Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRASL **430,** L6–L9 (2013) doi:10.1093/mnrasl/sls037

Binary mass ratios: system mass not primary mass

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Accepted 2012 November 16. Received 2012 November 16; in original form 2012 September 17

ABSTRACT

Binary properties are usually expressed (for good observational reasons) as a function of primary mass. It has been found that the distribution of companion masses – the mass ratio distribution – is different for different primary masses. We argue that system mass is the more fundamental physical parameter to use. We show that if system masses are drawn from a log-normal mass function, then the different observed mass ratio distributions as a function of primary mass, from M-dwarfs to A-stars, are all consistent with a universal, flat, system mass ratio distribution. We also show that the brown dwarf mass ratio distribution is not drawn from the same flat distribution, suggesting that the process which decides upon mass ratios is very different in brown dwarfs and stars.

Key words: binaries: general – stars: formation.

1 INTRODUCTION

It has been known for a long time that many stars are physically associated in binary and multiple systems (Mitchell 1767). Recent studies suggest that many, possibly most, stars in the field are in multiple systems (e.g. Duquennoy & Mayor 1991; Fischer & Marcey 1992; Lada 2006; Bergfors et al. 2010; Raghavan et al. 2010; de Rosa et al. 2012; Janson et al. 2012). Numerical experiments have shown that it is extremely difficult to dynamically produce a binary in star-forming environments (Clarke & Pringle 1991; Kroupa 1995), which suggests that almost all binaries form as binaries. Therefore, the properties of binaries should contain a significant amount of information on the star formation process.

Observational binary surveys often take the approach of selecting a sample of stars of a particular spectral type and examining them for the existence of companions (e.g. Duquennoy & Mayor 1991; Fischer & Marcey 1992; Kouwenhoven et al. 2007; Bergfors et al. 2010; Raghavan et al. 2010; de Rosa et al. 2012; Janson et al. 2012). This is a perfectly sensible observational strategy; however, it means that the results are presented as binary fractions, separation distributions, mass ratio distributions etc. as *a function of primary mass*. In this Letter, we will show that our interpretation of binary data can change if we look at distributions of binary properties by *system mass* rather than by primary mass.

Binaries can be described in terms of four basic parameters. Each system will have a mass ratio, q, between the primary star (mass $M_{\rm p}$) and secondary (mass $M_{\rm s}$), $q = M_{\rm s}/M_{\rm p}$. The system will also have orbital parameters of semimajor axis and eccentricity. Within a population (however that may be defined) there is also a 'binary fraction' that measures what fraction of that population are binaries (see Reipurth & Zinnecker 1993). It is in the distributions of these properties that we hope to find information about the star formation process (see e.g. King et al. 2012a,b).

Most stars spend at most a few Myr in the fairly dense (compared to the field) star-forming regions in which they are born before dispersing into the field (Lada & Lada 2003). However, the interpretation of binary properties is complicated by the fact that many binaries are quite easy to dynamically destroy in their relatively dense birth environments (Heggie 1975; Hills 1975). In particular, the binary fractions and semimajor axis distributions of populations can be significantly altered, and how they are altered depends strongly on the density of the environment (see Kroupa 1995; King et al. 2012b and references therein).

Recently, Parker & Goodwin (2012) showed that the mass ratio distribution of binaries is generally not significantly altered by dynamics. This suggests that examining mass ratio distributions is a way of probing the outcome of star formation without having to account for the many potential problems of dynamical processing. Therefore, in this Letter, we will examine the mass ratio distributions of binary systems which are often modelled as having the form $f(q) \propto q^{\alpha}$ where $\alpha > 0$ favours more equal-mass systems, and $\alpha < 0$ favours more unequal-mass systems.

It is known that the binary mass ratio distributions are inconsistent with random pairing from the initial mass function (IMF; see Kouwenhoven et al. 2009; Reggiani & Meyer 2011). Random pairing from the IMF is probably not what is expected from physical arguments (see Kouwenhoven et al. 2009). However, it is unclear what physics of star formation does set the mass ratio distributions of binaries. An interesting observation is that the mass ratio distribution for G-dwarfs is independent of separation (Metchev & Hillenbrand 2009); however, it is completely unclear if this observation extends to other primary masses.

We take four ranges of *primary* masses for which there is reasonable observational data on the mass ratio distributions.

(1) Brown dwarf primaries with masses $0.04 < M_{\rm p}/{\rm M}_{\odot} < 0.08$. Brown dwarfs strongly favour equal-mass companions (Burgasser

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et al. 2007). Examination of the very low mass binary (VLMB) Archive[1] shows that of 97 VLMBs, only 7 have $q < 0.6$, and 47 have $q > 0.9$. A very rough fit suggests $\alpha \sim +1.5$. Brown dwarfs have a low binary fraction of around 10–20 per cent (Burgasser et al. 2007).

