DISCOVERY OF TWO VERY LOW MASS BINARIES: FINAL RESULTS OF AN ADAPTIVE OPTICS SURVEY OF NEARBY M6.0–M7.5 STARS

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ABSTRACT

We present updated results of a high-resolution, magnitude-limited (K, < 12 mag) imaging survey of nearby low-mass M6.0–M7.5 field stars. The observations were carried out using adaptive optics at the Gemini North, VLT, Keck II, and Subaru telescopes. Our sample of 36 stars consists predominantly of nearby (<30 pc) field stars, five of which have been resolved as binaries. Two of the binary systems, 2MASSI J0429184–312356 and 2MASSI J1847034+552243, are presented here for the first time. All five of the discovered binary systems have separations between 0′08 and 0′53 (2–9 AU) with similar mass ratios (q > 0.8, ∆K, < 1 mag). This result supports the hypothesis that wide (q > 20 AU), very low mass (VLM; M₆tot < 0.19 M☉) binary systems are rare. The projected semimajor axis distribution of these systems peak at ~5 AU, and we report a sensitivity-corrected binary fraction of 9±4 % for stars with primaries of spectral type M6.0–M7.5 with separations ≥3 AU and mass ratios q ≥ 0.6. Within these instrumental sensitivities, these results support the overall trend that both the semimajor axis distribution and binary fraction are a function of the mass of the primary star and decrease with decreasing primary mass. These observations provide important constraints for low-mass binary star formation theories.

Subject headings: binaries: general — instrumentation: adaptive optics — stars: low-mass, brown dwarfs

Online material: color figures

1. INTRODUCTION

One of the main motivations for measuring the binary fraction of stars is to better understand the process of star formation itself. After all, stars like our own Sun are preferentially produced in multiple systems (Duquennoy & Mayor 1991). The classic stellar formation mechanism of molecular cloud core collapse and fragmentation, however, has a hard time explaining the tightest systems. While this mechanism can explain wide binary systems (semimajor axis ≥10 AU), it has some difficulties explaining the formation of tight systems (Bate et al. 2002). In addition, the multiplicities of the lowest mass stars and brown dwarfs appear to be statistically different from those of more massive systems (Close et al. 2003 and references within). These differences, if proven to be real, provide important clues and constraints for theoretical stellar formation models.

The continuously improving statistics of binary stars brings clarity to the paradigm that the binary fraction and semimajor axis distribution are functions of the central star mass. Surveys of G dwarfs estimate a multiplicity fraction of approximately 50% for separations of 3 AU and greater (Duquennoy & Mayor 1991). Other surveys with similar sensitivity of systems wider than 3 AU have found that early M dwarfs (M0–M4) have measured binary fractions of ~32% (Fischer & Marcy 1992), while late M/early L dwarfs (M8–L0.5) estimate fractions of ~15% (Close et al. 2003). The trend appears to continue to the coolest objects—L dwarfs reporting ~10%–15% (Bouy et al. 2003; Gizis et al. 2003) and T dwarfs at ~10% (Burgasser et al. 2003). The same surveys indicate semimajor-axis separations to also be a function of primary mass. While G and early M dwarfs (M0–M4) show broad separation peaks of ~30 AU, late M (≥M8), L, and T dwarfs appear to have separations tightly peaked at ~4 AU (Close et al. 2003). A similar result has been shown to apply to the sequence of members in the Pleiades cluster, from solar-type stars to brown dwarfs (Martin et al. 2003). Together, these results are providing both clues and empirical constraints on star formation mechanisms, as well as potentially helping to calibrate the mass-luminosity relation for VLM stars.

In Siegler et al. (2003, hereafter Paper I), we presented results from the largest flux-limited (K, < 12 mag) survey of nearby field M6.0–M7.5 dwarfs. The binary fraction of this narrowly defined spectral type range had not been quantified as those of stars slightly earlier (M0–M4; Fischer & Marcy 1992) and later (M8–L0.5; Close et al. 2003). Considering the differences in binary characteristics as a function of mass as discussed above, would M6.0–M7.5 binaries have intermediary characteristics similar to their main-sequence neighbors, or would they resemble the ultracool dwarfs?

Paper I’s sample consisted of 30 stars and presented the discovery of three new binary systems using the University of Hawaii visitor adaptive optics (AO) system Hokupa’a (Graves et al. 1998) at the Gemini North telescope. The discoveries followed characteristics of other VLM binary systems, namely, relatively equal mass components (q > 0.8) with projected separations less than 16 AU. In this paper we present our two latest binary discoveries from this spectral range, 2MASSI J0429184–312356 and 2MASSI J1847034+552243 (hereafter 2M 0429 and 2M 1847, respectively). These binaries were discovered with the VLT and the Subaru AO facilities, respectively. The total M6.0–M7.5 sample size is increased to 36, and we update the binary fraction results with those presented in Paper I. We present our observations and results in the following section and examine the systems’

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derived characteristics such as distance, age, temperature, spectral type, and mass in § 3. In § 4 we conclude by discussing the binary frequency and separation distribution of M6.0–M7.5 dwarfs.

