ABSTRACT

We present results of a high-resolution, near-infrared survey of 41 nearby, young (≤500 Myr) M0–M5.0 dwarfs using the Altair natural guide star adaptive optics system at the Gemini North telescope. Twelve of the objects appear to be binaries, seven of which are reported here for the first time. One triple system was discovered. Statistical properties are studied and compared with earlier (F to K) and later (≥M6 very low mass [VLM]) populations. We find that the separation distribution of the binaries in this sample peaks at 13±4 AU, which is consistent with previous measurements of early M binaries. Hence, early M binaries seem to occur in—on average—tighter systems than G binaries. At the same time they are significantly wider than field VLM binary stars. The distribution of mass ratios q of primary and secondary stars was found to show an intermediate distribution between the strongly q→1 peaked distribution of field VLM systems and the almost flat distribution of earlier type stars. Consequently, we show evidence for relatively young, early M binaries representing a transition between the well-known earlier star distributions and the recently examined field VLM population characteristics. Despite the fact that this survey was dedicated to the search for faint brown dwarf and planetary mass companions, all planetary mass candidates were background objects. We exclude the existence of physical companions with masses greater than 10 Jupiter masses (MJ) at separations of ≥40 AU and masses greater than 24MJ for separations ≥10 AU around 37 of the 41 observed objects.

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

Online material: color figures

1. INTRODUCTION

Binary and multiple stars have long provided a highly effective method of testing stellar evolution theory. As coeval systems, the intrinsic properties deduced for individual components (luminosity, effective temperature, color) should be consistent with models drawn from the same isochrone. Alternatively, parameters that are observationally well determined for one component (such as distance or metallicity) can be associated with the other component(s). This is particularly useful in characterizing the intrinsic properties of faint companions, including both low-mass stars (e.g., Gould & Chanamé 2004) and brown dwarfs (e.g., Kirkpatrick et al. 2001) — of F, G, and early K main-sequence stars or subdwarfs.

There is a long astronomical tradition of inverting the latter technique and searching the environs of nearby stars for low-luminosity companions. Effectively, the main-sequence stars act as cosmic lamp posts, each illuminating a small corner of the solar neighborhood. The efficiency of this search process is well illustrated by its success in identifying the archetypical ultracool M dwarf, VB 10 (van Biesbroeck 1944), the first L dwarf, GD 165B (Becklin & Zuckerman 1988), and the first T dwarf, Gl 229B (Nakajima et al. 1995). Subsequent studies have built on this foundation, using a variety of methods, including coronagraphy (e.g., Oppenheimer et al. 2001), wide-field ground-based imaging (e.g., Simons et al. 1996), and high-resolution imaging with both the Hubble Space Telescope (HST; e.g., Golimowski et al. 2004) and ground-based adaptive optics (AO) systems (e.g., Close et al. 2003; Siegler et al. 2005; Burgasser et al. 2006, and references within).

This paper describes our use of AO techniques on the Gemini telescope to search for low-mass brown dwarf and planetary mass companions around young, early M dwarfs in the vicinity of the Sun. Section 2 describes the sample selection and §3 describes our observations. Sections 4 and 5 outline reduction and derived system parameters, and §6 discusses their implications.

2. SAMPLE SELECTION

The primary goal of our observing program is to identify very low mass brown dwarfs as companions to nearby stars. That goal constrains our choice of targets. The probability of detecting a companion depends on the contrast with respect to the underlying flux distribution of the primary. The contrast, in turn, depends on the relative luminosity of primary and secondary, the angular separation, and the point-spread function (PSF).

Lacking a long-lived central energy source, brown dwarfs cool and fade over relatively rapid timescales; moreover, low-mass brown dwarfs cool faster than high-mass brown dwarfs (L ∝ r−1.3M−2.64, Burrows et al. 2001). Thus, all other factors being equal, targeting young stars maximizes the probability of detecting low-mass brown dwarf companions. The nearest young star-forming regions, however, lie at distances of more than ~150 pc, while even the 10 to 20 Myr old members of field associations, such as TW Hya and Tucana, are at distances of 50 to 100 pc from the Sun (Zuckerman & Song 2004). Thus, the advantages offered by youth need to be balanced against the concomitant disadvantages of loss of linear resolution and flux.