(2) M-dwarf primaries with masses $0.1 < M_{\rm p}/{\rm M}_{\odot} < 0.5$. Samples of field M-dwarf binaries have been investigated recently by Janson et al. (2012; see also Bergfors et al. 2010). Janson et al. (2012) find from a detailed analysis of their large sample that an underlying uniform mass ratio distribution is most likely, i.e. $\alpha \sim 0$ (see their section 7.1). M-dwarfs have a binary fraction of around 30–40 per cent (Fischer & Marcey 1992; Lada 2006; Bergfors et al. 2010; Janson et al. 2012).

(3) G-dwarf primaries with masses $0.9 < M_{\rm p}/{\rm M}_{\odot} < 1.1$. The mass ratio distribution of G-dwarfs is uncertain. Metchev & Hillenbrand (2009) find a tendency to lower mass companions with $\alpha \sim -0.4$, but Raghavan et al. (2010) find a roughly uniform distribution with $\alpha \sim 0$ (but with a significant $q \sim 1$ peak). The binary fraction of G-dwarfs appears to be 50–60 per cent (Duquennoy & Mayor 1991; Metchev & Hillenbrand 2009; Raghavan et al. 2010).

(4) A-star primaries with masses $2 < M_{\rm p}/{\rm M}_{\odot} < 3$. We take two A-star surveys, de Rosa et al. (2012) for the field and Kouwenhoven et al. (2007) for Sco OB. Both find a mass ratio distribution that favours lower mass companions with a distribution roughly $f(q) \propto q^{-0.4}$ (Kouwenhoven et al. 2007). It should be noted that both samples are of relatively distant visual companions, typically at several hundred au. Shatsky & Tokovinin (2002) found a similar result for B-stars in Sco OB with $f(q) \propto q^{-0.5}$. The binary fraction in A-stars is high at around ∼80 per cent in A-stars (Kouwenhoven et al. 2007; de Rosa et al. 2012; Peter et al. 2012).

In this Letter, we first argue that system mass is the underlying physical distribution in which we should be interested. We then perform a simple Monte Carlo experiment picking system mass from a log-normal system mass function and examining the variation mass ratio with primary mass and comparing it with the observations.

2 SELECTING BY SYSTEM MASS

We argue that to compare binaries one must examine the distributions of binary properties by system mass rather than by primary mass. If most binaries are primordial (as we argued above) then some physical process acts to fragment (or not) a system into two components and distributes the mass between the two components.[2] Therefore, the fundamental mass is the system mass, $M_{\rm sys} = M_{\rm p} + M_{\rm s}$, not just the mass of the primary star.

For example, when comparing three systems of component masses (1) 0.6 $\rm M_{\odot}$ + 0.6 $\rm M_{\odot}$, (2) 1 $\rm M_{\odot}$ + 0.2 $\rm M_{\odot}$ and (3) 1 $\rm M_{\odot}$ + 0.8 $\rm M_{\odot}$ we would argue that it is systems (1) and (2) that should be considered similar (they both have system mass 1.2 $\rm M_{\odot}$), not systems (2) and (3) (which have primary masses of 1 $\rm M_{\odot}$, but very different system masses).

2.1 A Monte Carlo experiment

To see what the differences selecting by system mass rather than primary mass can make, we perform a simple Monte Carlo experiment.

[1] Data as of 2012 August, http://vlmbinaries.org/.

[2] We will ignore if a system fragments into more than two objects; however, we will discuss higher order multiplicity in the conclusions.

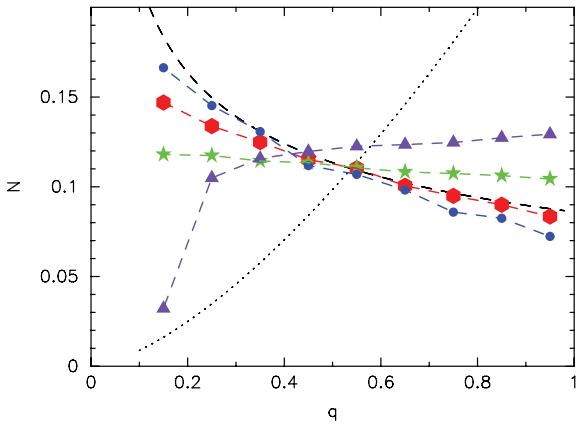

Figure 1. The mass ratio distributions (normalized to unity) of systems with brown dwarf (purple triangles), M-dwarf (green stars), G-dwarfs (red hexagons) and A-stars (blue circles) from an underlying flat system mass ratio distribution. For reference, the $f(q) \propto q^{-0.4}$ (black dashed line) and $f(q) \propto q^{1.5}$ (black dotted line) distributions are shown.

