A DISTANCE-LIMITED IMAGING SURVEY OF SUBSTELLAR COMPANIONS TO SOLAR NEIGHBORHOOD STARS

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ABSTRACT

We report techniques and results of a Palomar 200 inch (5 m) adaptive optics imaging survey of substellar companions to solar-type stars. The survey consists of Ks coronagraphic observations of 21 FGK dwarfs out to 20 pc (median distance ~17 pc). At 1'' separation (17 projected AU) from a typical target system, the survey achieves median sensitivities 7 mag fainter than the parent star. In terms of companion mass, this corresponds to sensitivities of 50 Mj (1 Gyr), 70 Mj (solar age), and 75 Mj (10 Gyr), using the evolutionary models of Baraffe and colleagues. Using common proper motion to distinguish companions from field stars, we find that no system shows positive evidence of a previously unknown substellar companion (searchable separation ~20–250 projected AU at the median target distance).

Key words: methods: data analysis – stars: low-mass, brown dwarfs – surveys – techniques: high angular resolution

1. INTRODUCTION

The discovery of the brown dwarf GJ 229B (Nakajima et al. 1995) heralded a stream of direct detections of substellar objects. In particular, field surveys like the Sloan Digital Sky Survey (SDSS; Gunn & Weinberg 1995), the Two Micron All Sky Survey (2MASS; Skrutskie et al. 1997), and the Deep Near Infrared Survey (DENIS; Epchtein 1997) have helped to raise the number of brown dwarf (L- and T-type) identifications today to over 600 (Gelino et al. 2008). However, the number of brown dwarfs identified as companions to main-sequence stars remains few. At the time of writing this paper, there are only a handful of brown dwarfs confirmed as companions to main-sequence stars. Brown dwarfs that are part of stellar systems are particularly interesting because they often yield insights into brown dwarf and planet formation around stars. For instance, statistics on the frequency of brown dwarf companions may shed light on the differences among planet, brown dwarf, and star formation. And unlike the case of discovered field brown dwarfs, the presence of a central star often reveals additional information, such as distance, metallicity, and age, on the presumably coevolved brown dwarf.

A number of high-contrast surveys have attempted to improve our knowledge of the moderate-to-wide separation (40 AU to a few hundred AU) substellar companion population around stars. For example, Biller et al. (2007) and Metchev & Hillenbrand (2004) each surveyed samples (45 targets, 101 targets, respectively) of young (age \( \lesssim 250 \) Myr, \( \lesssim 400 \) Myrs), relatively nearby (\( \lesssim 50 \) pc, \( \lesssim 160 \) pc) stars using adaptive optics (AO) systems on the Very Large Telescope (VLT) and Palomar/Keck telescopes, respectively; Lowrance et al. (2005) used the Hubble Space Telescope (HST) Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) to survey 45 young (median age \( \sim 150 \) Myr), nearby (average distance \( \sim 30 \) pc) stars for substellar companions; Lafrenière et al. 2007 used Gemini AO to observe 85 young (median age \( \sim 150 \) Myr), nearby (average distance \( \sim 22 \) pc) stars; and Carson et al. (2005, 2006) used Palomar AO to survey 80 nearby (median distance \( \sim 17 \) pc) stars with unknown ages. These references represent some of the larger direct-imaging, high-contrast surveys, but there are a number of other surveys as well.

The observations described in this document largely provide an extension to Carson et al. (2005), although the new target list is focused more strongly on solar-type stars (the Carson et al. 2005, 2006 surveys looked mostly at K and M dwarfs). Most of the competing surveys (e.g., Biller et al. 2007; Metchev & Hillenbrand 2004; Lowrance et al. 2005; Lafrenière et al. 2007, and others) have focused on observing the youngest nearby stars. While this allows for a maximal substellar-object self-luminosity (Baraffe et al. 2003), it inherently requires that one examines stars at somewhat larger distances in order to achieve a large enough original sample to glean the youngest stars. Surveying only younger stars also leads to selection biases, as certain types of stars lend themselves better to age determinations than others (Mamajek & Hillenbrand 2008). For our survey, we avoid age requirements in an effort to achieve a more uniform census of the substellar companion population around the nearest solar-type stars.

