On the frequency of close binary systems among very low-mass stars and brown dwarfs

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ABSTRACT

We have used Monte Carlo simulation techniques and published radial velocity surveys to constrain the frequency of very low-mass star (VLMS) and brown dwarf (BD) binary systems and their separation (\(a\)) distribution. Gaussian models for the separation distribution with a peak at \(a = 4\) au and \(0.6 \leq \sigma_{\log(a/\text{au})} \leq 1.0\), correctly predict the number of observed binaries, yielding a close \((a < 2.6\) au\) binary frequency of 17-30 per cent and an overall VLMS/BD binary frequency of 32-45 per cent. We find that the available N-body models of VLMS/BD formation from dynamically decaying protostellar multiple systems are excluded at \(> 99\) per cent confidence because they predict too few close binary VLMS/BDs. The large number of close binaries and high overall binary frequency are also very inconsistent with recent smoothed particle hydrodynamical modelling and argue against a dynamical origin for VLMS/BDs.

Key words: binaries: general – stars: low-mass, brown dwarfs.

1 INTRODUCTION

In the last decade a proliferation of free-floating very low-mass stars (VLMS, < 0.15 M\(_\odot\)) and brown dwarfs (BDs, < 0.075 M\(_\odot\)) have been found in the field and young clusters – they are more numerous than stars with higher mass (e.g. Chabrier 2003). Explaining their origin is a crucial component of any complete star formation theory.

A typical Jeans mass in a molecular cloud is more than 1 M\(_\odot\), so a key question to answer is 'do VLMS/BDs form by a mechanism that is just an extension of that for higher mass stars or must different processes be invoked?'. Some models suggest that VLMS/BDs can form like higher mass stars by turbulent fragmentation, allowing fragments much smaller than a typical Jeans mass to form (e.g. Padoan & Nordlund 2004). Others accept that fragmentation may initially produce objects of a few Jupiter masses, but that these should then accrete and grow to much higher (stellar) masses (e.g. Boss 2002). A promising class of solution is that VLMS/BDs initially form by fragmentation like higher mass stars but as part of small, unstable protostellar multiple systems from which the least massive fragments are dynamically ejected on short timescales (< 0.1 Myr). The ejection process strips the outer accretion envelope, prematurely truncates the accretion phase and leaves a free-floating very low-mass stellar 'embryo' (Reipurth & Clarke 2001; Boss 2001).

It is probable that the specific formation mechanism will leave an imprint on the properties of binary systems. Hydrodynamical and N-body simulations are now becoming capable of predicting these properties (e.g. Bate, Bonnell & Bromm 2002; Sterzik & Durisen 2003; Delgado-Donate et al. 2004; Bate & Bonnell 2005). Binary statistics at large separations suggest field VLMS/BDs have a binary frequency of 15 ± 7 per cent (for \(a > 2.6\) au) – significantly smaller than the 30-50 per cent binary frequency of early M to G dwarfs in the same \(a\) range. The peak in the \(a\) distribution shifts from \(30\) au in G dwarfs to approximately 4 au in BDs, and there is a deficit of wide binaries (\(a > 15\) au) among VLMS/BDs compared with higher mass stars, where separations of \(a > 100\) au are not uncommon (e.g. Close et al. 2003, but see also Bouy et al. 2003; Burgasser et al. 2003; Siegler et al. 2005).

The lack of wide VLMS/BD binaries seen among field VLMS/BDs may offer support to the ejection hypothesis. It seems likely that the low binding energy of a wide BD-BD pair would not prevent their disruption during an ejection event. However, Luhman (2004) has found an example of a BD binary system with a projected separation of 240 au in the Cha I star forming region, suggesting that BD formation does not necessarily require an ejection event. An alternative explanation for the dearth of wide systems could be that VLMS/BDs do form in such configurations via a 'star-like' fragmentation process, but are then broken up during the first few Myr of life in the reasonably dense cluster environments where most field BDs may have originated.

