDSS J12314753+0847331 | 1.03 | 182 | 16.54 | >5.5 | T4 | 4 |
| 2MASS J12314753+0847331 | 1.51 | 228 | 15.57 | >6.4 | T5,5 | 6, 8 |
| 2MASS J08251968+2115521 | 0.62 | 241 | 15.10 | 5.5 | L7,5 | 1, 2, 3 |
| SDSS J12314753+0847331 | 1.03 | 182 | 16.54 | >5.5 | T4 | 4 |
| 2MASS J08251968+2115521 | 0.62 | 241 | 15.10 | 5.5 | L7,5 | 1, 2, 3 |
| 2MASS J15530228+1532369 | 0.44 | 294 | 15.83 | >6.2 | T7 | 5, 6, 13 |
unknown asteroids. The triangles are uncorrelated with the ecliptic (solid line) so it is unlikely they are asteroids, extremely red objects, or extremely high proper motion objects. Since open triangles are likely artifacts in the 2MASS catalog but could be unknown asteroids. The 13 2MASS objects that do not have an identified SDSS source were also detected. The DR5 has the longest time baseline between the 2MASS and SDSS images allowing for the more numerous slower proper motion objects to be identified. The 13 2MASS objects that do not have an identified SDSS source (open triangles) are likely artifacts in the 2MASS catalog but could be unknown asteroids, extremely red objects, or extremely high proper motion objects. Since the triangles are uncorrelated with the ecliptic (solid line) it is unlikely they are unknown asteroids.

3. ANALYSIS

3.1. Survey Results

The proper motions of the 36 newly discovered HPM objects are all less than 1" yr\(^{-1}\) although objects moving ten times faster would likely have been detected or at least identified as having no SDSS counterpart. The fastest moving non-solar system object detected in this survey was a white dwarf (GJ 518) with a motion of 3.9 yr\(^{-1}\). Several more known objects, including L and T dwarfs (Table 1), moving well over 1" yr\(^{-1}\) were also detected.

All the newly discovered HPM objects are quite faint, with many being fainter than 20th magnitude in \(r'\) and thus not efficiently detected in earlier optical surveys such as the DSS. The colors of the new HPM objects are given in Table 4. \(J - K_s\) versus \(i' - J\), \(r' - i'\) versus \(i' - J\), and \(J - K_s\) versus \(r' - i'\) color–color diagrams are shown in Figures 2–4, respectively. The large scatter in the \(J - K_s\) colors of the L dwarfs (Figure 2) has been ascribed to variations in the properties of their condensate clouds (Tsuji et al. 1996; Knapp et al. 2004), surface gravities (Burrows et al. 2006), and possible unresolved binaries (Liu & Leggett 2005). This scatter has been found to be even higher for the lower temperature T dwarfs (Dahn et al. 2002; Harris et al. 2003). Figure 3 shows a significant turn over in the object’s \(r' - i'\) colors resulting from the formation of Ti-bearing condensates that begin in the late-type M dwarfs (Kirkpatrick et al. 2000; Dahn et al. 2002; Liebert & Gizis 2006).

The rough spectral types for the new HPM objects were estimated using their \(i' - J\) colors (Table 4) and a linear fit to known ultracool dwarfs with known spectral types as shown in the Dwarf Archives (Figure 5). We found that the spectral type of an ultracool dwarf is shown to follow the relation

\[
\text{SpecType} = -9.4 + 4.7(i' - J) \tag{1}
\]

where SpecType is the spectral type of the object with 10 = L0, 15 = L5, 20 = T0, 25 = T5 etc. The average spectral typing error using Equation (1) (i.e., the \(i' - J\) information) on the sample of objects shown in Figure 5 is about ±1 sub-class. Equation (1) is nearly linear down to at least the early M types (\(i' - J \sim 2\); Hawley et al. 2002). Thus even though Equation (1) was determined based on L and early-type T dwarf data

