SPITZER/IRAC SEARCH FOR COMPANIONS TO NEARBY, YOUNG M DWARFS

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ABSTRACT

We present the results of a survey of nearby, young M stars for wide low-mass companions with the Infrared Array Camera (IRAC) on the Spitzer Space Telescope. We observed 40 young M dwarfs within 20 pc of the Sun, selected through X-ray emission criteria. A total of ten candidate companions were found with IRAC colors consistent with T dwarfs. Extensive ground-based NIR follow-up observations rejected all these candidates. Two additional candidates were discovered via common proper motion measurements, one of which was rejected as a background object and the other is a bona fide companion to GJ 2060, a member of the AB Doradus moving group.

Key words: binaries: visual – stars: formation – stars: low-mass, brown dwarfs

Online-only material: color figures

1. INTRODUCTION

The past decade has seen an extraordinary increase in our understanding of the lower reaches of the main sequence. Stimulated largely by a new generation of near-infrared (NIR) sky surveys, a wealth of low-luminosity dwarfs has been uncovered, requiring the addition of two new spectral classes to the standard canon: L, spanning an approximate temperature range of ∼2000 K to 1300 K (Kirkpatrick et al. 1999), and T, methane dwarfs, reaching temperatures as low as ∼700 K (Burgasser et al. 2002, 2006; Geballe et al. 2002). Many L dwarfs and all T dwarfs are substellar-mass brown dwarfs.

Current efforts focus on extending coverage to even lower temperatures, where spectral changes are expected to require yet another spectral class, provisionally designated Y (Kirkpatrick et al. 1999). Finding isolated examples of such objects in the general field is hampered by their low luminosities (Mbol > 19, MJ > 17) and correspondingly low surface densities in even deep NIR surveys, such as UKIDDS (Dye et al. 2006). Even the optimistic assumption of equal numbers of brown dwarfs and stars (a mass function, Ψ(M) ∝ M−1) predicts only ∼4000 brown dwarfs within 25 parsecs or a surface density of ∼1 per 10 deg2 (Reid et al. 2004; Cruz et al. 2007). At least half of those dwarfs are expected to have T < 300 K, and absolute magnitudes MJ > 19 and M4.5µm > 18 according to synthetic mass function estimates (Burgasser 2004; Allen et al. 2005), taxiing ground, and space-based surveys to their limit.

Field surveys are not the only option available to searches for low-mass dwarfs. Indeed, the most successful method of extending the main sequence has been searching for low-luminosity companions of stars that are already known to be close neighbors of the Sun. This approach led to the discovery of the first ultracool dwarf (Gl752B, or VB10, spectral type M8), as the companion of an M3 dwarf (van Biesbroeck 1944); the first known L dwarf (GD 165B), a close companion of a DA white dwarf (Becklin & Zuckerman 1988); and the first T dwarf (Gl 229B), the resolved companion of an M0.5 dwarf at a distance of 6 parsecs from the Sun (Nakajima et al. 1995). Y dwarfs are likely to be the next step.

Companion searches offer significant advantages in determining the fundamental properties of low-mass dwarfs. Even if direct trigonometric parallaxes are unavailable, reliable distance estimates, and hence luminosities, can be derived using the photometric and/or spectroscopic properties of the main-sequence primary. Moreover, detailed observations of the primary can provide crucial information on the metallicity, kinematics and, particularly, the age of the system, allowing an estimate of the mass of a brown dwarf companion. Finally, an inventory of the frequency and mass ratio distribution of close, low-mass companions is vital to assessing the likely frequency of planetary systems.

Optimizing detection probabilities requires careful consideration of two factors: the luminosity contrast ratio between components and the likely angular separation of binary systems. Thus, while low-luminosity ultracool dwarfs are closest in luminosity to brown dwarf companions, only a handful of the known binaries have separations exceeding 15 AU (Burgasser et al. 2007). On the other hand, luminous G and K dwarfs overwhelm brown dwarf companions at moderate and small separations.