The frequency of close binary VLMS/BDs may offer less ambiguous evidence. Binaries with separations below the limiting fragmentation scale of about 5 au must have
been brought together by dynamical and hydrodynamical hardening processes (see Bate et al. 2002). Models producing VLMS/BDs by early ejection suggest these processes may be ineffective so that very few close VLMS/BD binaries should exist (Delgado-Donate et al. 2004; Umbreit et al. 2005).

The search for close binaries by resolved imaging is ineffective for \( a \lesssim 2\) au, so little is known about the frequency and separation distribution of closer VLMS/BD binary systems. Guenther & Wuchterl (2003 – hereafter GW03) observed 24 VLMS/BDs with VLT/UVES at multiple epochs and identified 3 close binaries from their radial velocity (RV) variations. Joergens (2005 – hereafter J05) found 2 RV variables (at the 2\( \text{km s}^{-1} \)) level) among 11 VLMS/BDs of the Cha I star formation region. Kenyon et al. (2005 – hereafter K05) found several candidate close binary systems in a sample of about 60 VLMS/BDs in the \( \sigma \) Ori cluster.

In this letter we outline a technique for the analysis of sparse RV datasets that can constrain the properties of the VLMS/BD close binary population, without the need to obtain orbits for individual systems. We apply this technique to the published VLMS/BD RV surveys and investigate whether these data already rule out certain scenarios for VLMS/BD formation.

2 ANALYSIS

2.1 The sample

We have constructed a sample of 47 VLMS/BDs with RV measurements obtained at more than one epoch from the results of GW03, J05 and K05 as follows. We have used the RV shifts and errors as tabulated by GW03 for their sample of 24 VLMS/BDs. The model described below predicts the RV of the more massive component (primary), so for the double-lined spectroscopic binary 2MASSWJ2113029-10094 we used the values 2\( \text{km s}^{-1} \) and 6.5\( \text{km s}^{-1} \) based on the appearance of the cross-correlation function described by GW03. The exact values chosen have no effect on our analysis. The mass of the primary for each object was estimated using the spectral types reported by GW03, the relationship between spectral type and effective temperature in Leggett et al. (2002) and the ‘dusty’ VLMS/BD evolutionary models of Chabrier et al. (2000) with an assumed age of 1 Gyr. For the objects found in the young Upper Scorpius association we use an alternative calibration between spectral type and mass given by Luhman (2003). For LP944–20, which is younger than 1 Gyr, we use the mass quoted in Tinney & Reid (1998). The masses derived are all in the range 0.06\( \text{M}_\odot \) to 0.1\( \text{M}_\odot \). We included 14 VLMS/BDs with two RV measurements tabulated by K05 in our analysis. The masses of these objects derived from Fig. 9 of that paper are all in the range 0.045\( \text{M}_\odot \) to 0.11\( \text{M}_\odot \). The separation in time between the two observations was taken to be 0.993d. We also included in our analysis the RV measurements and errors for 10 VLMS/BDs with masses in the range 0.05\( \text{M}_\odot \) to 0.1\( \text{M}_\odot \) taken from the figures presented by J05. We used the mass estimated for each VLMS/BD by J05 in our analysis.

We identified the VLMS/BDs in our sample with variable RVs by calculating the value of \( \chi^2 \) for a constant value as a fit to the RV measurements. GW03 report RV shifts, so the value of the constant for these data is 0. For the other data the value of the constant is the weighted mean of the measured RVs. If the probability of obtaining the observed value of \( \chi^2 \) or higher from normally distributed random fluctuations is less than \( 10^{-3} \) (i.e., \( \log p < -3 \)), we flag the VLMS/BD as an RV variable.

We compared the observed distribution of \( \log p \) values for \( \log p > -3 \) to that expected from random fluctuations alone to check the reliability of the error estimates in each subsample. We found that we needed to add 0.4\( \text{km s}^{-1} \) in quadrature to the error estimates of GW03 to make the distributions of \( \log p \) values consistent. The corresponding value for this ‘external noise’ for the data of K05 is 4.5\( \text{km s}^{-1} \). We found that there is no need to add any external noise to the data of J05.

