

# Testing the universality of star formation – II. Comparing separation distributions of nearby star-forming regions and the field

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## ABSTRACT

We have measured the multiplicity fractions and separation distributions of seven young star-forming regions using a uniform sample of young binaries. Both the multiplicity fractions and separation distributions are similar in the different regions. A tentative decline in the multiplicity fraction with increasing stellar density is apparent, even for binary systems with separations too close (19–100 au) to have been dynamically processed. The separation distributions in the different regions are statistically indistinguishable over most separation ranges, and the regions with higher densities do not exhibit a lower proportion of wide (300–620 au) relative to close (62–300 au) binaries as might be expected from the preferential destruction of wider pairs. Only the closest (19–100 au) separation range, which would be unaffected by dynamical processing, shows a possible difference in separation distributions between different regions. The combined set of young binaries, however, shows a distinct difference when compared to field binaries, with a significant excess of close (19–100 au) systems among the younger binaries. Based on both the similarities and differences between individual regions, and between all seven young regions and the field, especially over separation ranges too close to be modified by dynamical processing, we conclude that multiple star formation is not universal and, by extension, the star formation process is not universal.

**Key words:** binaries: general – stars: formation – stars: kinematics and dynamics – open clusters and associations: general.

## 1 INTRODUCTION

Observations of the field show that at least one-third, and possibly over half of stars are in binary systems<sup>1</sup> (e.g. Michell 1767; Heintz 1969; Abt & Morgan 1976; Duquennoy & Mayor 1991; Fischer & Marcy 1992; Lada 2006; Bergfors et al. 2010; Raghavan et al. 2010). Young stars appear to have an even greater multiplicity than field stars, with some star-forming regions having almost all their stars in multiple systems (e.g. Mathieu 1994; Patience et al. 2002). This suggests that binaries are a very significant, if not the most significant, mode of star formation. Any theory of star formation must explain the properties of the binary systems observed, such as the multiplicity fraction (MF) and separation distribution, and

why the degree of multiplicity apparently falls between young star-forming regions and the field.

An important question in star formation is the universality of the star formation process: do stars (often multiples) always form in fundamentally the same way? Are massive star-forming regions such as 30 Doradus, which form  $> 10^5 M_{\odot}$  of stars, in some way just scaled-up versions of sparse, low-density regions such as Taurus, or are they fundamentally different? Are regions with similar densities and masses, such as Ophiuchus and IC 348, basically the same? That the initial mass function (IMF) appears to be universal (Bastian, Covey & Meyer 2010) might argue for universal star formation, but examining binary properties in different regions provides another method to test this hypothesis.

Unlike the apparently universal IMF, the binary properties of the field and young star-forming regions appear to be different. The most common interpretation of this interesting discrepancy is that young binaries are ‘processed’ – that is, some proportion of young multiple systems are destroyed by dynamical interactions, and/or that the decay of higher order multiples dilutes the multiplicity of stars over time (Heggie 1975; Hills 1975; Kroupa 1995a,b; Goodwin

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<sup>1</sup> There is evidence that a large number of systems are higher order multiples rather than simply binaries (Law et al. 2010). Although the majority of the observations in this paper are binary systems, the reader should bear in mind that this may be too simplistic a view.

& Kroupa 2005; Parker et al. 2009; Kroupa & Petr-Gotzens 2011; Marks, Kroupa & Oh 2011).

Some degree of processing *must* occur, but its importance is an open question. Processing occurs more efficiently in denser environments: there are more, and closer, encounters between systems in denser environments. Therefore, if most stars are born in (or go through) a dense environment, then processing may be very important (e.g. Parker et al. 2009; Marks & Kroupa 2012).

This is the second in a series of papers in which we analyse and interpret observations of binary systems in the context of examining the universality (or otherwise) of star formation. A serious complication we face in analysing observations of binary systems is that different surveys of different populations have different selection effects. Surveys can be sensitive to different separation ranges, primary masses and minimum companion masses. To alleviate this problem, we presented data sets for five young star-forming regions with which we constructed uniform samples to allow direct and meaningful comparisons of the MFs (King et al. 2012, hereafter Paper I). This was done for five regions: Taurus, Chamaeleon I, Ophiuchus, IC 348 and the Orion nebula Cluster (ONC). In this paper, we add two more regions – Corona Australis (CrA) and Upper Scorpius (USco).

In this paper, we examine the binary fractions and separation distributions of binary systems in our different regions. The processing of binaries is expected to lower the binary fraction, and this has been the focus of much previous work. However, processing should also alter the separation distribution of binaries: wider binaries should be more susceptible to destruction, possibly leading to fewer wider binaries in denser regions than initially formed in those environments.

## 2 BINARY PROPERTIES AND PROCESSING

In this section, we will briefly review how binary properties are characterized and how binary populations are expected to be processed.

### 2.1 Binary properties

The binary properties of a particular population can be characterized by a number of quantities. The multiplicity, or binary fraction, is a measure of the fraction of stars in binary (or higher order) systems and can be formulated in a number of useful ways (see Reipurth & Zinnecker 1993). In this paper, we will use the MF defined as

$$\text{MF} = \frac{B + T + Q}{S + B + T + Q}, \quad (1)$$

where S, B, T and Q are the numbers of single, binary, triple and quadruple systems, respectively.

For any given system, the four most important properties are the primary mass,  $M_p$ , and the secondary mass,  $M_s$ , which give the mass ratio  $q = M_s/M_p$ , and the two orbital elements of semi-major axis,  $a$ , and eccentricity,  $e$ . Within any population, there will be a distribution of  $M_p$  and  $M_s$  (related to the IMF), and of both  $a$  and  $e$ .

It is important to remember that for visual binaries (especially those considered in this paper<sup>2</sup>) we observe the instantaneous projected separation on the sky,  $s$ . This depends on  $a$  and  $e$ , but also on

<sup>2</sup>Although the observational samples used include optically and speckle interferometry-resolved binaries, we refer to them collectively as visual binaries.

the unknown phase, orientation and inclination of the orbit. In this paper, we analyse the *instantaneous projected separation distribution*, that is, the distribution of separations on the sky. This is the raw observed quantity and will be related to  $a$  and  $e$  in a non-trivial way (see Maxted & Jeffries 2005; Allen 2007).

### 2.2 Binary processing

Multiple systems can be processed in two ways: externally and internally. Internal processing is the rapid decay of unstable high-order multiples. Many systems with  $N > 2$  will be unstable and decay on a time-scale of roughly 100 crossing times (see Anosova & Orlov 1989; Sterzik & Durisen 1998). Usually the lowest mass member is ejected and the remaining system has lower energy and so becomes closer (harder, see below). This will change the binary fraction of a region (e.g. a triple becomes a binary and a single) and alter the separation distribution (see Goodwin & Kroupa 2005). However, this process is extremely rapid (time-scales of  $< 10^5$  yr) and will occur during the early stages of star formation (Goodwin & Kroupa 2005), probably at much younger ages than the young stars in our sample.

