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The dynamical evolution of very low mass binaries in open clusters

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ABSTRACT

Very low mass binaries (VLMBs), with system masses $<0.2\,M_\odot$ appear to have very different properties to stellar binaries. This has led to the suggestion that VLMBs form a distinct and different population. As most stars are born in clusters, dynamical evolution can significantly alter any initial binary population, preferentially destroying wide binaries. In this paper, we examine the dynamical evolution of initially different VLMB distributions in clusters to investigate how different the initial and final distributions can be.

We find that the majority of the observed VLMB systems, which have separations <20 au, cannot be destroyed in even the densest clusters. Therefore, the distribution of VLMBs with separations <20 au now must have been the birth population (although we note that the observations of this population may be very incomplete). Most VLMBs with separations >100 au can be destroyed in high-density clusters, but are mainly unaffected in low-density clusters. Therefore, the initial VLMB population must contain many more binaries with these separations than now, or such systems must be made by capture during cluster dissolution. M-dwarf binaries are processed in the same way as VLMBs and so the difference in the current field populations either points to fundamentally different birth populations or significant observational incompleteness in one or both samples.

Key words: methods: numerical – binaries: general – brown dwarfs – stars: formation – stars: low-mass – open clusters and associations: general.

1 INTRODUCTION

It has been suggested that brown dwarf-brown dwarf binaries or, more generally, very low mass binaries (VLMBs) with system masses $<0.2\,M_\odot$ form in a different way to stellar binaries. The main argument for this scenario is that the binary fraction and separation distributions of VLMBs are very different to those of stars. Thies & Kroupa (2007) point out that the binary fraction of very low mass systems is only 15–25 per cent, compared to 42 per cent for higher mass M dwarfs. Also, the separation distribution for most stellar binaries (higher mass M, K and G dwarfs) has the same mean (30 au) and variance ($\sigma_{\log_{10}} a = 1.53$, where a is the semimajor axis in au), and differs only in the multiplicity of the primary in the particular mass range (Duquennoy & Mayor 1991; Fischer & Marcy 1992). However, the observed separation distribution of VLMBs (see e.g. Burgasser et al. 2007) shows the data (when fitted with a $\log_{10}$-normal) to have a mean of 4.6 au with a much smaller variance. In addition, Thies & Kroupa (2007, 2008) argue that the observations of VLMBs are not consistent with a continuous initial mass function (IMF) over the hydrogen-burning limit. Thies & Kroupa (2007) interpreted this as evidence that VLMBs form through a different mechanism to stellar binaries.

However, it is known that binary populations can undergo significant dynamical processing, with many, especially wider systems, being destroyed (Heggie 1975; Kroupa 1995a,b; Kroupa, Petr & McCaughrean 1999; Kroupa et al. 2003; Parker et al. 2009). Therefore, the currently observed binary population, especially in the field, is not the same as the birth population (Goodwin 2010).

In this paper, we examine to what extent an initial VLMB population can be altered by dynamical processing and so how different the initial VLMB and stellar binary populations can be at birth. We extend the work of Kroupa et al. (2003) who examine the evolution of a mixed population of star and very low mass object (VLMO) binaries and find that, dynamically at least, VLMBs must form a separate population (see also Thies & Kroupa 2007, 2008). Here, we assume that VLMBs are a separate population and examine what range of initial binary fractions and separations can reproduce the current observations. In Section 2 we review the available VLMB data, in Section 3 we describe the set-up of our simulations, we present our results and discussion in Sections 4 and 5 and we conclude in Section 6.

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2 SUMMARY OF THE OBSERVATIONS

Data on VLMBs – binaries with a total system mass of $<0.2\,M_\odot$ – have been collated in the Very Low Mass Binaries Archive (VLMBA; see Burgasser et al. 2007).[1] Given that the majority of these systems have primary masses less than the hydrogen-burning limit ($m_H = 0.08\,M_\odot$), the VLMBA data have the potential to provide an excellent constraint on the hypothesis that substellar binaries form via a different mechanism or in a different environment to stellar binaries.

As of 2010 September, the VLMBA lists 99 systems, four of which lack robust separation measurements and a further system has a planetary-mass companion. That leaves 94 systems to compare with numerical simulations.

2.1 Multiplicity

We define the multiplicity of VLMBs as

$$f_{VLMB} = \frac{B}{S + B}, \tag{1}$$

where B is the number of binary systems and S is the number of single systems. We ignore triple and higher order systems for the remainder of this paper.

The overall multiplicity of VLMBs is open to debate. Based on potentially undiscovered systems, Basri & Reiners (2006) suggest a value of 0.26 ± 0.10. This would argue in favour of the VLMBs as a continuous population, as the multiplicity of M and G dwarfs is 0.42 and 0.58 respectively (Duquennoy & Mayor 1991; Fischer & Marcy 1992), possibly indicating a smooth decrease in multiplicity with decreasing primary mass. However, Thies & Kroupa (2007) argue that the VLMBA data are consistent with an overall multiplicity of 0.15, representing a distinct cut-off from the stellar binary regime.

2.2 Separation distribution

In Fig. 1 we plot the separation distribution of the observed VLMBs, distinguishing between systems observed in the Galactic field (the hashed histogram) and systems observed in various clusters (the open histogram). The majority of these systems lie in a small separation range (∼1–30 au with a peak around 5 au). The total area of the histogram corresponds to the observed binary fraction of VLMOs, 0.15 (Close et al. 2003).

It is important to note that most of the observed VLMBs are in the field. This means that their birth cluster has disrupted and that we are mostly observing an already dynamically processed VLMB population. Unfortunately we have no information on the birth clusters of these systems.

Several authors have attempted to fit the VLMB data with $\log_{10}$-normal distributions similar to those that are used to fit G, K and M dwarfs in the field (Duquennoy & Mayor 1991; Mayor et al. 1992; Fischer & Marcy 1992, respectively).[2] Thies & Kroupa (2007) fit the VLMB separation distribution with a $\log_{10}$-normal distribution with mean 4.6 au and variance $\sigma_{\log_{10} a} = 0.4$, and an overall substellar multiplicity of 0.15 (the solid brown line in Fig. 1).

[1] See http://www.vlmbinaries.org/ for an up-to-date census of the known VLMBs, maintained by N. Siegler, C. Gelino and A. Burgasser.

[2] Whilst the fit to the G-dwarf data is $\log_{10}$-normal, the K- and M-dwarf separation distributions suffer from poorer statistics and may not be a straightforward scaling down of the G-dwarf distribution as a function of the multiplicity of the primary component (as multiplicity decreases as a function of primary mass in binaries in the field).