Four binary systems are found with \( \log p < -3 \). These are 2MASSWJ2113029–10094 and LHS 292 from GW03, Cha Ho 08 from J05 and star 72 from K05. These are shown in Fig. 1 along with the distribution of \( \log p \) values for the other objects. If the additional external noise had not been added then a further two binaries (BRIB0246–1703 and LP944–20 from GW03) would have been found.

2.2 Monte Carlo simulation.

If binarity is the only cause of variable RVs, the probability that a given VLMS/BD is flagged as an RV variable is given by \( \epsilon_0 p_{\text{detect}} + (1 - \epsilon_0)10^{-3} \), where \( \epsilon_0 \) is the overall binary fraction for VLMS/BDs and \( p_{\text{detect}} \) is the probability that \( \log p < -3 \) for the object assuming that it is a binary.

We have used a Monte Carlo simulation to calculate the value of \( p_{\text{detect}} \) for every VLMS/BD in our sample given various assumptions about the distribution of binary properties. The simulation generates 1 million virtual binary VLMS/BDs and predicts the RV of the more massive com-

Figure 1. The distribution of \( \log p \) values for the whole sample (histogram), together with the (parameter free) expected distribution of \( \log p \) given the observed numbers of single and binary stars (curve). The solid lines show the case where additional RV errors have been added to each sample – 4 binaries are detected and the observed \( \log p \) distribution is a good match to theoretical expectations. The dashed lines show the case where these additional errors are not added – resulting in 6 detected binaries but a poor match between the observed \( \log p \) distribution and theory at \( \log p > -2 \).
ponent at the same times of observation as the actual observations of the VLMS/BD. The eccentricity, $e$, semi-major axis, $a$, mass ratio, $q$, and other properties of the binary star are randomly selected from the following distributions.

**Semi-major axis, $a$** We have explored four different distributions for the value of $\log a$. One is the $a$ distribution from Fig. 8 of Umbreit et al. (2005) transformed to a distribution of $\log a$. This represents the properties of BD binary systems produced by N-body models of the dynamical decay of primordial triple systems. The other three are Gaussian distributions truncated at $\log(a/\text{au}) > 1$ and with a peak at $\log(a/\text{au}) = 0.6$. The standard deviations of the Gaussians in units of $\log(a/\text{au})$ are $\sigma_{\log a/\text{au}} = 0.6, 1$ and 1.53. The latter figure is the width of the Gaussian distribution for solar-type binaries taken from Duquennoy & Mayor (1991). These models are normalised such that there is 15 per cent binarity for $2.6 < a/\text{au} < 10$ (Close et al. 2003).

**Mass ratio, $q$** We have used two mass ratio distributions, a ‘peaked’ distribution which is uniform in the range $q = 0.7–1$ and a ‘flat’ distribution which is uniform in the range $q = 0.2–1$. Observations of more widely separated VLMS/BD binaries suggest the former is more likely (e.g. Bouy et al. 2003).

**Eccentricity, $e$** We have assumed that all binaries with periods less than 10 d have circular orbits (Meibom & Mathieu 2005). Above this period, we assume that the value of $e$ is uniformly distributed in the range $0 < e < 0.9$.

**Primary mass, $m_p$** We have used a uniform distribution of half-width 0.002 $M_\odot$ centered on the adopted value of the mass for the primary star.

**Orbital phase** The orbital phase of the binary at the date of the first observation is randomly selected from a uniform distribution in the range 0 to 1.

**Inclination, $i$** The inclination is selected randomly from a distribution uniform in $\cos i$.

**Longitude of periastron, $\omega$** For eccentric binaries, $\omega$ is selected from a uniform distribution in the range 0 to $2\pi$.

The RVs predicted by each trial of the simulation are each perturbed by a random value from a Gaussian distribution with the same standard deviation as the random error of the actual observations. For each simulated set of RVs we calculate the value of $\log p$ and flag RV variables in the same way as we do for the observed sets of RV measurements. We can then find the fraction of binaries that are flagged as RV variables, $p_{\text{detect}}$. The results of these simulations are stored in a way that allows us to investigate the dependence of $p_{\text{detect}}$ on $\log(a)$, $q$ or any other parameter of the model.