2. OBSERVATIONS AND RESULTS

2.1. The Sample

We selected a flux-limited sample of 36 objects consisting of M6.0–M7.5 dwarfs with $K_s < 12$ mag and $J - K_s > 0.95$ mag from mainly 2MASS stars listed in Cruz et al. (2003), Reid et al. (2002), and Gizis et al. (2000). Paper I discusses the first 30 observations; here we report the most recent six. One of the six targets is a recently discovered high proper motion M dwarf, SO 025300.5+165258 ($\sim$3.6 pc away; Teegarden et al. 2003). We discuss this star further in § 2.5. We also note that at Subaru on 2003 July 10 (UT) we observed another recently discovered high proper motion M dwarf 2MASSI J1835379+325954 ($\sim$5.7 pc away; Reid et al. 2003). While not part of this sample because of its later spectral type (M8), it was observed at high resolution and found to have no $q > 0.8$ companions at separations greater than 0.1.

2.2. The Telescopes and their AO Systems

The 30 targets from Paper I were all observed at the Gemini North telescope. The six targets presented here were observed at the Subaru and VLT Observatories. Because of its recent discovery and proximity, we conducted additional long integrations of SO 025300.5+165258 with the Keck II telescope. Interestingly, the AO systems at these telescopes represent the three major waveform sensor (WFS) technologies currently in use today. Gemini North (at the time of our observations) and Subaru use 36 element curvature WFSs, the VLT has an infrared Shack-Hartman WFS, and the Keck II utilizes a visible Shack-Hartman WFS. This survey provided the opportunity to compare and contrast how different AO WFSs vary in their abilities to lock on faint targets.

As discussed in detail in Paper I, one of the challenges in utilizing AO is locating sufficiently bright guide stars near enough to one’s science targets to minimize uncertainty in the image quality introduced by isoplanicity. This is best achieved when using the target object itself as the AO guide star. This shifts the criterion of target selection from the availability of bright natural guide stars ($R \approx 15$ mag) to the sensitivity of the respective telescope’s AO system, in particular the WFS. This becomes quite important because the probability of locating a $R = 15$ mag star within 30$''$ of one’s science target is only about ~15% (Fig. 3.10 of Roddier 1999). The ability to guide using fainter stars also allows for both larger sample sizes and improved contrast ratios.

We were able to observe the faintest of our targets ($V \sim 19.0–19.5$ mag, $I \sim 15.5–16$ mag) only with the former Gemini North AO system Hokupa’a, where we conducted the majority of the observations. No other current AO system can lock onto such faint targets. Hokupa’a, decommissioned in 2003, was a curvature-based AO system that employed in its WFS red-sensitive, photon-counting avalanche photodiodes with effectively zero read-noise. Consequently, this type of sensor is ideally suited for guiding on intrinsically faint objects as long as they are relatively red ($V - I \sim 4$ mag). The Keck II telescope, with a more traditional Shack-Hartman WFS, allows for improved angular resolution with higher obtainable Strehl ratios but requires brighter targets ($V \sim 15$ mag). We compare and contrast the performance of these two types of WFS technologies in Siegler et al. (2002). At both Subaru and the VLT, we were able to lock on our faint low-mass targets with $I \leq 15.2$ mag ($K_s \leq 11.2$ mag).

2.3. Observations

The two discovered binary systems, 2M 0429 and 2M 1847, were detected at the VLT and Subaru observatories on 2003 February 13 (UT) and 2003 July 10 (UT), respectively. A total of six dwarfs from our sample were observed during these two runs. Table 1 lists the four low-mass dwarfs observed with no likely physical companion detections between ~0.1 and 15''. For completeness, we also include the 27 single stars observed in Paper I. Table 2 lists the observable properties of the two new binary systems along with the three systems presented in Paper I. Target stars were considered “observed” when a minimum corrected FWHM of ~0.15 in the $H$ band was achieved.

Each of the observations were made by dithering over four different quadrant positions on the infrared camera detector. For all targets we obtained both unsaturated $H$ or $K_s$ images (<10 s, “short” images), depending on seeing conditions, and saturated $H$ images (30 s, “deep” images) to gain sensitivity to potential faint companions.

At Subaru we used the Coronagraphic Imager with AO (CIAO) without using the coronagraphic mask feature. The detector is a 1024×1024 ALADDIN II InSb infrared hybrid array with a plate scale of 0.0217 pixel$^{-1}$ (Tamura et al. 2000). For 2M 1847 we took a total of 12×10 s short exposures at $H$ and $K_s$, 12×20 s at $J$, and 12×60 s deep exposures at $H$. At the VLT we used the Nasmuy AO System/NIR Imager and Spectrograph (NACO) system on UT4 (Yepun), which contains a 1024×1024 ALADDIN II InSb infrared hybrid array detector with a plate scale of 0.0271 pixel$^{-1}$. NACO is unique in that it utilizes an infrared WFS. We found that the infrared WFS was most efficient for objects with $K_s < 11.2$ mag. For 2M 0429 we took a total of 16×0.5 s short exposures at $H$, 8×0.5 s at $K_s$, 12×1 s at $J$, and 12×30 s deep $H$ frames.