External processing from encounters with other stars/systems is more interesting as it should occur differently depending on the environment. Binaries can be divided into two broad categories: ‘hard’ and ‘soft’ (Heggie 1975; Hills 1975). Hard binaries are so strongly bound that it is highly unlikely that an encounter with enough energy to destroy them will occur. Soft binaries are so weakly bound that they are almost certain to be destroyed. In between soft and hard binaries are ‘intermediate’ binaries whose destruction depends on chance as to whether they have a destructive encounter or not (see Parker & Goodwin 2012).

The chance of a binary surviving in an environment depends on the binding energy of the binary and the frequency and energy of encounters (to first order set by the density and age of the environment). Roughly speaking, an encounter is destructive if the relative velocity of the encounter is greater than the orbital velocity of the binary.

The boundary between hard and soft binaries is the separation significantly below which dynamical destruction is very unlikely (hard), and significantly above which dynamical destruction is almost certain (soft). For a  $0.5\text{--}0.5 M_\odot$  binary that encounters a  $0.5 M_\odot$  star, the hard–soft boundary,  $a_{hs}$ , is approximately

$$a_{hs} \sim 450 \left( \frac{\sigma}{\text{km s}^{-1}} \right)^{-2} \text{ au}, \quad (2)$$

where  $\sigma$  is the typical encounter velocity (see Binney & Tremaine 1987). The hard–soft boundary will be at closer separations if the binary is more massive, or if the encounter is with a higher mass star.

The time-scale,  $t_{enc}$ , for an encounter at a distance,  $d$ , in an environment with number density of systems/stars,  $n$ , with velocity dispersion,  $\sigma$ , is

$$t_{enc} \sim 10^{10} \left( \frac{n}{\text{pc}^{-3}} \right)^{-1} \left( \frac{\sigma}{\text{km s}^{-1}} \right)^{-1} \left( \frac{d}{1000 \text{ au}} \right)^{-2} \text{ yr}. \quad (3)$$

For a typical young star-forming region with  $\sigma \sim 2 \text{ km s}^{-1}$  and  $n = 10^2 \text{ pc}^{-3}$ , we expect an encounter at 1000 au every  $\sim 50$  Myr. Alternatively, one in every 50 systems/stars will have an encounter at 1000 au every Myr.

In summary, we expect dynamical processing to depend on the environment, with more numerous and more destructive encounters

in denser, higher velocity dispersion environments. Hard (close) binaries will almost never be destroyed, but the definition of hard depends on the density of the environment. It should be noted that the destruction of binaries around the hard–soft boundary is a stochastic process depending on the exact history of a particular binary. However, we expect denser environments to be more destructive and to preferentially destroy wider binaries (see Kroupa 1995b; Marks & Kroupa 2011; Marks et al. 2011; Parker & Goodwin 2012). Therefore, if binary formation is universal, then we would expect to see both a lower binary fraction and fewer wider binaries in dense regions than in low-density regions (see Marks et al. 2011). However, it should also be noted that it is the *maximum* density a region reaches/reached that sets the degree of destructiveness of encounters – not necessarily the current density (see Parker et al. 2009; Parker, Goodwin & Allison 2011) – and therefore differences/similarities between regions may be due to *past* differences/similarities.

It is interesting to examine a binary separation range which should be unaffected by dynamical processing. The velocity dispersion in our regions is at most  $\sim 2 \text{ km s}^{-1}$  (Frink et al. 1997; Kraus & Hillenbrand 2008) which suggests that binaries with separations of  $< 100 \text{ au}$  should be hard in all of our clusters. This means that we should be observing binaries almost certain to be unaffected by dynamical processing and we will refer to these binaries as ‘pristine’. For five of our regions (Cha, CrA, Oph, Tau and USco) we have data for the range 19–100 au.

### 3 BINARY STAR SAMPLES

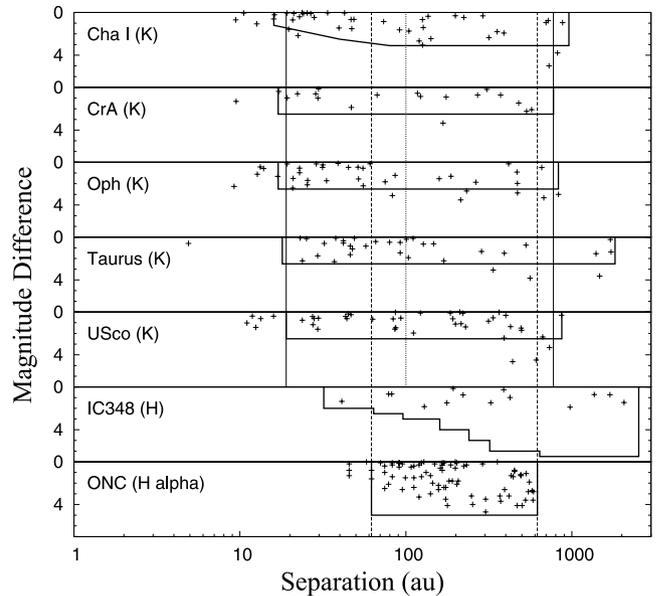
In Paper I, we compared the binary surveys of young stars in five well-studied regions: Cha I (Lafrenière et al. 2008), Ophiuchus (Ratzka et al. 2005), Taurus (Leinert et al. 1993), IC 348 (Duchêne et al. 1999) and the ONC (Reipurth et al. 2007). These regions were chosen both because they had been surveyed for binary companions and due to their well-known stellar membership, which was required to determine their stellar densities. In this paper, we have also included binary surveys of USco (Köhler et al. 2000) and CrA (Köhler et al. 2008). Unfortunately, the membership of these two new clusters is poorly known and so determining their densities is very difficult. The contrast and separation sensitivities of each survey are shown in Fig. 1 and summarized in Table 1.

#### 3.1 Binary surveys used

The binary surveys of Cha I (Lafrenière et al. 2008), IC 348 (Duchêne et al. 1999) and the ONC (Reipurth et al. 2007) were discussed in detail in Paper I and the same data are used in this study. However, the sample of stars considered in Taurus and Ophiuchus differs here from that presented in Paper I. For Taurus, we previously focused on the area of the northern filament, but here we have used the full survey of 104 targets from Leinert et al. (1993). For Ophiuchus, previously we had considered only those stars which were listed as members by Wilking, Gagné & Allen (2008). Here, we make use of the full binary survey of members identified by Ratzka et al. (2005).

