Close binary systems among very low mass stars and brown dwarfs

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Abstract. Using Monte Carlo simulations and published radial velocity surveys we have constrained the frequency and separation (a) distribution of very low mass star (VLM) and brown dwarf (BD) binary systems. We find that simple Gaussian extensions of the observed wide binary distribution, with a peak at 4 au and 0.6 < σ(log(a/au)) < 1.0, correctly reproduce the observed number of close binary systems, implying a close (a < 2.6 au) binary frequency of 17–30 per cent and overall frequency of 32–45 per cent. N-body models of the dynamical decay of unstable protostellar multiple systems are excluded with high confidence because they do not produce enough close binary VLMs/BDs. The large number of close binaries and high overall binary frequency are also completely inconsistent with published smoothed particle hydrodynamical modelling and argue against a dynamical origin for VLMs/BDs.

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

1. Introduction

Very low-mass stars (VLMs, M < 0.15 M⊙) and brown dwarfs (BDs, M < 0.075 M⊙) are now known to be common in our galaxy, possibly even outnumbering stars of higher mass. Yet their origins are still mysterious because the typical Jeans mass in a giant molecular cloud is an order of magnitude more massive.

Recent ideas, suggest that “turbulent” fragmentation might allow enhancements in local densities that can result in the formation of very small cores (e.g. Padoan & Nordlund 2004). However, the biggest problem for the formation of VLMs and BDs may be how to prevent these very small cores subsequently accreting too much and becoming higher mass stars (Boss 2002). One solution is if VLMs and BDs were originally part of unstable multiple systems and, as the least massive components, are ejected on timescales too short for significant mass accretion (Boss 2001; Reipurth & Clarke 2001).

These ideas have proved very persuasive and it is possible that observations of accretion disks or VLM/BD kinematics and spatial distributions (see other contributions in this volume) may ultimately provide crucial observational tests. A further observational constraint is offered by the frequency and separation distribution of binary systems and there have been many investigations along these lines in the last few years.

Binary systems should preserve information about their formation, particularly their dynamical origins. A plethora of studies have been published, which use high spatial resolution imaging, either Hubble Space Telescope or adaptive optics in the near-infrared, to find the frequency of binary systems among nearby field VLMs/BDs which have separations a > 1 au (e.g. Bouy et al. 2003; Burgasser et al. 2003; Close et al. 2003; Siegler et al. 2005). The lower cut-off to the separation range that can be probed is of course a result of limited angular resolution. The results of Close et al. are quoted below, but all of these studies are in reasonable agreement. The main findings are that the binary frequency for separations a > 2.6 au is 15 ± 7 per cent (see Fig. 1). This frequency is lower than found for G to M-type field stars (Duquennoy & Mayor 1991; Fischer & Marcy 1992), but these earlier studies counted binaries over a much wider range of separations, including close, spectroscopic binary systems.

Of more importance may be that all these studies failed to find binary VLMs/BDs with a > 15 au. This has been seized upon as supporting evidence for the “ejection” scenario where qualitatively, one expects fewer wide binary systems with low binding energies to survive the ejection process. There are several problems with this: (i) some wider VLM/BD binary systems are starting to be found (e.g. Luhman 2004; Phan-Bao et al. 2005); (ii) some theoretical models that produce BDs by what could be termed “ejection” are also producing some BD-BD binaries with wide separations (Bate & Bonnell 2005); (iii) there may yet be alternative
3 RESULTS AND DISCUSSION

The observed distribution of VLM/BD binaries as a function of log $a$ (from Close et al. 2003). Note that the point at log($a$/au) = 0 is significantly affected by incompleteness. Also shown are the various model log $a$ distributions used to simulate the VLM/BD binary population (see text). They are from Umbreit et al. (2005) or are Gaussian distributions with peaks at 4 au and with various indicated widths (truncated for $a > 10$ au). The model distributions are normalised such that the binary frequency is 15 per cent for 2.6 < $a$ < 10 au.