While explorations of the substellar space around nearby FGK stars are scientifically interesting in their own right, they also provide important reconnaissance observations for the next generation of planet-search imaging surveys, like expected programs with Subaru (HiCIAO; Tamura et al. 2006), Palomar (Project 1640; Hinkley et al. 2008), VLT (SPHERE; Beuzit et al. 2008), Gemini (GPI; Macintosh et al. 2006), and potential space missions, like Terrestrial Planet Finder Coronagraph (TPF-C)6 and Terrestrial Planet Finder Interferometer (TPF-I)7/Darwin.8 Information on the presence of brown dwarfs is important for these future planet surveys because the existence of an orbiting brown dwarf may affect the likelihood of there being a planet in that system. Even for southern hemisphere

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5 http://planetquest.jpl.nasa.gov/TPF-C
6 http://planetquest.jpl.nasa.gov/TPF-I
7 http://www.esa.int/science/darwin

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future planet searches, whose targets may not overlap with this
document’s survey, the statistical information (from our survey
and others) on brown dwarf frequencies may help guide southern
surveys’ overall target selection strategy. In addition to informa-
tion on orbiting brown dwarfs, future surveys will also benefit
from our survey’s reports on discovered field objects close to
nearby stars. Such information will ensure that future surveys do
not spend unnecessary time following up these field objects for
common proper-motion tests. This information will also guide
target selection, by providing information on field objects whose
interfering light might adversely affect high-contrast sensitivi-
ties.

In the sections below, we present techniques and results of our
recently completed survey. Section 2 presents our target sample.
Section 3 describes our observing techniques. In Section 4, we
present the data analysis techniques we used for this survey.
In Section 5, we summarize our survey sensitivities. Section 6
describes our results. In Section 7, we present our conclusions.

2. TARGETS

Our target selection process had its origins in work being
carried out at Jet Propulsion Laboratory (JPL) to select potential
candidates for the proposed TPF-C mission (Levine et al. 2006).
The main constraints for that selection process included FGK V
spectral type, no known stellar multiplicity, closeness (< 20 pc),
and visible brightness (V ≲ 7). For optimal observations
from Palomar Observatory, we set a declination lower limit
of −5◦. We also removed any targets from our list that were
already observed during the Cornell High-Order Adaptive
Optics Survey (CHAOS; Carson et al. 2005) and other AO
imaging programs, as determined by a standard literature search.
We confirmed systems’ lack of multiplicity by on-telescope
preliminary imaging. One target, GJ 564, had a previously
published brown dwarf binary companion (Potter et al. 2002).
This fact eluded us in our initial literature search and preliminary
imaging. Hence, we ended up observing this target and recording
its current astrometry.

Our final target list consisted of 21 main-sequence stars. This
included 2 F stars, 14 G stars, and 5 K stars. All stars possessed
well characterized proper-motion and parallax values as defined by
Hipparcos (Perryman et al. 1997). As nearby stars, they
typically possessed high proper motion (median target proper
motion ∼600 mas yr−1), thus facilitating an efficient common
proper motion follow-up strategy for candidate companions.
A complete list of the target set is given in Table 1.

3. OBSERVATIONS

3.1. Coronagraphic Search Observations

To conduct our survey, we used the Palomar Adaptive Optics
(PALAO) system (Troy et al. 2000) and the accompanying
PHARO science camera (Hayward et al. 2001) installed
on the Palomar 200 inch Hale Telescope. PALAO provided us
with the high resolution (FWHM is typically ∼0.14 in Ks
and the Strehl ratio is around 50%) necessary for resolving
close companions. The accompanying PHARO science cam-
era (wavelength sensitivity of 1–2.5 µm and plate scale of
40 mas pixel−1) provided us with a coronagraphic imaging ca-
pability, along with a maximal field of view (FOV; ∼30′). Our
general observing strategy was to align the coronagraphic mask
on a target star and take a series of Ks exposures, being care-
ful to not saturate many pixels in the detector. Occasionally,
we saturated at the edges of the coronagraphic mask, where
high noise levels already prevented any meaningful companion
search. We chose the Ks band because it provides high Strehl
ratios and a favorable relative flux between the substellar com-
ppanion and parent star. We planned our individual exposure
times and number of exposures per set to allow for no more than
∼5 minutes (including overheads) between any target frame and
the nearest sky image. This helped to ensure that sky conditions
did not significantly change between the target exposures and
accompanying sky exposures. The sky exposures consisted of
our taking, before and after the target sequence and with the
same setup as the target sequence, dithered images of a nearby
empty sky region. We spent a comparable amount of time on
sky as we did on the target. We repeated the process of sky-
target-sky as many times as was appropriate, with the goal of
being able to detect (at 5σ) an ∼18 mag (Ks) object at 5′′ sepa-
ration from the primary star. Once we completed the target/sky
sets, we inserted a neutral density filter in the optical path and
conducted dithered noncoronagraphic exposures of the target
star. These images allowed us to characterize and record instru-
ment and site observing conditions. Table 1 gives the relevant
observing information for the individual targets.