Table 2
Objects in the 2MASS PSC But Not in the SDSS PSC

| 2MASS Name                  | \(J^b\)  | \(H^b\)  | \(K_s^b\) | JD \(^d\)        | Comments^c |
|-----------------------------|---------|---------|----------|-----------------|------------|
| 2MASS J00461651+1419298     | 16.9    | 16.3    | 15.9     | 2451437.8263    | Diff       |
| 2MASS J08204794+2440364     | 16.9    | 16.2    | 15.8     | 2451506.9024    | Noise      |
| 2MASS J09581895+0143068     | 16.8    | 16.8    | 16.1     | 2451605.6786    | Noise      |
| 2MASS J10385877+2718553     | 16.9    | 16.3    | 15.7     | 2451557.7483    | Noise      |
| 2MASS J11262351+2708338     | 16.6    | 16.3    | 15.5     | 2451605.6786    | Noise      |
| 2MASS J11280132+0715387     | 16.9    | 16.2    | 15.9     | 2451605.6786    | Noise      |
| 2MASS J11254075+1338169     | 16.8    | 16.4    | 16.3     | 2451605.6786    | Noise      |
| 2MASS J1280132+0715387      | 16.9    | 16.2    | 15.9     | 2451605.6786    | Noise      |
| 2MASS J13300994+4912080     | 16.9    | 16.8    | 16.4     | 2451621.8835    | Noise      |
| 2MASS J14501038+2847574     | 16.5    | 16.1    | 15.3     | 2451621.8835    | Noise      |

Notes.

^a These are objects that were not linked to known asteroids, not seen in the SDSS and were not obvious artifacts or noise. These objects were cataloged by 2MASS in \(J, H,\) and \(K_s\). The above objects are all near the detection limit of 2MASS. Most of the objects are likely artifacts from scattered light of nearby bright stars but some could be unknown asteroids, extremely red objects (\(i' - J > 7\) mag), or extremely high proper motion stars or brown dwarfs (>10" yr\(^{-1}\)). Deep \(I\)-band imaging of these areas with the Du Pont 2.5 m telescope found no objects near any of the coordinates listed above.

^b The \(J, H,\) and \(K_s\) photometry from 2MASS. Most of these objects are near the limit of 2MASS detection and thus their uncertainties are higher than most 2MASS photometry and are generally between 0.2 and 0.4 mag.

^c Most of these objects are likely artifacts in the 2MASS data and here we comment on what they likely are: Diff = Differential diffraction spike from nearby bright star or Noise = Background Noise.

^d The Julian Date of the 2MASS image and coordinates.

Figure 1. Location of newly identified high proper motion objects with declination in degrees on the vertical axis and right ascension in hours on the horizontal axis. The shaded area is the 8000 deg\(^2\) where the 2MASS and SDSS data overlapped. Most of the 36 newly identified HPM objects are between about 15° and 30° declination since this is where the SDSS Data Release 5 (DR5) was focused. The DR5 has the longest time baseline between the 2MASS and SDSS images allowing for the more numerous slower proper motion objects to be identified. The 13 2MASS objects that do not have an identified SDSS source (open triangles) are likely artifacts in the 2MASS catalog but could be unknown asteroids, extremely red objects, or extremely high proper motion objects. Since the triangles are uncorrelated with the ecliptic (solid line) its unlikely they are unknown asteroids.
J1059+30424 was not detected in the SDSS. Hereafter we abbreviate the 2MASS and SDSS designations ascovering from $i' - J \approx 3.9 - 7.0$, we can extrapolate to bluer colors in order to spectral-type M dwarfs. Since the extremely red $(i' - J \sim 7.8)$ object 2MASS J1059+30424 was not detected in the SDSS $i'$ band we estimated its spectral type using its $z'$ vs. $J$ color. To do so we determined a relation for spectral type versus $z'$ vs. $J$ colors (Figure 6)

\[
\text{SpecType} = -23.0 + 14.2(z' - J) 
\]

where SpecType is the same as above. This technique is inferior to the $i' - J$ colors technique used above since the $z'$ band is closer in wavelength to the $J$ band but is useful for extremely red objects that are difficult to observe in the $i'$ band. The average spectral typing error using Equation (2) on the sample of objects shown in Figure 6 is about $\pm 3$ sub-classes. The spectral types found using Equation (1) or Equation (2) for each of the 36 new HPM objects are given in Table 4.