2.4. Reduction

The images were reduced using an AO data reduction pipeline written in the IRAF language, as first described in Close et al. (2002). The pipeline produces final unsaturated exposures in $J$, $H$, and $K_s$, with deep 720 s exposures at $H$ band for each observed binary system. The dithering of the shorter exposures produces a final 30''×30'' image with a high signal-to-noise ratio in a 10''×10'' box centered on the binary. In order to detect close companions within 1'' of the central star, we filter out the low spatial frequency components of the deep images leaving behind high-frequency residuals in the point-spread function (PSF; unsharp masking). No faint companions, however, were found within the halo of our central stars using this technique. Both binary systems were detected from reductions of the shorter exposures. Figures 1 and 2 show $K_s$ images of the two new systems.

Photometry for the more widely separated 2M 0429 was performed using the DAOPHOT PSF fitting photometry package in IRAF. The PSFs used were unsaturated single stars observed during the same night with similar IR brightness, spectral type, and air mass. The errors in $\Delta$mag, listed in Table 2, are the differences in the photometry between two similar PSF stars. DAOPHOT could not successfully separate the strongly blended components of 2M 1847 due to lower Strehl ratios caused by observing through a 1.4 air mass. (The Strehl ratio and, hence, resolution were better at an air mass of 1 when the binary was initially discovered and its components more clearly separated; however,
The technique gave reliable \( \Delta \)mag values and was verified on binary images with known \( \Delta \)mag values.

We calculate individual fluxes and their uncertainties from the measured binary flux ratios and the integrated 2MASS apparent magnitudes (2MASS All-Sky Point Source Catalog), along with their respective uncertainties. Table 3 lists the photometry and derived characteristics of the new binary systems.

### 2.5. An Example of Sensitivity: The Special Case of 2MASS 0253

One of our targets observed to have no stellar companions deserves special mention. 2M02530084+1652532 (hereafter 2M 0253) is a newly discovered M6.5 dwarf (Teegarden et al. 2003), remarkably only 3.6 pc away. It was discovered by a search of the SkyMorph database of the Near Earth Asteroid Survey (Neubauer et al. 2003).

**TABLE 1**

| 2MASS Name                      | Other Name | \( K_s \) | Spectral Type | Reference |
|---------------------------------|------------|-----------|---------------|-----------|
| 2MASS J0253008+165253          | SO 025300.5+165258 | 7.59      | M6.5          | 1         |
| 2MASSI J0300050+240528         | LP 356−770 | 11.36     | M7.0          | 2         |
| 2MASSI J0435161−160657         | LP775−31  | 9.34      | M7.0          | 3         |
| 2MASS J0752239+161215          |            | 9.82      | M7.0          | 3         |
| 2MASSI J0818580+233352         |            | 11.13     | M7.0          | 2         |
| 2MASS J1200329+204851          |            | 10.85     | M7.0          | 2         |
| 2MASS J1207270−211748          |            | 0.15      | 0.64          | 2         |
| 2MASS J1246517+314811          | LHS 2632   | 11.23     | M6.5          | 2         |
| 2MASS J1253124+403404          |            | 11.20     | M7.5          | 4         |
| 2MASS J1336504+475131          |            | 11.63     | M7.0          | 2         |
| 2MASS J1344582+771551          |            | 11.83     | M7.0          | 2         |
| 2MASS J1356414+434258          |            | 11.63     | M7.5          | 3         |
| 2MASS J1356414+434258          |            | 11.16     | M6.5          | 3         |
| 2MASS J1521010+505323a         |            | 10.92     | M7.5          | 3         |
| 2MASS J1525248+292538          |            | 10.15     | M7.5          | 5         |
| 2MASS J1527194+413047          |            | 11.47     | M7.5          | 5         |
| 2MASS J1543581+320642          | LP 328−36  | 11.73     | M7.5          | 2         |
| 2MASS J1546054+374946          |            | 11.42     | M7.5          | 2         |
| 2MASS J1550308+304103          |            | 11.92     | M7.5          | 2         |
| 2MASS J1757154+704201          | LP 44−162  | 10.37     | M7.5          | 2         |
| 2MASS J2052086−231809          | LP 872−22  | 11.26     | M6.5          | 2         |
| 2MASS J2221544+272907          |            | 11.52     | M6.0          | 2         |
| 2MASS J2223478+354747          | LP 288−31  | 11.88     | M6.0          | 2         |
| 2MASS J2235340+184029          | LP 460−44  | 11.33     | M7.0          | 2         |
| 2MASS J2306292−050227          | LP 461−11  | 10.29     | M7.5          | 2         |
| 2MASS J2313472+211729          |            | 10.42     | M6.0          | 2         |

**Note.**—For near-equal mass companions. For smaller companion masses with \( q < 0.8 \), sensitivity is a function of distance. See Figs. 3 and 7.