3.2. Common Proper Motion Observations

For candidate companions detected in the previous proce-
dures, we checked for physical companionship by using com-
mon proper-motion observations. The nearby stars that we ob-
served tend to have high proper motions (on the order of a few
hundred mas yr−1). The vast majority of false candidate com-
panions are background stars that tend to have very small proper
motions compared to the parent star. Therefore, after recording
our initial measurement, we waited for a timespan long enough
for the parent star to move a detectable distance from the origi-
nal position. In practice, this observable motion ended up being
a minimum of ∼3 pixels. After taking the second epoch observ-
ations, we checked whether the candidate maintained the same
position with respect to the parent star. Target stars re-observed
to check for common proper motion included GJ 895.4, 159,
230, 1095, 1085, 56.5, and 788. GJ 778 and 758 contained can-
didate companions, but were not reobserved due to scheduling
constraints (see discussion in Section 6).

4. DATA ANALYSIS

4.1. Reducing Images

We began our data reduction by median combining each of the
dithered sky sets. We then took each coronagraphed star image
and subtracted the median-combined sky taken closest in
time to the star image. The typical separation in time between
the target and sky image was ∼5.5 minutes. We divided each
of the sky-subtracted star images by a flat-field frame that we
created, using standard procedures, from dark-frames and the
dithered sky sets. We chose to use sky flats, instead of the
more conventional twilight or dome flats, in order to have a
flat-field frame that change their observable position (by a few pixels, perhaps) over the
course of the night.

After performing the flat fielding, we next median combined
each sequence of coronagraphic star frames. For this median
combination, we used the images’ residual parent star flux
filter, described in Carson et al. (2005), has been shown to function that minimized lower frequency signals. This Fourier version of the final image by an exponential transmission instrument reflection and residual parent star flux. The Fourier help remove non-point-like features such as unwanted internal deviating from the surrounding 8 pixels by $\sigma \lesssim 1$ pixel). We concluded that in-software realignment produced better overall sensitivities than just throwing out misaligned frames. Next, we applied a bad-pixel algorithm to remove suspicious pixels (defined as any pixel deviating from the surrounding 8 pixels by $\gtrsim 5\sigma$) and replace them with the median of their eight neighbors.

We next applied a Fourier filter to the resulting images to help remove non-point-like features such as unwanted internal instrument reflection and residual parent star flux. The Fourier filter application entailed our multiplying a Fourier-transformed version of the final image by an exponential transmission function that minimized lower frequency signals. This Fourier filter, described in Carson et al. (2005), has been shown to improve the signal-to-noise ratio ($S/N$) by $\sim 25\%$ for a typical PHARO high-contrast image. Along with this $S/N$ improvement, the typical point-spread function (PSF) FWHM decreased by about 10\% as a result of the Fourier filter application.

Finally, we investigated possibilities for taking advantage of the approximate symmetry of the coronagraphed PSF to self-subtract an inverted and/or a rotated version of the PSF from the noninverted image. We ended up deciding against using this technique, as the final improvement was either marginal or nonexistent.

### 4.2. Identifying Brown Dwarf Companions

Our first step in identifying candidate brown dwarf companions was to individually inspect each final Fourier-filtered and non-Fourier-filtered image for any potential companions. By choosing to examine both Fourier-filtered and non-Fourier-filtered final images, we effectively recognize that the filtering technique improves the $S/N$ in some instances and worsens it in others. For instance, Fourier-filtering works best in regions with a shallowly sloping unwanted signal, such as regions with internal instrument reflection. However, in other regions, the candidate companion $S/N$ may suffer since the filtering always removes some true candidate companion flux.