The approximate absolute magnitude, $M_J$, of the new HPM objects were estimated by using their $i' - J$ colors and data from Hawley et al. (2002; see Figure 7),

\[
M_J = -9.66 + 15.54(i' - J) - 4.81(i' - J)^2 + 0.72(i' - J)^3 - 0.04(i' - J)^4, 
\]

and are given in Table 4. Our absolute magnitude calculations are similar to ones used by Cruz et al. (2003) and Phan-Bao.
et al. (2008), but our analysis allows us to directly relate the \( i' - J \) colors to \( M_J \) for these newly observed ultracool dwarfs rather than using their unknown spectral types. The absolute magnitudes were used to determine the approximate distances to the objects through, \( d = 10^{0.4 (i' - M_J)/5} \) pc. These are very rough estimates for the new HPM objects identified in this survey and assume the objects are single. The distance estimates have uncertainties at about the 25% level based on comparing the results with known objects in Table 1. All the objects later than M8 appear to be less than about 100 pc from the Earth (Table 4). Several of the early M dwarfs that appear to be at very large distances would have unrealistic tangential velocities (\( \gtrsim 500 \text{ km s}^{-1} \)). These objects are good subdwarf candidates (see Section 4) and thus their absolute magnitudes and distances are likely unreliable since the distance estimates assume the objects to be dwarfs and not subdwarfs. The closest object found in this survey is the T dwarf 2MASS J1059+3042 which lies at a distance of \( \sim 25 \text{ pc} \) if it is a single brown dwarf.

### 3.2. Survey Consistency

The 2MASS data were taken between 1997 and 2001 (Skrutskie et al. 2006), while the SDSS data acquisition started...
Figure 2. $i' - J$ vs. the $J - K_s$ colors of the 36 newly discovered high proper motion objects (plus signs). Also plotted are the known ultracool dwarfs with spectral types L0 or later observed in the SDSS (filled circles) as of 2008 May 1. All colors were obtained through the 2MASS and SDSS point source catalogs. Approximate spectral types based on the average $i' - J$ colors of M, L, and T dwarfs are given (see text). It is apparent that most of the new high proper-motion objects are in the L dwarfs regime, the T dwarf is at the right. T dwarfs are extremely faint in the $i'$ band and thus very few have been observed in the SDSS. The known brown dwarf in the lower center of this figure is the L4 subdwarf, 2MASS J16262034+3925190 (Burgasser et al. 2004b).

Figure 3. $i' - J$ vs. $r' - i'$ colors of the 36 newly discovered high proper motion objects. There is an obvious turnover near $r' - i' \approx 3$ and $i' - J \approx 4$. This turnover has been associated with Ti-bearing condensates that begin in late-type M dwarfs (Kirkpatrick et al. 2000; Dahn et al. 2002; Liebert & Gizis 2006). The T dwarf candidate is not in this figure because its $r'$ magnitude is unknown.

Figure 4. $r' - i'$ vs. $J - K_s$ colors of the 36 newly discovered high proper motion objects. The T dwarf candidate is not in this figure because its $r'$ magnitude is unknown.

Figure 5. $i' - J$ colors vs. spectral type of known L and T dwarfs detected by the SDSS. All ultracool dwarfs plotted had their photometry taken from the SDSS and 2MASS data bases exactly as the 36 newly discovered objects found in this work to allow a direct comparison. The solid line is the best fit to the data and is used to estimate the spectral types of the newly observed objects (Table 4). The linear spectral type fit found for brown dwarfs using $i' - J$ is Spectral Type = $-9.4 + 4.8(i' - J)$, where the Spectral Type is 05 = M5, 10 = L0, 15 = L5, 20 = T0, 25 = T5 etc. Because T dwarfs are extremely faint in the $i'$ band few have been reliably observed in the SDSS. As shown by Hawley et al. (2002) this linear fit is good down to the earliest M type dwarfs. We extrapolate the spectral type based on the linearity of the fit for objects that have a $i' - J$ color less than 3.9 and greater than 7 mag.