### 3 RESULTS

Figure 2 shows the value of $p_{\text{detect}}$ averaged over every star in the our sample as a function of $\log(a/\text{au})$ for 3 combinations of mass ratio and eccentricity distribution. We refer to this quantity as $(p_{\text{detect}})(\log a/\text{au})$. We also show in Figure 2 the contribution to this function from each of the datasets of GW03, J05 and K05 for a ‘flat’ mass ratio distribution and $e_{\max} = 0.6$. We see that changing $e_{\max}$ has very little effect on $(p_{\text{detect}})(\log a/\text{au})$. Adopting the ‘peaked’ mass ratio distribution does make us a little more sensitive (5–10 per cent), although the upper cut-off in sensitivity is mainly a function of the precision of the RV measurements and the largest sampling interval in the RV datasets. Figure 2 also shows two of the $\log a/\text{au}$ distributions we have investigated. By comparing these distributions to $(p_{\text{detect}})(\log a/\text{au})$ it can also be seen straightforwardly that the $\log(a/\text{au})$ distribution of Umbreit et al. (2005) predicts that there should be very few RV variables in our sample, certainly compared to the truncated Gaussian with $\sigma_{\log a/\text{au}} = 1.53$.

The average number of RV variables, $N_{\bin}$, predicted for each $\log(a/\text{au})$, $q$ and $e$ distribution is given in Table 1. The average value of $p_{\text{detect}}$ for all stars in the sample and over all $\log a/\text{au}$ values is given in the same table in the column headed $(p_{\text{detect}})$. Also given in Table 1 is the overall binary frequency of each model (i.e. the binary frequency below $a = 2.6$ au plus 15 per cent), $e_\alpha$. For the sample of GW03, we have made allowance for the field stars being more likely to be binaries since they are brighter and so can be seen to greater distances. This bias has been studied by Burgasser (2003). We have followed their method to calculate the parameter $\alpha$ as we use in our analysis of Table 1 are typical of the range of values for $\alpha$ found using this method. The exact value of $\alpha$ chosen has a negligible effect on the results presented here.

The number of RV variables in the actual sample is 4. To determine whether a given model is reasonable we calculate the probability that the model would result in 4 or more RV variables, $P(N_{\bin} \geq 4)$, and similarly for $P(N_{\bin} < 4)$. If the values of $p_{\text{detect}}$ for every VLMS/BD were the same, this probability could be calculated from the binomial distribution. Since the values of $p_{\text{detect}}$ are different we use a Monte Carlo simulation to calculate these probabilities. The calculation uses 10,000 trials in which each of the 47 objects is randomly assigned binary status with probability $\epsilon_0 p_{\text{detect}} + (1 - \epsilon_0)10^{-3}$.

### 4 DISCUSSION

Table 1 demonstrates that the separation distribution from Umbreit et al. (2005, Fig. 2) significantly (at > 99 per cent confidence) underpredicts the number of RV variables in our sample, even if the mass ratio distribution is restricted to $0.7 < q < 1$ and high eccentricity binaries are permitted. On the other hand, broadening the distribution to a truncated Gaussian with $\sigma_{\log a/\text{au}} = 1.53$ (see Fig. 2) results in too many predicted RV variables and can also be ruled out at approximately 95 per cent confidence. Intermediate Gaussian distributions with $0.6 < \sigma_{\log a/\text{au}} < 1.0$ do much better, predicting an average of between 1.3 and 5.5 RV variables in the sample, depending on the details of the $q$ and $e$ distribution.