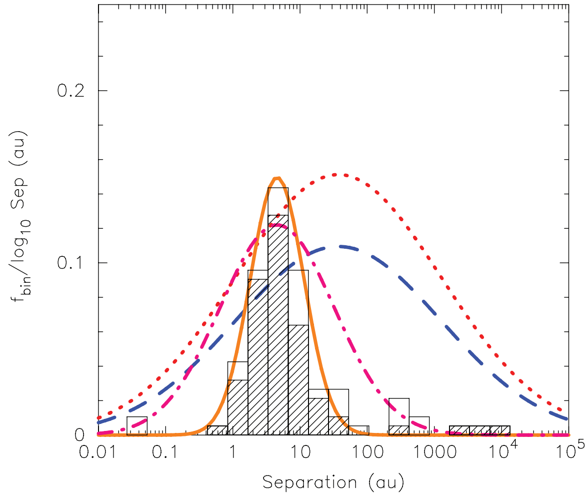


Figure 1. Data from the VLMBA (Burgasser et al. 2007). The hashed histogram represents binaries observed in the Galactic field, whereas the open histogram represents the few VLMBs observed in various star clusters. The total area of the histogram corresponds to the observed binary fraction of VLMBs, 0.15. The $\log_{10}$-normal fits to the data by Thies & Kroupa (2007, solid brown line) and Basri & Reiners (2006, the dot–dashed magenta line) are shown. For comparison, the $\log_{10}$-normal fits for field M dwarfs (Fischer & Marcy 1992, the dashed blue line) and field G dwarfs (Duquennoy & Mayor 1991, the dotted red line) are also shown.

However, there are some outlying systems with very short and long separations, and Basri & Reiners (2006) argue for a wider distribution, based on the hypothesis that there may be unresolved short-period VLMBs with separations less than 1 au (Maxted & Jeffries 2005) and (at the time) the tentative discovery of VLMBs with separations in excess of 100 au (e.g. Close et al. 2003; Bouy et al. 2006).

The former is still the subject of debate, with claims that the peak in the VLMB separation distribution may be between 1 and 3 au (Burgasser et al. 2007), though Joergens (2008) suggests that few VLMBs exist with separations <3 au. The latter appears to be partly vindicated by recent discoveries of wider systems in the field (Königstuhl-1 AB, $a = 1800$ au, Caballero 2007; 2M0126AB, $a = 5100$ au, Artigau et al. 2007; 2M1258AB, $a = 6700$ au, Radigan et al. 2009), although surveys should be sensitive to VLMBs with separations between 10 and 200 au (Burgasser et al. 2007).

Basri & Reiners (2006) proposed a wider $\log_{10}$-normal fit to the data with mean 4.6 au and variance $\sigma_{\log_{10} a} = 0.85$, and an overall substellar multiplicity of 0.26 (the dot–dashed magenta line in Fig. 1). For comparison, in Fig. 1 we also show the $\log_{10}$-normal fits for field M dwarfs (Fischer & Marcy 1992, the dashed blue line) and field G dwarfs (Duquennoy & Mayor 1991, the dotted red line). Details of the parameters for the $\log_{10}$-normal fits are given in Table 1.

2.3 Mass ratio distribution

It is also interesting to trace the possible evolution of the mass ratio distribution. For each system, the mass ratio, q, is defined as

$$q = \frac{m_s}{m_p}, \tag{2}$$

where m_p and m_s are the masses of the primary and secondary components, respectively.

Table 1. Parameters for the $\log_{10}$-normal fits to the data in Fig. 1. The columns contain, from left to right, the reference, mean, log of the mean, variance and the binary fraction used to normalize the distribution. The references are Thies & Kroupa (2007, TK07), Basri & Reiners (2006, BR06), Fischer & Marcy (1992, FM92) and Duquennoy & Mayor (1991, DM91).

Ref.	Mean (au)	Mean ($\overline{\log_{10} a}$)	Variance ($\sigma_{\log_{10} a}$)	$f_{\rm mult}$
TK07	4.6	0.66	0.40	0.15
BR06	4.6	0.66	0.85	0.26
FM92	30	1.57	1.53	0.42
DM91	30	1.57	1.53	0.58

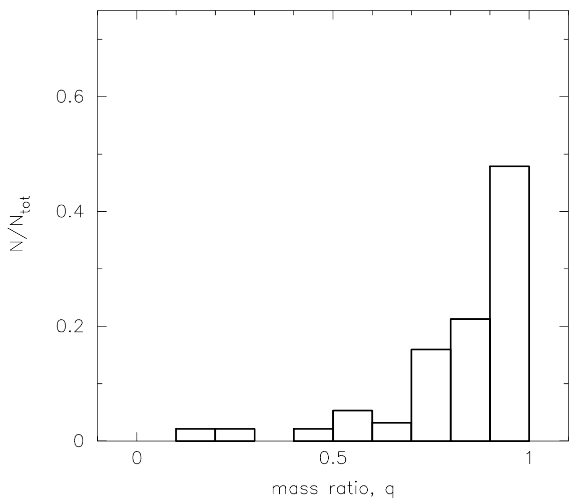


Figure 2. The mass ratio distribution of systems from the VLMBA (Burgasser et al. 2007). The bins are of width 0.1, and are normalized to the total number of systems used (94) to allow direct comparison with the simulations.

In Fig. 2 we show the observed mass ratio distribution of the VLMBA data, normalized to the total number of systems (94). Almost half the VLMBs in the sample have a mass ratio approaching unity, and the majority of the other systems have high (>0.7) values of q.

2.4 Other properties

Data on other dynamical properties of the VLMBs are not yet available. Therefore, we do not include a study on e.g. the possible effects of cluster evolution on the VLMB eccentricity distribution.

3 METHOD

3.1 Cluster set-up

We follow a similar method to the one described in Parker et al. (2009) to set up the clusters and *stellar binary*[3] systems in our simulations. The clusters are designed to mimic a 'typical' star cluster, similar to Orion with $N = 2000$ members and mass $\sim 10^3\,{\rm M}_\odot$.

For each set of initial conditions, we create a suite of 10 simulations, corresponding to 10 clusters, identical apart from the random number seed used to initialize the simulations.

We set our clusters up as initially virialized Plummer spheres (Plummer 1911) as described by Aarseth, Hénon & Wielen (1974). The prescription in Aarseth et al. (1974) provides the positions and velocities of the centres of mass of the systems in the Plummer sphere.