The frequency of close ($a < 2.6$ au) binary systems may provide more secure evidence, but little progress has so far been made. Guenther & Wuchterl (2003) found 3 radial velocity (RV) variables among 24 field VLMs/BDs; Joergens (2005) found 2 RV variables from a sample of 11 VLMs/BDs in the Chamaeleon I star forming region; and Kenyon et al. (2005) found evidence for 4 close binaries in a sample of 60 VLMs/BDs in the young Sigma Ori cluster. Taken together, these results hint at a surprisingly high (> 10 per cent) frequency for close VLM/BD binaries. In this contribution we examine this possibility with some statistical rigour and comment on the implications of our results for the formation mechanism of VLMs/BDs.

2. Analysis

We have collected RV measurements for VLMs/BDs from three main sources in the literature. Consideration is restricted to those objects with RV measurements at ≥ 2 epochs. There are 24 field objects with 0.06 < $M/M_⊙$ < 0.10 from Guenther & Wuchterl (2003), 10 objects with 0.05 < $M/M_⊙$ < 0.10 from Joergens (2005) and 14 objects with 0.045 < $M/M_⊙$ < 0.11 from Kenyon et al. (2005). Masses were either estimated from spectral types (assuming an age of 1 Gyr for field stars) or from isochrones in colour magnitude diagrams.

We identified possible binary systems by calculating the value of $\chi^2$ for a constant value fitted to the RV measurements of each object. Potential binaries are those for which the $\chi^2$ value corresponds to a probability, $p$, of a constant RV that is less than $10^{-3}$. This threshold was chosen to avoid contaminating what turns out to be a low number of binaries with any spurious statistical detections. During the course of this procedure we found, by investigating the distribution of $p$ values, that the RV uncertainties were underestimated in the case of the Guenther & Wuchterl (2003) and Kenyon et al. (2005) data (for details see Maxted & Jeffries 2005). Errors amounting to 0.4 and 4.5 km s$^{-1}$ respectively were added in quadrature to RV uncertainties from these two datasets. We identified four objects as binaries: 2MASSWJ2113029-10094 and LHS 292 from Guenther & Wuchterl, Cha Ho 8 from Joergens (2005), and KJNOM 72 from Kenyon et al.

A Monte-Carlo simulation has been used to predict how many binary systems we ought to have found, given the sensitivity and time sampling of the data and for various assumptions about the frequency, and distributions of $a$, eccentricity and mass ratio for binary systems. The details are provided by Maxted & Jeffries (2005) but briefly, we have assumed various Gaussian extensions of the observed log $a$ distribution of VLM/BD binary systems, peaking at 4 au and with widths ranging from $\sigma_{\log(a/au)} = 0.6$ to $\sigma_{\log(a/au)} = 1.53$ (corresponding to the width of the field G-star distribution found by Duquennoy & Mayor 1991). These distributions were truncated at $a = 10$ au in order to better match what is known about wider binary systems. We also trialled the prediction from a triple-body decay calculation for BD binaries from Umbreit et al. (2005) (see Fig. 1). The eccentricities were taken as $e = 0$ for binary periods less than 10 days and then randomly distributed between 0 < $e$ < $e_{\text{max}}$ for longer periods, with $e_{\text{max}} = 0.6$ or $e_{\text{max}} = 0.9$. The mass ratio distribution was assumed either uniform for 0.2 < $q$ < 1.0 (the “qflat” distribution) or uniform for 0.7 < $q$ < 1.0 (the “qpeak” distribution). These $q$ distributions seem reasonable compared with what is already known about wider low-mass binary systems (e.g. see Bouy et al. 2003). It is possible, that, as in more massive binary systems, there is a shift towards equal masses among very close binary systems. Simulated targets were randomly assigned binary status on the basis of a total binary frequency which was normalised such that the frequency was 15 per cent for $a > 2.6$ au and hence matched the observational constraints for wider binaries.

3. Results and Discussion

The outputs from our modelling are a prediction of the sensitivity of each of the target observations (for each star) to binaries of a given separation (averaged over all mass ratios and eccentricities). We plot the average sensitivity for all targets in Fig. 2 and also show how the data from each of the three datasets contributes to this average (i.e. the lower curves are the sum of the detection efficiencies for each target in that dataset, divided by the number of targets in all three datasets). It is clear from this that we are sensitive to binaries with $a \leq 1$ au. It is also clear that we cannot simply say binaries are all detectable out to some limiting separation and cannot be detected beyond that. Even as a function of log $a$, the detection efficiency rolls over rather gradually.
and combined with the (probable) increasing number of binary systems as \( \log a \) increases, this demonstrates why a detailed simulation is demanded. From Fig. 2 we can see that narrower \( a \) distributions such as that of Umbreit et al. (2005) predict far fewer binaries will lie within our sensitive range. This is further illustrated in Fig. 3 where we show the simulated distribution of \( \log p \) values (where \( p \) is the probability that a set of RV measurements represent a constant value) for a million binary systems with orbital separations taken from the various models. The number of detected binary systems (with \( \log p < -3 \)) is expected to vary by an order of magnitude depending upon the adopted \( a \) distribution.

