AN ADAPTIVE OPTICS SURVEY OF M8–M9 STARS: DISCOVERY OF FOUR VERY LOW MASS BINARIES WITH AT LEAST ONE SYSTEM CONTAINING A BROWN DWARF COMPANION

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ABSTRACT

Use of the highly sensitive Hokupa’a/Gemini curvature wave-front sensor has allowed, for the first time, direct adaptive optics guiding on M8–M9 very low mass (VLM) stars. An initial survey of 20 such objects (spectral type = M8–M9) discovered four binaries. Three of the systems have separations of less than 4.2 AU and similar mass ratios (ΔK < 0.8 mag; 0.85 < q < 1.0). One system, however, did have the largest mass ratio (ΔK = 2.38 mag) and separation (14.4 AU) yet observed for a VLM star with a brown dwarf companion. Based on our initial flux-limited (K_s < 12 mag) survey of 20 M8–M9 stars over 14h26m < R.A. < 1h430" from the sample of Gizis et al., we find a binary fraction in the range of 14%–24% for M8–M9 binaries with separations of less than 3 AU. This is likely consistent with the 23% ± 5% measured for more massive (M0–M6) stars over the same separation range. It appears that M8–M9 binaries have a much smaller semimajor axis distribution peak (~4 AU; with no systems wider than 15 AU) compared with M and G stars that have a broad peak at larger ~30 AU separations.

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

1. INTRODUCTION

Since the discovery of Gl 229B by Nakajima et al. (1995), there has been intense interest in the direct detection of brown dwarfs and very low mass (VLM) stars. According to the current models of Burrows et al. (2000) and Chabrier et al. (2000), stars with spectral types of M8–M9 will be just above the stellar/substellar boundary. However, most fainter companions to such primaries should themselves be substellar. Therefore, a survey of M8–M9 stars should detect binary systems with VLM primaries with VLM or brown dwarf secondaries.

The binary frequency of M8–M9 stars is interesting in its own right, since little is known about how common M8–M9 binary systems are. It is not clear currently if the M8–M9 binary separation distribution is similar to that of M0–M6 stars; in fact, there is emerging evidence that VLM L dwarf binaries tend to have smaller separations but similar binary frequencies as more massive M and G stars (Martín, Brandner, & Basri 1999; Reid et al. 2001b).

In this Letter, we present three newly discovered M8–M9 binaries (2MASSW J1426316−204705, and 2MASSW J2140293−040618, hereafter 2M2140, 2M2206, and 2M2331, respectively). Earlier in this survey, we discovered another M9 binary, 2MASSJ 1426316+155701 (hereafter 2M1426), for which a detailed description was already published in Close et al. (2002). However, we have reanalyzed the data from Close et al. (2002) and include 2M1426 here for completeness since we have revised the mass estimate for this system.

These four new binaries are a significant addition to the approximately nine VLM binaries known to date (Reid et al. 2001b; Close et al. 2002). With relatively short periods, these new systems will likely play a significant role in the mass-luminosity calibration for VLM stars and brown dwarfs. It is also noteworthy that we can start to characterize this new population of M8–M9 binaries. We will outline how M8–M9 binaries are both similar and different from their more massive M and G counterparts.

2. AN ADAPTIVE OPTICS SURVEY OF NEARBY M8–M9 FIELD STARS

As outlined in detail in Close et al. (2002), we utilized the University of Hawaii curvature adaptive optics (AO) system Hokupa’a (Graves et al. 1998; Close et al. 1998), which is a visitor AO instrument on the Gemini North Telescope. This highly sensitive curvature AO system is well suited to locking onto nearby, faint, red M8–M9 stars and producing 0.13 images (which are close to the 0.07 diffraction limit in the K′ band). We utilized this unique capability to survey the nearest extreme M stars (M8.0–M9.5) in order to characterize the nearby M8–M9 binary population.