The Palomar AO characteristic PSF “waffle pattern” (see Figure 1) is often seen as undesirable by observers, as the pattern degrades the potential PSF sharpness. While this is true in principle, the characteristic “waffle pattern,” in practice, provided an important way for us to distinguish true celestial objects (which had a well patterned four-cornered PSF) from statistical outliers in the image noise, which typically took on more arbitrary shapes. Thus, it provided an important first step in candidate companion identification.

While individual inspection of waffle patterns proved useful, we chose to also use an automated detection system to deliver more quantifiable sensitivity levels. Our automated algorithm operated by centering on every other pixel in the final reduced image and rejecting the PSF from the noninverted image. We ended up deciding against using this technique, as the final improvement was either marginal or nonexistent.

### Table 1

| Parallax (mas) | R.A. (mas yr$^{-1}$) | Decl. (mas yr$^{-1}$) | $V$ (mag) | Name | Dates of Coronagraphic Net Exposure | Observations | Time (s) |
|---------------|----------------------|-----------------------|----------|------|-------------------------------------|--------------|---------|
| 52.00         | 151.2                | $-252.0$              | 5.38     | GJ 159 | 2006 Dec; 2007 Nov                  | 2006 Dec     | 581     |
| 55.20         | 78.1                 | $-297.1$              | 6.43     | GJ 230 | 2005 Dec; 2007 Nov                  | 2005 Dec     | 2149    |
| 59.31         | 29.4                 | $-186.1$              | 5.54     | GJ 1095 | 2006 Dec; 2007 Nov                  | 2006 Dec     | 586     |
| 59.46         | $-34.1$              | $-34.45$              | 7.17     | GJ 56.5 | 2006 Dec; 2007 Nov                  | 2006 Dec     | 581     |
| 64.25         | 62.4                 | $-230.7$              | 5.97     | GJ 1085 | 2006 Dec; 2007 Nov                  | 2006 Dec     | 595     |
| 69.52         | $-171.2$             | $-1164.2$             | 6.97     | GJ 295 | 2006 Dec                           | 2006 Dec     | 340     |
| 57.57         | $-359.8$             | 139.3                 | 5.95     | GJ 484 | 2006 Dec                           | 2006 Dec     | 283     |
| 56.92         | 268.5                | $-268.8$              | 5.91     | GJ 788 | 2006 May; 2006 Dec                 | 2006 May     | 3054    |
| 64.71         | $-122.3$             | $-103.3$              | 6.76     | GJ 227 | 2005 Dec; 2006 Dec                 | 2005 Dec     | 1982    |
| 52.25         | $-191.1$             | $-115.4$              | 5.95     | GJ 334.2 | 2006 Dec                         | 2006 Dec     | 297     |
| 71.04         | $-315.9$             | 55.2                  | 5.03     | GJ 407 | 2005 Dec; 2006 May                  | 2006 May     | 2046    |
| 56.82         | 223.7                | $-477.5$              | 6.25     | GJ 547 | 2006 May                           | 2006 May     | 1113    |
| 55.11         | 132.5                | $-298.4$              | 6.61     | GJ 614 | 2006 May                           | 2006 May     | 1338    |
| 64.54         | 82.0                 | 162.9                 | 6.37     | GJ 758 | 2006 May                           | 2006 May     | 361     |
| 67.14         | $-529.2$             | $-428.9$              | 5.37     | GJ 376 | 2006 May                           | 2006 May     | 2028    |
| 55.73         | 144.7                | 32.4                  | 5.86     | GJ 564 | 2006 May                           | 2006 May     | 487     |
| 69.61         | $-571.2$             | 52.6                  | 6.66     | GJ 611 | 2006 May                           | 2006 May     | 476     |
| 55.37         | 123.5                | 85.4                  | 6.76     | GJ 651 | 2006 May                           | 2006 May     | 1427    |
| 64.17         | $-1002.8$            | $-912.6$              | 7.28     | GJ 778 | 2006 May                           | 2006 May     | 1517    |
| 70.07         | $-27.7$              | 87.9                  | 5.63     | GJ 311 | 2006 Dec                           | 2006 Dec     | 297     |