2MASS and SDSS images (the images were taken too close in time), and thus would not be expected to be detected in our survey. One of the 17 objects was located close (about 5 arcmin) to a nearby bright star ($J \sim 1$ mag), and thus was not expected to be detected by our survey because of the large amount of scattered light. Four of the 17 were not clearly detected in the $K_s$ band in the 2MASS data and thus were rejected by our search algorithm. Five of the 17 objects were closer than 2".35 to another source in the SDSS data and thus also would have been rejected by our search algorithm. In total, we found 100% (15/15) of the known L and T dwarfs that our survey was expected to find. As another measure of the efficiency of our survey, we found about 60% (15/25) of the known L and T dwarfs within our survey that had obvious motion between the 2MASS and SDSS data (>2")..
3.3. Follow-up Observations

3.3.1. du Pont

We observed all 36 objects listed in Table 4 with a Tektronix 2048 × 2048 CCD (0.259 per pixel) on the du Pont 2.5 m telescope at Las Campanas, Chile in 2007 December, 2008 February, and 2008 March. These 200 s I-band images confirmed 35 of these objects as having high proper motions. The only object not seen in the I-band du Pont data was 2MASS J1059+3042. We thus observed this object in 2008 May with LDSS-3 on the 6.5 m Magellan telescope in both the i’ and z’ bands. 2MASS J1059+3042 was easily detected and confirmed as a HPM source in two 100 s z’-band exposures. 2MASS J1059+3042 was only marginally detected in one 200 s i’-band exposure demonstrating the extreme redness (i’ – J ~ 7.8) of this object (Table 4). In addition, we observed all the unidentified objects listed in Table 2 with the du Pont telescope to search for faint I-band counterparts that the SDSS would not have detected. These 200–600 s exposures found no obvious objects of interest near any of the locations listed in Table 2.

3.3.2. IRTF/SpeX

NIR spectra of six of the new HPM objects with estimated spectral types later than M9 V were obtained with SpeX (Rayner et al. 2003) mounted on the 3 m NASA Infrared Telescope Facility on 2008 June 13 and 18 (UT). A log of the observations, including the UT date, total integration time, and A0 V standard star are given in Table 5. We used the 0.5′ wide slit with the low-resolution prism mode which provides a resolving power of R ≡ λ/Δλ ≈ 150. A series of 120 s exposures were obtained at two different positions along the 15″ long slit to facility sky subtraction. An A0 V standard star with a similar airmass (Δ sec z < 0.1) was observed after each science target for telluric correction and flux calibration purposes. All observations were conducted at the parallactic angle in order to minimize slit losses and spectral slope variations due to differential atmospheric refraction. Finally, exposures of internal flat field and Ar arc lamps were obtained for flat fielding and wavelength calibration purposes.

The data were reduced using SpeXtool, the data reduction package for SpeX (Cushing et al. 2004). The package performs nonlinearity corrections, flat fielding, optimal extraction of spectra, and wavelength calibration. The spectra were then corrected for telluric absorption and flux calibrated using the observed A0 V standard star and the technique described in Vacca et al. (2003). The spectra of the six candidates are shown in Figure 8. The S/N of the spectra range from 20 to 200 except for 2MASS J1230+2827 which ranges from 10 to 50. Five of the six dwarfs exhibit features typical of late-type M and L dwarfs including broad H2O absorption at ~1.4 and ~1.8 μm, the Wing-Ford FeH band head at 0.99 μm, K I and Na I doublets from 1.15 to 1.3 μm, and the CO overtone band heads at ~2.29 μm. The extremely red object (i’ – J ~ 7.8), 2MASS J1059+3042, exhibits CH4 absorption bands at 1.2, 1.6, and 2.2 μm, indicating that it is a T dwarf.

Spectral types for the six dwarfs were determined in two ways. First, each spectrum was compared to the ~250 spectra of M, L, and T dwarfs (obtained with the same instrument setup as our data) in the SpeX Prism Spectral Library.5 The best-fitting library spectrum for each dwarf was found by minimizing the sum of the squared residuals between our spectrum and the library spectra (after all spectra are normalized to unity over the 2.1–2.2 μm wavelength range) and are overplotted in Figure 8. 2MASS J1059+3042 is well matched by the T4 NIR standard 2MASS J2254188+312349 (Burgasser et al. 2006) so we assign it a spectral type of T4. The remaining five dwarfs are

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5 http://www.browndwarfs.org/spexprism
well matched by their respective library spectra, but assigning them spectral types by direct comparison is difficult since there are no spectral standards for M and L dwarfs in the NIR; the spectral types given in Figure 8 were derived from red optical data. We have, therefore, also derived the spectral types of the 5 M and L dwarfs using various spectral indices from the literature (Reid et al. 2001; Testi et al. 2001; Burgasser et al. 2002, 2006, 2007b, 2008; Allers et al. 2007) as well as the Geballe et al. (2002) indices that are used to define NIR L dwarf subtypes. The resulting spectral types are given in Table 6, and a summary of the spectral types derived by the various methods is given in Table 7. With the exception of 2MASS J1059+3042, the spectral types derived by the various methods are in reasonable agreement.

