

Detection of Nine M8.0–L0.5 Binaries: The Very Low Mass Binary Population and Its Implications for Brown Dwarf Formation Theories

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Abstract. Use of the highly sensitive Hōkūpa‘a/Gemini curvature wave-front sensor has allowed for the first time direct adaptive optics (AO) guiding on very low mass (VLM) stars with SpT=M8.0-L0.5. A survey of 39 such objects detected 9 VLM binaries (7 of which were discovered for the first time to be binaries). Most of these systems (55%) are tight (separation < 5 AU) and have similar masses ($\Delta K_s < 0.8$ mag; $0.85 < q < 1.0$). However, 2 systems (LHS 2397a, and 2M2331016-040618) have large $\Delta K_s > 2.38$ mag and consist of a VLM star orbited by a much cooler L6.5-L8.5 brown dwarf companion. Based on our initial flux limited ($K_s < 12$ mag) survey of 39 M8.0-L0.5 stars (mainly from the sample of Gizis et al. 2000) we find a binary fraction in the range $19 \pm 7\%$ for M8.0-L0.5 binaries with separations > 2.6 AU. This is slightly less than the $32 \pm 9\%$ measured for more massive (M0-M4) stars over the same separation range (Fischer & Marcy 1992). It appears M8.0-L0.5 binaries (as well as L and T dwarf binaries) have a much smaller semi-major axis distribution peak (~ 4 AU) compared to more massive M and G stars which have a broad peak at larger ~ 30 AU separations. We also find no VLM binaries ($M_{tot} < 0.18M_{\odot}$) with separations > 20 AU. We find that a velocity “kick” of ~ 3 km/s can reproduce the observed cut-off in the semi-major axis distribution at ~ 20 AU. This kick may have been from the VLM system being ejected from its formation mini-cluster.

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 M8.0-L0.5 will be just above the stellar/substellar boundary. However, most fainter companions to such primaries should themselves be substellar. Therefore, a survey of M8.0-L0.5 stars should detect binary systems consisting of VLM primaries with VLM or brown dwarf secondaries.

The binary frequency of M8.0-L0.5 stars is interesting in its own right since little is known about how common M8.0-L0.5 binary systems are. It is not clear currently if the M8.0-L0.5 binary separation distribution is similar to that of

M0-M4 stars; in fact, there is emerging evidence that very low mass L dwarf binaries tend to have smaller separations but similar binary frequencies as their more massive M and G star counterparts (Martín, Brandner, & Basri (1999) & Reid et al. (2001a)).

Despite the strong interest in such very low mass binaries, only 13 such systems have been detected to date. In our paper, Close, Siegler, & Freed (2002), a detailed history of each these detections is given in the Introduction.

During our adaptive optics survey, we have detected 12 VLM binaries (10 of these are new discoveries) out of 69 VLM stars (30 M6.0-M7.5 & 39 M8.0-L0.5 stars). Three of these new binary systems (LP415-20, LP475-855, & 2MASSW J1750129+442404) have M7.0-M7.5 spectral types and are discussed in detail elsewhere (Siegler et al. (2002)) with the other 30 M6.0-M7.5 stars. In this paper, we discuss the remaining 9 cooler binaries from the sample of 39 M8.0-L0.5 targets observed in our survey (referred herein as M8.0-L0.5 binaries even though they may contain much cooler L1-L7.5 companions; see Table 1 for a complete list of these systems).

Two of these systems (2MASSW J0746425+200032 and 2MASSW J1047127+402644) were in our sample yet have been imaged previously in the visible by HST and found to be binaries (Reid et al. (2001a); Reid et al. (2002)) however we present the first resolved IR observations of these 2 systems. The seven remaining systems were all discovered to be binaries during this survey. The first 4 systems discovered in our survey (2MASSW J1426316+155701, 2MASSW J2140293+162518, 2MASSW J2206228-204705, and 2MASSW J2331016-040618) have brief descriptions in Close et al. (2002b). However, we have re-analyzed the data from Close et al. (2002b) and include it here for completeness with slightly revised mass estimates. The very interesting M8/L7.5 system LHS 2397a discovered during this survey is discussed in detail elsewhere (Freed, Close & Siegler (2002)) yet is included here also for completeness. The newly discovered binaries 2MASSW J1127534+741107 and 2MASSW J1311391+803222 are presented here for the first time. See Close, Siegler, & Freed (2002) for a more complete discussion of these binaries and our observational methods.