Notes. Parallax, proper motion, and $V$ magnitude are from Hipparcos (Perryman et al. 1997). All names follow the Gliese catalog system (Gliese & Jahreiss 1991).
Figure 1. Two example reduced $K_s$ images of GJ 230, taken in 2007 November, using the Palomar 200 inch AO and accompanying PHARO science camera. The image on the left is a noncoronagraphic GJ 230 image taken with a neutral density filter. The slight elongation of the central PSF feature toward the lower left direction is an artifact of the neutral density filter, and does not occur in nonneutral density filter images. The image on the right was taken with no neutral density filter, but with a 0.9′′ opaque spot positioned over the star. The images illustrate PALAO’s characteristic AO-reconstructed PSF as seen in both coronagraphic and noncoronagraphic imaging.

Each detection, it voided a 0.4′′ radius around the detected candidate object. This procedure continued until there were no more positions with S/N values greater than or equal to 5. Of course, for many images, no positions possessed S/N levels greater than 5. After the algorithm identified the candidate sources, we re-examined the final images to ensure that the algorithm had indeed detected a true source as opposed to a systematic effect. Again, we searched for the Palomar AO signature “waffle pattern” to ensure a true physical source. We also made comparisons with images taken at other sources to ensure that the feature was indeed unique to the target image. In practice, we found that individual image inspection, by eye, produced the most thorough identification of candidate companions. However, we felt that the automated detection was important as well, in order to provide quantifiable detection sensitivities and a second check for our visual inspections.

We acknowledge that the use of our automated detection routine has some drawbacks. Notably, there are instances where the algorithm overestimates noise levels. For instance, close to the parent star PSF, the algorithm can mistake what may be a well ordered parent star PSF slope for a random fluctuation in background noise. Additionally, the algorithm may also overestimate the noise close to field stars; if a field star happens to fall in the sky annulus, the algorithm will determine that region to have excessively high background noise. Thus, only the brightest candidate objects would be detected near these field star positions. While these instances are not ideal, we conclude that that is an acceptable compliment to our careful visual inspections. In Section 5, we discuss how we may generate limiting magnitudes and brown dwarf mass limits from these algorithm-generated noise maps.

In cases where we positively identified a potential brown dwarf companion, we next estimated its apparent $K_s$ magnitude by comparing its flux with the noncoronagraphic parent-star calibration images and published 2MASS $K$ magnitudes (Skrutskie et al. 1997). Resulting magnitudes are displayed in Table 2. Once we established an apparent $K_s$ magnitude, we derived a corresponding absolute $K_s$ magnitude, assuming that the candidate had a distance equal to the parent system. Thanks to observational surveys such as Hipparcos (Perryman et al. 1997), all of our parent stars had well defined parallaxes and, therefore, distances. With an approximate absolute $K_s$ magnitude in hand, we combined published brown dwarf observational data (Leggett et al. 2000, 2002; Burgasser et al. 1999, 2000, 2002, 2003; Geballe et al. 2002; Zapatero Osorio et al. 2002; Cuby et al. 1999; Tsvetanov et al. 2000; Strauss et al. 1999; Nakajima et al. 1995) with theoretical data from Baraffe et al. (2003) to extrapolate constraints on the object’s mass. An object whose potential mass fell within acceptable brown dwarf restrictions was designated for common proper motion follow-up observations.

For our follow-up observations, we used Hipparcos published common proper-motion values (Hipparcos catalogue; Perryman et al. 1997) to determine the expected movement of the parent system. Since background and field stars are unlikely to possess proper motions identical to the parent system’s, we used common proper motion as a strong support for a physical companionship. For candidate companions, we used the PSF central peak to identify position. For the obscured parent star, we used the waffle-pattern four corners (which resided outside the opaque coronagraph spot) to create well defined cross-hairs that revealed the central position. We could typically constrain the relative offset between the parent star and candidate companion by fractions of a pixel, depending on S/N levels. Measuring the candidate companion’s relative position over the two epochs, we were able to distinguish physical companionships from chance alignments. We record positions in Table 2.

