Submitted Oct 30, 2001; accepted Jan 23, 2002, to be published in March 2002 ApJ Letters

An Adaptive Optics Survey of M8-M9 stars: Discovery of 4 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 wavefront sensor has allowed for the first time direct adaptive optics (AO) guiding on M8-M9 very low mass (VLM) stars. An initial survey of 20 such objects (SpT=M8-M9) discovered 4 binaries. Three of the systems have separations of less than 4.2 AU and similar mass ratios ($\Delta K < 0.8$ mag; $0.85 < q < 1.0$). One system, however, did have the largest $\Delta K = 2.38$ mag and $sep = 14.4$ AU yet observed for a VLM star with a brown dwarf companion. Based on our initial flux limited ($Ks < 12$ mag) survey of 20 M8-M9 stars over $14:26 < RA < 4:30$ hours from the sample of Gizis et al. (2000) we find a binary fraction in the range $14-24\%$ for M8-M9 binaries with $sep > 3$ AU. This is likely consistent with the $23 \pm 5\%$ measured for more massive (M0-M6) stars over the same separation range. It appears M8-M9 binaries have a much smaller semi-major axis distribution peak (~ 4 AU; with no systems wider than 15 AU) compared to M and G stars which 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. (2001), 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 very low mass 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. 2001a)).

In this letter we present 3 newly discovered M8-M9 binaries (2MASSW J2140293+162518, 2MASSWJ 2206228-204705, and 2MASSW J2331016-040618 –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 re-analyzed the data from Close et al. (2002) and include 2M1426 here for completeness since we have revised the mass estimate for this system.

These 4 new binaries are a significant addition to the ~ 9 very low mass binaries known to date (Reid et al. (2001a) & 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 & G counterparts.

2. An AO 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) to characterize the nearby M8-M9 binary population.

Here we report the results of our second observing run on UT Sept 22, 2001. 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 $Ks < 12$ mag over the RA range 14:26-04:30 hours. The four systems not observed due to time constraints were 2MASSW J145739+451716, J1553199+140033, J1627279+810507, J2349489+122438, all other M8-M9 stars with $Ks < 12$ in the RA range 14:26-04:30 hours 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 > 20 degrees; from $0 < RA < 4.5$ hours $DEC < 30$ degrees; and there are gaps in the coverage due to the past availability of the 2MASS scans.

Four of our 20 targets were clearly tight binaries ($sep < 0.5''$). We observed each of these objects by dithering over 4 different positions on the QUIRC NIR 1024x1024 detector with $0.0199''$/pix (Hodapp et al. (1996)). At each position we took 3x10s exposures at J, H, K', and 3x60s exposures at H. Resulting in unsaturated 120s exposures at J, H, and K' with deep 720s exposure at H band for each binary system.

3. Reductions & Analysis

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

This pipeline produced final unsaturated 120s exposures at J ($FWHM \sim 0.15''$) , H ($FWHM \sim 0.14''$), and K' ($FWHM \sim 0.13''$) with a deep 720s exposure ($FWHM \sim 0.14''$) at H band for each binary system. The dithering produces a final image of $30\text{x}30''$ with the most sensitive region ($10\text{x}10''$) 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 4 new binaries from both runs. The photometry was based on DAOPHOT PSF fitting photometry (Stetson 1987). The PSF used was the reduced 12x10s 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 airmass. The resulting $\Delta magnitudes$ are listed in Table 1. The errors in Δmag are the differences in the photmetry between 2 similar PSF stars. The individual fluxes were calculated from the flux ratio measured by DAOPHOT (assuming $\Delta K' = \Delta Ks$) and the total flux of the binary in a $15''$ aperture scaled to the published 2MASS fluxes of the blended binary.