Optimizing the contrast between primary and secondary presents a similar dilemma. In principle, very low luminosity primaries offer the best prospects of detecting even lower luminosity secondaries; hence, (young) ultracool dwarfs (spectral types later
than M7) might appear to be the best targets for our program. However, recent surveys have shown that the binary frequency decreases toward later spectral types, primarily because the maximum separation is a strong function of the total system mass. Few ultracool binaries are found in the field with separations exceeding 10 AU (Reid et al. 2001; Close et al. 2003; Burgasser et al. 2003, 2006; Bouy et al. 2003; Gizis et al. 2003; Martín et al. 2003; Siegler et al. 2005), and it is helpful for any survey for very low mass companions to focus on systems within the immediate solar neighborhood. The space density of ultracool dwarfs is relatively low, with only ∼80 L dwarfs within 20 pc of the Sun (Cruz et al. 2003). Most of those systems are likely to be older than ∼500 Myr (Allen et al. 2005).

Given these competing factors, we have chosen to target early M dwarfs in the present survey. While these systems are more luminous than L dwarfs (6 < $M_J$ < 11 as compared with 11 < $M_J$ < 15), they are much more numerous (∼2500 systems within 20 pc) and support binary systems with separations as wide as 400 AU. Moreover, the relative level of coronal activity provides a mechanism for selecting the youngest systems for observation in our program.

M dwarfs have active chromospheres and coronae, characterized by optical emission (Ca II H and K and Balmer lines) and X-ray emission, respectively. Figure 1 shows X-ray activity (plotting $F_X/F_{bol}$, where $F_X$ is the flux measured by ROSAT) as a function of spectral type and $V-J$ color for stars from the TW Hydrae association (∼10 Myr; Reid 2003), the Pleiades (∼100 Myr; Micela et al. 1999), the Hyades (∼600 Myr; Reid et al. 1995b), and local field stars (Hünsch et al. 1999). There is a clear decrease in activity with age, with most of the field stars lying well below the cluster members.

Using the data plotted in Figure 1 as a guide, we have defined selection criteria in the [$\log(F_X/F_{bol}), V-J$] plane that are designed to identify M dwarfs with activity levels comparable to or exceeding those of Pleiades members:

$$\log \frac{F_X}{F_{bol}} > -3.7 + 0.3(V-J), \quad (V-J) > 3.0.$$ 

Given the dispersion in activity levels at a given age, most single stars in this sample are likely to have ages younger than ∼300 Myr.
We have applied these criteria to two data sets: ~800 proper-motion stars from the 2MASS-based NStars survey described by Reid et al. (2004); and ~380 previously-uncataloged late-type field dwarfs that show significant motion between the POSS I and 2MASS surveys (the “Moving M” sample; I. N. Reid et al. 2006, in preparation). Most of the former stars are drawn from the NLTT proper-motion catalog (Luyten 1980), but the sample also includes lower motion dwarfs from the Third Catalogue of Nearby Stars (CNS3; Gliese & Jahreiss 1991). The effective proper-motion limits of both samples correspond to ~0.2\'' yr\(^{-1}\), or a tangential velocity of 19 km s\(^{-1}\) at 20 pc. It is important to note that this threshold does not bias against young stars. Systems like the Pleiades, with a relative velocity of ~29 km s\(^{-1}\) with respect to the Sun (Jones et al. 1996), or TW Hydrae, with a relative motion of ~23 km s\(^{-1}\) with respect to the Sun (Reid 2003), offer exemplary proof that young stellar objects do not need to have velocities within a few kilometers per second of the local standard of rest. Distance estimates are based primarily on photometric or spectroscopic parallaxes. Both samples are drawn from the area covered by the 2MASS Second Incremental release (~44% of the sky), and both were cross-referenced against the ROSAT bright and faint source catalogs (Voges et al. 1999, 2000), searching for counterparts within 15\'' . Matched with ROSAT sources are 196 stars from the first sample and 81 from the second.

Figure 2 compares the coronal activity of the stars in these two samples against our selection criteria. A total of 92 stars exceed the Pleiades-like (100 Myr) activity threshold. However, 36 of these stars are known to be spectroscopic binaries, and it is likely that the high activity reflects rapid rotation in tidally locked systems. We have excluded those stars from consideration in the current program, limiting observations to systems that are currently identified as single stars. Nonetheless, it is probable that some of the stars targeted in this program will eventually prove to be unrecognized spectroscopic binaries, rather than Pleiades-age single stars.

3. OBSERVATIONS

The current paper presents observations of a subset of the X-ray-active stars from the NLTT/CNS3 and Moving M samples. All targeted objects are estimated to lie within 20 pc of the Sun. All observations were taken in queue mode with the 8 m Gemini North Telescope using the facility Near-Infrared Imager (NIRI; Hodapp et al. 2003) in conjunction with the Altair AO system. The detector is a 1024 \times 1024 InSb Aladdin infrared hybrid array with 27 \( \mu \)m pixels. The f/32 camera was used, providing a 0.022'' pixel\(^{-1}\) plate scale and 22'' \times 22'' field of view. The observations were conducted with the Cassegrain rotator purposefully disabled, leading to a fixed image pupil relative to camera and detector.