These nine M8.0-L0.5 binaries are a significant addition to the other 11 very low mass M8-T6 binaries known to date (Basri & Martín(1999), Martín, Brandner, & Basri (1999), Koerner et al. (1999), Martín et al. (2000), Reid et al. (2001a), Potter et al. (2002a), Burgasser et al. (2002)). With relatively short periods our 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 M8.0-L0.5 binaries. We will outline how M8.0-L0.5 binaries are both similar and different from their more massive M & G counterparts.

Table 1. Summary of the new binaries' A & B components

Name	J	K_s	M_{K_s}	SPT ^a	Mass ^b M_{\odot}	D_{phot}^c (pc)	Sep (AU)	P ^d (yr)
2M0746A	12.23 ± 0.08	11.04 ± 0.07	10.25 ± 0.39	L0.5	0.082 ^{+0.001} _{-0.004}	12 ± .1	1.5 ± 0.11	11 ⁺³ ₋₂
2M0746B	12.83 ± 0.21	11.48 ± 0.16	10.69 ± 0.42	L2	0.078 ^{+0.001} _{-0.009}			
2M1047A	12.85 ± 0.08	11.80 ± 0.07	9.95 ± 0.39	M8	0.092 ^{+0.009} _{-0.012}	23 ± 4	2.9 ± 0.6	11 ⁺⁵ ₋₃
2M1047B	13.70 ± 0.26	12.31 ± 0.16	10.46 ± 0.42	L0	0.084 ^{+0.006} _{-0.016}			
LHS2397aA	11.86 ± 0.05	10.80 ± 0.03	10.03 ± 0.09	M8	0.090 ^{+0.001} _{-0.001}	14 ± .4	3.9 ± 0.18	22 ⁺³ ₋₃
LHS2397aB	15.69 ± 0.60	13.57 ± 0.10	12.80 ± 0.12	L7.5	0.068 ^{+0.007} _{-0.017}	34 ± 6	8.3 ± 1.5	57 ⁺²⁶ ₋₁₅
2M1127A	13.66 ± 0.06	12.60 ± 0.05	9.96 ± 0.37	M8	0.092 ^{+0.009} _{-0.008}			
2M1127B	13.99 ± 0.13	12.85 ± 0.08	10.21 ± 0.38	M9	0.087 ^{+0.007} _{-0.003}			
2M1311A	13.49 ± 0.06	12.39 ± 0.04	10.07 ± 0.37	M8.5	0.089 ^{+0.011} _{-0.007}	29 ± 5	7.7 ± 1.3	51 ⁺²⁴ ₋₁₃
2M1311B	13.62 ± 0.11	12.53 ± 0.07	10.21 ± 0.38	M9	0.087 ^{+0.007} _{-0.013}			
2M1426A	13.30 ± 0.04	12.18 ± 0.05	10.09 ± 0.37	M8.5	0.088 ^{+0.009} _{-0.010}	26 ± 4	3.9 ± 0.7	19 ⁺⁹ ₋₅
2M1426B	14.08 ± 0.06	12.83 ± 0.11	10.74 ± 0.38	L1	0.076 ^{+0.008} _{-0.007}			
2M2140A	13.37 ± 0.04	12.22 ± 0.04	10.17 ± 0.37	M9	0.088 ^{+0.007} _{-0.012}	26 ± 4	3.9 ± 0.6	19 ⁺⁹ ₋₅
2M2140B	14.14 ± 0.06	12.97 ± 0.05	10.92 ± 0.37	L2	0.078 ^{+0.004} _{-0.020}			
2M2206A	13.10 ± 0.04	12.06 ± 0.04	9.93 ± 0.37	M8	0.092 ^{+0.009} _{-0.011}	27 ± 4	4.4 ± 0.7	22 ⁺¹⁰ ₋₅
2M2206B	13.27 ± 0.05	12.14 ± 0.05	10.01 ± 0.37	M8	0.091 ^{+0.008} _{-0.011}			
2M2331A	13.02 ± 0.04	12.03 ± 0.04	9.81 ± 0.36	M7.5	0.095 ^{+0.010} _{-0.011}	28 ± 5	16 ± 3	157 ⁺⁷² ₋₄₁
2M2331B	15.80 ± 0.05	14.47 ± 0.05	12.25 ± 0.37	L7	0.069 ^{+0.001} _{-0.028}			