We have chosen to focus on Spitzer observations of nearby, young, mid-type M dwarfs. These stars provide a better contrast ratio for companion detection than higher mass GK stars at moderate orbital separation for low-mass companions and a sufficiently high space density to provide statistically significant numbers in the immediate solar neighborhood. Spitzer 4.5 µm observations offer the potential of detecting companions ∼7.5 mag fainter than the primary at separations exceeding ∼15 arcsec. Brown dwarfs cool and fade on relatively rapid timescales, so targeting young systems maximizes the probability of detecting very low-mass companions. Our observations have not resulted in the detection of any new ultracool companions; however, we can set upper limits to the frequency of wide, low-mass companions to stars in this mass range.

The paper is organized as follows: Section 2 describes target selection, outlining how we use X-ray data to identify relatively young M dwarfs near the Sun; Section 3 discusses our Spitzer/IRAC data reduction procedures and candidate selection criteria; Section 4 outlines our follow-up data; Section 5 discusses our results; and Section 6 summarizes our conclusions.

2. TARGET SELECTION

The X-ray activity is a powerful indicator of stellar youth. Observations of open clusters show a consistent and relatively rapid decline in emission strength with an increasing age at a
given spectral type. This is illustrated in Figure 1, which plots \( X \)-ray data for members of TW Hydrae association (\( \tau \sim 10 \) Myr; Reid 2003), the Pleiades (\( \tau \sim 120 \) Myr; Stauffer et al. 1994; Micela et al. 1999), and the Hyades (\( \tau \sim 450 \) Myr; Stern et al. 1981; Reid et al. 1995), together with data for local field dwarfs (Huensch et al. 1999).

We are currently compiling a census of K and M dwarfs within 20 parsecs of the Sun, concentrating on late-type dwarfs within the 48% of the sky covered by the Two Micron All Sky Survey (2MASS) second release (Reid et al. 2004, 2007, and references within). So far, we have identified over 950 stellar systems that are likely to lie within our distance limits, including 320 additions to the nearby star catalog. We have identified active stars by cross-referencing this dataset against the \textit{ROSAT} bright source catalogue (Voges et al. 1999). Twenty percent of the stars in this sample have \( X \)-ray counterparts.

Seventy-nine stars meet these criteria. Thirty-six of these active stars (40%) are known to be in binary systems. Activity is often enhanced by interactions and spin–orbit coupling in close binaries, and we also wish to avoid secondary stars with earlier type primaries, so we have excluded those stars from the \textit{Spitzer} observations.

Of the remaining 43 apparently single, active M dwarfs (spectral types M0 to M6), two (AD Leo and AU Mic) are included in \textit{Spitzer} GTO programs. The remaining 41 stars were targeted for observations in the present program (see Table 1). Given the dispersion in activity at a given age, we do not expect all of these stars to be as young as the Pleiades. However, these stars are likely to include the youngest constituents of the immediate solar neighborhood and, as a consequence, offer the best prospects of detecting extremely low-mass brown dwarf companions.

3. \textit{Spitzer}/IRAC DATA

3.1. Observations

Our \textit{Spitzer}/IRAC observations of 40 out of 41 targets were obtained throughout Cycle-1 (see Table 1). One target, Wo 9520, was not observed because, for an unknown reason, that observation was replaced by a repeated observation of a previously observed target. We adopted short exposure times of 12 s to minimize persistence problems, since the primaries are all bright (\( 7 < K < 9 \)). The 40 targets were observed in a combination of full-frame and high dynamic range (HDR) mode. The HDR mode was used for the ten brightest targets.
Figure 2. X-ray selection of young nearby stars: we have computed the X-ray/J-band flux ratio for the 196 stars in our 20 parsec sample that are included in the ROSAT bright source catalogue, and plot those data against $(V - J)$ color (solid triangles). Similar data are shown for nearby stars from the Huensch et al. catalog (crosses) and for Pleiades stars from Micela et al.’s HRI survey (open circles). The dotted lines outline the selection criteria that we have used to select the 20 parsec M dwarfs most likely to have Pleiades-like ages.

This mode takes a short 0.6 s exposure followed by the long 12 s exposure at the same dither position. In this way, we can obtain accurate photometry for bright sources that are saturated in the longer exposures. Those targets observed in the HDR mode are indicated in Table 1. All other sources were observed in a full frame mode with 12 s exposures at each pointing. We used a nine-point random dither pattern, as prescribed in the Observer’s Manual, to remove detector defects and improve our angular resolution. The small-scale dither pattern was used to optimize sub-pixel sampling.