4. DISCUSSION

The original goal of this survey was to identify brown dwarfs that were close to the Sun and to understand whether or not there is a color bias in previous surveys that use color as a selection criterion. Although no brown dwarfs located very close to the Sun were identified, our results suggest that a color bias does exist in current surveys. As shown in Figure 2, six of the eight L dwarfs identified in this survey have \( J - K_s \) colors that lie at the extrema of the distribution of L dwarfs colors (about a 3.5 sigma event assuming a binomial distribution for early L dwarfs in \( J - K_s \) colors). Follow-up spectroscopy shows that 2MASS J1434+2202 appeared as a possible L subdwarf from follow-up spectroscopy and is the bottom most point at the far right of this figure near the known L subdwarf 2MASS J1626+3925. Most of the newly identified HPM objects are in the far right of this figure which indicates that most are dwarf type objects. The one T dwarf discovered in this survey is not shown since its \( r^* \) magnitude is unknown.

\[ \text{Reduced Proper Motion} = r^* + \frac{\mu}{2} \]

Figure 9. \( r^* - J \) colors vs. the reduced proper motion (RPM) for the 36 newly identified high proper motion objects (squares), white dwarfs discovered in this survey (x’s), known M subdwarfs (plus signs) as found in the SDSS and confirmed by Marshall (2008) and Lepine & Scholz (2008) and the known L4 subdwarf 2MASS J1626+3925 (asterisk) that was detected in this survey and identified as a subdwarf by Burgasser et al. (2007a). The white dwarfs occupy the left portion of the figure and none of the newly identified HPM objects are near this region. The subdwarfs occupy the center and lower portions of the figure. Several of the newly identified HPM objects are near the subdwarf region and thus are good subdwarf candidates (see Table 4). 2MASS J1434+2202 was identified as a possible L subdwarf from follow-up spectroscopy and is the bottom most point at the far right of this figure near the known L subdwarf 2MASS J1626+3925. Most of the newly identified HPM objects are in the far right of this figure which indicates that most are dwarf type objects. The one T dwarf discovered in this survey is not shown since its \( r^* \) magnitude is unknown.
Table 6
Spectral Indices of Late M and Early L Dwarfs

| Index | Spectral Type |
|-------|---------------|
|       | 2MASS 1230 | 2MASS 1237 | 2MASS 1253 | 2MASS 1431 | 2MASS 1434 |
| H2O  | M0 V        | M7.5 V     | L0.5      | L5.5      | L3.5      |
| H2O# | L1.5        | M8 V       | L0        | L4.5      | L3.5      |
|       | Reid et al. (2001) |
|       | Testi et al. (2001) |
|       |         | H2O      | L1.5      | L0       | L1.5      | L0.5 |
|       |         | H2O      | L1.5      | L0       | L4       | L2.5 |
|       |         | H2O      | L1.5      | L0       | L2       | L5.5 |
|       |         | H2O      | L1.5      | L0       | L2.5      | L1.5 |
|       | Burgasser et al. (2002) |
|       |         | H2O      | L1.5      | M6.5 V   | M8 V     | L2      | L0.5 |
|       |         | H2O      | M8.5 V    | M6.5 V   | M8.5 V   | L6     | L4   |
|       |         | H2O      | L2        | M5 V     | M8 V     | L5.5   | L2   |
|       | Geballe et al. (2002) |
|       |         | H2O      | L0.5      | <L0      | <L0      | <L0    |
|       |         | CH4      | L3        | L4       | <L3      | L4     |
|       | Burgasser et al. (2006, 2007) |
|       |         | H2O      | L2.5      | L0       | L0.5     | L3.5   | L3.5 |
|       |         | H2O      | M9.5      | <L0      | <L0      | L1     | L0   |
|       |         | CH4      | L1.5      | L2.5     | L0.5     | <L0    | L3   |
|       | Allers et al. (2007) |
|       |         | H2O      | L0.5      | M7.5 V   | M8.5 V   | L3.5   | L2   |
|       | Burgasser et al. (2008) |
|       |         | H2O      | L3.5      | M8 V     | L0       | L2.5   | L0   |

Note.
* Mean spectral type not including upper limits (e.g., <L0). The error is the RMS error.

et al. 2005; Marshall 2008). The RPM can be thought of as a rough luminosity class (or absolute magnitude) using only proper motion (\( \mu \)) and apparent magnitude (\( r' \)) by assuming they are directly related. This assumption is usually valid, though many factors make the scatter in the relationship large. The RPM is a simple technique to allow identification of object types that differ from the normal main sequence. This technique is useful when looking for a crude way to identify white dwarfs and subdwarfs since they will have bluer colors or fainter RPMs for a given color.