^aSpectral types estimated by $SPT = 3.97 \times M_{K_s} - 31.67$ where $SPT = 10 = L0$ (see Siegler et al. (2002) for the fit to the 2MASS M_{K_s} ; derived from the trigonometric parallaxes of Dahn et al. (2002)) the scatter in this fit is ± 1.5 spectral subclasses of error in these estimates). LHS 2397a's SpT is derived separately in Freed, Close & Siegler (2002).

^bMasses (in solar units) from the models of Chabrier et al. (2000) –see Figures 3–11 of Close, Siegler, & Freed (2002).

^cPhotometric distances estimated for the primaries by $M_{K_s} = 7.71 + 2.14(J - K_s)$ which is valid for $M7.5 < SpT < L1$ and has a scatter of 0.36 mag (see Siegler et al. (2002) for the fit to the 2MASS M_{K_s} ; derived from the trigonometric parallaxes of Dahn et al. (2002)). However, the distances for both LHS 2397a and 2M0746 are from their own trigonometric parallaxes (van Altena, Lee, & Hoffleit (1995), Dahn et al. (2002); respectively).

^dPeriods estimated assuming face-on circular orbits. In the cases of 2M0746 and LHS 2397a the larger of the 2 observed separations (2.7 AU & 3.86 AU from Reid et al. (2001a) and Freed, Close & Siegler (2002) respectively) have been used to more accurately estimate the period.

2. Discussion

2.1. The binary frequency of M8.0-L0.5 stars

We have carried out the largest flux limited ($K_s < 12$) high-resolution survey of M8.0-L0.5 primaries. Around these 39 M8.0-L0.5 targets we have detected 9 systems that have companions (see Table 1). Since our survey is flux limited we need to correct for our bias toward detecting equal magnitude binaries that “leak” into our sample from further distances.

More exactly, 88% of our binary systems are with 29.1 pc and 88% of our single stars are within 23.4 pc. Therefore, we are probing $\sim (29.1/23.4)^3 = 1.92$ times more volume with the brighter binaries compared to the single (hence fainter) M8.0-L0.5 stars. Hence, the corrected binary frequency is $9/39/1.92 = 12\%$.

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 are only sensitive to companions of $\Delta K' \lesssim 1\text{mag}$ at $0.1 - 0.2''$ separations. Much fainter companions ($\Delta K' \sim 5\text{mag}$) could be detected at slightly wider ($\sim 0.25''$) separations, and very low mass companions ($\Delta H \sim 10\text{mag}$) could be detected at $\sim 1''$ separations. Therefore, we are likely not detecting faint ($\Delta K' > 1.0$) companions in the separation range of $0.1 - 0.2''$. However, if we assume that the mass ratio distribution (q) for M8.0-L0.5 stars is similar to that of M0-M4 binaries, then we would expect as least as many binaries with $\Delta K' > 1.0$ as $\Delta K' < 1.0$ mag Fischer & Marcy (1992). Although we do not have enough data currently to derive the q distribution for M8.0-L0.5 binaries, we can note that for the 4 systems with separations $> 0.2''$ we observed an equal number of $\Delta K' > 1.0$ as $\Delta K' < 1.0$ mag systems. So it appears reasonable that there should also be an equal number of $\Delta K' > 1.0$ as $\Delta K' < 1.0$ mag systems in the range $0.1 - 0.2''$. Then based on our detection of 5 systems with $\Delta K' < 1$ mag with separations of $0.1 - 0.2''$ we would expect to have ~ 5 systems with $\Delta K' > 1.0$ in the range $0.1 - 0.2''$. In reality we detected no systems with $\Delta K' > 1.0$ with separations $0.1 - 0.2''$. Therefore, to correct for instrumental insensitivity we need to increase the number of binary systems by 5 in the range $0.1 - 0.2''$. Based on this assumption about the mass ratio distribution there should be ~ 10 binaries from $0.1 - 0.2''$ when correcting for our instrumental insensitivity. Therefore, the total count for all separations $> 0.1''$ should be 14 ± 4 systems assuming a Poisson error. Therefore, the corrected M8.0-L0.5 binary frequency would be $14/39/1.92 = 19 \pm 6\%$ for separations $> 0.10''$ or $\gtrsim 2.6\text{AU}$.