The platescale and orientation of QUIRC was determined from a short exposure of the Trapezium cluster in Orion and compared to published positions as in Simon, Close & Beck (1999). From these observations a platescale of $0.0199 \pm 0.0002''$/pix and an orientation of the Y-axis (0.3 ± 0.3 degrees E of north) was 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 > 20 degrees above the galactic plane we do not expect many background late M or L stars in our images. In the $1.8x10^4$ square arcsecs already surveyed, we have not detected a $J - Ks > 0.8$ mag background object in any of the fields. Therefore, we estimate the probability of a chance projection of such a red object within $< 0.5''$ of the primary is $< 4\text{x}10^{-5}$. 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 $J - Ks$ 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. (2001b) our observed $J - Ks$ colors can best be fit by the spectral types in the 7^{th} column of Table 2. It is important to note that these spectral types are only a guide since the conversion from $J - Ks$ 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 K magnitudes which can be estimated by $M_K = 7.593 + 2.25(J - Ks)$ for M8-M9 stars (Gizis et al. 2000). This relationship has a 1σ error of 0.36 mag which has been added in quadrature with the J & Ks photometric errors to yield the primary component's M_K values plotted in Figure 2.

4.4. What are 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 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 ($V_{tan} < 10$ km/s) 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 (~ 5 Gyr) M8-M9 stars in the survey. Therefore, we assign a slightly younger age of $3.0^{+4.5}_{-2.4}$ Gyr to these 2 systems (2M2140 and 2M2206), but leave large error bars allowing ages from 0.6-7.5 Gyr (~ 3 Gyr is maximum age for the kinematically young stars found by Caloi et al. (1999)). The other binary system 2M2331 appears to have a normal V_{tan} and so is more likely to be an older system. Hence we assign an age of $5.0^{+2.5}_{-4.4}$ 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 1600-2600 K. Recently such a calibration has been performed by two groups using dynamical measurements of the M8.5 Gl569B brown dwarf binary. From the dynamical mass measurements of the Gl569B binary brown dwarf (Kenworthy et al. (2001), and Lane et al. (2001)) it was found that the Chabrier et al. (2001) and Burrows et al. (2000) evolutionary models were in reasonably good agreement with observation. In Figure 2 we plot the latest DUSTY models from Chabrier et al. (2001).

4.6. The masses of the components

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

At the younger ages ($< 1Gyr$), the primaries may be on the stellar/substellar boundary, but they are most likely VLM stars. The substellar nature of the companion is very likely in the case of 2M2331B, possible in the cases of 2M1426B and 2M2140B, to unlikely in the case of 2M2206B which appears to be a VLM star like its primary. Hence 3 of the companions may be brown dwarfs.

4.7. The binary frequency of M8-M9 stars

We have carried out a flux limited ($Ks < 12$) survey of 20 M8-M9 primaries. Around these 20 M8-M9 targets we have detected 4 systems that have companions. Since our survey is flux limited we need to correct for our bias towards detecting binaries that "leak" into our sample from further distances. Our selection of $Ks < 12$ leads to 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 to the single (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 which prevents detection of very faint companions very close to the primaries. We were only sensitive to companions of $\Delta K' \sim 1mag$ at $0.13 - 0.17''$ separations. Much fainter companions ($\Delta K' \sim 5mag$) could be detected at slightly wider ($\sim 0.25''$) separations, and very low mass companions ($\Delta H \sim 10mag$) 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. as least as many binaries with $\Delta K > 1.0$ as $\Delta K < 1.0$ mag (Fischer & Marcy 1992)), then based on our detection of 3 systems with $\Delta K < 1$ mag with separations of $0.13 - 0.17''$ we likely missed at least ~ 3 other systems with $\Delta K > 1$ mag with separations in the range $0.13 - 0.17''$. Based on this assumption about the mass ratio distribution there should be ~ 6 binaries from $0.13 - 0.17''$ when correcting for our instrumental insensitivity. Therefore, the total count should be 7 systems. Therefore, the corrected M8-M9 binary frequency would be $7/20/1.46 = 24\%$ for separations $> 0.13''$. Hence we have a range of possible binary frequencies from 14% (if there are no binaries with $\Delta K > 1$ mag with separations of $0.13 - 0.17''$) up to 24% if the q distribution is similar to M0-M6 stars and we correct for insensitivity. *In any case, we can state that for systems with separations greater than* $sep > 3$ *AU (or* $P > 15$ *yr) the M8-M9 binary frequency is likely within the range* $14 - 24\%$.

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 ($P > 15yr$). However, the M8-M9 binaries are very different from the M stars in the distribution of their semi-major axis. The M8-M9 binaries appear to peak at $sep \sim 4$ AU which is significantly tighter than the ~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 $sep > 20 - 600$ 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 semi-major 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. (2001a) a survey of 8 L binaries finds a similar binary frequency of 20% and a maximum separation of only 9 AU. Therefore it appears both M8-M9 and L binaries may have similar binary frequencies and smaller separations than their more massive M and G counterparts.