The current half-mass radius of Orion is 0.8 pc (McCaughrean & Stauffer 1994; Hillenbrand & Hartmann 1998; Köhler et al. 2006). However, Parker et al. (2009) argue that Orion was originally much denser than it is now and that the effects of gas expulsion (Tutukov 1978; Hills 1980; Goodwin 1997; Kroupa, Aarseth & Hurley 2001; Goodwin & Bastian 2006) and dynamical interactions (Kroupa et al. 1999, van den Berk, Portegies Zwart & McMillan 2007; Parker et al. 2009, and references therein) have caused it to expand to its current size. We therefore adopt initial half-mass radii of 0.1 pc and 0.8 pc for the clusters in our simulations, thereby covering a wide range of cluster densities.

Observations suggest that the ratio of stars with masses $<1\,{\rm M}_\odot$ to brown dwarfs is $\sim$5:1 (e.g. Andersen et al. 2008). In our simulations, we place one substellar system (either single or binary) in the cluster for every five stellar systems.

3.2 Stellar binary properties

It is thought that the star formation process should produce binary stars in preference to singles (Goodwin & Kroupa 2005; Goodwin et al. 2007, and references therein). Therefore, all the clusters in our simulations are formed with an initial stellar binary fraction, $f_{\rm stellar} = 1$ (i.e. all stars form in binary systems; there are no singles or triples, etc.), where

$$f_{\rm stellar} = \frac{B}{S + B}, \tag{3}$$

and S and B are the numbers of single and binary systems, respectively.

The mass of the primary star is chosen randomly from a Kroupa (2002) IMF of the form

$$N(M) \propto \begin{cases} M^{-1.3} & m_1 < M/{\rm M}_\odot < m_2, \\ M^{-2.3} & m_2 < M/{\rm M}_\odot < m_3, \end{cases} \tag{4}$$

where $m_1 = 0.106\,{\rm M}_\odot, m_2 = 0.5\,{\rm M}_\odot$, and $m_3 = 50\,{\rm M}_\odot$. Note that the lower mass limit, m_1, is higher than in our previous papers (e.g. Parker & Goodwin 2009; Parker et al. 2009). This is to prevent a stellar binary or single star from having mass components ($m_{\rm p}$ and $m_{\rm s}$) that would overlap with the VLMBA data.[4] In several test simulations, we found that varying m_1 by a few per cent causes a negligible difference to the results.

Secondary masses are drawn from a flat mass ratio distribution with the constraint that if the companion mass is $<0.106\,{\rm M}_\odot$ or the total mass of the binary, $m_{\rm tot} < 0.2\,{\rm M}_\odot$ it is reselected, thereby removing the possibility of creating VLMBs in the stellar domain. Note that this method does not produce the input IMF, exactly due to the way that secondaries are chosen.

[3] From this point in the paper, we adopt the phrase 'stellar binary' when describing systems with component masses both exceeding $0.106\,{\rm M}_\odot$, and 'VLMB' when describing systems with both component masses less than $0.106\,{\rm M}_\odot$. $0.105\,{\rm M}_\odot$ is the mass of the most massive VLMB primary component in the archive.

[4] We note that in their work, Thies & Kroupa (2007) deliberately allowed an overlap in the mass range 0.08–0.1 ${\rm M}_\odot$, so that objects could be either stars or brown dwarfs.

In accordance with the observations of Duquennoy & Mayor (1991) and Fischer & Marcy (1992), the periods of stellar binary systems are drawn from a $\log_{10}$-normal distribution of the form:

$$f(\log_{10} P) \propto \exp\left\{\frac{-(\log_{10} P - \overline{\log_{10} P})^2}{2\sigma^2_{\log_{10} P}}\right\}, \quad (5)$$

where $\overline{\log_{10} P} = 4.8$, $\sigma_{\log_{10} P} = 2.3$ and P is in days. The periods are then converted to semimajor axes.

Eccentricities of stellar binaries are drawn from a thermal eccentricity distribution (Heggie 1975; Kroupa 1995a, 2008) of the form:

$$f_{\rm e}(e) = 2e. \quad (6)$$

Binaries with small periods but large eccentricities would expect to undergo the tidal circularization shown in the sample of G dwarfs in Duquennoy & Mayor (1991). We account for this by reselecting the eccentricity if it exceeds the following period-dependent value $e_{\rm tid}$:

$$e_{\rm tid} = \frac{1}{2}\left[0.95 + \tanh(0.6 \log_{10} P - 1.7)\right], \quad (7)$$

with $\log_{10} P$ in days.[5] This ensures that the eccentricity–period distribution matches the observations of Duquennoy & Mayor (1991).

3.3 VLMB properties

In three sets of simulations, we use the VLMBA data (Burgasser et al. 2007) to randomly choose binaries and use their masses and semimajor axes as initial values for substellar binaries in the cluster.

We run simulations with semimajor axes drawn from the Thies & Kroupa (2007) fit to the VLMB separation distribution, with Gaussian parameters of $\overline{\log_{10} a} = 0.66$, where a is the semimajor axis in au (0.66 corresponds to 4.6 au), and variance $\sigma_{\log_{10} a} = 0.4$; and also the fit by Basri & Reiners (2006), which accounts for the outlying binaries in the VLMB separation distribution by adopting the same $\log_{10}$-normal peak but increasing the variance ($\overline{\log_{10} a} = 0.66$, $\sigma_{\log_{10} a} = 0.85$). For completeness, we run simulations in which the substellar binaries have the same separation distribution as the stellar binaries ($\overline{\log_{10} P} = 4.8$, $\sigma_{\log_{10} P} = 2.3$; P in days).

In each case, we adopt an initial VLMB fraction; either 0.5 (cf. the stellar binaries in the fields; Duquennoy & Mayor 1991), 0.25 (to account for potentially undiscovered VLMBs; Basri & Reiners 2006) or 0.15 [the Thies & Kroupa (2007) fit to the observations].

In the simulations that choose separations from the various $\log_{10}$-normal distributions, the masses of the substellar binary components are chosen by randomly assigning the primary a mass in the range $0.01\,{\rm M}_{\odot} < m_{\rm p} \leq 0.106\,{\rm M}_{\odot}$. We then adopt a flat mass ratio (q) distribution to choose the mass of the secondary component ($0.01\,{\rm M}_{\odot} \leq m_{\rm s} < m_{\rm p}$).

This mass range allows a direct comparison between the VLMBA and the simulations. We find that reducing the upper limit of the VLMB primaries to $0.08\,{\rm M}_{\odot}$ has a negligible effect on the results.