##### 3.1.1 *Corona Australis*

The CrA star-forming region has been recognized as a host to young stars since at least the 1960s (Herbig 1960), but the high level of extinction in the central cloud ( $A_V \sim 45$ ) has hindered the identification of the full stellar population. In their review of this region, Neuhäuser & Forbrich (2008) presented a compilation of the



**Figure 1.** The contrast of each multiple system found in the seven surveys shown as a function of separation. The boxes demarcate the completeness of each survey and the vertical lines mark the bounds of our three separation ranges, 19–774 au (solid line), 19–100 au (first solid and dotted line) and 62–620 au (dashed line). The labels identify the clusters and the filter used in the observations.

**Table 1.** A summary of the separation ranges and contrasts from each binary survey used.

Region	Separation range (arcsec)	Separation range (au)	Contrast	Reference
Taurus	0.13–13.0	18–1820	$\Delta K \leq 2.5$	1
Oph	0.13–6.4	17–830	$\Delta K \leq 2.5$	2
Cha I	0.10–6.0	16–960	$\Delta K \leq 3.1$	3
CrA	0.13–6.0	17–774	$\Delta K \leq 2.5$	4
USco	0.13–6.0	19–870	$\Delta K \leq 2.5$	5
IC 348	0.10–8.0	32–2530	$\Delta H \leq 6.5$	6
ONC	0.15–1.5	62–620	$\Delta H\alpha \leq 5.0$	7

References: (1) Leinert et al. (1993), (2) Ratzka, Köhler & Leinert (2005), (3) Lafrenière et al. (2008), (4) Köhler et al. (2008), (5) Köhler et al. (2000), (6) Duchêne, Bouvier & Simon (1999), (7) Reipurth et al. (2007).

known members. Although too little is known of the full population to determine the density of this cluster, Köhler et al. (2008) surveyed the binary properties of the optically visible stars with near-infrared speckle interferometry and AO imaging. From 47 target systems, they found 19 binaries and no higher order systems. They reported an MF of  $36 \pm 9$  per cent within a separation range of 0.13–6.0 arcsec, corresponding to 17–774 au at a distance of 130 pc (Casey et al. 1998), where their observations were fully sensitive to flux ratios  $\geq 0.1$ . From the density of stars in the field, none of their observed binaries are expected to be a result of projection effects. Including previously reported single and multiple systems, Köhler et al. (2008) determined an MF of  $46 \pm 10$  per cent (CSF =  $52 \pm 10$  per cent).

##### 3.1.2 *Upper Scorpius*

USco is the most compact of the three regions which constitute the Scorpius–Centaurus (Sco–Cen) OB association, but still covers

$\sim 150 \text{ deg}^2$  on the sky at a mean distance of  $145 \pm 2 \text{ pc}$  (de Zeeuw et al. 1999). Due to the dispersion of this cluster, searches for members are incomplete, but  $> 100$  high-mass members have been identified through their proper motion and parallaxes (de Zeeuw et al. 1999) and  $\sim 100$  low-mass members with the *Einstein* and *ROSAT* X-ray observations of Walter et al. (1994) and Kunkel (1999). de Bruijne (1999) showed that the line-of-sight depth of USco could be up to 50 pc, adding to the uncertainty of measures of binary separations. Until recently, USco was thought to be approximately 5 Myr old, considerably younger than the other subgroups of the association (de Geus, de Zeeuw & Lub 1989; Preibisch & Zinnecker 2002). Recently, however, Pecaut, Mamajek & Bubar (2012) revised the age to  $\sim 11 \text{ Myr}$  based on the luminosities of its F-type stars.

Köhler et al. (2000) presented a binary survey of 118 young stellar systems in the Sco–Cen OB association where, after correction for X-ray selection bias and projected companions, they found an MF of  $32.6 \pm 6.1$  per cent within a separation range of 0.13–6.0 arcsec (corresponding to 19–870 au at 130 pc) and flux ratios  $\geq 0.1$ . For this analysis, we have restricted the Köhler et al. sample to those 70 targets labelled as USco-A, the majority of which were identified as members of USco by Preibisch et al. (1999).

### 3.2 Matching sample sensitivities

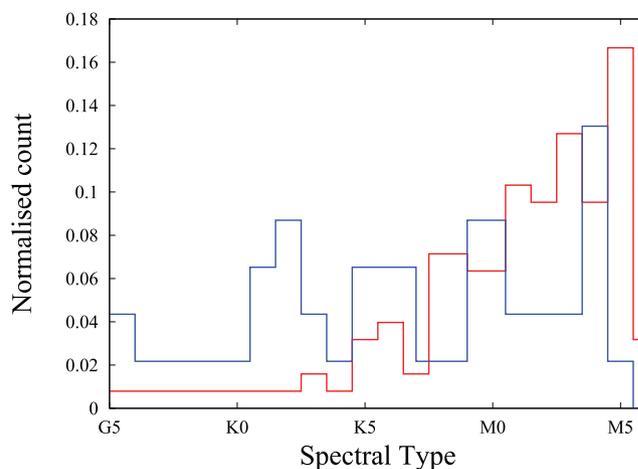
To allow fair comparisons between the samples of binary stars from different surveys, we applied identical cuts to the spectral type of the target stars, the contrast between primary and companion, and the projected physical separation of the binary. These limits were chosen such that all surveys were equally sensitive to binary systems, allowing us to compare what has been observed without having to apply uncertain corrections.

As in Paper I, we consider only targets with spectral types from G5 to M6 (limiting the primary masses to  $\sim 0.1\text{--}3.0 M_{\odot}$ ) and binaries with a contrast of  $\Delta K \leq 2.5$  (or equivalently,  $\Delta H \leq 2.7$ ,  $\Delta H\alpha \leq 5.0$ ). To maximize the separation range probed, we present a comparison over three different separation ranges. The widest separation range over which this contrast is achievable is 19–774 au, applicable to all regions except IC 348 and the ONC (the two most distant regions). As described in Section 2, we compare five regions over the ‘pristine’ range of 19–100 au, unaffected by dynamical evolution, and for all seven regions, we also compare companion separations over the common separation range of 62–620 au.