In Figure 9 we plot the \( r' - J \) colors versus the RPM for the newly discovered HPM objects discovered in this survey along with some white dwarfs found in this survey, the L4 subdwarf 2MASS J1626+3925 also found in this survey and several confirmed M subdwarfs seen in both the SDSS and 2MASS from Marshall (2008) and Lepine & Scholz (2008). It can clearly be seen that the white dwarfs occupy the far left in the figure while the subdwarfs occupy the center and lower portions of Figure 9. Several of our newly identified HPM objects are near the center and lower portions of Figure 9 and are thus good subdwarf candidates (see Table 4). In fact, 2MASS J1434+2202, which is near the known subdwarf 2MASS J1626+3925 in Figure 9, has been identified as a likely subdwarf from our NIR spectroscopy (see Table 7). Most of our newly found HPM objects are on the far right of Figure 9 and thus not likely subdwarfs and are definitely not white dwarfs. Because the scatter is rather large a more detailed spectroscopic observational campaign will be required to determine which of these objects are subdwarfs.

Table 7
Summary of Spectral Types for Objects Observed with SpeX

| Object           | \( r' - J \) | Direct Comparison | Spectral Indices |
|------------------|--------------|-------------------|-----------------|
| 2MASS J1059+3042 | T8           | T4                |                 |
| 2MASS J1230+287 | L0           | L2                | \( L1 \pm 1.5 \) |
| 2MASS J1237+3028 | L0           | M7.5 V            | M8.5 V \( \pm 2.5 \) |
| 2MASS J1253+2728 | M9 V         | M8.5 V            | M9.5 V \( \pm 1 \) |
| 2MASS J1431+1436 | L2           | L2                | L3.5 \( \pm 1.5 \) |
| 2MASS J1434+2202 | L1           | sdM9              | L2.5 \( \pm 1.5 \) |

5. SUMMARY

About 8000 deg² from the 2MASS and SDSS catalogs were compared to find low-mass (red), HPM objects. Thirty-six new HPM objects were discovered in the analysis. All objects were confirmed as having high proper motions with deep imaging at the du Pont 2.5 m and Magellan 6.5 m telescopes. Their red optical and NIR colors indicate that 27 are M dwarfs, 8 are early-type L dwarfs, and 1 is a late-type T dwarf. Through comparing the colors and reduced proper motions of our newly identified HPM objects we find several are good subdwarf candidates.

The newly identified L dwarfs appear to have \( J - K_s \) colors at the extreme of known L dwarf colors. This may hint at a color bias in brown dwarf detections through color surveys (about a 3.5 sigma result). Follow-up NIR spectroscopy of six of the late-type objects show that 2MASS J14313097+1436539 and 2MASS J14343616+220463 exhibit peculiar spectral features similar to other peculiar “blue” L dwarfs. Spectroscopy also
shows that 2MASS 14343616+2202463 could be an L subdwarf and 2MASS 10595185+3042059 is a T dwarf. From their estimated absolute magnitudes it appears that all of the brown dwarfs found in this survey are within 100 pc of the Earth.

In addition, several hundred previously known HPM objects were also detected, as well as ten known L- and five known T-dwarfs. For the first time we determined the proper motions and position angles for known T-dwarfs SDSS J085834.42+325627.6 and SDSS J125011.65+392553.9 as well as the late L-dwarf 2MASS J15261405+2034414. An additional 13 objects that appeared to be real in the 2MASS catalog but are not identified or correlated with any objects in the SDSS were found. Deep du Pont 2.5 m I-band imaging of these locations found no interesting counterparts. These objects are likely artifacts in the 2MASS catalog but are not identified or correlated with any objects in the SDSS.

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