The eccentricities are drawn from a thermal eccentricity distribution and then tidally circularized (equations 6 and 7).

A summary of the different mass, semimajor axes and eccentricity distributions used to create the substellar binaries is given in Table 2.

[5] A more elaborate 'eigenevolution' algorithm, which accounts for pre-main-sequence tidal circularization and protostellar disc accretion is described in Kroupa 2008. We elect not to use it here, as the disc accretion mechanism in this algorithm also alters the mass ratio distribution.

Table 2. A summary of the different substellar binary configurations adopted in the simulations. From left to right, the columns show the initial cluster half-mass radius, $r_{1/2}$; the separation distribution [either the $\log_{10}$-normal distributions of Duquennoy & Mayor (1991, DM91), Basri & Reiners (2006, BR06) and Thies & Kroupa (2007, TK07) or values taken directly from the VLMBA]; the initial multiplicity; the masses of the two components in a system (either randomly selected with a flat mass-ratio distribution or taken from the VLMBA). See Section 3.3 for full details.

$r_{1/2}$	Separation distribution	$f_{\rm VLMB}$	Mass range
0.1 pc	VLMBA	0.25	VLMBA
0.8 pc	VLMBA	0.25	VLMBA
0.8 pc	VLMBA	0.15	VLMBA
0.1 pc	TK07	0.15	Random, flat q
0.1 pc	BR06	0.5	Random, flat q
0.1 pc	BR06	0.25	Random, flat q
0.1 pc	DM91	0.5	Random, flat q
0.8 pc	DM91	0.5	Random, flat q

3.4 *N*-body integration

By combining the primary and secondary masses of the stellar and VLMBs with their semimajor axes and eccentricities, the relative velocity and radial components of the stars/VLMOs in each system are determined. These are then placed at the centre of mass and centre of velocity for each system in the Plummer sphere.

Simulations are run using the KIRA integrator in Starlab (e.g. Portegies Zwart et al. 1999, 2001, and references therein) and evolved for 10 Myr. We do not include stellar evolution in the simulations.

4 RESULTS

4.1 Finding bound binary systems

We use the nearest neighbour algorithm described by Parker et al. (2009) (and independently verified by Kouwenhoven et al. 2010) to determine whether a star/VLMO is in a bound binary system.

4.2 The evolution of the VLMB separation distributions

In this section we discuss the effects of cluster evolution upon the various initial separation distributions used to define the VLMB population in the clusters.

4.2.1 The $\log_{10}$-normal fit by Thies & Kroupa

In one ensemble of clusters, we select separations from the $\log_{10}$-normal fit to the VLMBA data by Thies & Kroupa (2007). In Fig. 3 we show the results of dynamical evolution in a dense cluster with a half-mass radius of 0.1 pc. When using the Thies & Kroupa (2007) $\log_{10}$-normal separation distribution as an initial condition, it is impossible to dynamically disrupt many of the systems. Thies & Kroupa (2007) used a binary fraction of $f_{\rm VLMB} = 0.15$ to fit the observational data. We show in Fig. 3 that the observations can only be recovered if an initial binary fraction of $f_{\rm VLMB} = 0.15$ is used. Any other (higher) fraction hugely overpopulates the distribution around its peak, even when adopting a dense cluster model.

This initial separation distribution does not account for the wide systems, which are observed in both young clusters and in the field. No initial binary fraction coupled with the Thies & Kroupa (2007) $\log_{10}$-normal fit can reproduce them in any cluster. This is analogous

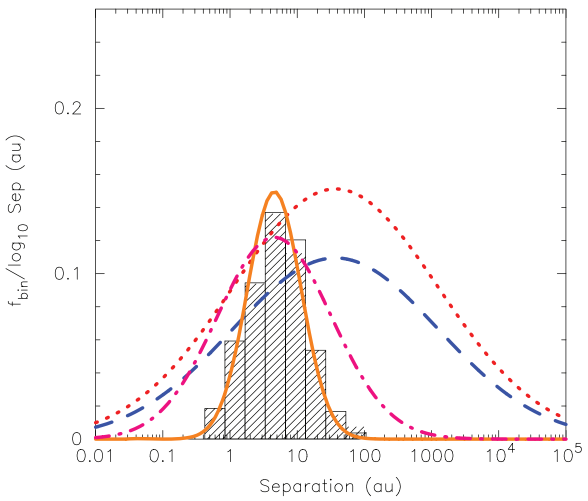


Figure 3. The evolution of the separation distribution for VLMBs with initial separations drawn from the $\log_{10}$-normal fit to the observed data by Thies & Kroupa (2007, the solid brown line). The wider fit to the data by Basri & Reiners (2006, the dot–dashed magenta line) is shown. The initial VLMB fraction is $f_{\rm VLMB} = 0.15$, and the half-mass radius of the cluster is 0.1 pc. The open histogram shows the initial distribution, and the hashed histogram shows the distribution after 1 Myr. For comparison, the $\log_{10}$-normal fits for field M dwarfs (Fischer & Marcy 1992, the dashed blue line) and field G dwarfs (Duquennoy & Mayor 1991, the dotted red line) are also shown.

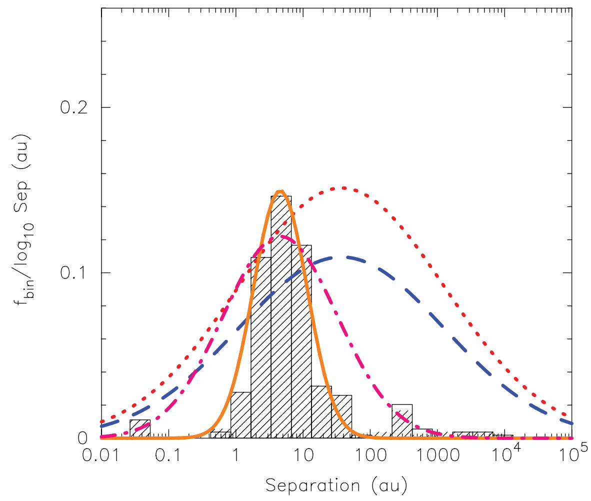


Figure 5. The evolution of the separation distribution for VLMBs with initial separations and masses drawn from the VLMBA. The initial VLMB fraction is $f_{\rm VLMB} = 0.15$, and the half-mass radius of the cluster is 0.8 pc. The open histogram shows the initial distribution, and the hashed histogram shows the distribution after 1 Myr. The $\log_{10}$-normal fit to the observed data by Thies & Kroupa (2007, the solid brown line) and the wider fit to the data by Basri & Reiners (2006, the dot–dashed magenta line) are shown. For comparison, the $\log_{10}$-normal fits for field M dwarfs (Fischer & Marcy 1992, the dashed blue line) and field G dwarfs (Duquennoy & Mayor 1991, the dotted red line) are also shown.

