Three Newly Discovered M-Dwarf Companions of Solar Neighborhood Stars

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Received 2001 February 14; accepted 2001 March 26

ABSTRACT. We present low-resolution spectroscopy of newly discovered candidate companions to three stars in the solar neighborhood. All three companions are M dwarfs, with spectral types ranging from M4 to M9.5. In two cases, G85-55B (M6) and G87-9B (M4), we have circumstantial evidence from spectroscopy, photometry, and limited astrometry that the systems are physical binaries; in the third, G216-7B (M9.5), comparison of POSS II IIIaF plate material and the 2MASS image indicates common proper motion. The primary star in this system, G216-7A (M0), is itself an unresolved, nearly equal-mass binary. All three low-mass companions are highly likely to be stellar in nature, although G216-7B lies very close to the hydrogen-burning limit.

1. INTRODUCTION

The constituents of the immediate solar neighborhood provide a snapshot of the average population of the Galactic disk. Identifying and characterizing those constituents has been a major focus of stellar research since the early 20th century, yet our current catalogs patently remain incomplete, even for distance limits as small as 10 pc. The last few years have seen a renewed emphasis on this issue with, in particular, the emergence of the NASA/NSF NStars initiative (Backman et al. 2000). As part of that project, the present authors, together with other collaborators, are using a variety of techniques to exploit the potential of the new generation of near-infrared sky surveys, notably 2MASS (Skrutskie et al. 1997), in searching for previously unrecognized nearby stars and brown dwarfs. This paper presents some of our first results.

As with any census, nearby star catalogs are most incomplete for the least prominent members of the community: some, like brown dwarfs, are born to insignificance; others, like white dwarfs, acquire insignificance; still others, through their proximity to more massive and more luminous companions, have insignificance thrust upon them. Here, we describe observations of stars in the last category: three M dwarfs, each a candidate companion of a solar neighborhood late-K/early-M dwarf. Section 2 outlines the identification of those candidates and our spectroscopic observations; § 3 describes the three systems; and § 4 summarizes our conclusions.

2. TARGET IDENTIFICATION AND OBSERVATIONS

The three M dwarfs discussed in this paper were identified as candidate companions of nearby dwarfs based on photometry from the 2MASS database. All three potential primaries have annual proper motions of $\mu \sim 0\''3$ yr$^{-1}$ and were discovered in the course of the Lowell Observatory Proper Motion Survey (Giclas, Burnham, & Thomas 1971). Two of the fainter stars (the candidate companions to G85-55 and G87-9) were
found (by J. D. K.) as part of a larger survey aimed specifically at searching the environs of known nearby stars for candidate companions; the third (G216-7B) was uncovered (by K. L. C.) as part of an NStars photometric survey for candidate M and L dwarfs within 20 pc of the Sun. Table 1 lists 2MASS astrometry and photometry of each component of these candidate binary systems, and Figure 1 plots their location on the \((J - H, H - K_s)\) plane. The three brighter stars have colors consistent with late-type K or early-type M dwarfs, while the fainter stars lie on the M-dwarf sequence, with G216-7B close to the M/L boundary.

### 2.1. Spectroscopy

The three candidate companions were observed spectroscopically using the Low-Resolution Imaging Spectrograph (LRIS; Oke et al. 1995) on the Keck I 10 m telescope. The instrumental setup matches our previous observations of ultracool dwarfs: we use the 400 line mm\(^{-1}\) grating blazed at 8500 Å with a 1” slit to provide coverage from 6300 to 10100 Å at a resolution of 9 Å. The spectra were extracted and wavelength- and flux-calibrated using standard techniques described by Kirkpatrick et al. (1999); Figure 2 plots the resultant spectra.

All three stars are clearly M dwarfs. We have determined spectral types using the TiO5 index defined by Reid et al. (1995),

\[
\text{TiO5} = \frac{\langle F(7126 - 7135) \rangle}{\langle F(7042 - 7046) \rangle},
\]

which measures the overall depth of the 7050 Å TiO bandhead. As shown in their Figure 2, this index has a bimodal distribution with spectral type, decreasing in a near-linear manner from...