Let us take the log-normal system mass function with $\mu = -0.7$ and log-dispersion $\sigma = 0.6$ from Chabrier (2003). We then split each system into a binary with a mass ratio distribution $f(q) \propto q^{\alpha}$ with a minimum allowable value of $q = 0.1$. We also limit the lower mass of a secondary to be 0.01 $\rm M_{\odot}$ which has the effect of raising the minimum-q for very low-mass systems.

We will then select binaries by the mass of the primary star and examine the mass ratio distribution as a function of primary mass. We take the four primary mass ranges described above: brown dwarfs of 0.04–0.08 $\rm M_{\odot}$, M-dwarfs of 0.1–0.5 $\rm M_{\odot}$, G-dwarfs of 0.9–1.2 $\rm M_{\odot}$ and A-stars of 2–3 $\rm M_{\odot}$.

It turns out that the most interesting underlying mass ratio distribution is the simplest – when it is flat, i.e. $\alpha = 0$ always.

In Fig. 1, we show the resulting mass ratio distributions by primary mass. Brown dwarfs are shown by purple triangles, M-dwarfs by green stars, G-dwarfs by red hexagons and A-stars by blue circles. For reference the dashed line shows the distribution for $\alpha = -0.4$ (the observed value for A-stars), and the dotted line for $\alpha = +1.5$ (a rough fit to the brown dwarf observations).

It is clear in Fig. 1 that despite a universal system mass ratio distribution, the mass ratio distributions by primary mass are different. The underlying system mass ratio distribution is flat, but both A-stars and G-dwarfs show a preference for more unequal-mass companions, whilst M-dwarfs are flat, and brown dwarfs favour somewhat more equal-mass companions (note that the low number of brown dwarf systems in the first bin with $q = 0.1$–0.2 is mainly due to the constraint that $M_{\rm s}$ be greater than 0.01 $\rm M_{\odot}$).

The reason for this is that for a binary to have a primary mass of $M_{\rm p}$ the system must have a mass of $\sim M_{\rm p} < M_{\rm sys} \leq 2M_{\rm p}$ (formally, if $M_{\rm sys} = M_{\rm p}$, then the system is a single star). If $M_{\rm sys} = 2M_{\rm p}$, then $q = 1$; if $M_{\rm sys}$ is only a little greater than $M_{\rm p}$, then the system has low q.

Because the system masses are drawn from a log-normal distribution then the number of systems of different masses changes depending on which side of the peak the systems are found.

For a brown dwarf primary binary to have a low q, it must come from a lower mass system than a binary with high q. If the primary mass is $M_{\rm p} = 0.06$ $\rm M_{\odot}$, then systems with $q < 0.5$ must come from systems of mass 0.06–0.09 $\rm M_{\odot}$, and if $q > 0.5$ it must come from systems of mass 0.09–0.12 $\rm M_{\odot}$. The Chabrier (2003) system IMF has a peak at about 0.2 $\rm M_{\odot}$, and so there are fewer 0.06–0.09 $\rm M_{\odot}$

systems than 0.09–0.12 $M_\odot$ systems and so it would be expected that high q brown dwarf systems are more likely than low q.

The reverse argument holds for A-star binaries. For a 2.5 $M_\odot$ primary to be in a $q < 0.5$ system, the mass of the system must be 2.5–3.75 $M_\odot$. Such system masses are more common than the 3.75–5 $M_\odot$ systems a $q > 0.5$ binary must form from.

Therefore, the mass ratio distributions selected by primary mass are different to the underlying system mass ratio distribution.

As can be seen in Fig. 1, a uniform flat system mass ratio distribution does a good job of explaining the mass ratio distributions by primary mass of the stars ($M_p > 0.1\ M_\odot$). M-dwarfs, being near the peak of the system mass function, retain the flat form of the system mass ratio distribution as is observed (Janson et al. 2012). G-dwarfs are slightly biased towards more unequal-mass systems [in between the flat and $\alpha = -0.4$ distributions from Raghavan et al. (2010) and Metchev & Hillenbrand (2009), respectively]. And A-stars have a mass ratio distribution close to $\alpha = -0.4$ (the dashed line in Fig. 1, found by Kouwenhoven et al. 2007; de Rosa et al. 2012).