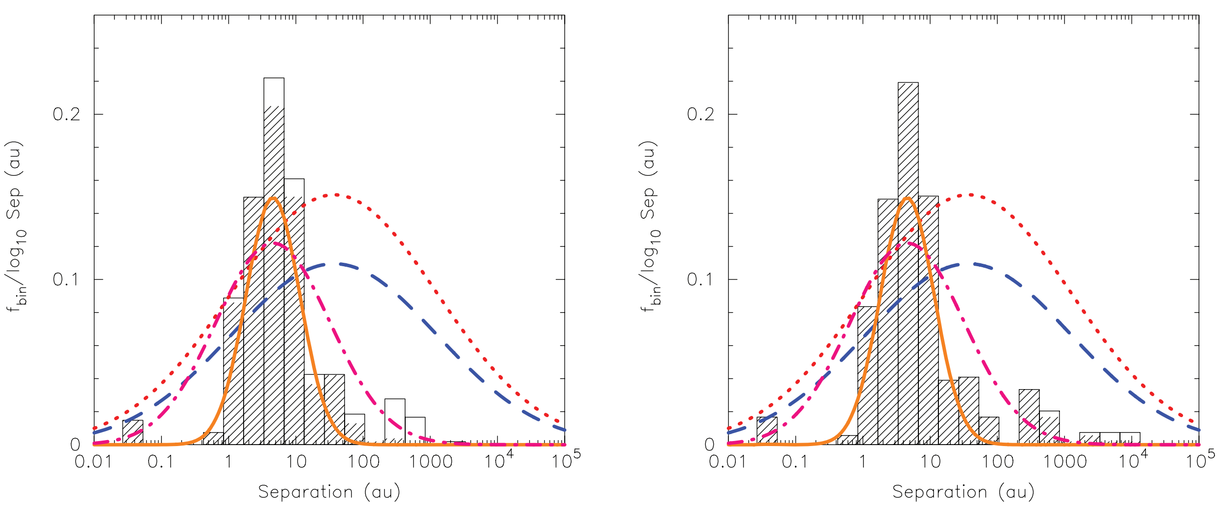
to the result found by Kroupa & Burkert (2001), who demonstrated that it is impossible to widen the stellar binary separation distribution through dynamical evolution in clusters.

4.2.2 *The VLMBA data*

In one subset of cluster models, we created the VLMB population by selecting systems at random from the online VLMBA. This leads to the separation distribution shown in Fig. 1.

We dynamically evolve three ensembles of clusters containing these VLMBs. One is a very dense cluster with a half-mass radius of 0.1 pc, and an initial binary fraction $f_{\rm VLMB} = 0.25$. The second is a low-density cluster with a half-mass radius of 0.8 pc (similar to that of Orion today), and an initial $f_{\rm VLMB} = 0.25$; and the third is a low-density cluster with a half-mass radius of 0.8 pc, and an initial $f_{\rm VLMB} = 0.15$. The results are shown in Figs 4 and 5.

In the dense cluster ($r_{1/2} = 0.1$ pc, Fig. 4a), the wide VLMBs in the range 100–1000 au are all destroyed, and the very wide binaries



(a) $r_{1/2} = 0.1$ pc

(b) $r_{1/2} = 0.8$ pc

Figure 4. The evolution of the separation distribution for VLMB with initial separations and masses drawn from the VLMBA. The initial VLMB fraction is $f_{\rm VLMB} = 0.25$, and the half-mass radius of the cluster is (a) 0.1 pc and (b) 0.8 pc. The open histogram shows the initial distribution, and the hashed histogram shows the distribution after 1 Myr. The $\log_{10}$-normal fit to the observed data by Thies & Kroupa (2007, the solid brown line) and the wider fit to the data by Basri & Reiners (2006, the dot–dashed magenta line) are shown. For comparison, the $\log_{10}$-normal fits for field M dwarfs (Fischer & Marcy 1992, the dashed blue line) and field G dwarfs (Duquennoy & Mayor 1991, the dotted red line) are also shown.

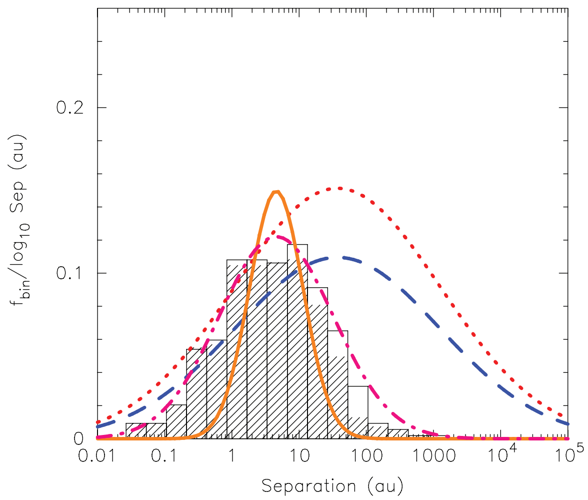


Figure 6. The evolution of the separation distribution for VLMBs with initial separations drawn from the $\log_{10}$-normal fit to the observed data by Basri & Reiners (2006, the dot–dashed magenta line). The initial multiplicity is $f_{\rm VLMB} = 0.25$ and the initial half-mass radius is 0.1 pc. The open histogram shows the initial distribution, and the hashed histogram shows the distribution after 1 Myr. The $\log_{10}$-normal fit to the observed data by Thies & Kroupa (2007, the solid brown line) is shown. For comparison, the $\log_{10}$-normal fits for field M dwarfs (Fischer & Marcy 1992, the dashed blue line) and field G dwarfs (Duquennoy & Mayor 1991, the dotted red line) are also shown.

(>1000 au) cannot form at all. This is because the average distance between stars in clusters of this density is ∼2000 au, making it highly unlikely that the wide binaries will be bound systems, even before dynamical evolution (see Parker et al. 2009, for a detailed discussion). There is some disruption of the intermediate (4–100 au) VLMBs, but not enough to drastically alter the initial distribution.

When we adopt an initial half-mass radius of 0.8 pc (Fig. 4b), all the VLMBs placed in the clusters are found to be bound systems by our algorithm. However, dynamical evolution acts to break up the widest (>5000 au) VLMBs and systems with separations less than this are unaffected.