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**TABLE 1**

| Name        | 2MASSI JH K S J | \(J\) \(H\) \(K_s\) \(J - K_s\) |
|-------------|----------------|-------------------|------------------|
| G85-55A     | J0514169+195258| 7.40 ± 0.01       | 6.88 ± 0.03      | 6.74 ± 0.01      |
| G85-55B     | J0514171+195307| 12.53 ± 0.07      | 11.90 ± 0.05     | 11.58 ± 0.03     |
| G87-9A      | J0649358+350826| 7.68 ± 0.01       | 7.09 ± 0.02      | 6.90 ± 0.01      |
| G87-9B      | J0649360+350820| 10.61 ± 0.03      | 10.10 ± 0.08     | 9.76 ± 0.03      |
| G216-7A     | J2237298-392251| 6.63 ± 0.01       | 6.04 ± 0.03      | 5.86 ± 0.02      |
| G216-7B     | J2237325-392239| 13.35 ± 0.03      | 12.68 ± 0.03     | 12.15 ± 0.03     |

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![Fig. 1.—The \((J - H, H - K_s)\) diagram: crosses are data for nearby stars, spectral types A to M; L dwarfs are plotted as open squares; T dwarfs Gl 229B and Gl 570D are plotted as five-pointed stars. The extremely red M dwarf is 2M 0149+20 (M9.5 pec). The six points with error bars plot the 2MASS colors for the six stars discussed in this paper: open circles for G85-55A/B; open triangles for G87-9A/B; and solid points for G216-7A/B.](image1)

![Fig. 2.—Keck LRIS spectra of the three M-dwarf companions discussed in the text. The spectra have been sky subtracted but not corrected for telluric absorption.](image2)
Table 2
Published Photometry and Astrometry

| Name       | V   | U−B | (B−V) | (V−R)K | (V−I)c | (V−K)S | μ (arcsec yr⁻¹) | θ (deg) | π (mas) | References |
|------------|-----|-----|-------|---------|---------|---------|-----------------|---------|---------|------------|
| G85-55A    | 9.47| 1.11| 1.17  | ...     | ...     | 2.73    | 0.31            | 131     | 42 ± 6  | 1, 2, 3    |
| G87-9A     | 10.18| 1.27| 1.33  | 0.79    | 1.54    | 3.28    | 0.348           | 132     | 36.16 ± 1.82 | 1, 4, 5   |
| G216-7A    | 9.41 | ... | ...   | 0.83    | 1.68    | 3.55    | 0.341           | 176.4   | 52.94 ± 1.94 | 4, 5       |

References.—(1) Sandage & Kowal 1986: UBV; (2) Giclas, Burnham, & Thomas 1965: μ, θ; (3) Heintz 1994: π; (4) Weis 1987: VRI (transformed to Kron-Cousins following Bessell & Weis 1987); (5) ESA 1997: μ, θ, π.

3. THE SYSTEMS

The individual stars in each system are discussed in more detail in this section. Table 2 collects published photometric and astrometric observations of the potential primaries. Table 3 gives the derived luminosities, masses, and level of chromospheric or coronal activity.

3.1. G85-55

The brighter star in this system is also known as HD 248184, BD +19°872, LTT 11613, and GJ 3338. As Table 2 shows, this is the bluest of the three potential primaries. Although the SIMBAD database lists a spectral type of K5, there is no recent published spectroscopy, and the optical/near-infrared colors suggest that the spectral type is closer to K4. Heintz (1994) has determined an absolute trigonometric parallax of 42 ± 6 mas. As Figure 3 shows, this places G85-55A slightly below the (Mv, V−Ks) main sequence, although Sandage & Kowal’s (1986) UBV measurements indicate near-solar metal abundance. Figure 4 shows similar agreement in the (Mv, J−Ks) plane.

G85-55B lies only 9.4 from G85-55A and is not detectable on either POSS I or POSS II. The 2MASS observations, made on 1997 November 3, therefore provide the first-epoch astrometry of this system. Our IRTF observations provide a baseline of 3.2 yr, allowing a first test for common proper motion.3 The relative offset between the two stars (A to B) in the 2MASS

Table 3
Luminosities, Masses, and Activity

| Name       | Mv  | Mj  | Mmed | Reference | Mass | Reference | log(Fd/F⊙) | log(L/Lo) |
|------------|-----|-----|------|-----------|------|-----------|------------|----------|
| G85-55A    | 7.58±0.25 | 5.5 | 7.1  | 1         | 0.70 | 1         | ...       | ...      |
| G85-55B    | 10.65 | 12.6| 2    | 0.07−0.10 | 2    | −4.07     | ...       | ...      |
| G87-9A     | 8.41±0.11 | 5.91| 7.6  | 1         | 0.65 | 1         | ...       | ...      |
| G87-9B     | 8.84 | 10.6| 2    | 0.18      | 3    | ...       | ...       | ...      |
| G216-7A    | 8.03±0.07 | 5.25| 6.8  | 3         | 0.6+0.6 | 1         | ...       | −4.88    |
| G216-7B    | 11.97 | 14.0| 2    | 0.06 to 0.08 | 2 | −5.60     | ...       | ...      |