\* Results are from this paper, otherwise Paper I.

**REFERENCES.**—(1) Teegarden et al. 2003; (2) Gizis et al. 2000; (3) Cruz et al. 2003; (4) Kirkpatrick et al. 1991; (5) Reid et al. 2002.

### TABLE 2

**The New Binary Systems**

| System                  | \( \Delta \)J | \( \Delta \)H | \( \Delta K_s \) | Sep. (mas) | P.A. (deg) | Date Observed (UT) | Telescope     |
|-------------------------|---------------|---------------|-----------------|------------|------------|-------------------|--------------|
| LP 415−20\*            | 0.84 ± 0.15   | 0.77 ± 0.10   | 0.66 ± 0.06     | 119 ± 8    | 91.2 ± 0.7 | 2002 Feb 07       | Gemini North |
| LP 475−855\*           | 0.48 ± 0.05   | 0.43 ± 0.04   | 0.48 ± 0.03     | 294 ± 5    | 131.6 ± 0.5 | 2001 Sep 22       | Gemini North |
| 2MASS J0429014+312356\* | 1.20 ± 0.12   | 1.10 ± 0.08   | 0.98 ± 0.08     | 531 ± 2    | 298.9 ± 0.2 | 2003 Feb 13       | VLT           |
| 2MASS W J1750129+442404 | 0.74 ± 0.15   | 0.73 ± 0.15   | 0.64 ± 0.10     | 158 ± 5    | 339.6 ± 0.7 | 2002 Apr 25       | Gemini North |
| 2MASS W J1847034+552243\* | 0.26 ± 0.18   | 0.34 ± 0.15   | 0.16 ± 0.10     | 82 ± 5     | 91.1 ± 1.4 | 2003 Jul 10       | Subaru        |

\* Also known as Bryja 262.

\* Also known as [LHD94] 042614.2+13312 and 2MASSW J0429028+133759.

\* Results are from this paper, otherwise Paper I.
Tracking project (Pravdo et al. 1999) as a high proper motion object (5 yr\(^{-1}\)). The star’s proximity presented a rare observational window for the direct imaging of several Jupiter-mass, extrasolar planets. We were able to probe both semimajor axis separations to within ~3 AU of the star, comparable to the separations of known extrasolar planets detected through radial velocity studies (~6 AU)\(^{6}\), and outside the speckle-dominated region on the detector (~1")\(^{6}\). We were the first to observe this object with high resolution on 2003 July 14 (UT) using the NIRC2 camera and AO (Wizinowich et al. 2000) on the W. M. Keck II telescope. The 0.01 pixel\(^{-1}\) plate scale mode was used on the 1024 × 1024 pixel array.

2M 0253 was only observable for approximately 1 hr in the early morning. We achieved sensitivity to companions of \(H = 19.6\) at 15 in 24 minutes of total integration time (49 × 30 s frames in a four-dither pattern). We fully saturated the central star so as to allow for the detection of any massive faint Jupiter planets orbiting ~1'' (>2.6 AU) from the central star. No faint companions were detected.

The 24 minutes of total integration time enable us to establish upper limits on planetary masses orbiting this star. We construct an unsaturated PSF of the star by replacing the saturated core with scaled unsaturated pixels from a short exposure. We determine maximum \(H\)-band \(\Delta\text{mag}\) contrasts by combining scaled models of faint companions (with appropriate PSFs) at various radial distances until a 5 \(\sigma\) detection is obtained. Figure 3 shows the resulting 5 \(\sigma\) limiting magnitudes at several radial distances from the central star. The horizontal dashed lines indicate the \(H\)-band \(\Delta\text{mag}\) required for the detection of 5 Gyr, 10 \(M_{J}\), and 25 \(M_{J}\) objects using the models of Burrows et al. (2003). We use the peak of their \(H\)-band spectra to estimate the flux emission in this exercise. The star’s age is not known, but on the basis of its high tangential velocity, we can assume it is an older object (Wielen 1974). The figure demonstrates sensitivity to an 11\(M_{J}\) extrasolar planet at only ~4 AU (175) away. In Figure 4 we show the fully reduced Keck image of 2M 0253 spatially filtered of its low-frequency halo, leaving behind high-frequency residuals in the core (superspeckles). This image also illustrates that with conventional AO, speckle noise limits the detection of faint companions within the inner ~1'' of the halo.