It is clear that the simulations have too high an initial multiplicity if we are to match the observational data. In Fig. 5, we show the $r_{1/2} = 0.8$ pc simulation with a lower initial multiplicity ($f_{\rm VLMB} = 0.15$). This produces the correct distribution for the intermediate binaries, but underproduces the number of very wide (>1000 au) binaries required to be consistent with the observational data.

4.2.3 *The $\log_{10}$-normal fit by Basri & Reiners*

We also conduct simulations in which separations are chosen from the wider $\log_{10}$-normal fit to the observed data by Basri & Reiners (2006), in a dense cluster with a half-mass radius of 0.1 pc. The initial multiplicity is $f_{\rm VLMB} = 0.25$; we find that any higher multiplicity (e.g. $f_{\rm VLMB} = 0.5$) vastly overproduces the number of binaries compared to the observations, even after dynamical evolution.

The resultant separation distribution after 1 Myr for the cluster with $f_{\rm VLMB} = 0.25$ is shown in Fig. 6. There is some dynamical processing of binaries with separations in excess of around 10 au, so that in a dense cluster the Basri & Reiners (2006) separation distribution is not recovered. And, like the Thies & Kroupa (2007) separation distribution, this distribution cannot produce the very wide systems initially (and even if it did they would be destroyed in a dense cluster).

4.2.4 *The $\log_{10}$-normal fit for field G dwarfs*

In the final subset of cluster ensembles, the semimajor axes of the VLMBs are chosen from the same distribution (Duquennoy & Mayor 1991) as those of the stellar binaries. In Fig. 7a we show the separation distribution of the VLMBs initially (open histogram), and after 1 Myr (hashed histogram) for a dense cluster ($r_{1/2} = 0.1$ pc) with an initial multiplicity of $f_{\rm VLMB} = 0.5$.

The resultant dynamical processing of the binaries in this dense environment causes the separation distribution to evolve into a Basri & Reiners (2006) $\log_{10}$-normal, albeit with some overproduction of binaries with separations <1 au.

In Fig. 7(b) we repeat the simulation, but adopt an initial half-mass radius of $r_{1/2} = 0.8$ pc for the cluster. With this initial condition, the cluster is not as dense, and we overproduce VLMBs at all separations >10 au as dynamical destruction is very ineffective in such low-density clusters.

4.3 Multiplicity fraction

In each simulation, we determine the multiplicity fraction at each time-step. For simplicity (and owing to the very few higher order systems that form in the simulations), we ignore triples, quadruples, etc. and simply determine the binary fraction of the VLMBs. We show the evolution of the VLMB fraction for two of our simulations in Figs 8 and 9.

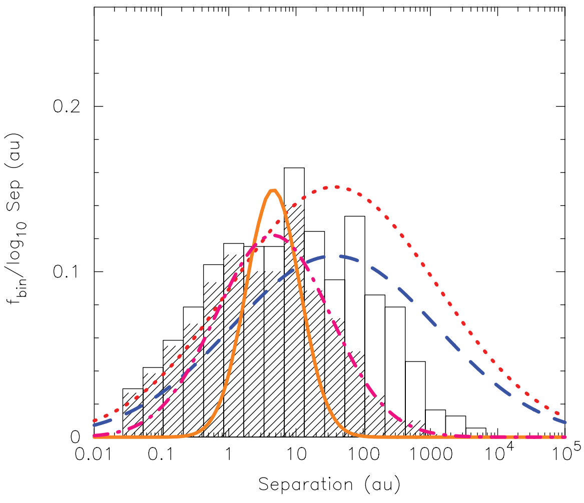
When the initial binary fraction is 0.5 and separations are drawn from the Duquennoy & Mayor (1991) distribution (Fig. 8), there is considerable break-up of (wide) systems within the first few crossing times within a cluster with an initial half-mass radius of 0.1 pc (as detailed for stellar binaries in Parker et al. 2009). The initial binary fraction is calculated to be 0.42, due to the widest binaries inputted into the simulations not being bound within the dense cluster (Parker et al. 2009). The final binary fraction is 0.29, within the uncertainty associated with the determination of Basri & Reiners (2006) of 0.26 ± 0.10. If we assume a less dense initial cluster configuration of 0.8 pc (to enable the formation and preservation of the widest VLMBs observed in the field), then the final multiplicity becomes 0.4, which does not agree with the upper limit of the observed value.

We also examine the change in binary fraction in a simulation using the VLMBA data as initial conditions. During the cluster evolution, the initially lower binary fraction of $f_{\rm VLMB} = 0.25$ is also reduced (Fig. 9), but only by 0.05. This is due to the majority of systems being close, and hence not susceptible to break up, but also a lower initial binary fraction will be dominated by the single VLMOs – any break-up of the small number of binaries will do little to the global binary fraction.

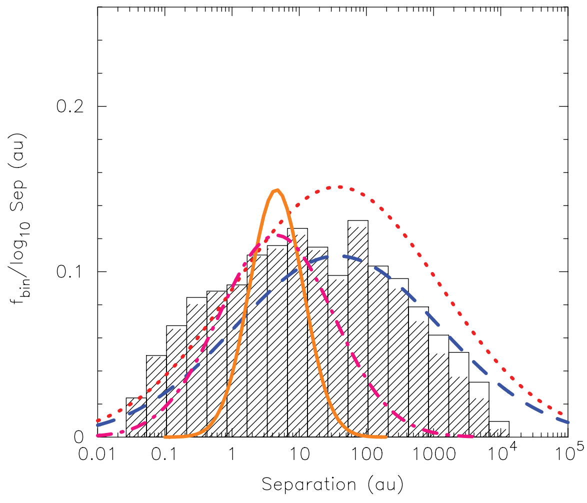
4.4 The evolution of the VLMB mass ratio distribution

In Fig. 10 we show the effect of cluster evolution on the mass ratio distribution of the VLMBs. The results in the plot are for a cluster with an initial half-mass radius of 0.1 pc, with separations and masses chosen from the VLMBA. The initial distribution is shown by the open histogram and the final distribution is shown by the hashed histogram. The distributions are both normalized to the total number of *initial* binaries.

Fig. 10 clearly shows that even in a dense cluster, the dynamical interactions do not change the mass ratio distribution of VLMBs.