Hence we have a range of possible binary frequencies from 12% (in the unlikely case the frequency of systems with $\Delta K' > 1$ mag with separations $0.1 - 0.2''$ falls to 0% from the 50% observed for systems with separations $> 0.2''$) up to $19 \pm 6\%$ correcting for insensitivity to tight $0.1 - 0.2''$ systems with faint $\Delta K' > 1$ companions. *In any case, we can state that for systems with separations $a > 2.6$ AU the M8.0-L0.5 binary frequency is within the range $19 \pm 7\%$.* Our binary fraction of $19 \pm 7\%$ is therefore slightly lower than the $32 \pm 9\%$ observed for (M0-M4) stars with $a > 2.6$ AU by Fischer & Marcy (1992). Hence it appears VLM binaries ($M_{tot} < 0.18M_{\odot}$) are slightly less common than (M0-M4) binaries over the whole range $a > 2.6$ AU. This difference may

disappear once surveys for spectroscopic and even tighter visual VLM binaries are completed.

2.2. The separation distribution function for M8.0-L0.5 binaries

The M8.0-L0.5 binaries are very different from M0-M4 stars in the distribution of their semi-major axes (see Figure 1). The M8.0-L0.5 binaries appear to peak at separations ~ 4 AU (see the histogram in Figure 1) which is significantly tighter than the broad ~ 30 AU peak of both the G and M star binary distributions (Fischer & Marcy (1992), Duquennoy & Mayor (1991)). Note the peak of Fischer & Marcy (1992) distribution may shift slightly to smaller values if a few low ($q < 0.4$; $\Delta K \lesssim 5\text{mag}$) binaries were missed in the speckle data used by Fischer & Marcy (1992) in the range 1-10 AU. But we estimate that this a small effect since very few ($< 10\%$) M binaries have ($q < 0.4$) Fischer & Marcy (1992).

We detect no low mass binary systems wider than 16 AU. This cannot be a selection effect since we are highly sensitive to all M8.0-L0.5 binaries with $sep > 20-600$ AU (even those with $\Delta H > 10$ mag). *Therefore, we may conclude that M8.0-L0.5 stars likely have just slightly lower binary fractions than G and M stars, but they have significantly smaller semi-major axes on average, and currently no very wide ($a > 20$ AU) systems are known.*

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) an HST survey of 20 L stars found 4 binaries and a similar binary frequency of 20%. The widest L dwarf binary in Koerner et al. (1999) had a separation of only 9.2 AU. A smaller HST survey of 10 T dwarfs by Burgasser et al. (2002) found 3 T binaries and a similar binary frequency of $20 \pm 6\%$ with no systems wider than 5.2 AU. Therefore, it appears all M8.0-L0.5, L, and T binaries may have similar binary frequencies $\sim 20\%$ (for $a > 3$ AU) and smaller maximum separations (no system wider than 16 AU) than their more massive M and G counterparts.