However, a single flat system mass ratio distribution fails completely to fit the brown dwarf mass ratio distribution with $\alpha \sim +1.5$ (the dotted line in Fig. 1, see VLMB archive data). No universal system mass ratio distribution can fit both the brown dwarfs and the stars at the same time.

It is worth considering the mass ratio distribution of companions to massive stars. In a model with a universal flat mass ratio distribution B- and O-stars will have a mass ratio distribution tending to low-mass companions very similar to that of A-stars (for the same reason). This appears at odds with observations of high mass ratios for massive binaries (e.g. Sana et al. 2012 and references therein). This could suggest different binary formation (possibly in a similar way to brown dwarfs). However, observational selection effects mean that low-mass or distant companions to O-stars are extremely difficult to detect, making drawing any conclusions from the current data extremely difficult.

2.2 The meaning of a flat mass ratio distribution

It is worth considering what a flat mass ratio distribution actually means for the distribution of mass in a system.

If one considers mass ratios by primary mass, then a flat mass ratio distribution simply means that the companion is equally likely to have any mass $\leq M_p$.

However, within a system the meaning of a flat mass ratio distribution is slightly more involved. The primary must (by definition) have a mass $M_p \geq M_{sys}/2$. A flat mass ratio distribution means that the primary is equally likely to have any mass $M_{sys}/2 \geq M_p > M_{sys}$. It does *not* mean that the mass is randomly distributed between the two components (and whichever is the most massive is then the primary). If the mass is randomly distributed, then low q systems are more likely (as a 0.9–0.1 split and a 0.1–0.9 split are equally likely, the distribution is roughly $f(q) \propto q^{-0.5}$). We will consider how mass might be distributed between stars in a system in a later Letter.

3 CONCLUSIONS

We have examined the mass ratio distributions of stars and brown dwarfs. We have chosen to examine the mass ratio distributions as they are the least likely to have been altered by any dynamical processing (see Parker & Goodwin 2012).

We have shown that the different mass ratio distributions of *stars* when selected by primary mass can all be explained by a universal, flat, system mass ratio distribution. However, the mass ratio distribution of brown dwarfs is very different and cannot be explained by a universal system mass ratio distribution.

This result would seem to suggest that all binary *star* systems (at least from 0.2 to 6 $M_\odot$) select their mass ratio distributions in the same way – i.e. that the same physical process(es) act to decide how mass is distributed between the components in a binary. It also suggests that this process is very different in low-mass systems and results in far more equal-mass systems for some reason. We might speculate that brown dwarf formation (or at least the formation of binary brown dwarfs) is fundamentally different to that of stars in some way (Thies & Kroupa 2007; Whitworth et al. 2007).

The details of the results will change if a different form of the system mass function is taken. It is always true that a non-constant system mass function will change the form of the mass ratio distribution by primary mass from the underlying distribution and so the conclusions of this Letter are valid unless one believes that system masses are drawn from a flat distribution. The underlying mass ratio distribution is always recovered for system/primary masses near the peak of the distribution (M-dwarfs for the Chabrier system mass function). It is difficult to change the system mass function significantly from the Chabrier form and recover a standard IMF.

It is important to keep in mind a number of caveats to this work.

First, we have ignored binary fractions and just considered systems that form a binary system. This is for the good reason that binary fractions can change with time and depending on environment; however, to understand star formation we obviously need to understand how and why some systems fragment into multiple systems whilst others do not, and how many systems are destroyed by dynamics.

Secondly, we have ignored higher order multiplicity. Much recent evidence suggests that triples and even higher order multiples are far more common than once thought (e.g. Tokovinin et al. 2006; Eggleton & Tokovinin 2008; Peter et al. 2012). Indeed, Peter et al. (2012) find that half of their A-star multiples are triples (and that is probably a lower limit). How triples and higher order multiples fit into the picture of multiple formation is still very unclear.

Thirdly, we have taken the observations at face value. Different samples have different selection effects and biases, and it is unclear how these should be dealt with (see e.g. King et al. 2012a,b).

However, even with these caveats, it is clear that we can have different interpretations of binary properties depending on if we group systems by primary mass or system mass. We argued above that system mass is probably the more physical mass to take – even if it is observationally much more difficult to produce a systematic survey by system mass (although *Gaia* should produce such a survey). And we have shown that if we do sample by system mass, then different masses of (stellar) system might well all have the same underlying mass ratio distribution.

ACKNOWLEDGMENTS

Part of this work was done at the International Space Science Institute (Bern, Switzerland) as part of an International Team.

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