Table 1 also shows that these conclusions are insensitive to the exact form of the $q$ and $e$ distributions. We have also checked whether the results change significantly if the additional RV errors discussed in section 2 are not included. We find that the $\log(a/\text{au})$ distribution of Umbreit et al. becomes less likely, the $\sigma_{\log(a/\text{au})} = 1.0$ distribution can be rejected at > 95 per cent confidence and that the Duquennoy & Mayor (1991) separation distribution can only be rejected
Table 1. The number of binaries predicted by each combinations of log($a$/au), $q$ and $e$ distribution, $N_{\text{bin}}$. See section 3 for details.

| $p(a)$ | $p(q)$ | $\epsilon_{\text{max}}$ | $p_{\text{detect}}$ | $e_b$ | $\alpha$ | $N_{\text{bin}}$ | $P(N_{\text{bin}}^{\text{obs}} \geq 4)(\%)$ | $P(N_{\text{bin}}^{\text{obs}} < 4)(\%)$ |
|--------|--------|----------------|-------------------|------|--------|------------|------------------|------------------|
| Umbreit flat | 0.6 | 0.04 | 0.26 | 1.6 | 0.53 | 1.0 | 99.9 |
| Umbreit flat | 0.9 | 0.04 | 0.26 | 1.6 | 0.54 | 0.1 | 99.9 |
| Umbreit peaked | 0.6 | 0.05 | 0.26 | 2.4 | 0.72 | 0.4 | 99.9 |
| Umbreit peaked | 0.9 | 0.05 | 0.26 | 2.4 | 0.73 | 0.4 | 99.9 |
| $\sigma = 0.6$ flat | 0.6 | 0.07 | 0.32 | 1.6 | 1.31 | 3.4 | 99.3 |
| $\sigma = 0.6$ flat | 0.9 | 0.07 | 0.32 | 1.6 | 1.30 | 3.6 | 99.3 |
| $\sigma = 0.6$ peaked | 0.6 | 0.09 | 0.32 | 2.4 | 1.81 | 9.5 | 97.3 |
| $\sigma = 0.6$ peaked | 0.9 | 0.09 | 0.32 | 2.4 | 1.79 | 9.5 | 96.9 |
| $\sigma = 1.0$ flat | 0.6 | 0.18 | 0.45 | 1.6 | 4.34 | 64.8 | 55.4 |
| $\sigma = 1.0$ flat | 0.9 | 0.18 | 0.45 | 1.6 | 4.25 | 62.9 | 57.6 |
| $\sigma = 1.0$ peaked | 0.6 | 0.21 | 0.45 | 2.4 | 5.48 | 82.5 | 33.6 |
| $\sigma = 1.0$ peaked | 0.9 | 0.20 | 0.45 | 2.4 | 5.39 | 81.4 | 35.4 |
| $\sigma = 1.53$ flat | 0.6 | 0.30 | 0.59 | 1.6 | 9.10 | 99.2 | 3.1 |
| $\sigma = 1.53$ flat | 0.9 | 0.29 | 0.59 | 1.6 | 8.97 | 98.9 | 3.3 |
| $\sigma = 1.53$ peaked | 0.6 | 0.33 | 0.59 | 2.4 | 10.75 | 99.8 | 0.8 |
| $\sigma = 1.53$ peaked | 0.9 | 0.33 | 0.59 | 2.4 | 10.61 | 99.9 | 0.8 |

The overall picture we have is of a binary frequency that decreases only gradually with mass, but that this evolution is confined mainly to widely separated binary systems. Observations of resolved binary systems show that close ($2.6 < a/\text{au} < 10$) VLM/BD binary systems are more common than in systems with G to M-dwarf primaries, and the analysis we have presented here extends this conclusion to even closer binary systems. This poses considerable problems for current ideas of how VLMs and BDs form. When multiplicity systems form by fragmentation, the closest separation of the fragments is likely set by the opacity limit at around 5-10 au. Closer binaries may then be produced by dynamical hardening interactions in initially unstable multiple systems or through orbital decay driven by accretion of material with low specific angular momentum or interaction with a circumbinary disc (Bate et al. 2002). N-body models of the decay of unstable multiple systems, such as those produced by Sterzik & Durisen (2003) or Umbreit et al. (2005) do predict a most likely separation for VLM/BD binaries of a few au and that wide binaries should be rare. As these models do not take into account all the possible binary hardening processes it is perhaps not surprising that they predict almost no close VLM/BD binaries and are hence rejected with 90 per cent confidence. Perhaps the only caveat to our results is that the small number of identified close binaries could be contaminated by objects with RV deviations unassociated with binarity. The lack of additional error required to model the distribution of log $p$ in the J05 data (even at the 100 m s$^{-1}$ level) suggests that jitter associated with atmospheric effects is unlikely to explain any of the identified binary systems, although the jitter could be a little larger in the older, more rapidly rotating objects of the GW03 sample. There is also the possibility that the RV variable objects are not genuine VLMs/BDs, although this seems unlikely (see K05). Finally, analysis errors in the original papers for a small number of objects/RVs may also be possible.