For all observed targets, both short (<10 s) and deep (30 s) exposures in the \( H \) and \( K_s \) filter bands were obtained. Each of the targets were imaged in a five-position, 7'' offset dithering pattern; three images were taken per dither position. The short frames were designed to primarily obtain unsaturated target images so as to reveal any near-equal mass companions at separations \( \lesssim 0.08'' \). They also served to provide astrometry and PSF sources. In a few cases even the minimum integration time of 0.2 s allowed by the NIRAIR camera led to saturated short frames due to the brightness of the target star. In these cases other unsaturated sources were used for PSF fitting. All of the discovered physical binary systems were detected in the short frames.

The deep frames were designed to saturate the target star to gain sensitivity to potential very faint companions (\( \Delta H > 5 \) mag) at radial distances \( \geq 1'' \). Integrated counts were typically \( \sim 200\% - 500\% \) in excess of full well depth at both \( H \) and \( K_s \) in the primary’s core. Through the use of co-adds, 30 s integration times were obtained per image; three images per dither position gave 7.5 minutes of total integration time per target.

Forty-one of the 56 objects from our survey sample were observed with the Gemini North Telescope during semesters 2005A,
We do not have spatially resolved spectra of any of the new multiple systems. Moreover, intrinsic scatter in the $H - K_s$ colors of M dwarfs do not allow us to derive accurate spectral types from our observed $(H - K_s)_A$ and $(H - K_s)_B$ colors. However, we can estimate component spectral types and absolute magnitudes using averaged absolute $M_K$ magnitudes for each spectral type [see Fig. 5 for the function $M_K(SpT)$]. Component spectral types were estimated by assuming a flux-weighted relation between component and integrated spectral types of $SpT_{int}$, since the TiO and VO band strengths from which the spectral types are derived are quite linear for M0–M7 (Cruz & Reid 2002). The above relation defines possible pairs of spectral types ($SpT_A$, $SpT_B$) for each binary. Another restriction on spectral types is given by $M_K(SpT)$ in combination with our measured values for $\Delta K_s$: $\Delta K_s = M_K(SpT_B) - M_K(SpT_A)$ defines another relation between $SpT_A$ and $SpT_B$. Intersecting these two relations we find an unambiguous combination of $SpT_A$ and $SpT_B$ for each binary. Typically, $\Delta K$ is small—for example G 172-1 has $\Delta K = 0.49$ and $SpT_{int} = M4$ —and so we find $SpT_A \approx M4$ and $SpT_B \approx M4.5$. However, in the case of G 1180-11 $\Delta K = 1.97$; therefore, we estimate $SpT_A = M4 \pm 0.5$ and $SpT_B = M7 \pm 2.0$ from $SpT_{int} = M4.5$. Equivalent considerations were made to derive parameter values for the A, B, and C components of the triple system 2M1036, exploiting the fact that the B and C components are of equal magnitude.

**4. REDUCTION**

The data reduction used an AO data reduction pipeline written in the IRAF language as described in Close et al. (2002). The pipeline outputs final unsaturated exposures in $H$ and $K_s$ band (FWHM $\approx 0.08''$) and deep 450 s (15 $\times$ 30 s) exposures for each observed object. The dithering produces a central 10$''$ $\times$ 10$''$ high signal-to-noise ratio (S/N) region in a 30$''$ $\times$ 30$''$ final image centered on the object.

Since the Cassegrain rotator was disabled, the residual PSF aberrations including telescope primary and secondary structures remained static and fixed in the final images, allowing for comparative identification of faint companions without confusion from rotating PSF artifacts. The pipeline compensates for this by rotating each image by the parallactic angle before combining as described in Close et al. (2003). In order to detect faint companions within 1$''$ distance to the central star, we filtered out the low spatial frequency components of the deep images, leaving behind only the high-frequency residuals in the PSF (unsharp masking). Figure 3 shows images of the discovered binaries; Figure 4 shows the triple system.