*Fig. 2.* The average binary detection efficiency. The upper three curves show the effects of differing models for the mass ratio and eccentricity distributions (see text). The lower curves show the contributions to the average from each of the three RV surveys considered (i.e. the sum of these gives the average). To illustrate the binary population we might be sensitive to, we show the two extreme model \( a \) distributions we have investigated (see Fig. 1).

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Table 1. The number of binaries, \( n_{\text{bin}} \), predicted from the Monte-Carlo simulations. The total binary fraction is \( f_b \) and probabilities (as percentages) are quoted for whether the simulations would result in 4 or more, or 4 or fewer detected binaries in the observational dataset.

| \( F(\log a) \) | \( f_b \) | \( n_{\text{bin}} \) | \( P(n_{\text{obs}} \geq 4) \) | \( P(n_{\text{obs}} \leq 4) \) |
|-----------------|---------|-----------------|------------------|------------------|
| Umbreit         | 0.26    | 0.5–0.7         | 0.1–0.4          | 99.9–99.9        |
| \( \sigma = 0.6 \) | 0.32    | 1.3–1.8         | 3.4–9.5          | 96.9–99.3        |
| \( \sigma = 1.0 \) | 0.45    | 4.2–5.5         | 62.9–82.5        | 33.6–57.6        |
| \( \sigma = 1.53 \) | 0.59    | 9.0–10.8        | 98.9–99.9        | 0.8–3.3          |

The key numerical results are given in Table 1, where we give the \( a \) distribution assumed, the implied total binary frequency, the range for the expected number of detected binary systems (summed over the three datasets for various combinations of the \( e \) and \( q \) distributions) and the probabilities that we would have observed either 4 or more, or 4 or fewer binary systems in the real data. We find that the chosen \( e \) or \( q \) distribution make little difference to the number of binary system detections expected (as implied by the similar average detection efficiency curves shown in Fig. 2). If binaries are really concentrated towards lower \( q \) values then we would expect to detect fewer of them and so would require a higher binary frequency to explain the data. Conversely, the minimum binary frequency would arise from a population with \( q = 1 \).

Fig. 3. The distribution of \( \log p \) (averaged over all the objects included in the RV surveys and where \( p \) is the probability of the measured RVs being consistent with a constant value) for a simulated population of \( 10^6 \) binaries. Separate curves are shown for binary separations which were drawn from each of the considered model \( a \) distributions. The straight line is the predicted locus for single stars.

The expected number of detected binaries is very sensitive to the \( a \) distribution, ranging from \(< 1 \) for the Umbreit et al. (2005) distribution to 11 for the \( \sigma_{\log(a/au)} = 1.53 \) distribution. The narrowest (Umbreit et al.) \( a \) distribution is ruled out by the observations at the \( > 99 \) per cent level. There are too many binaries detected in the RV data. The broadest (\( \sigma_{\log(a/au)} = 1.53 \)) \( a \) distribution is also highly unlikely for the opposite reason. The intermediate width distributions are in satisfactory agreement with the observed number of close binaries and imply overall binary frequencies of 32–45 per cent, with 17–30 per cent at \( a < 2.6 \) au. This high close binary frequency is larger than for either G-dwarfs (14 per cent, Duquennoy & Mayor 1991) or M-dwarfs (\( \sim 10 \) per cent, Fischer & Marcy 1992). However, this is merely a continuation of the trend which is already apparent in the binaries with \( 2.6 < a < 10 \) au.