Here we report the results of our second observing run on 2001 September 22, UT. We targeted M8–M9 VLM stars identified by Gizis et al. (2000). We have observed 20 out of 24 of the published (Gizis et al. 2000) M8.0–M9.5 stars with K_s < 12 mag over the range 14h26m < R.A. < 4h30". The four systems not observed due to time constraints were 2MASSW J145739+451716, J1553199+140033, J1627279+810507, and J2349489+122438; all other M8–M9 stars with K_s < 12 in the 14h26m < R.A. < 4h30" range have been observed from the list of Gizis et al. (2000). It should be noted that the M8–M9 list of Gizis et al. (2000) has some selection constraints: Galactic latitudes are all greater than 20° (from 0 hr < R.A. < 4.5 hr, decl. < 30°), and there are gaps in the coverage due to the past availability of the 2 Micron All Sky Survey (2MASS) scans.
Four of our 20 targets were clearly tight binaries (with separations of less than 0.5). We observed each of these objects by dithering over four different positions on the Quick Infrared Camera (QUIRC) near-IR detector with 0.0199 pixel$^{-1}$ (Hodapp et al. 1996). At each position, we took 3 × 10 s exposures at $J$, $H$, and $K'$ and 3 × 60 s exposures at $H$ that resulted in unsaturated 120 s exposures at $J$, $H$, and $K'$ with a deep 720 s exposure at the $H$ band for each binary system.

### 3. Reductions and Analysis

We have developed an AO data reduction pipeline in the IRAF language that maximizes sensitivity and image resolution. This pipeline is a standard IR AO data reduction and is described in detail in Close et al. (2002).

This pipeline produced final unsaturated 120 s exposures at $J$ (FWHM $\sim 0.15$), $H$ (FWHM $\sim 0.14$), and $K'$ (FWHM $\sim 0.13$) with a deep 720 s exposure (FWHM $\sim 0.14$) at the $H$ band for each binary system. The dithering produces a final image of 30$''$ × 30$''$ with the most sensitive region (10$''$ × 10$''$) centered on the binary. See Figure 1, which illustrates $K'$ images of each of the new systems. We made the small conversion from the $K'$ magnitudes to $K$ with the calibration of $K-K' = 0.22(H-K)$, which was derived for similarly reddened stars (Wainscoat & Cowie 1992).

In Table 1, we present the analysis of the images taken of the new binaries from both runs. The photometry was based on DAOPHOT point-spread function (PSF) fitting photometry (Stetson 1987). The PSF used was the reduced 12 × 10 s unsaturated data from the next (single) brown dwarf observed after each binary. The PSF "star" always had a similar IR brightness, a late M spectral type, and was observed at a similar air mass. The resulting Δmagnitudes are listed in Table 1. The errors in Δmag are the differences in the photometry between two similar PSF stars. The individual fluxes were calculated from the flux ratio measured by DAOPHOT (assuming $\Delta K' = \Delta K$) and the total flux of the binary in a 15$''$ aperture scaled to the published 2MASS fluxes of the blended binary.

The plate scale and orientation of QUIRC were determined from a short exposure of the Trapezium cluster in Orion and were compared with published positions as in Simon, Close, & Beck (1999). From these observations, a plate scale of 0.0199 ± 0.0002 pixel$^{-1}$ and an orientation of the Y-axis (0.3 ± 0.3 east of north) were determined. The astrometry for each binary was based on the PSF fitting. The astrometric errors are based on the range of values observed at the different wavelengths and the systematic errors in the calibration added in quadrature.

### 4. Discussion

#### 4.1. Are the Companions Physically Related to Primaries?

Since Gizis et al. (2000) only picked objects greater than 20$''$ above the Galactic plane, we do not expect many background late M or L stars in our images. In the 1.8 × 10$^4$ arcsec$^2$ already surveyed, we have not detected a $J-K_s > 0.8$ mag background object in any of the fields. Therefore, we estimate that the probability of a chance projection of such a red object within less than 0.5 of the primary is less than 4 × 10$^{-5}$. We conclude that all these very red, cool objects are physically related to their primaries and hereafter refer to them as 2M1426B, 2M2140B, 2M2206B, and 2M2331B.