(a) $r_{1/2}$ = 0.1 pc



(b) $r_{1/2}$ = 0.8 pc

Figure 7. The evolution of the separation distribution for VLMBs with initial separations drawn from the same $\log_{10}$-normal distribution as the stellar binaries. The initial multiplicity of the VLMBs is $f_{\rm VLMBs} = 0.5$, and we show the results for two different half-mass radii: (a) 0.1 pc and (b) 0.8 pc. The $\log_{10}$-normal fits to the data by Thies & Kroupa (2007, the solid brown line) and Basri & Reiners (2006, the dot–dashed magenta line) are shown. For comparison, the $\log_{10}$-normal fits for field M dwarfs (Fischer & Marcy 1992, the dashed blue line) and field G dwarfs (Duquennoy & Mayor 1991, the dotted red line) are also shown.

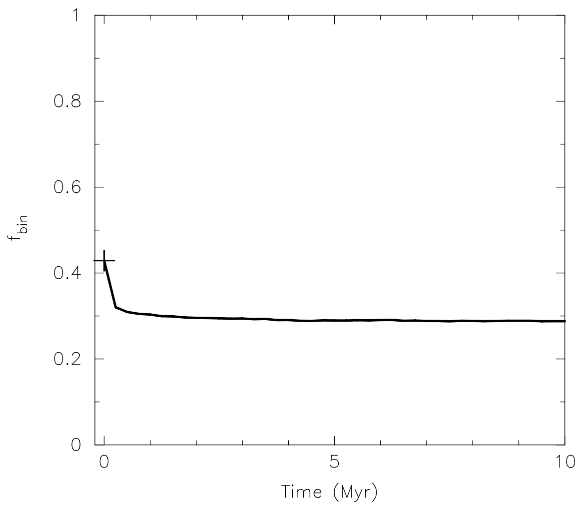


Figure 8. The evolution of the VLMB fraction over 10 Myr for a cluster with the VLMB separations drawn from the Duquennoy & Mayor (1991) distribution and an initial binary fraction of $f_{\rm VLMB} = 0.5$. The cross shows the initial binary fraction. The initial half-mass radius of the cluster is 0.1 pc.

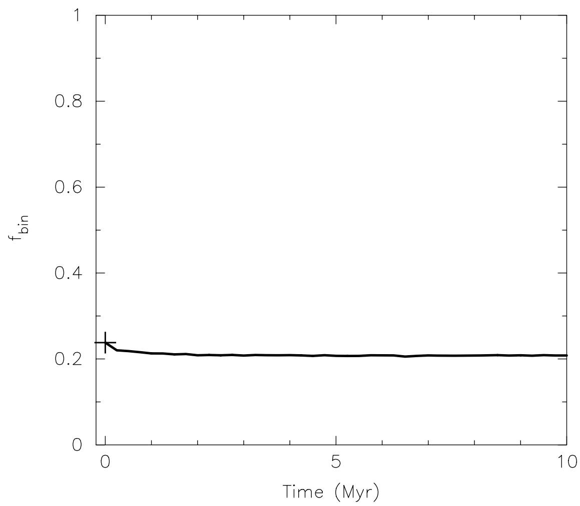


Figure 9. The evolution of the VLMB fraction over 10 Myr for a cluster with the VLMB separations drawn from the VLMBA and an initial binary fraction of $f_{\rm VLMB} = 0.25$. The cross shows the initial binary fraction. The initial half-mass radius of the cluster is 0.1 pc.

5 DISCUSSION

We have examined the dynamical evolution of the binary fractions and separations of a separate VLMB population in star clusters. Our aim is to investigate what the initial VLMB multiplicity and separation distribution could have been to reproduce the current observations.

Before starting, there are two key points to be considered in this discussion.

First, many binaries are susceptible to destruction in clusters (as seen above, also see Heggie 1975; Kroupa 1995a,b; Kroupa et al. 1999, 2003; Parker et al. 2009). How likely a binary is to be disrupted depends on its separation and the density of the cluster in which it was born. In low-density environments almost all VLMBs can survive, whilst in dense clusters VLMBs with separations >100 au are susceptible to disruption (see Fig. 7).

Secondly, the field is the sum of star formation from clusters of all masses and densities, and the field population has already been dynamically processed. Therefore, in the field we are not seeing the birth population of binaries, but a mixed and evolved population (Goodwin 2010). As the bulk of observed VLMBs are in the field we are not seeing their birth population.

5.1 Separation distribution

Several authors have attempted to parametrize the present-day separation distribution of the VLMBs. We set up the VLMBs in our clusters with four different initial separation distributions to

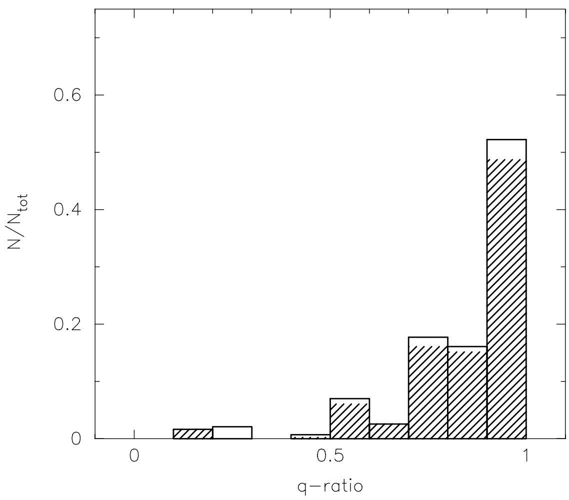


Figure 10. The evolution of the mass ratio distribution of VLMBs with initial masses and separations drawn from the VLMBA. The initial half-mass radius of the cluster is 0.1 pc and the data are normalized to the number of initial binaries. The open histogram shows the initial distribution, and the hashed histogram shows the final distribution.

investigate whether any of these evolve into the observed distribution, depending on the initial density of the cluster (defined by the half-mass radius) and multiplicity of the population.

In the simulations in which we use the Thies & Kroupa (2007) $\log_{10}$-normal fit to the data as the initial VLMB separation distribution, we find that dynamical processing in even the most dense clusters does not have a significant effect on the initial binary population. The initial separation distribution does not, by construction, contain wide VLMBs, and these are not formed *within* clusters. However, this distribution could be the initial VLMB distribution if the very wide binaries are able to form via capture during the cluster dissolution phase as proposed by Kouwenhoven et al. (2010) and Moeckel & Bate (2010) for very wide stellar binaries. In this case, the initial binarity of the VLMB population must be low at formation as few binaries are destroyed (and conversely a few very wide systems may be created).