### 3.3 Spectral type distributions

Observations of binarity across the full range of stellar and substellar masses suggests that the binary fraction increases with stellar mass and the peak of the separation distribution moves outwards (Duquennoy & Mayor 1991; Fischer & Marcy 1992; Mason et al. 1998; Preibisch et al. 1999; Close et al. 2003; Basri & Reiners 2006; Burgasser et al. 2006). This implies that the separation distribution in a population is sensitive to the masses of the stars surveyed. To address this concern, we have investigated the distribution of spectral types among the target stars in all seven binary surveys. To build comparable samples, we have restricted the range of spectral types considered to G5–M6 ( $\sim 0.1\text{--}3.0 M_{\odot}$  at  $\sim 1\text{--}2 \text{ Myr}$ ), except for the ONC where the targets of Reipurth et al. (2007) are not identified.

Fig. 2 illustrates the distribution of spectral types for the targets of the binary surveys of Cha I and CrA (the most different distributions). Among the six regions with member lists with measured spectral types, the fraction of targets with spectral types from G5 to K5 range from  $\sim 10\text{--}40$  per cent.



**Figure 2.** The distribution of spectral types among the targets of the binary surveys of Cha I (red) and CrA (blue).

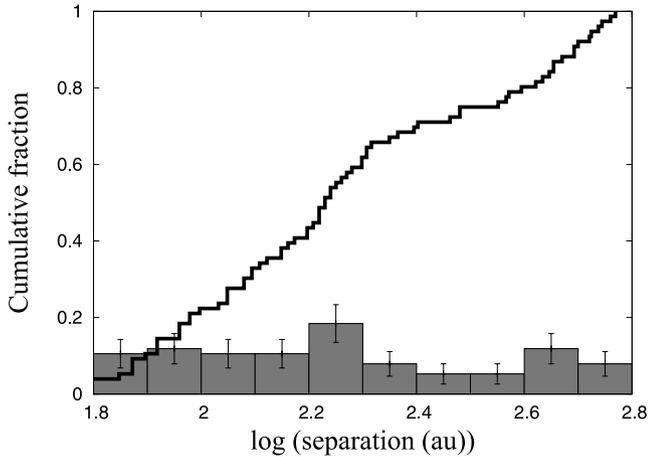
Since all the target regions have ages of  $\sim 1\text{--}2 \text{ Myr}$ , the targets have not yet reached the main sequence and so evolve to earlier spectral types as they age. Using the evolutionary models of Siess, Dufour & Forestini (2000) and the colour-effective temperature relation of Kenyon & Hartmann (1995), a 2 Myr old G5 (K4, K5, M6) star will evolve to a spectral type of A0 (F6, G6, M6) by 1 Gyr. The majority of the  $\sim 2 \text{ Myr}$  old cluster primaries (G5–M6) therefore cover approximately the same range in mass as the field binary surveys of Duquennoy & Mayor (1991) and Fischer & Marcy (1992).

### 3.4 Cumulative distribution functions

In this paper, we concentrate on the separation distributions of multiple systems. For visual binaries, observations record the instantaneous projected separation on the sky of the system.<sup>3</sup> This separation depends not only on the semimajor axis and eccentricity of the system, but on the unknown phase, orientation and inclination of the orbit. Distributions of instantaneous separations can be statistically analysed to find the most probable underlying distributions of semimajor axis and eccentricity (e.g. Maxted & Jeffries 2005; Allen 2007), but in this paper we analyse the observed instantaneous projected separations.

The distributions of binary separations are generally presented as binned histograms in log-separation or log-period (note that determining the period relies on knowing the semimajor axis which is not directly observed). Such histograms have the advantage of including both the binary fraction and separation distribution in a single figure, but they also confuse the comparison between different separation distributions. Therefore, in this paper, we will examine both the MF as a function of binned separation and the cumulative distribution functions (CDFs) of binary separations. A comparison of these approaches is shown in Fig. 3, which includes the separation distribution of the binary systems in the ONC as both a binned histogram and a CDF. Both show a relatively flat separation distribution, but the slight excess of binaries around a separation of  $\sim 200 \text{ au}$  [ $2.3$  in  $\log_{10}(s)$ ] is more distinct in the CDF than the histogram (indeed, without the CDF this feature is unclear).

<sup>3</sup> Some nearby visual binaries have been observed sufficiently long (often  $> 100 \text{ yr}$ ) for orbital solutions to have been found, but our point holds for the vast majority of visual binaries, especially those in star-forming regions.



**Figure 3.** A comparison of the cumulative separation distribution and a binned histogram for the binary companions in the ONC within the separation range 62–620 au.

In this paper, we analyse the separations of *all companions*, not simply all binary companions. This means that multiple systems will contribute more than one separation to the CDF. We feel this is a more consistent approach than the alternative of including only one companion per system, or limiting any comparison to binary systems. However, we feel it is important for the future to develop some more consistent way of including higher order multiples, but this is beyond our remit in this paper.

#### 4 ANALYSIS

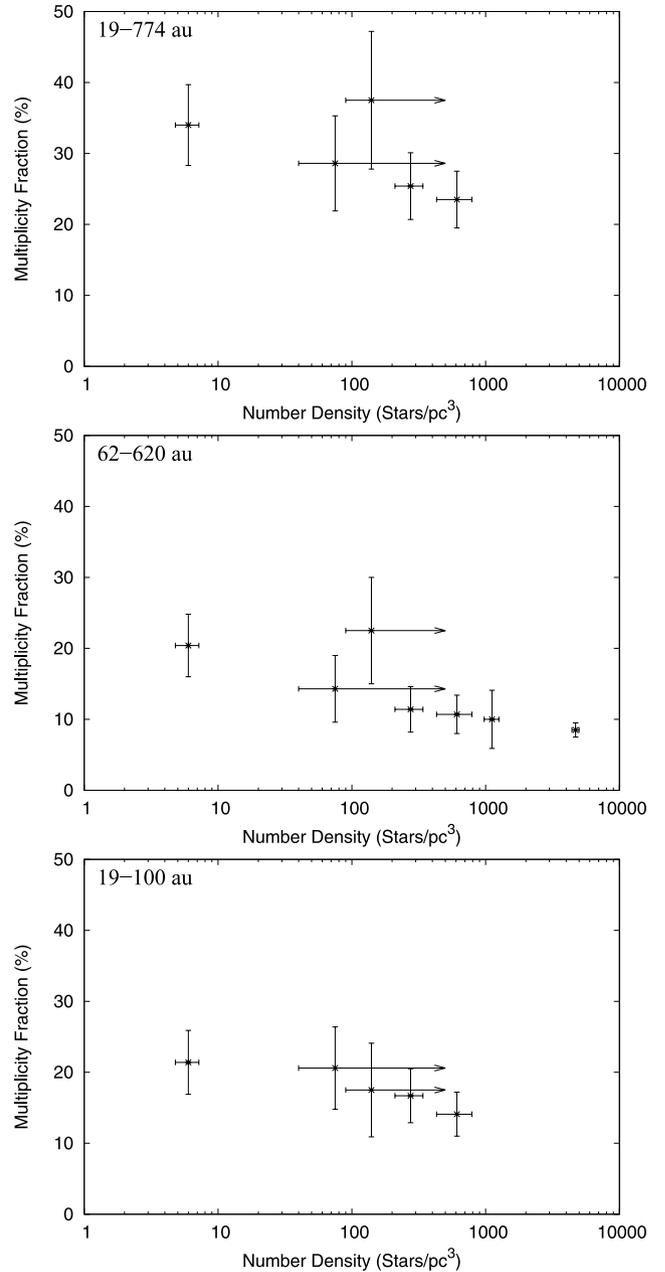
In this section, we examine the variation of the MF in each of three separation ranges of 19–774, 62–620 and 19–100 au. We then examine the binary separation distributions in the same three separation ranges comparing young regions with each other and with the field.