3. ANALYSIS

3.1. Are the Companions Physically Related to the Primaries?

From the total of 69 objects already observed in both this survey and a companion survey of M8.0–L0.5 stars by Close et al. (2003), we did not detect any additional unknown red (\(J - K_s > 0.8\) mag) background objects in 6.2 × 10\(^4\) arcsec\(^2\). Therefore, we estimate the probability of a chance projection of a comparably red object within 0.5 of the primary to be less than 1.3 × 10\(^{-5}\). As we argued in Paper I, with an M6–M8 dwarf density of 0.007 pc\(^{-3}\) in the local solar neighborhood (Reid & Gizis 1997), the probability of an apparent companion being just a background star at, for example, twice the distance of the target star (hence fainter by a \(\Delta\text{mag}\) value of 1.5 mag) and appearing within 0.5 of any of our targets is estimated to be only ~3 × 10\(^{-7}\). In addition, none of the companion images appear...
spatially extended as might be expected of background galaxies. Therefore, we conclude that both of the very red companions are physically associated with their primaries, and we hereafter refer to them as 2M 0429B and 2M 1847B.

### 3.2. Distances

Neither of the two binary systems have published trigonometric parallaxes. We estimate distances to both primaries from a color-magnitude diagram developed in Paper I using the trigonometric parallaxes of other well-studied, late-M field dwarfs from Dahn et al. (2002). Using corresponding 2MASS photometry for each star with a trigonometric parallax, we estimated a linear least-squares fit of $M_K = 7.65 + 2.13 (J - K_s)$ for the spectral range M6.5–L1. This relationship has a 1σ error of 0.33 mag, which has been added in quadrature to the $J$ and $K_s$ photometric errors to yield the primary’s $M_K$ values reported in Table 3. We then use the distance modulus of the primary to estimate the distances to the binaries. The calculated distances are listed in Table 3.

### 3.3. Spectral Types and Temperatures

We do not have spatially resolved spectra of the individual components in either of the two new systems. We estimate the spectral types of each of the binary components by using the relation $\text{SpT} = 3.54M_K - 27.20$ with ±1.5 spectral subclasses of error in these estimates, as derived in Figure 6 of Paper I. $\text{SpT} = 10$ is defined as an L0; valid for M6.5 < $\text{SpT}$ < L1.

### 3.4. Ages and Masses

Estimating the age of late-type field dwarfs without Li measurements or established cluster membership is difficult. Consequently, we conservatively assume a mean age of ~5 Gyr for our objects with uncertainty spanning the range of common ages in the solar neighborhood (0.6–7.5 Gyr; Caloi et al. 1999).

To estimate the masses of these objects, we rely on luminosity-mass-age models for VLM stars and brown dwarfs. We utilize the DUSTY models to provide theoretical estimates for both stellar and substellar masses as a function of both absolute $K_s$ magnitude and age. The tracks are calibrated for the $K_s$ bandpass (I. Baraffe 2002, private communication), and we extrapolate the isochrones from 0.10 to 0.11 $M_\odot$ in order to constrain the
upper mass limits of our central stars. The companion’s absolute magnitude is simply determined by adding the measured $M_{K}$ of the primary star $M_{K}$ to its secondary star's $M_{K}$. The crosses in Figures 5 and 6 indicate the best estimates of the positions of the binary components on the 5 Gyr tracks, and their uncertainties are represented by the shaded polygons enclose each component's region of uncertainty.

The components' derived $M_{K}$ is listed in Table 3. With no knowledge of the binary's age, we conservatively assign a mean age of 5 Gyr and uncertainties spanning the range of ages in the solar neighborhood (0.6–7.5 Gyr; Caloi et al. 1999). The model suggests a primary mass of $0.094^{+0.010}_{-0.012} M_{\odot}$ and a temperature of $2690^{+170}_{-160}$ K. For the companion, the model predicts a mass of $0.079^{+0.005}_{-0.018} M_{\odot}$ and a temperature of $2240^{+260}_{-190}$ K. The isochrones plotted are (left to right) 0.6, 0.85, 1.2, 1.7, 3.0, 5.0, 7.5, and 10.0 Gyr (the oldest four isochrones are indistinguishable at the given scaling).

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We update the binary fraction statistics of M6.0–M7.5 stars combining the latest results presented here (two binaries resolved out of six) with those from Paper I (three binaries out of 30). This implies an observed, uncorrected binary fraction of 14.5±2.5% using a Poisson distribution for the uncertainty (Burgasser et al. 2003). However, this sample was originally drawn from a magnitude-limited sample, and hence the observed binary fraction is biased as a result of the leakage of equal magnitude binaries into our sample from further distances (Malmquist bias). We therefore need to correct our result due to this bias, as well as consider sample incompleteness due to undetected very tight lower mass companions.

To compensate for the fainter single stars not included in our flux-limited sample, we first adjust for a larger observed volume due to the discovered binaries by a volume correction factor. This factor is simply the ratio of the spherical volume containing 95% of our target objects. This results in a volume correction factor of $3/(36\times2)$ or $7.5\%$.