5. SURVEY SENSITIVITIES

5.1. Determining Limiting Magnitudes

To quantify detection sensitivities from the algorithm-generated noise maps described in Section 4.2, we looked to determine the faintest detectable magnitude as a function of angular separation from each parent star. We began by sampling each noise map (including those derived from Fourier-filtered and non-Fourier-filtered images) and selecting, for each pixel, the smaller of the two noise values. The resulting composite noise map array, therefore, reflected the best sensitivities from each of the two final images. Figure 2 displays a sample image sequence, where a Fourier-filtered and non-Fourier-filtered images are combined to create a composite noise map.

For the composite noise map, we next determined the median values in a series of concentric 0.20′′ thick rings centered on the noise map center. The median values, therefore, represented...
Notes. All detections represent $> 5\sigma$ S/N levels.

a Separation from the central star.
b Position angle, measured counterclockwise from the central star’s north-south axis.

* The field object described in this row is a published brown dwarf companion (Potter et al. 2002). We refrained from measuring the magnitude of this object as blending made photometry difficult.

typical noise as a function of distance from the central star. For each noise value, we then determined the minimum apparent $K_s$ magnitude where the signal exceeded the combined Poisson noise and ring noise by a factor greater than or equal to 5; we were able to convert noise values (in units of detector counts) to $K_s$ magnitudes using parent star calibration data described in Section 3.1. In Figure 3, we plot resulting measurements for median survey sensitivities (middle curve), the best 10% of observations (lower curve), and the worst 10% of observations (top curve). Refer to Table 3 for a summary of minimum detectable magnitudes for each of the individual targets.

Another commonly used statistic for describing sensitivities for high-contrast companion surveys is the limiting differential magnitude as a function of angular separation from the parent
star. In other words, how many times dimmer may a companion object be before we lose it in the parent star noise? Figure 4 plots differential magnitudes for median survey sensitivities as well as the best and worst 10% of observations.

5.2. Mass Sensitivities

Determining sensitivities according to companion mass is complicated by the fact that brown dwarfs of a given mass dim over time. Nonetheless, to get a general idea of detectable masses, we may assume different test ages and then use models by Baraffe et al. (2003) to transform our minimum detectable brightnesses into brown dwarf masses. Figure 5 shows a comparison of median sensitivities assuming 1 Gyr, solar age, and 10 Gyr target ages.

6. RESULTS

After conducting all of our data analysis, we concluded that zero systems showed positive evidence of a brown dwarf companion (that was not previously known). We did redetect the brown dwarf binary orbiting GJ 564, discovered by Potter et al. (2002). In total, we detected 48 field objects (including the binary brown dwarf) around 10 target stars. Both the GJ 778 and GJ 758 fields contained candidate companions, but were not re-observed for common proper motion follow-up tests due to scheduling constraints. 2MASS data (Skrutskie et al. 1997) reports $K$-band field star densities of $\sim$12 stars and $\sim$6 stars per PHARO FOV, for the respective GJ 778 and GJ 758 star neighborhoods. Given the relatively high field star densities for these regions, the chances of these candidates being field stars are high. In the end, however, we cannot confirm or reject that one of these candidates may be a brown dwarf companion. Instead, we simply report the photometry and astrometry for the detected objects. Table 2 presents the measurements for these objects and all the other field objects detected in our survey.

7. DISCUSSION

As mentioned in the previous paragraph, our survey found no evidence of new brown dwarf companions, for orbital separations akin to our own outer solar system. However, even for targets with no candidate companions, we cannot rule out the possibility that one or more new brown dwarfs exist around the targeted stars, even at the semimajor axes for which our survey
is most sensitive. For instance, a substellar companion near conjunction, in an orbit close to edge-on, may be impossible to resolve from the parent star PSF, regardless of the companion’s luminosity or semimajor axis. Furthermore, even for a bright brown dwarf with a face-on orbital inclination, a brown dwarf’s orbital eccentricity might lead to a range of possible projected separations, which could lead to a null detection.