##### 4.1 Multiplicity fraction and density

In Table 2 and Fig. 4, we present the MF in each of our young regions and also give an estimate of the average volume densities (in stars  $\text{pc}^{-3}$ ). The two new regions introduced in this paper are USco with a density of  $\gtrsim 80$  stars  $\text{pc}^{-3}$  and CrA with a density of  $>150$  stars  $\text{pc}^{-3}$ . Due to the incomplete memberships of both regions, these estimates are necessarily lower limits, as indicated with arrows in Fig 4. CrA is a particularly problematic region in that its membership is very poorly known and, with the relatively high

**Table 2.** The densities (second column) and MFs in each separation range (third to fifth column) for each of our young regions (named in the first column). The error on the MF is the Poisson error, and the number in parentheses are the observed number of companions in each range for each region.

Region	Density (stars $\text{pc}^{-3}$ )	Multiplicity fraction (per cent)		
		19–100 au	19–774 au	62–620 au
Taurus	6	$21 \pm 5$ (22)	$37 \pm 6$ (38)	$21 \pm 5$ (22)
USco	$\gtrsim 80$	$21 \pm 6$ (13)	$29 \pm 7$ (18)	$14 \pm 5$ (9)
CrA	$>150$	$18 \pm 7$ (7)	$38 \pm 10$ (15)	$23 \pm 8$ (9)
Cha I	280	$16 \pm 4$ (19)	$28 \pm 5$ (32)	$11 \pm 3$ (13)
Oph	610	$14 \pm 3$ (21)	$24 \pm 4$ (36)	$11 \pm 3$ (16)
IC 348	1100	–	–	$9.7 \pm 4$ (6)
ONC	4700	–	–	$8.6 \pm 1$ (76)



**Figure 4.** The stellar MFs of our regions as a function of stellar density when we consider the same contrast cuts and stellar masses within the separation ranges 19–774 au (top), 62–620 au (middle) and 19–100 au (bottom). The densities are calculated within a projected distance of 0.25 pc from the cluster centre, except in the case of Taurus where a radius of 1 pc is used. For CrA and USco these densities are lower limits due to the incomplete census of their stellar members.

levels of extinction, the density may be significantly underestimated. Although its density is extremely uncertain, we assume that the MF and separation distribution are not biased by only sampling a subset of the members.

From our discussion of binary processing (see Section 2), it might well be expected that the MF will decrease with increasing density as encounters are closer, more energetic and more frequent. In Paper I, we found that the MF does not seem to decrease significantly with density, rather that Taurus could well be an outlier with an unusually

high MF. With the addition of two more regions, we can revisit this analysis.

Consistent with the results of Paper I, there is no *significant* correlation of MF with density. In Fig. 4, we show the MF against density over three separation ranges. From the middle panel which shows the 62–620 au range common to all seven regions, one might argue for a trend of decreasing MF with density with a halving of the MF over three orders of magnitude in density between Taurus ( $\sim 6$  stars  $\text{pc}^{-3}$ ) and the ONC ( $\sim 5000$  stars  $\text{pc}^{-3}$ ). However, it should be noted that only Taurus and CrA have an MF more than 1-sigma above that of the ONC, and the uncertain densities of CrA and USco significantly impact the interpretation of Fig. 4.

While it could be argued that there is some trend of decreasing MF with density in the 19–774 and 62–620 au separation ranges, in-line with the predictions of dynamical processing, it is very interesting to note that the 19–100 au separation range (bottom panel of Fig. 4) may also show the same trend – and this cannot be due to dynamical processing. Unfortunately, we do not have separations in this range for our two densest regions (USco and the ONC).

Rather frustratingly, the data on MFs with density give no clear results. There may or may not be a decrease in MF with density in the 62–620 au range (which universal star formation would predict), and there may or may not be a decrease in MF with density in the 19–100 au range (which universal star formation would not predict).

## 4.2 Comparisons of separation distributions

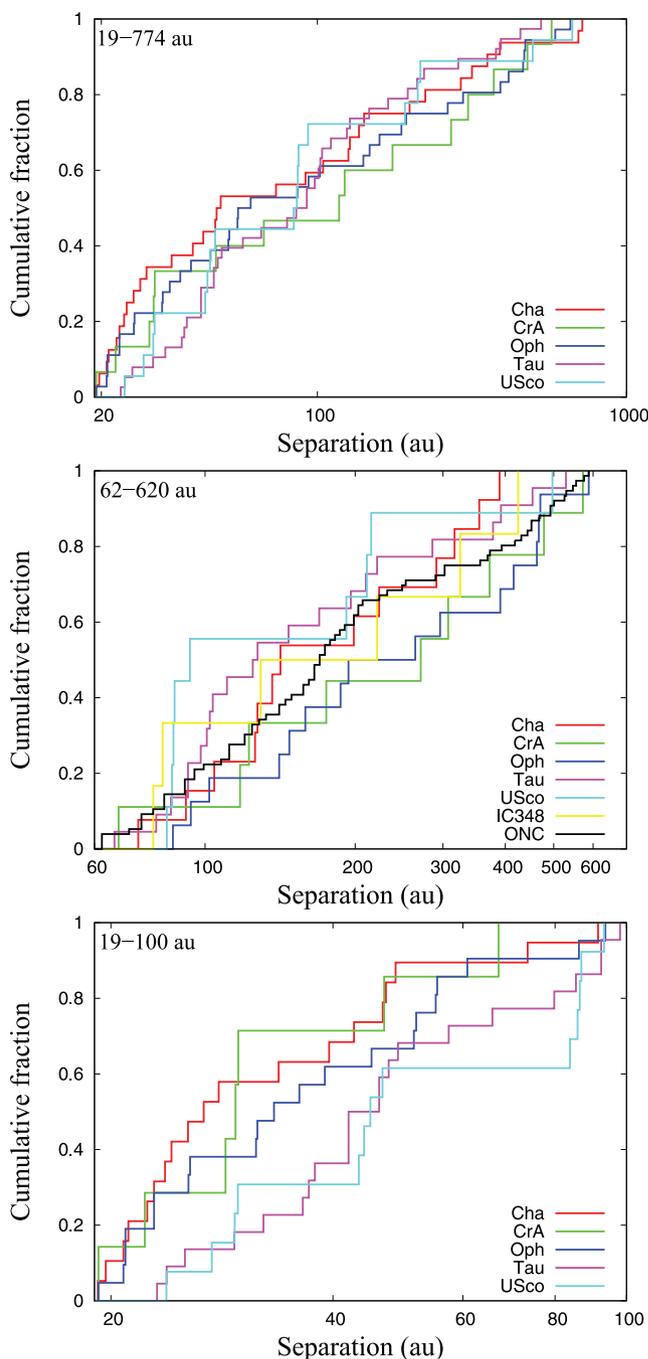
The separation distributions of the regions provide another observational test of dynamical processing. To summarize: universal star formation would predict fewer wide binaries in denser regions and would predict identical separation distributions for close binaries. It would also predict that the sum of all young regions would be the same as the field.