The Hokupa'a AO observations were supported by the University of Hawaii AO group. (D. Potter, O. Guyon, P. Badouz and A. Stockton). Support for Hokupa'a comes from the National Science Foundation. We thank the anonymous referee for comments that led to an improved analysis of the data and an all round better paper. LMC acknowledges support by the AFOSR under F49620-00-1-0294. We would also like to send a big *mahalo nui* to the Gemini operations staff (especially Simon Chan) for a flawless night. These results were based on observations obtained at the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the Particle Physics and Astronomy Research Council (United Kingdom), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), CNPq (Brazil) and CONICET (Argentina).

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Table 1. The new binary systems observed Sept 22, 2001

System	ΔJ	ΔH	$\Delta K'$	ΔK	Sep. ($''$)	PA	Age (Gyr)	Est. D (pc)[a]
2M1426[b]	0.78 ± 0.05	0.70 ± 0.05	0.65 ± 0.10	0.57 ± 0.14	0.152 ± 0.006	$344.1 \pm 0.7°$	$0.8^{+6.7}_{-0.2}$[b]	23.6 ± 6.0
2M2140	0.77 ± 0.05	0.73 ± 0.04	0.75 ± 0.04	0.76 ± 0.13	0.155 ± 0.005	$134.3 \pm 0.5°$	$3.0^{+4.5}_{-2.4}$	23.9 ± 6.0
2M2206	0.17 ± 0.04	0.08 ± 0.04	0.08 ± 0.03	0.08 ± 0.14	0.168 ± 0.007	$68.2 \pm 0.5°$	$3.0^{+4.5}_{-2.4}$	24.68 ± 6.8
2M2331	2.78 ± 0.04	2.64 ± 0.05	2.44 ± 0.03	2.38 ± 0.16	0.573 ± 0.008	$302.6 \pm 0.4°$	$5.0^{+2.5}_{-4.4}$	25.2 ± 6.8

[a] photometric distances of the primaries calculated from M8-M9 relation of $M_K = 7.593 + 2.25(J - Ks)$ from Gizis et al. (2000))

[b] 2M1426 observations made on June 20, 2001 Close et al. (2002); the young age of 2M1426 is motivated in Close et al. (2002)

Table 2. Summary of the new binaries' A & B components

Name	J	H	Ks	K	$J - Ks$	SpT[a]	Est. Mass[b]	Sep. (AU)	P (yr)[c]
2M1426A	13.36 ± 0.06	12.63 ± 0.05	12.20 ± 0.07	12.07 ± 0.08	1.16 ± 0.12	M8.5	$0.083^{+0.010}_{-0.014}$	3.6 ± 0.9	17^{+10}_{-7}
2M1426B	14.13 ± 0.06	13.34 ± 0.10	12.80 ± 0.14	12.64 ± 0.14	1.33 ± 0.12	L1	$0.075^{+0.009}_{-0.020}$		
2M2140A	13.37 ± 0.06	12.72 ± 0.04	12.22 ± 0.04	12.07 ± 0.09	1.15 ± 0.12	M8.5	$0.087^{+0.008}_{-0.017}$	3.7 ± 0.9	18^{+10}_{-7}
2M2140B	14.15 ± 0.06	13.44 ± 0.04	12.97 ± 0.04	12.83 ± 0.09	1.19 ± 0.14	L0	$0.075^{+0.007}_{-0.018}$		
2M2206A	13.12 ± 0.06	12.46 ± 0.06	12.06 ± 0.05	11.94 ± 0.08	1.06 ± 0.12	M8.0	$0.090^{+0.008}_{-0.014}$	4.1 ± 1.1	20^{+9}_{-7}
2M2206B	13.27 ± 0.06	12.54 ± 0.06	12.14 ± 0.05	12.02 ± 0.08	1.13 ± 0.14	M8.5	$0.088^{+0.008}_{-0.014}$		
2M2331A	13.08 ± 0.04	12.38 ± 0.04	12.04 ± 0.04	11.94 ± 0.07	1.04 ± 0.12	M8.0	$0.091^{+0.008}_{-0.013}$	14.4 ± 3.9	139^{+86}_{-57}
2M2331B	15.86 ± 0.06	15.03 ± 0.06	14.48 ± 0.06	14.32 ± 0.10	1.38 ± 0.14	L3	$0.062^{+0.010}_{-0.020}$		

[a] Spectral types estimated from J-Ks colors and calibrations of Reid et al. (2001b) with ±1.5 spectral subclasses of error in these estimates.