Using the currently observed VLMBA data as the initial distribution also does not reproduce the observations. Again, the close binaries in the main peak are virtually unaffected by dynamical disruptions. In this case very wide VLMBs can survive in low-density clusters, but they are destroyed in high-density clusters. Therefore starting with the observed population cannot reproduce the observed population unless, once again, some very wide binaries are produced during cluster dissolution.

Adopting the much wider Basri & Reiners (2006) distribution as an initial condition has some success in reproducing the observed population in that it starts with a number of wider VLMBs and so, even after dynamical processing some wider binaries remain. However, this distribution requires us to believe that a large close VLMB population exists which is currently unobserved (Maxted & Jeffries 2005; Burgasser et al. 2007), though see Joergens (2008), and also that a significant population of VLMBs with separations of tens of au also remains unobserved, which is rather more controversial as direct imaging surveys are sensitive to this separation regime in both clusters *and* the field (Burgasser et al. 2007; Joergens 2008).

Using the current field initial M-dwarf separation distribution as the initial VLMB distribution in part fails to match the current VLMB population. Whilst high-density clusters can be evolved to something resembling the Basri & Reiners (2006) distribution, low-density clusters hardly process their VLMB population at all resulting in far too many wide- and intermediate-separation VLMBs.

Therefore, we can conclude fairly robustly that *the currently observed VLMB fraction and separation distribution are not those of the birth population*. This raises the obvious question of what are the binary fraction and separation distribution of the birth VLMB population? To answer this we have to address two interrelated questions.

First, do all clusters produce the same birth populations? And secondly, what is the mixture of cluster densities that contribute to the field? It is the combination of cluster densities rather than masses that is important, as it is density that controls dynamical processing. Any high-density cluster will process its wide binaries, whilst a low-density cluster will not, regardless of its mass (Parker et al. 2009).

If all clusters do not produce broadly similar birth populations, then it becomes almost impossible to draw many conclusions about birth populations other than that after dynamical processing they sum up to make the currently observed population (see Goodwin 2010). However, if we accept as a starting point that star formation is roughly universal and that the birth populations of VLMBs in all clusters are roughly the same, then we are able to draw some conclusions.

The pertinent points are all illustrated in Fig. 7. In this figure, we see two key points: high-density clusters are extremely efficient at destroying VLMBs with separations >20–100 au, whilst low-density clusters leave their birth populations relatively intact; and that no cluster can effectively alter the birth populations of VLMBs with separations <20 au. Therefore, the VLMB population with separations <20 au must be very close to the birth population, and the birth population of VLMBs with separations >20 au will have been dynamically processed and must have contained many more systems initially than are observed in the field.

This implies that the (putative universal) birth VLMB fraction is higher than we now observe, and that the birth separation distribution must have a significant excess of systems with wide separations (see Kroupa 1995b, for a similar argument for stellar binaries).

How much higher the birth binary fraction must have been depends on the density distribution of star clusters. It should be noted that this is not the *current* density distribution, but rather the range of maximum densities clusters have reached during their evolution. There are suggestions that many clusters undergo an early dense phase in which their densities can reach those simulated by the 0.1 pc half-mass radius clusters we model here (see Kroupa, Petr & McCaughrean 1999; Moraux, Lawson & Clarke 2007; Bastian et al. 2008; Allison et al. 2009; Parker et al. 2009; Goodwin 2010). If many clusters do indeed undergo an early dense phase, then the initial VLMB population may need to be similar to the very wide $f_{\rm mult} = 0.5$ population illustrated in Fig. 7(a). If, on the other hand, many stars are created in low-density associations, the initial VLMB population would only need to contain slightly more wide binaries than are now observed.

What is clear is that VLMBs and M dwarfs [taking the Fischer & Marcy (1992) distribution] must have had very different birth populations. M dwarfs are subject to exactly the same dynamical processing as VLMBs (only slightly modified by their larger masses), and to have such significantly different separation distributions in the field means they must have been born with significantly different distributions.

The key regime in which more observations are required is in examining if there are more wide and, especially, intermediate separation VLMBs. The confirmation of either presence or lack of a significant VLMB population with separations of ∼100 au where we know that there are significant numbers of M-dwarf binaries is crucial in order to determine how different the initial binary populations are.

5.2 Mass ratio distribution

As demonstrated in Fig. 10, the effect of dynamical evolution on the mass ratio distribution of the VLMBs is negligible, even in the most dense clusters. What is clear is that there is no preferential break-up of systems with a particular q value; the distribution is uniformly lowered by dynamical processing, in agreement with the evolution of the mass ratio distribution for low-mass stars ($0.1\,M_\odot \leq m_p \leq 1.1\,M_\odot$ and $0.1\,M_\odot \leq m_s \leq 1.1\,M_\odot$) in clusters found by Kroupa et al. (2003). This means that the current mass ratio distribution represents the birth mass ratio distribution.

6 CONCLUSIONS

We present the results of N-body simulations of the effect of dynamical evolution on VLMBs in 'typical' $N = 2000$ Orion-like star clusters with various initial densities. In each cluster, we place a separate population of VLMBs and follow the effects of dynamical interactions on these systems.

Our conclusions can be summarized as follows.

(i) VLMBs with separations <10–20 au cannot be disrupted, even in the densest clusters. Therefore, the currently observed VLMB population with separations <10–20 au must be the primordial population. However, we note that the VLMB population at these separations is poorly known.

(ii) Many VLMBs with separations >100 au can be destroyed in very dense clusters (with half-mass radii of 0.1 pc), but are relatively unaffected in low-density clusters (with half-mass radii of 0.8 pc, so 512 times less dense).

(iii) If all star clusters produce the same *birth* VLMB population, then the birth VLMB binary fraction must have been somewhat higher than we observe in the field. The initial VLMB distribution must also have significantly more wide VLMBs than are currently observed unless capture during cluster dissolution is an effective wide binary formation mechanism.

(iv) The mass ratio distribution of VLMBs is unchanged by dynamical processing and so is a probe of the birth mass ratio distribution.

(v) M-dwarf binaries are also processed by clusters in the same way as VLMBs, and so the very different field populations must reflect very different birth populations.

Further work to better constrain (and improve the statistics of) the separation distribution of both VLMBs and M-dwarf binaries in the field would be beneficial in determining whether the transition in separations between M-dwarf and VLMBs is as abrupt as Fig. 1 suggests. If not, then the trend in decreasing multiplicity with primary mass, and fewer wide VLMBs than wide G-dwarf binaries, suggests a possible continuation through the hydrogen-burning limit from the stellar to the substellar regime.

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