### 4.2.1 Comparisons between regions

In Fig. 5, we compare the CDFs of separations for the young regions. The top panel covers the widest range 19–774 au for Cha, CrA, Oph, Tau and USco. The middle panel shows the range 62–620 au for all regions (Cha, CrA, Oph, Tau, USco, IC 348 and the ONC) and the bottom panel is for the ‘pristine’ range of 19–100 au for the same five regions as the 19–774 au range. The most striking feature of these figures, especially in light of our previous discussion of binary processing, is that all of the separation distributions look remarkably similar, *except* in the limited pristine range.

A KS test on the separation CDF of all pairs of clusters in both full separation ranges (19–774 and 62–620 au, top two plots in Fig. 5) shows no statistically significant differences. In the wider 19–774 au separation range, the lowest value of the KS probability is 0.15 (between Tau and Cha) which on its own is a very marginal result, and given that we have 10 comparisons in total we would expect one to be different at the 10 per cent level. In the more limited 62–620 au range the lowest KS probability is 0.08 (between Oph and USco), which again is at the level we would expect from chance as we have 21 pairs to compare. Typically, the KS probability is between 0.2 and nearly unity. In many cases, low-number statistics makes finding a statistically significant difference very difficult, but an examination by eye of Fig. 5 also shows that they all appear very similar.

Another interesting feature is that they all appear to be roughly flat in log-space (see Kraus et al. 2008, 2011), although there is



**Figure 5.** The cumulative separation distributions for the companions in our comparable samples for clusters within the separation ranges 19–774 au (top), 62–620 au (middle) and 19–100 au (bottom). The line colour corresponding to each cluster is shown in the figures.

a tendency to have more low-separation (19–50 au) binaries than expected from a completely log-flat distribution.

Very interestingly, in the 19–100 au range of hard binaries there is tentative evidence for differences between the separation distributions. The statistics in this range are limited, but KS tests comparing regions to each other do suggest that Tau is different to both Cha (with a KS probability of 0.025) and CrA (with a KS probability of 0.063).

The examination of the bottom panel of Fig. 5 shows that both Tau and USco appear to have a fairly flat separation distribution whilst

Cha and CrA, in particular, have half of their binaries between 19 and 30 au. However, these apparent differences should be treated with some caution.

To investigate systems that should all be hard binaries, we have selected an arbitrary range of separations, limited at 19 au by observations and the choice of 100 au as a reasonable hard–soft boundary (see equation 2). Examination of the top panel of Fig. 5, which shows the widest range available from the observations, shows that USco has a ‘jump’ at just below 100 au separations. Clearly it is possible to select various arbitrary small ranges within the larger range that can find differences between separation distributions. This obviously raises the question as to what biases have been introduced by our (observationally constrained) choice of separation ranges.

#### 4.2.2 Field binary separation distributions

Separation distributions and MFs are very often compared to the field. The field provides a useful reference distribution, but most importantly, the field must be the sum of all past star formation in all different environments.

Duquennoy & Mayor (1991) compiled an extensive sample for nearby field G-dwarfs. They found that they could fit the semimajor axis distribution (after correcting for observational effects) with a log-normal distribution with mean  $\mu_{\log_{10}a} \sim 1.5$  (roughly 30 au) and variance  $\sigma_{\log_{10}a} \sim 1.5$ . A more recent study by Raghavan et al. (2010) finds a similar distribution. These samples have a huge advantage of being volume limited and complete for almost all separations, therefore providing an ideal reference sample for primaries of  $\sim 0.8\text{--}1.6 M_{\odot}$ .

The separation distribution for stars other than G-dwarfs, however, is less certain. Mayor et al. (1992) found that K-dwarfs appear to have a similar separation distribution to G-dwarfs, but with lower number statistics. Fischer & Marcy (1992) compiled data for M-dwarfs from a variety of sources: their results are possibly consistent with the G-dwarf separation distribution, but could well favour a lower mean (see also Bergfors et al. 2010). For A-stars it is possible that the typical separation is wider than for G-dwarfs, but limited observed separation ranges and low-number statistics mean that this is very difficult to confirm (Kouwenhoven 2006).

#### 4.2.3 Comparisons between the young regions and the field

We have chosen to compare our separation distribution with that of Raghavan et al. (2010). The primary stars in the Raghavan et al. sample have spectral types from F6 to K3. To better match the young region sample we remove from their sample of 259 companions, 10 L- and T-type brown dwarfs (to better match our sample of stellar companions) leaving 186 companions with measured separations, 48 with spectroscopically determined orbital elements and 15 with only estimates of the orbital period. For all of the Raghavan et al. spectroscopic binaries, the periods are short enough that the instantaneous separation will always be smaller than the lower limit to our separation ranges (19 au) and for 13 of the 15 systems with estimated periods, those periods (or direct imaging) also imply maximum separations below 19 au. We neglect the two systems for which we have no useful information (HD 16673 Aa,Ab and HD 197214 Aa,Ab) and use the 186 companions with measured separations to make a comparison with our cluster samples. Applying the same separation cuts to the Raghavan sample, we are left with 48, 60 and 97 companions in separation ranges 19–100, 62–620 and 19–774 au, respectively.

We add together all of the systems in our young regions to produce a single combined young sample. The apparent similarities between all young regions in the 19–774 and 62–620 au ranges (see above) make this (we hope) not a completely unreasonable thing to do.