[b] Masses (in solar units) from the models of Chabrier et al. (2001) –see Figure 2

[c] Periods estimated assuming face-on circular orbits

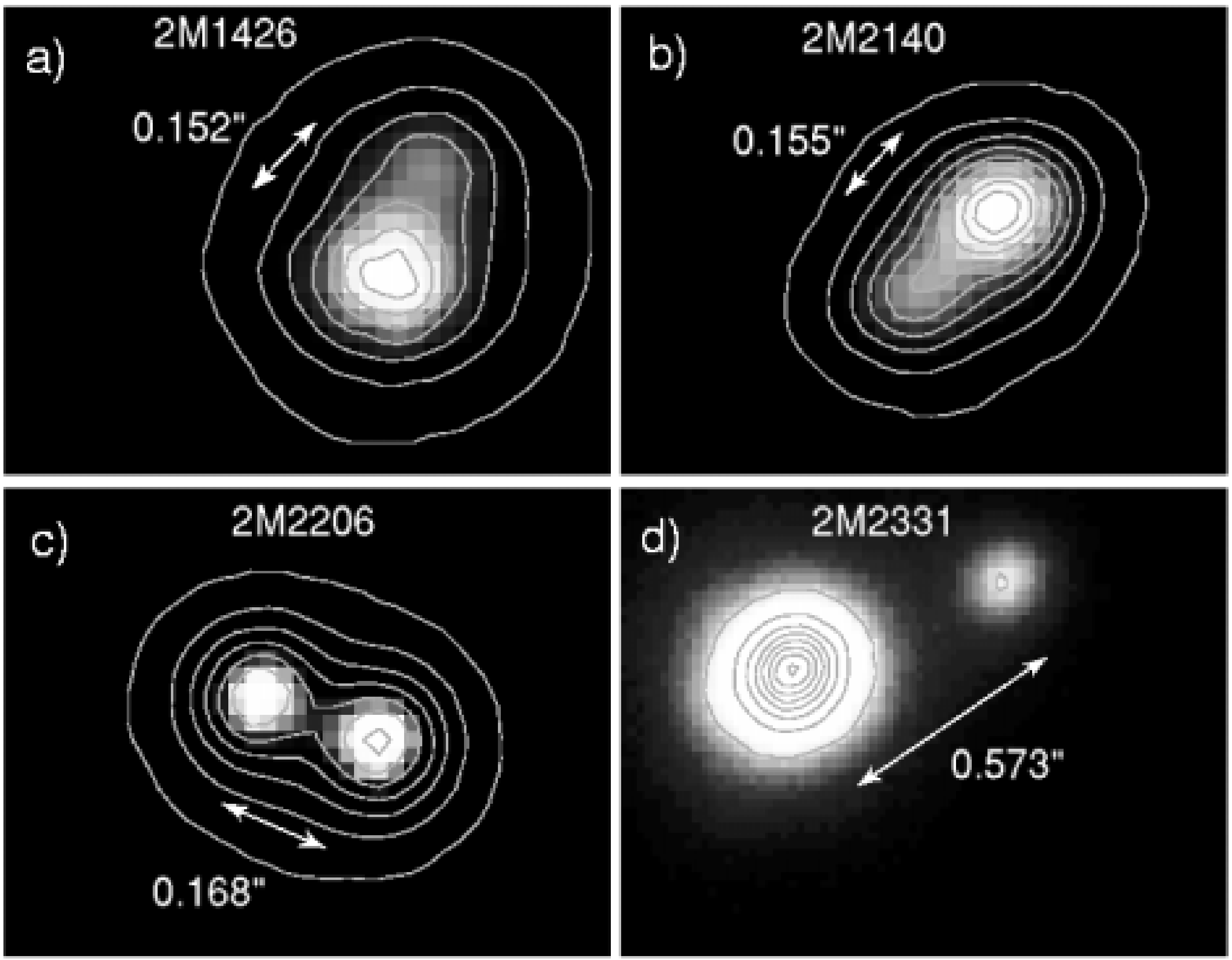

Fig. 1.— In figure (a) we see the 12x10s K' image of the 2MASSJ 1426316+155701 binary discussed in Close et al. (2002) at a resolution of $0.131''$. In Figure (b-d) we show K' images of the new binaries 2MASSW J2140293+162518, 2MASSWJ 2206228-204705, and 2MASSWJ 2331016-040618, respectively. The pixels are $0.0199''$/pix. The contours are linear at the 90, 75, 60, 45, 30, 15, and 1% levels. North is up and East left in each figure.