Photometry was performed using the ALLSTAR PSF-fitting task in IRAF. PSF stars were selected from similar magnitude targets observed either the same night (if available) or as close as possible to the observation date, at similar air mass. Uncertainties in $\Delta$mag and separations listed in Table 2 were determined by comparing the results employing two distinct PSF stars for each binary. In the case of GJ 2060, however, saturated raw images ruled out the use of ALLSTAR. Instead, we used an artificial ghost that appeared in every bright image in the $H$ filter at fixed separation and orientation relative to the detector. This ghost, probably due to secondary reflection in the $H$ filter, remained unsaturated in the long exposures and responded linearly to the flux of the generating object. By averaging the ratio of ghost flux difference to binary flux difference of two similar binaries (LP 717-36 and G39-29) we were able to estimate $\Delta H$ for GJ 2060. Since there is no ghost in the $K_s$ images, $\Delta K_s$ was assumed, which is reasonable given that on average $\Delta H - \Delta K_s$ for the other binaries is consistent with 0. To account for uncertainties in this case, a larger error was assumed. The binary data are listed in Table 2.

**4.1. Spectral Types, Absolute Magnitudes, and Distances**

| 2MASS Name | Other Name | $K_s$ | Spectral Type | Reference |
|------------|------------|------|---------------|-----------|
| J00115302+22590471... | LP 348-40 | 8.00 | M3.5 | 1 |
| J01531393-07125171... | 8.08 | M4.0 | 2 |
| J01531133-21054331... | LP 828-89 | 7.14 | M1.0 | 1 |
| J02085359+49265651... | G173-39 | 7.58 | M3.5 | 3 |
| J03472335-01581931... | HIP 17695 | 6.93 | M3.0 | 2 |
| J03494254+25194061... | II Tau | 8.94 | M4.0 | 1 |
| J04244260-06473131... | 8.63 | M4.5 | 2 |
| J04373746-22292522... | Steph 497 | 6.41 | M0.5 | 1 |
| J05081359+21060941... | LHS 5134 | 6.52 | M2.5 | 1 |
| J10193634+19521221... | GI 388 | 4.59 | M3.0 | 3 |
| J11032125+13735711... | LP 491-51 | 7.91 | M3.5 | 1 |
| J11115767+33321111... | G119-62 | 7.50 | M3.0 | 3 |
| J14130492-12012626... | GI 540.2 | 8.16 | M4.5 | 3 |
| J14200478+39030141... | Steph 1145 | 7.71 | M2.5 | 1 |
| J15251291+20583944... | Wo 9520 | 8.07 | M4.0 | 1 |
| J15305048+44574464... | GI 783 | 8.28 | M3.0 | 3 |
| J18021660+61454451... | LP 71-82 | 7.65 | M4.5 | 5 |
| J18130657+26015191... | LP 390-16 | 8.07 | M4.0 | 1 |
| J19311257+36073001... | G 125-15 | 8.83 | M4.5 | 1 |
| J20464360-11481312... | LP 756-3 | 8.44 | M4.0 | 4 |
| J22431835-21415355... | BD-22 5866 | 6.72 | M0.5 | 1 |
| J22464980+44200301... | GI 873 | 5.30 | M3.5 | 3 |
| J22513534+31451533... | GI 875.1 | 6.87 | M3.0 | 3 |

* No companions with mass >10 M$\odot$ in more than 40 AU separation or >24 M$\odot$ in more than 10 AU separation. Sensitivity limits are examined in §4.3 and Fig. 7.

References.—(1) Reid et al. 2004; (2) I. N. Reid et al. 2006, in preparation; (3) Reid et al. 1995a; (4) Riaz et al. 2006; (5) Reid et al. 2003.
1.26 to account for random inclinations and eccentricities, as 0.035. From apparent and absolute magnitudes distances were
third law, assumed to be small compared to our uncertainties in spectral type. We expect a sufficiently high accuracy for the 300 Myr models.

much younger and there exists only little observational data con-

estimate (see § 4 for more detail).

d From I. N. Reid (2006, in preparation).

c From Reid et al. (1995a).

REFERENCES.—(TP) this paper; (1) Jao et al. 2003; (2) Beuzit et al. 2004; (3) Zuckerman et al. 2004; (4) McCarthy et al. 2001.

0.05 mag in \( K \).

4.2. Masses and Periods

We estimate masses for each of the binary components from their \( M_2 \) magnitudes using 300 Myr evolutionary models from Baraffe et al. (1998). Delfosse et al. (2000) compared 5 Gyr Baraffe models to observational data finding very good agreement in \( K \) band. Although the objects in this paper are believed to be much younger and there exists only little observational data constraining a mass-luminosity relation for these low-mass objects, we expect a sufficiently high accuracy for the 300 Myr models. The inaccuracies of the models (see Close et al. 2006) are assumed to be small compared to our uncertainties in spectral type. From this the binary periods are estimated by applying Kepler’s third law, \( P = a^{3/2}/\sqrt{M} \), using separations scaled by a factor of 1.26 to account for random inclinations and eccentricities, as derived in Fischer & Marcy (1992).