#### 4.2. What Are the Spectral Types of the Components?

We do not have spatially resolved spectra of both components in any of these systems; consequently, we can only try to fit the observed $J-K_s$ colors in Table 2 to spectral templates. Unfortunately, the exact relationship between IR colors and brown dwarf spectral types is still under study. However, according to the observations of Reid et al. (2001a), our observed $J-K_s$ colors can best be fitted by the spectral types in the seventh column of Table 2. It is important to note that these spectral types are only a guide since the conversion from $J-K_s$...
to spectral type carries at least ±1.5 spectral subclasses of uncertainty. Fortunately, none of the following analysis is dependent on these spectral type estimates.

### 4.3. What Are the Distances to the Binaries?

Unfortunately, there are no published trigonometric parallaxes to any of these systems. We can estimate, however, the distance based on the trigonometric parallaxes of other M8–M9 stars. The distances of all the primaries were determined from the absolute distance based on the trigonometric parallaxes of other M8–M9 dwarfs. Calibrated theoretical evolutionary tracks are required for objects in the temperature range of 1600–2600 K. Recently, such a calibration has been performed by two groups using dynamical measurements of the M8.5 brown dwarf binary Gl 569B. From the dynamical mass measurements of Gl 569B (Kenworthy et al. 2001; Lane et al. 2001), it was found that the Chabrier et al. (2000) evolution models were in reasonably good agreement with observation. In Figure 2, we plot the latest DUSTY models from Chabrier et al. (2000).

We can estimate the masses of the components based on the age range of 0.6–7.5 Gyr and the range of $M_p$ values. The maximum mass relates to the minimum $M_p$ and the maximum age of 7.5 Gyr. The minimum mass relates to the maximum $M_p$ and the minimum age of 0.6 Gyr. These masses are listed in Table 2 and illustrated in Figure 2.

At the younger ages (<1 Gyr), the primaries may be on the stellar/substellar boundary, but they are mostly likely VLM stars. The substellar nature of the companion is very likely in the cases of 2M1426B and 2M2140B, and unlikely in the case of 2M2206B, which appears to be a VLM star like its primary. Hence, three of the companions may be brown dwarfs.

### 4.4. What Are the Ages of the Systems?

Estimating the exact age for any of these systems is difficult since there are no Li measurements yet published (which could place an upper limit on the ages). For completeness, we have assumed that the whole range of common ages in the solar neighborhood (0.6–7.5 Gyr) may apply to each system (Caloi et al. 1999). However, Gizis et al. (2000) observed very low proper motion ($V_{\text{tan}} < 10 \, \text{km} \, \text{s}^{-1}$) for the 2M2140 and 2M2206 systems. These two systems are among the lowest velocity M8’s in the entire survey of Gizis et al. (2000). This suggests a somewhat younger age since these systems have not yet developed a significant random velocity like the other older (∼3 Gyr) M8–M9 stars in the survey. Therefore, we assign a slightly younger age of 3.0–4.5 Gyr to these two systems (2M2140 and 2M2206) but leave large error bars, allowing ages from 0.6 to 7.5 Gyr (∼3 Gyr is the maximum age for the kinematically young stars found by Caloi et al. 1999). The other binary system 2M2331 appears to have a normal $V_{\text{tan}}$ and so is more likely to be an older system. Hence, we assign an age of 5.0–7.5 Gyr, which is an average age for a star in the solar neighborhood (Caloi et al. 1999).

### 4.5. The Masses of the Components

To estimate masses for these objects, we will need to rely on theoretical evolutionary tracks for VLM stars and brown dwarfs. Calibrated theoretical evolutionary tracks are required for objects in the temperature range of 1600–2600 K. Recently, such a calibration has been performed by two groups using dynamical measurements of the M8.5 brown dwarf binary Gl 569B. From the dynamical mass measurements of Gl 569B (Kenworthy et al. 2001; Lane et al. 2001), it was found that the Chabrier et al. (2000) evolution models were in reasonably good agreement with observation. In Figure 2, we plot the latest DUSTY models from Chabrier et al. (2000).