Extracting rigorous companion statistics is, therefore, complicated by factors such as unknown orbital characteristics. For example, if typical brown dwarf orbits are highly eccentric, the typical semimajor axis regime that our survey covers is most likely narrower than the projected orbital separation that we probe, as shown in orbital simulations presented in Carson et al. (2006). Furthermore, extracting the companion fraction for a given substellar mass range is complicated by the fact that one must assume a system age in order to translate the survey sensitivity floor (in terms of $K_s$, mag) into a minimum detectable mass (see discussion in Section 5.2). Since most of our stars have unknown ages, to extract a companion fraction, one must resort to a statistical inference of target star ages, using a method such as galactic birth models (like that used in Burgasser 2004) or stellar metallicity relations (like that used in Carson et al. 2006). Alternative age determination methods, such as those using Ca ii emission, lithium abundance, and X-ray activity, provide poor...
constraints for target sets older than a couple hundred Myrs, and are, therefore, not useful for our applications.

The extractable companion frequency also depends on the relative mass function of substellar companions. For example, even if we limit ourselves to a constrained mass range (such as $20-40 \ M_J$), the companion fraction uncertainties may sensitively depend on whether the majority of brown dwarfs resides near the lower boundary or the higher boundary of our mass range; if the majority resides near the lower mass boundary, there is a greater chance that our null result is due to limiting sensitivities, as opposed to a true lack of companions.

It is possible for one to make educated assumptions for all of the aforementioned factors and then run detailed Monte Carlo population simulations to conclude a companion fraction (e.g., Nielsen et al. 2008; Carson et al. 2006). Published Monte Carlo population analyses have shown that a large target data set ($\geq 60$ stars) is typically required to provide meaningful results. For instance, Carson et al. (2006), using an 80 star sample, concluded a brown dwarf companion ($25-100 \ AU$ semimajor axis) fraction of $0\%-9\%$. Nielsen et al. (2008) concluded, from a 60 star sample, a planet/brown-dwarf ($> 4 \ M_J$) companion ($20-100 \ AU$ semimajor axis) fraction of $0\%-20\%$. Considering these relatively large uncertainties, and that our 21 star sample is significantly smaller than these other surveys, we believe that we cannot conclude meaningful companion fractions from our data set alone. We postpone for a future paper a detailed Monte Carlo population analysis that combines several surveys’ data sets to derive the most meaningful companion fractions.

In addition to explorations of brown dwarf companions, our survey also reported astrometry and photometry for all detected field objects. The reporting of such objects may have potential benefits to future surveys, by providing possible reference star candidates, preventing future brown dwarf candidate false identifications, and yielding data on objects whose interfering light might impede future planet-search observations.

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### Table 3

| Target Name | 2"/0 | 3"/0 | 5"/0 |
|------------|------|------|------|
| GJ 10 11.4 | 15.0 | 16.0 | 17.7 |
| GJ 10 10.1 | 13.8 | 15.4 | 17.2 |
| GJ 1 10.7 | 13.5 | 15.1 | 16.9 |
| GJ 2 11.3 | 14.7 | 15.7 | 17.2 |
| GJ 2 11.9 | 15.3 | 16.6 | 17.8 |
| GJ 2 12.2 | 15.7 | 16.6 | 17.8 |
| GJ 3 11.7 | 15.3 | 16.3 | 17.8 |
| GJ 334 11.3 | 14.7 | 16.0 | 17.4 |
| GJ 3 11.9 | 15.3 | 16.3 | 17.8 |
| GJ 4 11.6 | 15.0 | 16.3 | 18.0 |
| GJ 4 11.6 | 15.0 | 16.0 | 17.5 |
| GJ 5 11.2 | 14.7 | 15.7 | 16.3 |
| GJ 5 12.1 | 15.3 | 16.6 | 17.8 |
| GJ 56 11.6 | 15.0 | 16.0 | 17.2 |
| GJ 6 14.0 | 17.5 | 18.2 | 18.7 |
| GJ 6 11.9 | 15.3 | 16.6 | 17.5 |
| GJ 6 12.5 | 15.1 | 16.1 | 17.8 |
| GJ 7 8.0 | 11.4 | 12.7 | 14.0 |
| GJ 7 12.5 | 15.7 | 16.9 | 17.8 |
| GJ 7 11.9 | 15.3 | 16.3 | 17.8 |
| GJ 895 11.6 | 15.7 | 16.6 | 17.8 |