The calculation of the period of the triple system is based on the assumption that components B and C orbit each other in a tight system, and they in turn orbit the primary component A in the same plane. This is a more or less likely assumption, given

that gravitationally bound systems consisting of three objects of comparable mass are normally stable in a hierarchical configuration like that assumed and a few pathological situations. Thus, we list two periods, one for the BC system and one for A(BC). However, we cannot exclude a nonrelaxed system in a more complicated configuration or a different hierarchy [e.g., the proximity of B and C being due to projection and therefore C revolving around (AB) in a wide orbit]. Table 3 lists estimated masses and periods for the binaries and the triple system.

4.3. Sensitivity to the Detection of Faint Companions

An instrument sensitivity estimation using modeled faint companions was made. Unsaturated images of LP 756-3 were scaled down and inserted into the fully reduced deep \( K_s \) image of the same star, which was considered to be a representative medium brightness star from our sample (2MASS \( K_s = 8.435, d = 15.7 \) pc; Scholz et al. 2005). These “fake planets” were adjusted in brightness to simulate a 5 \( \sigma \) detection in the unsharp masked image (an example is shown in Fig. 6). To determine the detection limit with sufficient accuracy, five fake planets were distributed randomly on a circle drawn around the primary. For each of these positions, four to six noise measurements from a 3 × 3 pixel region close to the companions’ positions were taken and averaged. The final S/N was calculated by averaging the individual ratios of peak and noise count. Figure 7 shows the sensitivity of our observation to the detection of faint close-in companions. Plotted are the maximum magnitude difference in \( K_s \) band versus distance to the central star in order to detect faint companions at the 5 \( \sigma \) level.

3 VizieR Online Data Catalog, 20211 (R. D. Scholz, H. Meusinger, & H. Jahreiss, 2005).
Our instrumental detection limits predict that objects with $\Delta K_s \approx 7.8$ can be detected at separations $\gtrsim 0.5''$ to the central star and objects with $\Delta K_s \approx 12$ at separations of $\gtrsim 2''$. With LP 756-3 as a reference, the absolute magnitudes of these hypothetical companions are $M_{K_s} \sim 15.2$ and $\sim 19.4$, respectively. All of our single stars are believed to have distances less than 20 pc to the Sun. Accordingly, conservatively assuming an age of 500 Myr, the models of Baraffe et al. (2003) translate the detection limit to $\sim 24 M_J$ at separations $\gtrsim 10$ AU and $\sim 10 M_J$ at separations $\gtrsim 40$ AU (see Fig. 8). Hence, we can exclude the existence of objects above these limits around the objects in Table 1. We are using these evolutionary models as a convenient guide, although there are likely uncertainties associated with these models at the lowest temperatures, and hence our sensitivities (in terms of the lowest masses) should be viewed as estimates only. Furthermore, the mass-luminosity relation of young planetary mass objects depends strongly on the exact age. The assumed age of 500 Myr serves as a conservative limit estimate, since our objects are probably less than 300 Myr old. The models of Baraffe et al. (2003) calculated for ages 100 and 500 Myr (Fig. 8), show a maximum difference of $\sim 9$ mag in the range of the lowest masses important for these observations. Hence, objects comparable to 300 Myr or even younger might be substantially brighter than the 500 Myr models predict, and therefore the mass limit would be lower than our estimated values above.

5. RESULTS

5.1. Notes on the Individual Multiples

5.1.1. G172-1

In our search for planetary companions we come to the same result as Zuckerman et al. (2004) of no faint companion candidates.
around G172-1. However, we were easily able to resolve this 0.426” binary for the first time into two almost equal-magnitude components.

5.1.2. G274-24

This binary was first observed by Jao et al. (2003) in 1999 as part of a triple system with a very wide B component with 37.84” ± 0.05” separation to the primary. This corresponds to a separation of 477 ± 87 AU when using our distance estimate of 12.6 ± 2.3 pc. We were not able to image the wide component due to our limited field of view of 30” × 30”.

5.1.3. G39-29

G39-29 was discovered to be a binary by Beuzit et al. (2004). Interestingly, there seems to be significant observable dynamics to the system, since their measurement of 0.81 mas yr⁻¹ relative to the primary. At the same time the position angle stayed approximately the same (299° in 2002, 300.6° in 2005). We therefore conclude that the system is probably highly inclined. Further observations will be needed to set constraints on orbital elements.