References.—Bolometric magnitudes: (1) Flower 1996: (B−V, BC); (2) BC data from Leggett et al. 1996 and Reid et al. 2001. (3) (BC, V−I) relation from Reid & Mahoney 2000. Masses: (1) Henry & McCarthy 1993: (M, log (mass)) relation; (2) Fig. 5, this paper; (3) Henry & McCarthy 1993: (M, log (mass)) relation.
observed offsets from the IRTF data are \(\Delta \alpha = 2^\circ 8 \pm 0^\circ 44, \Delta \delta = 9^\circ 0 \pm 0^\circ 20\); the proper motion of the primary is \(0^\circ 31 \text{ yr}^{-1}\), \(\theta = 131^\circ\), corresponding to relative motion of \(+0^\circ 265\) in right ascension and \(-1^\circ 23\) in declination if B is stationary with respect to A; our measured offsets in declination \(\delta = 9^\circ 8 \pm 0^\circ 25\). With such a short time baseline, these data do not provide conclusive evidence, but the observations are at least consistent with common proper motion between the two stars.

We can check whether the spectroscopic parallax of the companion is consistent with the near-infrared photometric properties. If we assume a parallax of \(42 \pm 6\) mas, the 2MASS photometry implies \(M_\alpha(B) = 9.7 \pm 0.3\). In comparison, the nearby M5.5 dwarfs Gl 65A and Gl 1116A have \(M_\alpha = 8.78\) and \(8.83\), the M6 dwarfs Gl 406 (Wolf 359) and Gl 65B (UV Ceti) have \(M_\alpha = 9.18\) and \(M_\alpha = 9.17\), and the M6.5 dwarfs LHS 3003 and GJ 1111 have \(M_\alpha = 9.96\) and \(9.46\); thus, an association with G85-55A is broadly consistent with the observed spectral type. Placing G85-55B at 42 pc also gives good agreement with the main sequence in the \((M_\alpha, J-K_s)\) plane, as illustrated in Figure 4.

While statistical arguments are always vulnerable when considering one object, we can also consider the probability of random association. Given the \((M_\alpha,\text{spectral type})\) results listed above, we assume that our spectral type estimate, M6 \(\pm 0.5\), corresponds to \(M_\alpha = 9.2 \pm 0.5\). In that case, we derive a spectroscopic distance of \(r_{\text{spec}} = 39.8 \pm 10.3\) pc and place the star within a spherical shell of volume \(\sim 4 \times 10^4\) pc\(^3\). There are 13 dwarfs with spectral types between M5.5 and M6.5 in the northern 8 pc sample (Reid & Hawley 2000, hereafter RH2000), corresponding to a space density of \(\rho_{\text{M6}} = 0.008\) stars pc\(^{-3}\). Our sampling shell therefore contributes a surface density of 0.078 M6 dwarfs deg\(^{-2}\) with the appropriate apparent magnitude. There is a corresponding probability of \(1.9 \times 10^{-6}\) of finding an M6 dwarf within 10\(^\circ\) of a randomly chosen position on the sky. While not conclusive, these results are strongly suggestive of a physical association between the K5 dwarf, G85-55A, and the M6 dwarf, G85-55B. If so, the physical separation is \(\sim 225\) AU.