As noted in Section 3.3, the sample of young regions contains primary stars with spectral types from G5 to M6, which will evolve to become main-sequence stars with spectral types of  $\sim A0\text{--}M6$ . Although the majority of our sample is comprised of late-type stars, the typically wider separations and higher multiplicity of high-mass stars (see Kouwenhoven 2006) may bias any comparison to a field survey of solar-type stars.

We therefore make two comparisons between the young binaries and the Raghavan et al. (2010) sample of field binaries by selecting subsets of similar primary mass. The first comparison involves young stars with spectral types K4–K7, which correspond to spectral types of  $\sim F6\text{--}K3$  at field ages (estimated from evolutionary models, see Section 3.3), the closest possible match to the Raghavan et al. targets. The second comparison includes all stars with spectral types later than K4, i.e. all stars of lower mass than  $\sim 1.6 M_{\odot}$ . Although the K4–M6 sample includes stars of lower mass than the Raghavan et al. study, the larger sample allows for a more statistically significant comparison, and is interesting to search for differences (or lack of) between the two young samples.

In Fig. 6, we show the comparisons between the separation distributions of the complete low-mass sample (K4–M6, blue line), comparable primary mass sample (K4–K7, red line) and field sample (black line). This is done for the widest 19–774 au sample (top panel), the 62–620 au range encompassing all young regions (middle panel) and the 19–100 au pristine range (bottom panel).

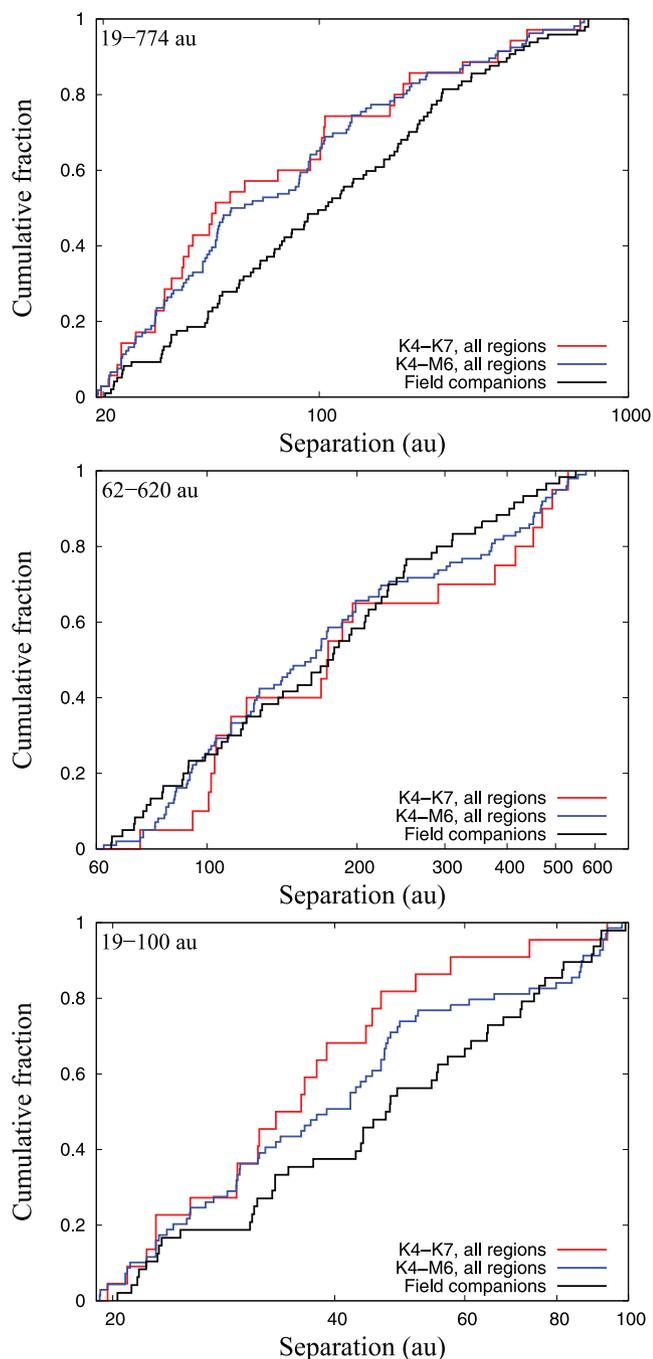
To supplement Fig. 6, the companion star fractions (CSFs) of the young samples in bins of separations are plotted in Fig. 7, where the black histogram shows the field CSF, the red histogram shows CSFs for all clusters in the limited 62–620 au range (cf. bottom panel of Fig. 6) and the blue histogram shows the CSFs for the five regions with uniform coverage in the 19–774 au range.

There are a number of very interesting features of Figs 6 and 7. First, the two young samples (K4–M6, blue, and K4–K7, red) in Fig. 6 are similar in all cases. The subset restricted to higher mass primaries has fewer stars within it as most of the primaries in the young regions are relatively low mass, but a KS test does not distinguish between the young region samples in any of the three ranges.

Secondly, the field separation distribution is significantly different to the young samples in two of the three ranges shown in Fig. 6. In the 19–100 au range the KS probability comparing the field and the K4–M6 sample is 0.16, whilst for comparable primary masses (K4–K7 sample) it is only 0.05. In the 19–774 au range the KS probability comparing the field and the K4–M6 sample is 0.01, whilst for comparable primary masses it is 0.03. In the 62–620 au range, however, the KS probability comparing the field and the K4–M6 sample is 0.65, whilst for comparable primary masses it is 0.81.

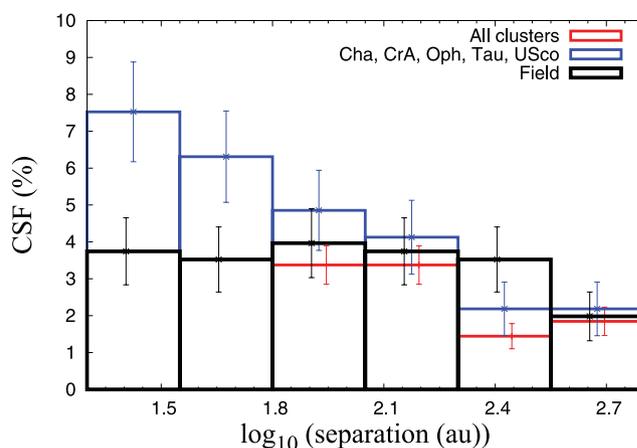
This illustrates a potential danger when using limited ranges of separation with a cumulative distribution plot. An interpretation using only the 62–620 au range in the middle panel of Fig. 6, would lead to the conclusion that the field and young cluster separation distributions were indistinguishable, but using the 19–774 au range in the top panel suggests very significant differences.