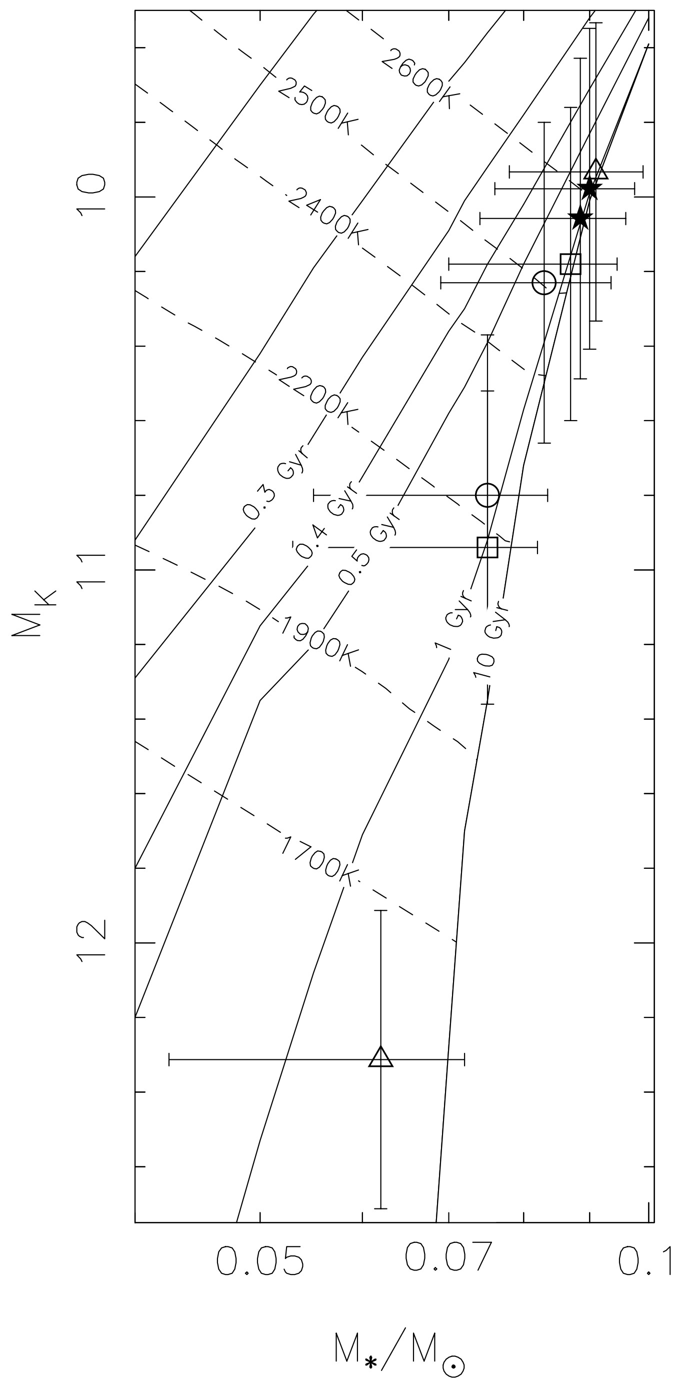

Fig. 2.— The latest Chabrier et al. (2001) DUSTY evolutionary models. The locations of the 2 components of 2M1426 are indicated by the circles, 2M2140 squares, 2M2206 solid stars, and 2M2331 by the triangles. The large error bars are due to the errors in the distance, photometry, and age of the systems $0.6 - 7.5$ Gyr. The M_K of each secondary is determined by the addition of ΔK 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.