Considering G85-55B itself, the spectral type of M6 implies an effective temperature of 2800 \(\pm 150\) K (Leggett et al. 1996). Figure 5 matches those limits against theoretical tracks from Burrows et al. (1993, 1997) and Baraffe et al. (1998). Briefly comparing those model predictions, the former tracks (Arizona models) predict higher temperatures (at a given age) than the latter tracks (Lyon models) for masses above \(0.08\) \(M_\odot\) but lower temperatures for masses below \(0.07\) \(M_\odot\). The hydrogen-burning limit lies at a slightly lower mass in the Lyon models, with a \(0.075\) \(M_\odot\) Lyon dwarf falling above the limit, while a \(0.075\) \(M_\odot\) Arizona dwarf is a transition object. Considering G85-55B, our spectroscopy failed to detect Li \(\lambda\lambda 6708\) but sets an upper limit of only 3 \(\AA\) equivalent width, while the expected equivalent width for no depletion at these temperatures is 1–2 \(\AA\). However, our temperature estimates allow us to set upper limits on the mass of G85-55B: if we adopt the Arizona models, we infer \(M \leq 0.1\) \(M_\odot\); in the case of the Lyon models, \(M \leq 0.11\) \(M_\odot\).
We can refine the mass estimate by considering the level of chromospheric activity, measured by the flux ratio $F_a/F_{bol}$; youthful dwarfs can be expected to have above average activity, and Figure 5 shows that we require $\tau < 0.25$ Gyr for $M < 0.075 M_\odot$. We can derive the Hα line flux directly from our spectrum as $F_a = 3.5 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$. Previous experience has shown that the $J$-band bolometric correction provides a robust method of estimating luminosities in M and L dwarfs (Reid et al. 2001). Leggett et al. (1996) derive BC$_J = 1.99$ mag for the M5.5/M6 binary Gl 65A/B and BC$_J = 2.06$ mag for the M6.5 dwarf Gl 1111. Given these results, we adopt BC$_J = 2.0$ mag for G85-55B and calculate $m_{bol} = 14.5$. Taking $M_{bol,\odot} = 4.75$, we find a ratio of $F_a/F_{bol} = 8.6 \times 10^{-5}$ (Table 3). This is $\sim 10\%$ below the average activity level of M6 dwarfs in both the Hyades cluster (Reid & Mahoney 2000) and the general field (Gizis et al. 2000). This suggests that G85-55B has an age $\tau > 0.6$ Gyr and a mass exceeding 0.08 $M_\odot$.

3.2. G87-9

The supposed primary of this system is also known as G103-65, LP 254-40, GJ 3411, and HIP 32723. Reid et al. (1995) derive a spectral type of K5 based on a TiO$_5$ index of 0.94. This is consistent with the optical/near-infrared colors listed in Table 2. The Hipparcos parallax indicates a distance of $27.6 \pm 1.3$ pc and $M_v = 8.4 \pm 0.1$. As Figures 3 and 4 show, this places the star close to the main sequence.

G87-9B lies only 6.5′ from G87-9A so, as with G85-55, the 2MASS observation, made on 1998 November 23, provides first-epoch relative astrometry. We measure $\Delta \alpha = +2.75'' \pm 0.73''$ (A to B) and $\Delta \delta = -6'' \pm 0.3''$. Our IRTF observations provide a baseline of only 2.145 yr, during which time the primary ($\mu = 0.32$ yr$^{-1}$, $\theta = 153^\circ$) is predicted to move 0.31 east and 0.6 south; we measure offsets of $\Delta \alpha = +3.1' \pm 0.25'$ and $\Delta \delta = -5.8' \pm 0.25'$. As with G85-55, the recent measurements are consistent with common proper motion, but they do not set strong constraints on the relative motion.

If we assume that the two stars are associated, then the absolute magnitude is $M_\rho(B) = 8.0$. The $(M_\rho, J-K_s)$ color-magnitude diagram offers no discriminatory power for mid-type M dwarfs, but we can compare the absolute magnitude for consistency against the measured spectral type, M4 $\pm 0.5$. There are 15 M4 dwarfs in the northern 8 pc sample (RH2000), 11 of which have K-band photometry; the average absolute magnitude is $\langle M_\rho \rangle = 7.50$, with an rms dispersion of $\sigma_\rho = \pm 0.46$ mag. In comparison, we derive $\langle M_\rho \rangle = 7.80$, $\sigma_\rho = \pm 0.69$ from K-band data for nine of the 13 M4.5 dwarfs listed by RH2000, and $\langle M_\rho \rangle = 7.27$, $\sigma_\rho = \pm 0.61$ from observations of nine of the 15 M3.5 dwarfs. While the constraints are relatively weak, the inferred absolute magnitude of G87-9B for $r = 27.6$ pc is consistent with the observed spectral type.

As with G85-55, we can calculate the probability of a chance association. Given the $(M_\rho, spectral type)$ values listed above, we take our spectral type estimate as corresponding to limits of $6.8 < M_\rho < 8.1$. These place a $K_s = 9.8$ mag M4 dwarf at a distance between 39.8 and 21.9 pc, within a spherical shell of volume $2.2 \times 10^5$ pc$^3$. There are 45 dwarfs in the RH2000 8 pc sample with spectral types between M3.5 and M4.5, which gives a space density $\rho_{stars} = 0.028$ stars pc$^{-3}$. This implies an expected surface density of 0.149 stars deg$^{-2}$ and a probability of $\sim 1.8 \times 10^{-6}$ of finding an M4 dwarf at the appropriate apparent magnitude within 7" of a randomly chosen point.