5.1.4. LP 717-36

We are the first to resolve this 0.53” binary. A recent distance estimate by Scholz et al. (2005) using low-resolution spectroscopy resulted in a value of 10.4 pc (±20%) for the unresolved object. Our value of 20.2 ± 4.7 pc agrees with that value on the ~1 σ level, taking the newly discovered binary into account by multiplying the Scholz et al. (2005) result by a factor of 1.4.

5.1.5. GJ 2060

The binarity of this highly interesting variable object with the alternative identifier V372 Pup was discovered by Zuckerman et al. (2004). Unfortunately, separation and position angle are not published, which would have allowed further analysis of this close 2.8 ± 0.5 AU projected separation (this paper) binary.

A trigonometric parallax was measured by the Hipparcos satellite (Perryman et al. 1997). Its value of 64.24 ± 2.68 mas corresponding to a distance of 15.57 ± 0.65 pc is in excellent agreement with our value of 15.8 ± 2.3 pc.

5.1.6. 2MASS J10364483+1521394

This object (subsequently 2M1036) is found to be a triple system. It shows a $K_s = 8.7$, $K_v = 8.5$ primary component accompanied by a pair of equal magnitude ($H = 9.9$, $K_v = 9.6$) objects at 1.06”, which themselves are separated by 0.19” (see Fig. 4).

5.1.7. LHS 2739

With a distance of 30.2 ± 7.7 pc, this high proper motion system was calculated to have the second largest distance of all objects in our sample. Its binary nature is reported here for the first time.

5.1.8. 2MASS 13345147+3746195

This binary (hereafter 2M1334) was discovered with a separation of 0.08”, just at the resolution limit of this survey of ~0.08”.

5.1.9. G180-11

After its binarity was first published by McCarthy et al. (2001) the primary was discussed by Cruz et al. (2003), as hosting either an 11,000 K white dwarf or an M6 companion. From our observed $\Delta K_v = 1.97$ and $H - K_v = 0.24$ for the companion we can exclude the possibility of a white dwarf companion, since we would expect $H - K_v$ to be less than 0 for a predicted 11,000 K white dwarf according to models of Bergeron et al. (1995). We therefore conclude the companion to be a late-type main-sequence star. Our spectral-type estimations yield a value of $M7 ± 2$ for the secondary, which is therefore the latest type companion in this sample.

The inferred mass of the secondary is possibly below the hydrogen burning limit ($M_\odot = 0.076 ± 0.025 M_\odot$), which makes this object a brown dwarf candidate. This is also the lowest mass companion found in this survey.

5.1.10. LP 331-57

Scholz et al. (2005) found a photometric distance of 12.7 pc (±20%) for the unresolved binary. This is in good agreement
with our value of 18.0 ± 1.2 pc when multiplying with a factor of √2 to account for the binarity discovered by our survey.

5.1.11. **Steph 2018**

The binary nature of this 1.571″ ± 0.003″ separated slow-moving system was first found by McCarthy et al. (2001).

5.1.12. **LP 642-48**

We were able to clearly resolve the components of this newly discovered tight 0.099″ binary.

5.1.13. **LP 764-40**

Our observations are the first to identify this system as a binary, with separation 1.9″. The optical spectrum (Beers et al. 1996) shows strong Balmer emission, consistent with the young age inferred from the strong X-ray flux.

5.2. **Rejected Very Faint Companion Candidates**

Our observations reveal a number of faint sources near the targeted stars that we have rejected as potential companions. Here, we outline the rationale behind those decisions for a selection of objects.

5.2.1. **Candidate Companion to G173-39 is a Background Object**

A very faint ∆H = 12.4 and ∆K_s = 12.2 pointlike object was found at a position angle of 134.5° at a distance of 3.73″ to the primary (see Fig. 9). Follow-up observations with the Gemini North Telescope were conducted 2 months after first detection to test for proper-motion correlation of the primary and companion candidate. From the two-epoch data a relative motion of the central object and companion was derived and compared with the known proper motion of 0.37″ yr^{-1} of the primary. We find that the data are consistent with a distant background object.

5.2.2. **Candidate Companion to LP 390-16 is a Background Object**

We detected a companion to LP 390-16 at only 2.81″ separation with a ∆mag of more than 7 mag in H and K band. Combining proper motion with point-source locations in old exposures from POSS I, however, we find the object to be consistent with a nonmoving object, and therefore conclude it to be a background star.

5.2.3. **Candidate Companions to G125-15 Are Background Objects**

Follow-up observations helped to reject seven companion candidates at separations between 2.9″ and 6.7″ to G125-15. After a
first observation in 2005 June the central object moved 0.16" due to proper motion until a second observation in 2006 April. This corresponds to /C24 5:7 pixels on the detector, which exposes the fixed companion candidates to be distant background stars.