The binary frequency at all separations (Table 1, column 5), for models which are consistent with the observed frequency of binaries in our sample implies an overall binary frequency of 32-45 per cent (17-50 per cent for $a < 2.6$ au). The lower values are more consistent with narrower log $a$ distributions with a ‘peaked’ $q$ distribution. The higher values require a broader log $a$ distributions with a flat $q$ distribution. It is notable that the close binary frequency ($a < 2.6$ au) for VLM/BDs is higher than for G stars (14 per cent – Duquennoy & Mayor 1991) and for M0-M4 dwarfs ($\geq 10$ per cent – Fischer & Marcy 1992). However, the overall binary frequency is lower than for G stars (57 ± 7 per cent – Duquennoy & Mayor 1991) but comparable to that for M0-M4 dwarfs (42 ± 9 – Fischer & Marcy 1992). The suggestion of a high binary frequency for VLMs/BDs, especially among closer systems is not unprecedented. Pinfield et al. (2003) deduced unresolved ($a \lesssim 100$ au) binary frequencies of about 50 per cent for VLMs/BDs in the Pleiades and Praesepe clusters by modelling the positions of cluster members in colour-magnitude diagrams.
by the observations. The high frequency of close binaries we have deduced for VLMS/BDs probably indicates that these hardening processes are important during their formation.

The smoothed particle hydrodynamic (SPH) models presented by Bate et al. (2002) and Bate & Bonnell (2005) fare little better. These models predict that most VLMS/BDs are produced by early ejection from unstable multiple systems – in agreement with the ejection hypothesis of Reipurth & Clarke (2001). However, the ejection process does not favour the formation of VLM/BD binary systems. Bate et al. (2002) explain that dynamical interactions featuring a VLM/BD binary rarely result in the ejection of that system because either the pair is broken up or the least massive object is ejected and replaced by a more massive star. Bate & Bonnell (2005) find a binary fraction of only 8 per cent among VLMS/BDs, with separations centred around 10 au. It seems to be a common feature of N-body and SPH models that VLM/BD binaries formed through the decay of initially unstable multiple systems are much rarer than their higher mass counterparts (Delgado-Donate et al. 2004; Hubber & Whitworth 2005).

The SPH models are not currently capable of following the evolution of binary separations below 1 au, because of the vast computational expense of such simulations. Instead, an artificial softening is introduced below separations of 4 au and increased gradually to limit the separation decrease induced by hardening processes. The indications are however, that systems with $a < 1$ au would rarely occur – only 1 of 5 VLMS/BD binaries produced in the Bate & Bonnell (2005) simulations has $1 < a < 4$ au. Unless the artificial softening results in the disruption of a significant number of binaries that would otherwise have gone on to become very close systems (see Delgado-Donate et al. 2004), then it seems that these SPH models are under-producing VLM/BD binaries by factors of at least 3.

5 CONCLUSIONS

We have estimated the frequency of close binary systems occurring among very low-mass stars and brown dwarfs using RV data for VLMS/BDs published in Guenther & Wuchterl (2003), Kenyon et al. (2005) and Joergens (2005). We find that the detection of 4 close binaries from a sample of 47 objects is already sufficient to rule out the separation distributions from N-body models such as those by Sterzik & Durisen (2003) and Umbreit et al. (2005), as these predict too few close binary systems. Instead we find that the binary frequency for $a < 2.6$ au must be in the range 17-32 per cent; that the data are consistent with truncated Gaussian distributions extrapolated from the observed distribution for resolved VLM/BD binaries providing $0.6 \leq \sigma_{\log a/au} \leq 1.0$; and that the overall binary frequency among VLMS and BDs rises to 30-45 per cent. The only significant caveats to these results are whether the small number of identified binary systems in the published data are genuine RV variables or genuine examples of VLMS/BDs.