Again, the available constraints favor the identification of G87-9B as a binary companion of G87-9A at a physical separation of 200 AU. Given the spectral type and the absence of both lithium absorption and Hα emission, G87-9B is likely to be a disk dwarf with $r > 1$ Gyr and a mass of $\sim 0.18 M_\odot$.

3.3. G216-7

This is the best studied of the three systems and the only confirmed binary. The primary is also known as G189-30, BD +38°4818, LTT 16634, HIP 111685, and GJ 4287. Reid et al. (1995) measure a spectral type of K7 based on a TiO$_5$ index of 0.81. Our LRIS spectrum of the secondary provides an opportunity for an independent measurement through the
presence of scattered light from G216-7A; we measure TiO5 = 0.75, which corresponds to a spectral type of M0. Weis (1987) has obtained VRK1 photoelectric spectra, and those colors are more consistent with the later spectral type.

G216-7A was observed by *Hipparcos* (ESA 1997) and lies at a distance of 18.980±0.065 pc, within the 25 pc limit of the NStars project. At that distance modulus, the star lies significantly above the main sequence in the ($M_v, V-K_s$) plane (Fig. 3) and, even allowing for the parallax uncertainties, is brighter than the earlier-type G87-9A in both $M_v$ and $M_K$ (Fig. 4). In fact, *Hipparcos* has resolved the star as a binary with separation 0.144±0.019 (P.A. = 35°, epoch 1991.25), with a magnitude difference $\Delta M_v = 0.44 ± 0.96$ mag. If we assume a $V$-band flux excess of 0.5 mag above the single-star main sequence, then the two components have absolute magnitudes of $M_v(Aa) \sim 8.5$ and $M_v(Ab) \sim 9.1$.

Given the relatively small magnitude difference, G216-7A might be resolved as a double-lined spectroscopic binary, while a close binary system might be expected to have unusually high chromospheric and coronal activity. J. E. Gizis, I. N. Reid, & S. L. Hawley (2001, in preparation) have a single high-resolution echelle spectrum, taken using McCarthy’s spectrograph on the Palomar 60 inch telescope, but there is no evidence for line doubling. Those data do permit measurement of the radial velocity, $V_r = -53.1 \pm 1.5$ km s$^{-1}$. Combined with the *Hipparcos* astrometry, this gives heliocentric space motions $(U, V, W)$ of $(20.8, -56.6, -11.1)$, where $U$ is positive toward the Galactic center. These motions are consistent with membership of the old-disk population.

The echelle spectrum also provides a measure of chromospheric activity: there is no detectable Balmer emission, with $H\alpha$ absorption with equivalent width 0.69 Å (comparable to Hyades M0 dwarfs); emission is present at Ca II H and K, with equivalent widths of 3.71 and 2.45 Å, respectively, but activity at this level is not unusual for late-K/early-M dwarfs. Huensch et al. (1999) derive an X-ray luminosity of $7.7 \times 10^{-27}$ erg s$^{-1}$ from *ROSAT* observations. Combined with our estimate of $f_{bol}$ (Table 3), we derive log ($L_x/f_{bol}$) = −4.88, a low level of coronal activity for early-type M dwarfs.

Turning to the companion, G216-7B lies 33.6 from the primary and, at that distance, is clearly visible on the POSS II IIIaF survey plate; indeed, the companion may be barely visible on the POSS I E plate (Fig. 6). In any case, the time baseline between the POSS II F plate (1989 September 3) and the 2MASS observation (1998 October 10) is sufficient to show that the position angle and separation between G216-7A and G216-7B remain unchanged, despite motion of almost 3°, confirming G216-7B as a physical companion at a separation of 635 AU.

While we have classed G216-7B as spectral class M9.5, it clearly lies very close to the L dwarf regime, as Figures 1 and 4 illustrate. With $M_I = 11.97$ and $M_K = 10.77$, it is over half a magnitude fainter than the archetypical M9.5 dwarf BRI 0021 and within 0.1 mag of the absolute magnitude of the L0.5 dwarf 2M 0746+20 (making due allowance for the fact that 2M 0746 is an equal-mass binary). Like most ultracool dwarfs, G216-7B exhibits a low level of chromospheric activity. The weak H$\alpha$ emission, equivalent width 0.7 Å, corresponds to a line flux of $F_\alpha = 4.2 \times 10^{-17}$ ergs s$^{-1}$. Assuming $BC_j \sim 2$ mag, we derive $m_{bol} = 15.35$, which gives $F_\alpha/F_{bol} = 2.5 \times 10^{-6}$.