The possibility that there were faint companions, both stellar and nonstellar, not detected as a result of instrument insensitivity is a real one. The curve in Figure 7 shows the instrumental sensitivity of our sample in the speckle noise-limited region ($\sim1''$, 30 AU for a star assumed 30 pc away) as a function of mass ratio and projected separation in AU. It is based on the modeling of a 5 Gyr (typical of the ages expected for field stars; Gizis et al. 2000), M6.5 dwarf placed at 30 pc (typical of the distances of our discovered binaries), observed at the 8 m Gemini North telescope. We use the DUSTY models to convert $\Delta H$ magnitudes to mass ratios. The reason we convert to mass ratios is because it allows us to use the observed mass ratio distributions for VLM binaries (Close et al. 2003) to predict the number of missed companions with $q < 0.6$. The five large asterisks in Figure 7 represent the five binary systems discovered by this survey. Interestingly, they are all found in the upper left corner of the sensitivity curve. The fact that some are so near the curve strongly indicates that binaries just below the sensitivity curve were most likely missed.

To apply an instrument-sensitivity correction, we need to estimate how many binaries went undetected in our sample. We generate a Monte Carlo simulation of 11,670 synthetic companions with the binary properties of VLM systems. For our model we use the mass ratio and separation distributions for VLM binaries and assume that the distributions are independent. For the mass ratio distribution we assume a power-law decline from unity to 0.6 from Close et al. (2003). We create the separation distribution profile by plotting the 42 most tightly separated and resolved VLM ($M_{\text{rot}} < 0.19 M_\odot$) binaries currently known (see Fig. 8; Table 4). We update the list originally

![Figure 7](image-url)

Fig. 7.—Results from a Monte Carlo simulation generating 11,670 companions distributed according to a bivariate distribution (mass ratio $q$ and separation $a$) is plotted over the instrumentation sensitivity curve (solid lines). We assume the two distributions are independent. We assume a power law declining from unity to 0.6 for the mass ratio distribution (Close et al. 2003) and the profile from Fig. 8 for the separation distribution for $a > 3$ AU. The instrumentation sensitivity curve is based on the modeling of a $\sim5$ Gyr M6.5 dwarf placed at 30 pc, typical of the distances of our discovered binaries. The DUSTY models (Chabrier et al. 2000) are used to convert $\Delta H$ magnitudes to mass ratios. The five discovered binary systems are indicated by large asterisks; 21% of the synthetic companions fall below the instrumentation sensitivity curve but above the instrument sensitivity mass ratio cutoff of $q = 0.6$. This results in a sensitivity correction of 1.3 binaries.
We define VLM binaries as systems whose total mass is less than 0.19 $M_\odot$. Very young evolving systems like GG Tau BaBb (White & Ghez 2001) are not included, nor are overluminous systems that are not resolved into binaries.

Note.—(1) Basri & Martin 1999; (2) Kenworthy et al. 2001; (3) Lane et al. 2001; (4) Bouy et al. 2003; (5) Burrows et al. 2003; (6) Potter et al. 2002; (7) McCaughrean et al. 2004; (8) Reid et al. 2001; (9) Close et al. 2003; (10) Bouy et al. 2004; (11) Reid et al. 2002; (12) Gizis et al. 2003; (13) Leinert et al. 2001; (14) Siegler et al. 2003; (15) Freed et al. 2003; (16) Martin et al. 1999; (17) Martin et al. 2003; (18) Koerner et al. 1999; (19) Delfosse et al. 1997; (20) Martin et al. 2000; (21) Chauvin et al. 2004; (22) Luhman 2004.

References.—(1) Basri & Martin 1999; (2) Kenworthy et al. 2001; (3) Lane et al. 2001; (4) Bouy et al. 2003; (5) Burrows et al. 2003; (6) Potter et al. 2002; (7) McCaughrean et al. 2004; (8) Reid et al. 2001; (9) Close et al. 2003; (10) Bouy et al. 2004; (11) Reid et al. 2002; (12) Gizis et al. 2003; (13) Leinert et al. 2001; (14) Siegler et al. 2003; (15) Freed et al. 2003; (16) Martin et al. 1999; (17) Martin et al. 2003; (18) Koerner et al. 1999; (19) Delfosse et al. 1997; (20) Martin et al. 2000; (21) Chauvin et al. 2004; (22) Luhman 2004.

Presented in Close et al. (2003) of all known VLM binaries and present it in Table 4. The definition of VLM binary having a total mass of less than 0.19 $M_\odot$ is selected to ensure that the binary components are of spectral type M6.0 or later and hence differentiated from more massive systems. The peak of this distribution, ~5 AU, is much tighter than the ~30 AU distribution peak of slightly more massive M0–M4 dwarfs (Fischer & Marcy 1992) and solar-mass stars (Duquennoy & Mayor 1991). The separation distribution is bound by the smallest separation the instruments were able to obtain in the $H$ band (~0.08 × 30 pc).
on the near side and the empirically sampled wider separation encompassing 95% of known VLM binaries (Table 4) on the far side.