3.2. Data Reduction

The Basic Calibrated Data were downloaded from the Spitzer archive via Leopard. We then used the Spitzer Science Center provided data reduction software MOPEX/APEX, to carry out our analysis. MOPEX was used to mask bad pixels and cosmic rays, smooth over electronic artifacts such as column pulldown and muxbleed, shift and add the dithered images, and perform aperture photometry. The HDR mode data were reduced separately from the full range mode data. Sources that were saturated in the long exposures were identified and photometry taken from the unsaturated shorter exposures, as available.

Final band-merged photometry lists for each field were generated by requiring identification of each source in at least the 3.6 μm and 4.5 μm channels. This eliminates many artifacts automatically. We also required sources to have magnitude uncertainties better than 0.15 mag as an additional quality check. The final factor taken into account is distance from the primary star; we exclude sources within a 15″ radius of the bright primary stars due to the likelihood of contamination by the primary point-spread function (PSF). As Figure 3 shows, the inner boundary of this search region lies on the wings of the Spitzer PSF at 3.6 μm. As a result, we effectively have a uniform sensitivity over the full area used for the companion search. The photometry

Figure 3. Example PSF derived from the 3.6 μm image of LP 776-25 (solid line) with the 5σ detection threshold (dashed line). The logarithm of the pixel value has been taken to more easily see the point at which the detection threshold is crossed.
the calibrated aperture photometry derived by MOPEX with the addition of the NIR 2MASS photometry it becomes brown dwarf companions to known nearby M dwarfs. However, 2MASS sources.

database (Skrutskie et al. 2006) via a Gator query within lists for sources at separations greater than 15"

The candidate selection was a multi-step process. We used Primary saturated in a 4.5 µm channel. (4) Primary saturated in 3.6 µm and 4.5 µm channels and mildly saturated in 5.8 µm and 8.0 µm channels. (5) Wide companion to LHS 5133. *Distance moduli are derived from photometric and spectroscopic parallaxes save for those with asterisks which are from Hipparcos parallaxes.

lists for sources at separations greater than 15"were then used to select candidate companions.

3.3. Companion Candidate Selection

The candidate selection was a multi-step process. We used the calibrated aperture photometry derived by MOPEX/APEX, described above, and FORTRAN scripts to parse the data. This resulted in 14,621 sources. Next, all the sources detected at both 3.6 µm and 4.5 µm were compared to the 2MASS database (Skrutskie et al. 2006) via a Gator query within 5 arcsecs of each IRAC source. This search yielded 2513 2MASS sources.

The primary purpose of this project is to search for very cool brown dwarf companions to known nearby M dwarfs. However, with the addition of the NIR 2MASS photometry it becomes possible to distinguish spectral type M and L companions from even hotter stars (FGK). M and L dwarfs have neutral IRAC colors, but have red 2MASS-IRAC colors which allow us to identify them photometrically. In addition, matching the IRAC data against 2MASS allows us to determine whether candidate photometric companions display common proper motion (CPM) with their putative primary stars. All sources detected in both our IRAC data and 2MASS were matched against color and magnitude criteria consistent with a M, L, or T dwarf. These criteria are based on Spitzer/IRAC photometry of known MLT dwarfs described in Patten et al. (2006). One of the cleanest selection techniques is to plot the $M_{Ks}$ versus $K_s - 4.5 \mu$m color–magnitude diagram. To construct this diagram, the sources in each field were assumed to lie at the distance of the targeted M dwarf. Distance estimates
are predominantly derived from photometric and spectroscopic parallaxes, with only eight sources having Hipparcos parallaxes, see Table 1. The results are displayed in Figure 4. Of the 2513 sources with 2MASS counterparts, only one has colors and magnitudes consistent with a MLT dwarf (see Table 2). However, this object does not display CPM with its putative primary, G1 173-29, and, given its 2MASS colors, is likely a white dwarf.

We have also searched for CPM companions that lie in otherwise crowded areas of color space. In our analysis we found two candidate companions, and also independently reacquired the wide M3 companion to G 274-24, as reported in Jao et al. (2003). The first candidate companion is in the field of LP 764-40, has neutral 2MASS–IRAC colors (Table 2), and is identified with LP 764-40. The second CPM candidate companion lies in the field of GJ 2060. This object, as will be discussed further in Section 4.2, is found to be a genuine companion. Thus, all sources with 2MASS counterparts, save one, are ruled out as potential companions.