Based on the spectral type, we estimate the effective temperature as $T_{eff} \sim 2100 ± 150$ K. Those limits are superimposed on the theoretical tracks plotted in Figure 5. As with G85-55B, our nondetection of lithium sets only weak constraints on the mass, since the expected equivalent width is only 0.5–1 Å, as in the M9.5 brown dwarf LP 944-20 (Tinney 1998). However, the inactivity of the M0 companion suggests an age at least comparable to that of the Hyades, and probably exceeding 1 Gyr. Under those circumstances, G216-7B is likely to have a mass in the range 0.065–0.08 $M_\odot$, regardless of whether one uses the Arizona or Lyon models as the reference. If $T_{eff} > 1.25$ Gyr, G216-7B is a transition object or a star, rather than a brown dwarf.

**4. SUMMARY AND CONCLUSIONS**

We have presented spectroscopic observations of three candidate low-mass companions to known nearby stars. Each was identified from the 2MASS catalog on the basis of its near-infrared colors. All three prove to be M dwarfs with spectral types M4, M6, and M9.5. None has detectable lithium ab-
discussed a possible correlation between the maximum separation exceeding 150 AU. Elsewhere, we have van Biesbroeck project.

Based on our spectroscopy, together with literature astrometric and photometric data, two of the three systems, G85-55A/B and G87-9A/B, can only be classed as probably binaries; the third, G216-7A/B, is confirmed as a common proper motion system based on comparison of POSS II plate material and 2MASS images spanning a baseline of 9.1 yr. With annual proper motions of ~0.3 yr⁻¹, similar confirming observations of the probable systems will be possible in the near future.

The available data indicate distances of 24 ± 3.5 pc for G85-55, 27.6 ± 1.4 pc for G87-9, and 18.9 ± 0.7 pc for G216-7, all based on trigonometric parallax measurements. In each case, the distance is derived from observations of the (hypothetical) primary. We note that, while all three are included in the latest version of the Nearby Star Catalogue (as indicated by the GJ designation), only G216-7 is unequivocally within 25 pc of the Sun and therefore eligible for inclusion in the NStars Database.

These three candidate binaries were uncovered in the first stages of our search through the 2MASS database for unrecognized members of the solar neighborhood. At present, the parent samples are not defined with sufficient precision, nor do we have sufficient examples in hand, to permit a reliable estimate of how many similar systems remain to be discovered. Nonetheless, it is likely that further examples will be discovered, particularly by the targeted wide-companion search (the van Biesbroeck project).

Finally, if confirmed, all three of these systems have component separations exceeding 150 AU. Elsewhere, we have discussed a possible correlation between the maximum separation of binary components and the total system mass (Reid et al. 2001). The systems discussed here include a K4+M6 (0.7+0.1 M_☉) binary at Δ = 225 AU, a K5+M4 (0.65+0.18 M_☉) binary at Δ ~ 200 AU and an (M0+M0)+M9.5 (0.6+0.6+0.08) triple at Δ ~ 635 AU. All three fall within the hypothetical (log Δ, M_☉) limits outlined in Figure 11 of Reid et al. (2001).

This NStars research was supported by a grant awarded as part of the NASA Space Interferometry Mission Science Program, administered by the Jet Propulsion Laboratory, Pasadena. We would like to thank Hartmut Jahnreiss for useful comments, particularly pointing out the separate listings of G87-9 on SIMBAD. I. N. R. and J. L. also acknowledge partial support through a NASA/JPL grant to 2MASS Core Science. J. D. K. acknowledges the support of the Jet Propulsion Laboratory, California Institute of Technology, which is operated under contract with the National Aeronautics and Space Administration. This publication makes use of data from the 2 Micron All-Sky Survey, a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center, funded by the National Aeronautics and Space Administration and the National Science Foundation. Our analysis also relies partly on photographic plates obtained at the Palomar Observatory 48 inch Oschin Telescope for the Second Palomar Observatory Sky Survey which was funded by the Eastman Kodak Company, the National Geographic Society, the Samuel Oschin Foundation, the Alfred Sloan Foundation, the National Science Foundation grants AST 84-08225, AST 87-19465, AST 90-23115, and AST 93-18984, and the National Aeronautics and Space Administration grants NGL 05002140 and NAGW-1710. This research also made use of the SIMBAD database, operated at CDS, Strasbourg, France.

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