5.2.4. Candidate Companions to LP 756-3 Are Background Objects

In 5.8" separation to the central object we detected two faint objects with a separation of 0.28". The proper motion of LP 756-3 (0.353 /C27 yr/ C61 ) and second-epoch data 10 months after our first observation were used to reveal their background nature.

5.3. Are the Companions Physically Bound to the Primaries?

Four of the 13 observed multiples already have published separations and position angles; proper motions are known for all. Comparing our data taken in 2005 with the earlier epoch data of the other groups we find that all four binaries are consistent with physically related companions.

Evidence for the physical nature of the other multiples is given by proper-motion arguments. Our sample consists of relatively nearby M stars that show significant proper motions. Looking at multiple epoch data, a background star mimicking a bound companion would remain fixed while the foreground object would move by. As the /C1 magnitudes of all observed binaries range from 0 to /C24 2 only (implying apparent magnitudes of 6.5 /C65 Ks /C10 ), these...
bright companions would show up in POSS I data taken at much earlier epoch. No bright background objects were found in the vicinity of any of the estimated secondary locations leading to the conclusion that these cool companions are physically bound to their primaries.

6. DISCUSSION

Observations of binaries and their inherent parameters are important for setting constraints on the formation mechanism of stars in general. This sample of young, early M dwarfs allows insight into a population of stars in between the well-known G and K star population and the distinctly different VLM population (Burgasser et al. 2006), which became analyzable only a few years ago with the development and employment of highly sensitive AO and the HST (Close et al. 2003; Gizis et al. 2003; Bouy et al. 2003).

6.1. The Multiple Star Fraction

We found 12 binaries and 1 triple system in our sample of 41 objects. In order to derive a multiple star fraction free of Malmquist bias, we consider only the systems in our sample whose distances are within 20 pc. Eight of the observed multiples are likely within 20 pc of the Sun, as are — estimatedly — all of the observed single stars. However, the distances of two of the eight objects (G172-1, 2M1036) are within 1 σ of the 20 pc limit, leaving a rather large probability that they are not part of the defined volume. Likewise, two binaries have estimated distances < 1 σ greater than 20 pc (LP 717-36 and LP 642-48), so they may be part of the limited sample. This therefore leaves 8 ± 2 confirmed binaries within 20 pc. To eliminate uncertainties caused by the distance dependence of the sensitivity, we conservatively cut the sample at a mass ratio of q = 0.1. There are 28 objects in this subsample other than the confirmed binaries. Four of these have candidate companions with q < 0.1. Hence, we include them in this binary fraction as single stars. In addition, we include one possible binary system in the upper limit estimate. This results in a total of 8 ± 2 multiples in a sample of 35 ± 2 objects (upper and lower limits correspond to each other, respectively), resulting in a nominal binary fraction of 23 ± 13% for q > 0.1 and sep > 1.6 AU (we use binomial statistics to estimate the uncertainty as described in Burgasser et al. 2003). The cut in separation is determined by the minimum resolution of FWHM = 0.08′′ at the distance limit of 20 pc. We note, however, that this examination of the binary fraction does not account for selection effects in the sample selection.

6.2. The Mass Ratio Distribution

Figure 10 shows the mass ratio q = M_B/M_A distribution derived from the 13 observed multiples using the masses listed in Table 3. The triple system 2M1036 is accounted for as two binaries, the binary BC and the A(BC) system. Mass ratios for these two objects are therefore q_{BC} = M_C/M_B and q_{A(BC)} = (M_B + M_C)/M_A. In the following paragraphs we sometimes refer to 14 “binaries,” but one should keep in mind that this means 12 binaries and 1 triple system.

Twelve out of the 14 have mass ratios of q ≥ 0.74; we regard this as evidence that equal-mass systems are preferred for young, early M dwarf primaries. Our observations are sensitive to binaries with mass ratios q < 0.1 for separations greater than ~ 8 AU (see Fig. 11). Observations have shown that there is a significant lack of very low mass objects around main-sequence stars for separations smaller than 5 AU (the “brown dwarf desert”; Marcy & Butler 2000). We therefore do not expect to have missed a large quantity of objects. However, we have to assume that for q < 0.1 the sample is likely incomplete.

This emphasis on q ~ 1 is not seen in the distributions of earlier type stars. Reid et al. (2002) show that for late F to K binaries with separations of less than 100 AU the distribution of mass ratios is rather flat, with only marginal tendency toward equal mass binaries. For field VLM binaries, however, the opposite effect is observed; recent statistical evaluations of all currently known VLM binaries (Burgasser et al. 2006) show a significant peak at q ~ 1. It is therefore possible that the mass ratio distribution of our early M binaries sample has an intermediate distribution between the flat F–K distribution and the strongly peaked field VLM distribution.