For sources with IRAC-only detections, it is not possible to distinguish companions warmer than T dwarfs, see Figure 5, so we focus our efforts here on T and cooler candidates. However, we can eliminate sources with IRAC-only colors consistent with dwarfs earlier than T0 since those sources ought to have JHK magnitudes brighter than the 2MASS limits if they actually were late-type companions of the target star. Thus, those sources are also eliminated (Figure 5). Again, our selection criteria are based on the IRAC photometry of known MLT dwarfs as described in Patten et al. (2006). Our first cut was in $M_{\lambda_{4.5 \mu m}}$ versus $3.6-4.5 \mu m$ (Figure 5). These criteria are defined for all objects with $3.6-4.5 \mu m > -0.35$

$$M_{\lambda_{4.5 \mu m}} \leq 1.25 \times [3.6-4.5 \mu m] + 13.0$$

$$M_{\lambda_{4.5 \mu m}} \geq 1.25 \times [3.6-4.5 \mu m] + 9.0.$$ (1)

A total of 45 candidates survived these cuts. Two further color cuts were applied, again based on Patten et al. For those sources detected at 5.8 $\mu m$ as well, we eliminated all sources with $4.5-5.8 \mu m$ colors greater than 0.6, see Figure 6. Finally, for those sources also detected at 8.0 $\mu m$, we eliminated all those objects with $3.6-4.5 \mu m < 2$ and with 5.8–8.0 $\mu m$ colors redward of the T dwarf sequence, see Figure 7. The last step was to compare the remaining candidates with the DPOSS plates. Since L and T dwarfs are very red, we would not expect a

### Table 2

| $m_{\lambda_{4.5 \mu m}}$ (mag) | $3.6-4.5 \mu m$ (mag) | $4.5-5.8 \mu m$ (mag) | $5.8-8.0 \mu m$ (mag) | Distance (pc) | $m_1^a$ (mag) | $m_2^a$ (mag) | $m_3^a$ (mag) | R.A. (hms) | Decl. (dms) | Primary | Follow Up Notes |
|-------------------------------|-----------------------|-----------------------|-----------------------|--------------|---------------|---------------|---------------|-------------|-------------|---------|----------------|
| 14.08                         | 0.60                  | ...                   | ...                   | 13.7         | 15.50         | 15.26         | 15.64         | 02 08 52.5  | +49 27 00.0 | G 173-39 | No CPM        |
| 7.96b                         | ...                   | 0.29                  | -0.01                 | 15.6         | 8.90          | 8.37          | 8.06          | 07 28 51.1  | -30 15 53.8 | GJ 2060 | CPM Companion: SpT M5 |
| 14.01                         | 0.08                  | -0.04                 | -0.01                 | 18.0         | 15.06         | 14.56         | 14.47         | 23 58 05.6  | -17 23 39.6 | LP 764-40 | SpT M4: Not a Companion |

Notes.

- Magnitudes from the 2MASS database.
- Saturated in channel 1 and nearing saturation in channel 2.
genuine low-mass dwarf to appear on the plates. Thus, any candidate seen on the DPOSS plates was eliminated. The final number of sources remaining after all of these cuts is only ten sources, which are listed in Table 3.

4. FOLLOW-UP OBSERVATIONS

4.1. IRAC-only Candidates

The most efficient means of establishing the nature of the IRAC-only candidates is to obtain NIR $JHK$ photometry. The latter observations were carried out, thanks to generous donations of time on three different telescopes, as indicated in Table 3. One candidate was observed using the imaging mode of Spex on the IRTF in Hawaii in 2005 June. The majority of the remaining observations (7 out of 10) were performed using the PANIC instrument on the Magellan telescope in Chile in 2005 November. The two final candidates were observed using SWIRC on the MMT in Arizona also in 2005 November. All of these candidates were either resolved as galaxies (4/10) or were found to have NIR-IRAC colors that are inappropriate for T (or Y) dwarfs (6/10). Those objects with wrong NIR-IRAC colors are all found to be too red, particularly in $J - K$. Given that nearly half of the candidates were resolved into galaxies and the very red NIR-IRAC colors, these unresolved objects are likely galaxies as well. Thus, we conclude that none of the IRAC-only sources are confirmed as a cool brown dwarf companion of a nearby young M dwarf.