The neglect of gas-dynamic hardening mechanisms may be responsible for the lack of close binary systems in the N-body models, but the very high binary frequency and its lack of extreme mass dependence are also incompatible with the most recent SPH simulations of VLM/BD formation that predict binary frequencies of only about 8 per cent (Bate & Bonnell 2005). The high overall observed binary frequency and the high frequency of close binary VLMS/BDs do not favour the ejection hypothesis or similar models for the production of VLMS/BDs involving the dynamical decay of unstable protostellar multiple systems. A means must be found that allows VLMS/BDs to evolve into close configurations without destroying pairs in dynamical interactions.

The location of the peak and the normalisation of the $\log a$ distribution are constrained by observations of visual binaries at $a > 2.6$ au, but the shape of the distribution at smaller separations is unknown. This uncertainty does not invalidate the results presented because the sample we have used has good sensitivity to binaries with a wide range of separations (Fig. 2). While the number of binaries alone makes it possible to rule out some models for the formation of VLMS/BDs, progress in this area now requires an RV survey of a much larger sample of VLMS/BDs and follow-up observations to establish the distribution of separation, eccentricity and mass ratio in these binaries.

REFERENCES

Bate M., Bonnell I., 2005, MNRAS, 356, 1201
Bate M., Bonnell I., Bromm V., 2002, MNRAS, 336, 705
Boss A., 2001, ApJ, 551, L167
Boss A., 2002, ApJ, 568, 743
Bouy H., Brandner W., Martín E. L., Delfosse X., Allard F., Basri G., 2003, AJ, 126, 1526
Burgasser A., Kirkpatrick J. D., Reid N., Brown M. E., Miskin C. L., Gizis J. E., 2003, ApJ, 586, 512
Chabrier G., 2003, PASP, 115, 763
Chabrier G., Baraffe I., 2000, ARA&A, 38, 337
Close L., Siegler N., Freed M., Biller B., 2003, ApJ, 587, 407
Delgado-Donate E. J., Clarke C. J., Bate M. R., Hodgkin S. T., 2004, MNRAS, 351, 617
Duquennoy A., Mayor M., 1991, A&A, 248, 485
Fischer D. A., Marcy G. W., 1992, ApJ, 396, 178
Guenther E. W., Wuchterl G., 2003, A&A, 401, 677
Hubber D. A., Whitworth A. P., 2005, A&A in press
Joergens V., 2005, in Roser S., ed., Reviews in Modern Astronomy, Vol. 18 John Wiley & Sons, New York, p. 201
Kenyon M. J., Jeffries R. D., Naylor T., Oliveira J. M., Maxted P. F. L., 2005, MNRAS, 356, 89
Leggett S. K. et al., 2002, ApJ, 564, 452
Luhman K. L., 2004, ApJ, 614, 398
Luhman K. L., Stauffer J. R., Muench A. A., Rieke G. H., Lada E. A., Bouvier J., Lada C. J., 2003, ApJ, 593, 1093
Melbom S., Mathieu R. D., 2005, ApJ, 620, 970
Padoan P., Nordlund A., 2004, ApJ, 617, 559
Pinfield D. J., Dobbie P. D., Jameson R. F., Steele I. A., Jones H. R. A., Katsiyannis A. C., 2003, MNRAS, 342, 1241
Reipurth B., Clarke C., 2001, AJ, 122, 432
Siegler N., Close L., Cruz K. L., Martín E. L., Reid I. N., 2005, ApJ, 621, 1023
Sterzik M. F., Durisen R. H., 2003, A&A, 400, 1031
Tinney C. G., Reid I. N., 1998, MNRAS, 301, 1031
Umbreit S., Burkert A., Henning T., Mikkola S., Spurzem R., 2005, ApJ, 623, 940