However, our sample of binaries is rather small. Further observations of a larger number of young M stars will be needed to show if this relation holds.

6.3. Mass Ratio versus Separation

Mass ratios q = M_B/M_A as a function of binary separation are shown in Figure 11. While at separations ≤ 20 AU systems are distributed over a broad range of mass ratios, all three binaries with separations > 25 AU show mass ratios of q = 1. The sensitivity of the observations would have allowed for the detection of much lower mass ratios at these separations (see Fig. 9, for example), indicating a real lack of objects with low-mass ratios and high separations. However, a sample of 14 binaries cannot fill the accessible space in the (q, separation) plane uniformly, limiting the significance of this result due to low-number statistics.

6.4. The Separation Distribution

Figure 12 shows the separation distribution of our set of 14 binaries. The physical projected separations range from 2.2 to 49.7 AU and possess a distribution that shows no significant peak. However, since the observations cover separations up to 15′′, which corresponds to 300 AU at a distance of 20 pc, we conclude that the decreasing number of detected objects for separations
higher than $\sim 50$ AU is a real effect. The underlying distribution therefore probably peaks within 0 to 50 AU. A least-$\chi^2$ fit of a Poisson distribution to the data suggests a peak at $13^{+14}_{-9}$ AU. This is consistent with earlier results, for instance by Fischer & Marcy (1992), who report a broad peak at 4–30 AU for M2–M4.5 binaries.

The separation distribution again shows evidence that young, early M binaries possess transitional characteristics between earlier and later type populations. With a distribution peaking at $\sim 30$ AU (Duquennoy & Mayor 1991), G stars seem to have—on average—greater separations than early M stars. Field VLM binaries, however, are preferably found in significantly tighter systems. The distribution of 70 binaries with spectral types later than M5.5 shows a significant peak at 3–10 AU (Burgasser et al. 2006) with a steep quantitative decrease of systems with higher separations.

G–K binaries are described by a mass ratio distribution and a separation distribution that are very different from the VLM binaries’ characteristics; young, early M binaries appear to show an intermediate behavior. The higher and the lower mass distributions are apparently connected through a smooth transition embodied by early M binaries.

7. SUMMARY

We have conducted a survey of 41 nearby, early M stars of ages comparable to the Pleiades cluster, searching for companions down to planetary masses using the Gemini North Telescope with its AO system Altair. Thirteen stars were observed to host fairly bright companions, eight of these multiples (seven binaries, one triple) are new discoveries. We derived physical parameters for each of the multiple components allowing for further analysis of the early M star population confirming existing statistical results and contributing additional empirical constraints on star and binary formation.

The binary fraction of this sample of young, early M stars was found to be $23^{+13}_{-6}$% for mass ratios $q > 0.1$ and sep $> 1.6$ AU. However, a full analysis of systematic errors and biases could not be made, this value might therefore differ significantly from the actual value for this group of stars.

The mass ratio distribution was analyzed and compared with distributions drawn from F–K stars and from VLM stars.
The young, early M binary data was shown to be best described as an intermediate distribution between the almost flat early-type star distribution and the strongly $q \rightarrow 1$ peaked field VLM distribution; however, our sample size is relatively small.

The most likely separation was found to be $13^{+4}_{-14}$ AU, which is less than the median value of the G binary distribution. Field VLM binaries, however, tend to be bound in significantly tighter systems. We conclude that early M binaries possess characteristics filling the gap between the very distinct field VLM population and stars earlier than M.

A sensitivity estimate to the detection of planetary mass companions was made using planetary evolution models. Since we found no faint physical companions around 37 of the observed sources, we can exclude—conservatively assuming an age of 500 Myr—companions more massive than $10M_\odot$ at separations of $\gtrsim 40$ AU and heavier than $23M_\odot$ at separations of $\gtrsim 10$ AU around all these objects.

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Note added in proof.—We recently obtained additional data from follow-up observations with the Gemini North Telescope (Program ID GN-2006B-Q-30). These include second-epoch observations of LP 776-35 (2MASS 04522441–1649219), which prove a faint companion candidate to be a distant background object. Reobservations of G3-35 (2MASS 02024428+1334335) show a round, PSF-shaped object, after it first had been observed with an elongated shape. Hence, we conclude it to be a single object rather than a tight equal-mass binary. The impact of this additional data on the numbers derived in § 6 is restricted to a slight improvement of the uncertainty limits of the multiple star fraction, which is, however, not significant.