4.2. GJ 2060

As mentioned in Section 3.3, one object in the field of GJ 2060 displays CPM with the primary. GJ 2060 (2MASS J07285137-3014490) is a M1 dwarf at a distance of 15.6 parsecs, which was recently resolved as a close binary via ground-based AO images (Daemgen et al. 2007). GJ 2060 has also been shown to be a likely member of the nearby ∼50 Myr old stellar association AB Dor (Zuckerman et al. 2004).

The primary reached the hard saturation limit in both the 3.6 $\mu$m and 4.5 $\mu$m channels (this field was not observed in the HDR mode) and is mildly saturated in the remaining channels. The companion is also nearing the hard saturation limit in all four channels of our IRAC observations. This renders the photometry for the primary as well as that of the secondary uncertain, see Table 1.

However, accurate astrometry can be obtained because short 0.6 s exposures are taken at the beginning of IRAC dithering.
sequences. Due to the nature of how the data are taken, these short exposures are only available in the 4.5 \( \mu m \) and 8.0 \( \mu m \) channels. Matching the unsaturated IRAC astrometry against 2MASS data leads to derived motions that are consistent between the primary and secondary given the 10–20 mas yr\(^{-1}\) against 2MASS data leads to derived motions that are consistent with each other. The most likely explanation is that the companion is itself a binary system.

Thus, we conclude that GJ 2060 is probably a quadruple system, composed of two widely separated equal-mass binaries. The combination of a good age estimate, the nearby distance, and the ability to obtain dynamical masses makes this an extremely interesting system for further study. Mass and age are two of the most important and elusive stellar parameters to measure.

5. DISCUSSION

This survey is complementary to the one carried out by Daemgen et al. (2007). The source sample is the same, but the data considered here are sensitive to companions at much wider separations. We excluded the area of each image around the target stars to a radius of 15′ (Figure 3). At this radius we have uniform sensitivity from the bright target stars out to the edge of the field, or about 2.5 arcmin. This corresponds to separations of \( \sim \)200 AU to \( \sim \)2200 AU at our typical target distance of 15 pc. This separation range is also complimentary with the \( \sim \)300 AU limit of the Daemgen et al. (2007) work. We update the overall results from the ground-based survey with the discovery of the quadruple nature of the GJ 2060 system. Thus, the total number of multiple systems of the 40 observed star sample becomes 11 binaries, one triple, and one quadruple, where the quadruple is GJ 2060.

Most of our sample yielded null results (38/40); thus it is important to characterize our sensitivity limits. The ultimate limiting factor in our selection of candidate companions is the 3.6 \( \mu m \) magnitude. This is because the final selection criteria used were the 3.6–4.5 \( \mu m \) color. While IRAC’s 4.5 \( \mu m \) channel is less sensitive than the 3.6 \( \mu m \) channel in terms of raw numbers (15 \( \mu Jy \) versus 12 \( \mu Jy \) for 3σ detections), we also need to consider the spectral energy distribution (SED) of a T dwarf. They are considerably fainter in 3.6 \( \mu m \) than in 4.5 \( \mu m \), with colors greater than 0.6–0.7 for mid- to late-T dwarfs, as well as for projected cooler spectral types (Burrows et al. 2003). However, the reddest color that we can detect near our survey limits corresponds to \( \sim \)0.25 mag. Thus, since we require detections in both the 3.6 \( \mu m \) and 4.5 \( \mu m \) channels, the actual limiting magnitude is in the 3.6 \( \mu m \) channel.

The limiting magnitudes in each field were determined automatically using the same photometry used to select candidates. The maximum magnitude detected in each field was determined by combing through the combined sources lists and looking for sources with magnitude errors less than 0.15, which were used in the selection process. The derived magnitude limits for each field are listed in Table 1. The median values are around \( m_{3.6} \sim 17.5 \) and \( m_{4.5} \sim 17 \).