2.3. Why are there no wide low mass binaries?

In Close, Siegler, & Freed (2002) it is suggested that a strong impulse (or velocity kick) of ~ 3 km/s could explain the lack of any low mass systems with $a > 20$ AU. Such a kick could disrupt any VLM/brown dwarf binaries with $a > 20$ AU while leaving systems with $a < 10$ AU relatively unaffected. This might support recent “ejection” theories of brown dwarf formation from Reipurth & Clarke (2002) and Bate et al. (2002). However, it is still not clear whether these “ejection” scenarios can reproduce the observed 20% binary fraction for separations > 2.6 AU (currently these models produce only 5% brown dwarf binary fractions Bate et al. (2002)). Future detailed models with more realistic treatments of the individual accretion disks should provide more insight into the plausibility of this formation process. *In any case this strong cut-off at a ~ 20 AU suggests that VLM/Brown dwarf binaries may form differently (perhaps due to ejection) than higher mass ($M_{tot} > 0.185M_{\odot}$) binaries which are much wider.*

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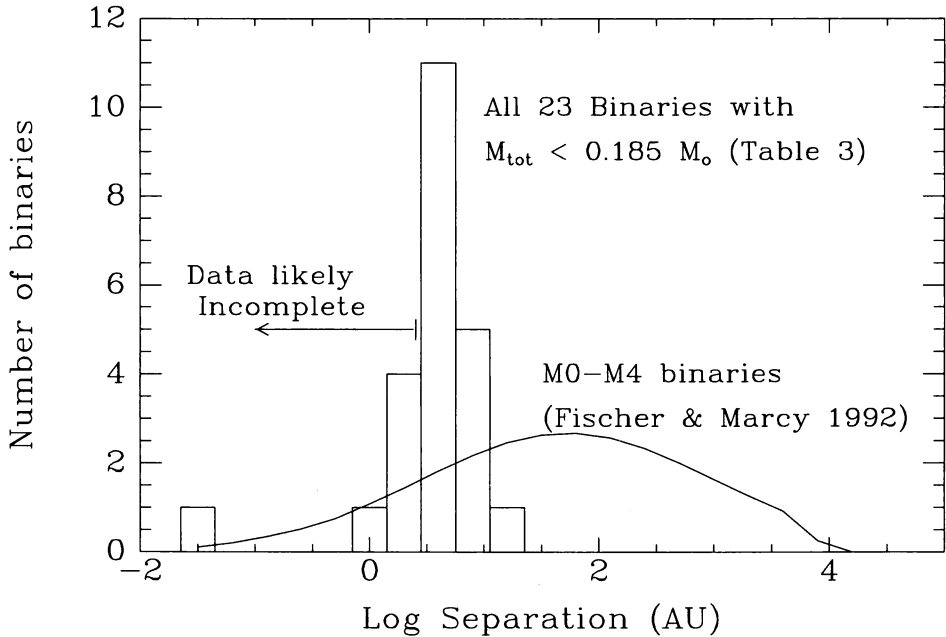


Figure 1. Here we plot (as a histogram) all 23 published VLM binaries ($M7 < SpT < T6$; Basri & Martín(1999), Martín, Brandner, & Basri (1999), Koerner et al. (1999), Reid et al. (2001a), Lane et al. (2001), Potter et al. (2002a), Burgasser et al. (2002), Close, Siegler, & Freed (2002)) listed in Table 3 of Close, Siegler, & Freed (2002). These include 12 systems found in our AO study. Note how low mass binaries appear to have smaller separations compared to the M0-M4 binaries of Fischer & Marcy (1992). Both distributions are normalized to have 23 system in total. We have not tried to correct for instrumental incompleteness. Hence we underestimate the number of VLM binaries with $a < 2$ AU. However, the sharp peak at 4 AU and the lack of any wide ($a > 20AU$) systems are real features of the distribution and are significantly different from that observed in more massive M0-M4 binaries. Binary systems with $M_{\text{tot}} < 0.185M_{\odot}$ appear quite a bit tighter compared to just slightly more massive M0-M4 binaries.

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From left to right: John Rayner (kneeling), Mark McCaughrean, Karen Teramura, Hans Zinnecker, and Laird Close. Andrew Pickles is in the background.