From this sample of nearly 12,000 simulated companions, 21% were below the instrument sensitivity curve (but above the instrument sensitivity mass ratio cutoff of $q = 0.6$), as shown in Figure 7. With five detected binaries, this predicts 1.3 companions were missed in our survey. Hence, we conclude that the binary fraction for M6.0–M7.5 stars is $(5 + 1.3)/36/2$, or $9\pm 4\%$. It should be pointed out, however, that the true fraction is most certainly larger than this figure, since we cannot rule out the possibility of the existence of low $q$-binaries as a result of the sensitivity of this survey. Therefore, our reported binary fraction, accurate within the uncertainties for M6.0–M7.5 dwarfs for separations $\geq 3$ AU, represents a low-end estimate to the intrinsic binary fraction.

With slightly improved statistics, this latest result for the binary fraction of M6.0–M7.5 stars is now more comparable with those of later spectral types: $15\% \pm 7\%$ for late M/early L dwarfs (Close et al. 2003), $10\% \sim 15\%$ and $15\% \pm 5\%$ for L dwarfs (Bouy et al. 2003; Gizis et al. 2003, respectively), and $9^{+15}_{-3}$ for T dwarfs (Burgasser et al. 2003). These cooler dwarfs, including the ones presented here, all have binary fractions significantly lower than the $\sim 32\%$ observed for earlier M0–M4 dwarfs (Fischer & Marcy 1992) and the $\sim 50\%$ for solar-mass stars (Duquennoy & Mayor 1991) over the same $a > 3$ AU separation range. Our conclusion from Paper I is strengthened: for spectral type M6.0–M7.5 binary systems with separations $3 \text{ AU} < a < 300 \text{ AU}$, the binary fraction from our survey is $9^{+4}_{-3}$, statistically consistent with that of cooler M, L, and T stars and significantly less common than that of G and early M stars.

4.2. The Separation Distribution Function

The 2M 0429 and 2M 1847 binary systems have best-estimate projected separations of 6 and 2 AU, respectively. In our total M6.0–M7.5 sample, we detect no binary separations wider than 10 AU (Table 3). When we analyze the semimajor axis separations of these binaries, we observe that there are no projected VLM binary separations greater than 15 AU. With our survey sensitive out to $\sim 15\%$ from the central star, this result appears to be real and not a result of a sensitivity selection effect. When examining the entire VLM sample of known binary systems from the literature (44; see Table 4), only three objects are currently known to have a projected separation greater than 15 AU. This indicates that while wide VLM binaries of $q > 0.6$ can exist, they are rare.

The median projected separation of our entire binary sample is $\sim 3$ AU, consistent with the $\sim 4$ AU peak distribution of late M/early L binaries (Close et al. 2003), L dwarfs (Gizis et al. 2003; Bouy et al. 2003), and T dwarfs (Burgasser et al. 2003).

This contrasts significantly with the $\sim 30$ AU broad separation peak of early M and G stars (Fischer & Marcy 1992; Duquennoy & Mayor 1991). We conclude that the projected semimajor axes of M6.0–M7.5 binaries appear consistent with those of late M, L, and T dwarf systems but are significantly smaller on average than early M and G stars.

5. SUMMARY

We have conducted the largest flux-limited ($K_s < 12$ mag) survey of nearby M6.0–M7.5 dwarfs using the Keck II, Gemini North, Subaru, and VLT AO systems. In this paper we present our two latest binary discoveries, 2M 0479 and 2M 1847, observed at the VLT and Subaru facilities, respectively. When added to our initial results from Paper I, the overall survey consists of 36 stars with five discovered binary systems. The two new components are of relatively equal mass ($q > 0.8$) with average projected separations of 2 and 6 AU. While none of the binaries have yet been confirmed by common proper motions, they are almost certainly bound, on the basis of space density arguments of very red companions. We have used observational and statistical arguments to characterize the VLM binary fraction and separations that contribute additional empirical constraints to binary formation mechanisms:

1. We estimate the binary frequency of spectral type M6.0–M7.5 main-sequence stars for separations $a > 3$ AU from this survey to be $9^{+4}_{-3}\%$. The figure is statistically consistent with later type ultracool M, L, and T dwarfs. The frequency is significantly less than that measured in studies of earlier M and G dwarfs, indicating that the binary fraction of stars is a function of the spectral type of the central star.

2. The separations of the five binary systems from our sample are all less than 10 AU. Projected separations of known VLM binaries greater than 15 AU are rare. This survey’s median separation of 5 AU is consistent with the separations of later type M, L, and T dwarfs (separation peak $\sim 4$ AU). This is in stark contrast with the broad peak separations of $\sim 30$ AU for the more massive M and G binaries.