The most interesting limiting quantity is the mass. However, in order to establish a mass limit we must use evolutionary models. These models are an essential ingredient in the study of substellar objects because brown dwarfs do not maintain stable hydrogen fusion. Thus, their luminosity is heavily age dependent and, given the lack of empirical measurements, the models are required to obtain mass estimates. We apply the same approach as in Allen et al. (2005), using the evolutionary models of Burrows et al. (2001) and the bolometric corrections from Golimowski et al. (2004). The bolometric corrections are required to transform the bolometric luminosity provided by the evolutionary models to an observed band pass magnitude. We used the Golimowski et al. (2004) \( L’ \) and \( M \) band bolometric corrections.

Table 4

| Quantity | GJ 2060AB | GJ 2060C |
|----------|----------|----------|
| \( m_J \) | 6.62 mag | 8.90 mag |
| \( m_H \) | 5.97 mag | 8.37 mag |
| \( m_K \) | 5.72 mag | 8.06 mag |
| \( PM_a \) | -105 mas yr\(^{-1}\) | -131 mas yr\(^{-1}\) |
| \( PM_b \) | -209 mas yr\(^{-1}\) | -209 mas yr\(^{-1}\) |
| Distance | 15.6 pc | … |
| SpT | M1V | M5V\( ^b \) |

Notes.

- Proper motions were measured for both objects using 2MASS as a first epoch and our IRAC data as a second epoch.
- Based on a low-resolution Spex spectrum.

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\( b \) Based on a low-resolution Spex spectrum.
metric corrections to stand in for IRAC channels 3.6 \( \mu \)m and 4.5 \( \mu \)m because there are no published corrections for IRAC channels.

We determined the mass that corresponds to the absolute limiting magnitude of each field for three different ages: 120 Myr (Pleiades-like), 500 Myr (Hyades-like), and 5000 Myr (field age). The first two ages were chosen because our sample is drawn from stars that were selected to have ages comparable to, or less than, that of the Hyades and are likely greater than the Pleiades. We also consider an average age for the general field age (5000 Myr, solid line).

The median limiting mass is lower with a younger age; the younger of limiting masses are displayed in Figure 9. Not surprisingly, the Pleiades. We also consider an average age for the general field age (5000 Myr, solid line).

Figure 9. Histograms of the mass limits of each target field for three ages: Pleiades-like (120 Myr, dotted line), Hyades-like (500 Myr, dashed line), and field age (5000 Myr, solid line).

We have conducted a survey of 40 nearby, young M dwarfs using the Spitzer Space Telescope to find wide, ultracool companions. The target stars were chosen to have X-ray activity levels that exceed those of Pleiades stars of a similar spectral type, and are therefore likely to have ages of a few hundred Myrs. Our observations are capable of detecting late-M, L, or T dwarfs at separations more than 15 arcsecs from the target stars, which tie at distances of 9 to 22 parsecs. No ultracool companions were detected in our sample, but we discovered a new quadruple system in GJ 2060. We also reconfirmed the known wide triple, G 274-24, in our CPM analysis. Our sensitivity limits indicate that we could have detected most, if not all, companions down to masses of six Jupiter masses. There is also some limited evidence in support of dynamical simulations of Sterzik & Durisen (2003) and Delgado-Donate et al. (2004). However, this conclusion is based on very small number statistics and will require substantial additional observations to confirm.

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6. SUMMARY

We have conducted a survey of 40 nearby, young M dwarfs using the Spitzer Space Telescope to find wide, ultracool companions. The target stars were chosen to have X-ray activity levels that exceed those of Pleiades stars of a similar spectral type, and are therefore likely to have ages of a few hundred Myrs. Our observations are capable of detecting late-M, L, or T dwarfs at separations more than 15 arcsecs from the target stars, which lie at distances of 9 to 22 parsecs. No ultracool companions were detected in our sample, but we discovered a new quadruple system in GJ 2060. We also reconfirmed the known wide triple, G 274-24, in our CPM analysis. Our sensitivity limits indicate that we could have detected most, if not all, companions down to masses of six Jupiter masses. There is also some limited evidence in support of dynamical simulations of Sterzik & Durisen (2003) and Delgado-Donate et al. (2004). However, this conclusion is based on very small number statistics and will require substantial additional observations to confirm.

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