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### 4.6. The Binary Frequency of M8–M9 Stars

We have carried out a flux-limited ($K < 12$) survey of 20 M8–M9 primaries. Around these 20 M8–M9 targets, we have detected four systems that have companions. Since our survey is flux-limited, we need to correct for our bias toward detecting binaries that “leak” into our sample from farther distances. Our selection of $K < 12$ leads to an incompleteness of single stars past $D \sim 22$ pc. Our detected binaries have an incompleteness past 25 pc. Therefore, we are probing 1.46 times more volume with the brighter binaries compared with the single (and hence fainter) M8–M9 stars. Hence, the corrected binary frequency is 4/20/1.46 = 14%.

Of course, there are other selection effects due to the instrumental PSF that prevents detection of very faint companions very close to the primaries. We were only sensitive to companions of $\Delta K \sim 1$ mag at 0′13–0′17 separations. Much fainter companions ($\Delta K \sim 5$ mag) could be detected at slightly wider ($\sim 0′25$) separations, and VLM companions ($\Delta H \sim 10$ mag) could be detected at $\sim 1′$ separations. Therefore, we likely are not detecting faint companions in the separation range of 0′13–0′17. However, if we assume that the mass ratio distribution ($q$) for M8–M9 stars is similar to that of M0–M6 binaries (e.g., at least as many binaries with $\Delta K > 1.0$ mag as with $\Delta K <$ $\Delta K <$...
1.0 mag; Fischer & Marcy 1992), then based on our detection of three systems with $\Delta K < 1$ mag with separations of $0^\prime.13$–$0^\prime.17$, we likely missed at least about three other systems with $\Delta K > 1$ mag with separations in the range of $0^\prime.13$–$0^\prime.17$. Based on this assumption about the mass ratio distribution, there should be approximately six binaries in the range of $0^\prime.13$–$0^\prime.17$ when correcting for our instrumental insensitivity. Therefore, the total count should be seven systems. Therefore, the corrected M8–M9 binary frequency would be $7/20/1.46 = 24\%$ for separations of greater than $0^\prime.13$. Hence, we have a range of possible binary frequencies from 14\% (if there are no binaries with $\Delta K > 1$ mag with separations of $0^\prime.13$–$0^\prime.17$) up to 24\% if the $q$-distribution is similar to M0–M6 stars and if we correct for insensitivity. In any case, we can state that for systems with separations greater than 3 AU (or $P > 15$ yr), the M8–M9 binary frequency is likely within the range of 14\%–24\%.

From Fischer & Marcy (1992), it appears that our M8–M9 binary fraction range of 14\%–24\% is likely consistent with the 23\% $\pm$ 5\% measured for more massive M stars (M0–M6) over the same separation/period range ($P > 15$ yr). However, the M8–M9 binaries are very different from the M stars in the distribution of their semimajor axes. The M8–M9 binaries appear to peak at separations of $\sim$4 AU, which is significantly tighter than the $\sim$30 AU peak of both the G and M star binary distributions. This cannot be a selection effect since we are highly sensitive to all M8–M9 binaries with separations greater than 20–600 AU (even those with $\Delta K > 10$ mag). Therefore, we may conclude that M8–M9 stars likely have similar binary fractions as G and M stars, but they have significantly smaller semimajor axes on average.

More observations of such systems will be required to see if these trends hold over bigger samples. It is interesting to note that in Reid et al. (2001b), a survey of eight L binaries finds a similar binary frequency of 20\% and a maximum separation of only 9 AU. Therefore, it appears that both M8–M9 and L binaries may have similar binary frequencies and smaller separations than their more massive M and G counterparts.

Fig. 2.—Latest Chabrier et al. (2000) DUSTY evolutionary models. The locations of the two components of 2M1426 are indicated by the open circles, 2M2140 by the open squares, 2M2206 by the filled stars, and 2M2331 by the open triangles. The large error bars are due to the errors in the distance, photometry, and age of the systems ($0.6/H_{11002}$ 7.5 Gyr). The $M_K$ of each secondary is determined by the addition of plus the $M_K$ of the primary. Note that 2M2331 has the largest mass ratio ($q = 0.68$) of any M8 binary known to date.

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In the Abstract, the phrase “with separations of less than 3 AU” should read “with separations of more than 3 AU.” The Press sincerely regrets this error.

In § 3, second paragraph, last sentence, “$K - K' = 0.22(H - K)$” should read “$K' - K = 0.22(H - K)$.”