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REFERENCES

Basri, G., & Martin, E. 1999, AJ, 118, 2460
Bate, M. R., Bonnell, I. A., & Bromm, V. 2002, MNRAS, 332, L65
Bouy, H., Brandner, W., Martin, E., Delfosse, X., Allard, F., & Basri, G. 2003, AJ, 126, 1526
Bouy, H., et al. 2004, A&A, 423, 341
Burgasser, A. J., Kirkpatrick, J. D., Reid, I. N., Brown, M. E., Miskey, C. L., & Gizis, J. E. 2003, ApJ, 586, 512
Burnows, A., Hubbard, W. B., Lunine, J. I., & Liebert, J. 2001, Rev. Mod. Phys., 73, 719
Burnows, A., Sadarsky, D., & Lunine, J. I. 2003, ApJ, 596, 587
Caloi, V., Cardini, D., D’Antona, F., Badiati, M., Emanuele, A., & Mazzitelli, I. 1999, A&A, 351, 925
Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P. 2000, ApJ, 542, 446
Chauvin, G., Lagrange, A.-M., Dumas, C., Zuckerman, B., Mouillet, D., Song, I., Beuzit, J.-L., & Lowrance, P. 2004, A&A, 425, L29
Close, L. M., Potter, D., Brandner, W., Lloyd-Hart, M., Liebert, J., Burrows, A., & Siegler, N. 2002, ApJ, 566, 1095
Close, L. M., Siegler, N., Freed, M., & Biller, B. 2003, ApJ, 587, 407
Cruz, K. L., Reid, I. N., Liebert, J., Kirkpatrick, J. D., & Lowrance, P. J. 2003, AJ, 126, 2421
Dahn, C. C., et al. 2002, AJ, 124, 1170
Delfosse, X., et al. 1997, A&A, 327, L25
Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485
Fischer, D. A., & Marcy, G. W. 1992, ApJ, 396, 178
Freed, M., Close, L., & Siegler, N. 2003, ApJ, 584, 453

Gizis, J. E., Monet, D. G., Reid, I. N., Kirkpatrick, J. D., Liebert, J., & Williams, R. J. 2000, AJ, 120, 1085

Gizis, J. E., et al. 2003, AJ, 125, 3302

Graves, J. E., Northcott, M. J., Roddier, F. J., Roddier, C. A., & Close, L. M. 1998, Proc. SPIE, 3353, 34

Kenworthy, M., et al. 2001, ApJ, 554, L67

Kirkpatrick, J. D., Henry, T. J., & McCamthy, D. W. 1991, ApJS, 77, 417

Koerner, D. W., Kirkpatrick, J. Davy, McElwain, M. W., & Bonaventura, N. R. 1999, ApJ, 526, L25

Lane, B. F., Zapatero Osorio, M. R., Britton, M. C., Martin, E. L., & Kulkarni, S. R. 2001, ApJ, 560, L390

Leinert, Ch., Jahreiss, H., Woitas, J., Zucker, S., Mazeh, T., Eckart, A., & Kohler, R. 2001, A&A, 367, 183

Luhman, K. L. 2004, ApJ, 614, 398

Martin, E. L., Brandner, W., & Basri, G. 1999, Science, 283, 1718

Martin, E. L., Brandner, W., Bouvier, J., Luhman, K. L., Stauffer, J., Basri, G., Zapatero Osorio, M. R., & Barrado y Navascués, D. 2000, ApJ, 543, 299

Martin, E. L., Barrado y Navascués, D., Baraffe, I., Bouy, H., & Dahm, S. 2003, ApJ, 594, 525

McCaughrean, M. J., Close, L. M., Scholz, R.-D., Lenzen, R., Biller, B., Brandner, W., Hartung, M., & Lodieu, N. 2004, A&A, 413, 1029

Potter, S. B., et al. 2002, ApJ, 567, L133

Pravdo, S. H., et al. 1999, AJ, 117, 1616

Reid, I. N., & Gizis, J. E. 1997, AJ, 113, 2246

Reid, I. N., Gizis, J. E., Kirkpatrick, J. D., & Koerner, D. W. 2001, AJ, 121, 489

Reid, I. N., Kirkpatrick, J. D., Liebert, J., Gizis, J. E., Dahn, C. C., & Monet, D. G. 2002, AJ, 124, 519

Reid, I. N., et al. 2003, AJ, 125, 354

Roddier, F. 1999, Adaptive Optics in Astronomy (Cambridge: Cambridge Univ. Press)

Siegler, N., Close, L. M., & Freed, M. 2003, Proc. SPIE, 4839, 114

Siegler, N., Close, L. M., Mamajek, E. E., & Freed, M. 2003, ApJ, 598, 1265 (Paper I)

Tamura, T., et al. 2000, Proc. SPIE, 4008, 1153

Tegarden, B. J., et al. 2003, ApJ, 589, L51

White, R. J., & Ghez, A. M. 2001, ApJ, 556, 265

Wielan, R. 1974, Highlights Astron., 3, 375

Wisinowich, P., et al. 2000, PASP, 112, 315