To clarify some points that might puzzle the reader, we note that: (i) We do not know the correct functional form for the \( a \) distribution, we have merely assumed a plausible form. To minimize the implied binary frequency requires an \( a \) distribution that is concentrated towards small \( a \) but which “joins on” to the observed distribution at large separations. Of course one could hypothesize a discontinuous distribution – for example a secondary peak of binaries at \( a < 0.1 \) au.
Whatever distribution is assumed, however, the binary frequency for $a < 2.6\text{ au}$ cannot be less than the 4/48 binaries we have observed even if we were 100 per cent efficient at detecting binaries out to that separation (which are not by some margin – see Fig. 2). (ii) The model $a$ distributions are normalised to 15 per cent for $a > 2.6\text{ au}$, but this number is uncertain. If it were increased to 22 per cent then tests show that narrower distributions would be allowed (though the Umbreit et al. distribution would still be ruled out at high significance), there would be slightly fewer binary systems at $a < 2.6\text{ au}$, but the overall binary frequency would be very similar. Conversely, a binary frequency of 8 per cent for $a > 2.6\text{ au}$ would require broader $a$ distributions to explain the number of observed RV variables, more close binary systems, but again the overall binary frequency would be almost the same. (iii) The 17–30 per cent figure for close binaries is not a formal error range - it is the range of frequencies implied if the Gaussian forms assumed for the $a$ distribution are correct and the observed binary frequency is 4/48. (iv) $q = 1$ binaries may be harder to detect than we have calculated. Our simulations assume the secondary star is “invisible”, but clearly an equal mass binary system will have an SB2 spectrum. For close systems this will be obvious, but more separated systems, where the orbital velocity amplitude is smaller than the spectral resolution (certainly the case at $a \approx 1\text{ au}$ for the datasets considered here), would not immediately reveal themselves and might appear to have constant RV. This effect can only act to increase the binary frequency inferred from the observations.

Our results pose considerable difficulties for current ideas of VLM/BD formation. When multiple systems form by fragmentation, the minimum separation should be $a \geq 10\text{ au}$ due to the opacity limit. Closer binaries subsequently require the operation of dynamical or hydrodynamical hardening mechanisms (Bate, Bonnell & Bromm 2002). N-body decay models of unstable multiple systems produce very few close binary systems (e.g. Sterzik & Durisen 2003; Umbreit et al. 2005). This is because dynamical interactions capable of hardening a VLM/BD binary usually result in the ejection of one of the components and its replacement by a more massive object. Hydrodynamical hardening process are of course not included in pure N-body models. The high close binary frequency we have deduced indicates that these mechanisms must be important and effective.

Smoothed particle hydrodynamic (SPH) models also have problems. Bate et al. (2002) and Bate & Bonnell (2005) present simulations which produce only $\approx 8$ per cent bina-

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### 4. Conclusions

From the detection of 4 close VLM/BD binary systems in several published RV surveys, we have been able to place strong constraints on the binary frequency and separation distribution of such systems. We find that there are too many detected close binaries to be consistent with the rather narrow separation distributions predicted by N-body models of dynamically decaying multiple systems. Instead we find that broader Gaussian distributions with 17–30 per cent binarity for $a < 2.6\text{ au}$ are favoured and overall binary frequencies of 32–45 per cent. The total binary frequency for VLMs/BDs is therefore only marginally lower than (if not similar to) that for M-dwarfs, but significantly lower than for G-dwarfs. Considering only separations $a < 10\text{ au}$, the binary frequency of VLMs/BDs is higher than for either G- or M-dwarfs.

The neglect of hydrodynamical hardening processes in N-body models may be responsible for their lack of predicted close binaries. However, recent SPH models also do not predict a significant population of very close BD binaries and yield overall binary frequencies of only $\sim 8$ per cent. The high overall binary frequency and the frequency of observed close binary VLMs/BDs do not favour the “ejection” hypothesis or similar models that produce BDs from the decay of dynamically unstable multiple systems. A mechanism is required that hardens VLM/BD binaries without disrupting them.

At present, these conclusions are limited only by the small numbers of detected binaries in the RV datasets. It is now important to increase these samples with further high precision RV surveys of VLMs/BDs. Such surveys will require sparse monitoring of large samples with baselines of a year or more and RV precisions of $\sim 1\text{ km s}^{-1}$. Not only can the techniques we have demonstrated yield the binary frequency, but modelling the observed log $p$ distribution (as shown in Fig. 3) offers a means of determining the actual form of the $a$ distribution at small separations, providing sufficient binaries can be detected.
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