Examination of the top panel of Fig. 6 shows the source of the apparent discrepancy. Around 50 per cent of young binaries in the range 19–774 au have a companion closer than  $\sim 50$  au, whilst only around 25 per cent of field stars do.



**Figure 6.** The cumulative separation distributions for young binaries within the separation ranges 19–774 (top), 62–620 (middle) and 19–100 au (bottom) compared to the Raghavan et al. (2010) observations of field binaries (black lines). The blue lines show the sample with K4–M6 primaries. The red lines show the K4–K7 primaries which correspond to the F6–K3 range of the field primaries, i.e. the fairest comparison to the Raghavan et al. field survey.

In Fig. 7, we can compare restricted separation ranges by binning the data. In this figure, it is clear that the overabundance of binaries with separations  $< 60$  au in the young regions compared to the field is real. In the first two bins of Fig. 7, we see that the young regions have roughly twice the binary fraction found in the field. However, it also illustrates that these bins only contain data from the lower density regions – IC 348 and the ONC have no observations at these close separations.



**Figure 7.** The separation distributions against the CSF for all companions to K4–M6 primaries in regions where we have sensitivity to separations of 19–774 au (blue histogram) and 62–620 au (red histogram) compared to the Raghavan et al. (2010) field survey (black histogram). The CSF is used here for both the field and young regions to avoid having to choose which separation to plot for systems with two or more companions.

## 5 DISCUSSION

To address the question of the universality of star formation, we examine if MFs and separation distributions (within given separation ranges) vary from region to region, and whether they differ from the field.

We have presented a sample of companions in seven young regions in which we have, as far as possible, produced comparable samples with the same selection criteria. This allows a comparison of MFs and separations in two ranges: 19–774 au for five clusters (Cha, CrA, Oph, Tau and USco) and 62–620 au for all clusters (also including IC 348 and the ONC). In addition, we selected a limited 19–100 au range in which all of the systems are expected to be unaffected by dynamical processing.

There is a possible weak trend of decreasing MF with increasing density in all separation ranges, including, unexpectedly, the 19–100 au unprocessed range. In the 62–620 au range, the separation distributions of all our young regions are similar to each other and to the field. In the wider 19–774 au range the separation distributions of the five young regions are similar to each other, but significantly different to the field due to an excess of close binaries ( $\lesssim 50$  au, roughly twice what is found in the field). The only range in which there is any statistical evidence for variations between separation distributions of individual young clusters is in the 19–100 au range.

We reiterate here that we are considering a limited range of binary separations of 19–774 au in which we can compare different regions. In particular, we only have data for all regions in a very limited range of 62–620 au (set by the observational constraints of the ONC sample of Reipurth et al. 2007).

### 5.1 Non-universal binary formation?

The ‘standard model’ of binary formation and processing suggests that the MFs and separation distributions at birth are the same in all regions (e.g. Kroupa 1995a,b,c; Goodwin & Kroupa 2005; Parker et al. 2009; Marks et al. 2011). It suggests that any differences between regions are due to dynamical processing which is more effective in denser regions, reducing both the MF and preferentially destroying wider binaries (see Section 2). Binary destruction is a rather stochastic process in the intermediate regime and so

the resulting separation distributions and MFs may vary somewhat, but the general picture of lowered MF and preferential destruction of wider binaries in denser environments usually holds (Parker & Goodwin 2012). Based on four main observations, *our analysis of the observational data strongly suggests that this standard model is incorrect.*

First, a trend of decreasing MF with density is expected in the standard model. However, we find that if any trend exists (for which the evidence is weak), it could also be present in the closest 19–100 au binaries where it cannot be due to dynamical processing (see Section 2).

Secondly, denser regions should process their wider binaries more strongly than low-density regions. It would be expected that both IC 348 and the ONC (the densest regions) should show a separation distribution with fewer wider (>300 au) binaries than low-density regions. Instead, all regions are indistinguishable in the 62–620 au range. It is possible, but unlikely, that *both* IC 348 and the ONC are unusual in the way they have processed their binaries – see Parker & Goodwin (2012).

Thirdly, the separation distributions of close binaries in the 19–100 au range cannot have been dynamically altered and consequently should always look the same (in different regions and in the field) in the standard model. However, this is the one region in which there *is* evidence for statistically significant differences.

Finally, the field is expected to match the sum of all star-forming regions. In particular, non-processable binaries in the 19–100 au range should match the field, but Figs 6 and 7 show that they do not. We note that we do not have data for our densest regions in the 19–100 au range, but for the sum of our regions to match the field, these two regions would have to have a very significant *lack* of 19–100 au binaries to balance the overabundance in our low-density regions.

This set of observational data strongly suggests that *binary formation is not the same everywhere* and therefore *star formation is not a single universal process.*

Probably the strongest evidence for this is the overabundance of 19–100 au binaries in the low-density regions compared to the field. This is extremely problematic as such binaries cannot be destroyed by dynamical processing in any nearby environment. Therefore, to match the field population, some regions *must* underproduce close binaries, or the nearby young regions on which we base our interpretation are not the source of most stars in the field. This second interpretation would be rather worrying as we base much of our understanding of star formation on these regions and to discover that they are not the source of most field stars would be problematic (to say the least).

Another unexpected observation is that the dense regions have the same distribution of intermediate binaries as the low-density regions. They have marginally fewer binaries in the 62–620 au range than the lower density regions, but the same fraction of their binaries are in the 62–300 au range as in the 300–620 au range. This is unexpected as denser regions should be much more effective at processing 300–620 au binaries than low-density regions. If anything, this suggests that high-density regions must produce *more* intermediate binaries than low-density environments which are then processed to a similar distribution as the low-density environments.

Recent observations suggest that this trend is not solely present in our compilation of data. Biller et al. (2011) find an excess of 10–50 au brown dwarf VLMS binaries in USco compared to the field. Kraus et al. (2011) also find an excess of 5–100 au binaries in Taurus compared to the field for low-mass (0.25–0.7  $M_{\odot}$ ) stars, but not for higher mass stars.

A possible model to explain these observations is that the denser an environment is, the wider the binaries it produces. That is, low-density regions overproduce close binaries compared to the field, but high-density regions underproduce them (and the sum results in the field values as no processing can occur). The similarities between separation distributions and MFs at 300–620 au between high- and low-density regions might suggest that high-density regions overproduce such binaries compared to the field and low-density regions. This is because such binaries are destroyed more effectively in high-density regions, therefore to look the same now, they must have started differently.

## 5.2 Altering close binaries

If the field is the sum of star-forming regions, then the overabundance of close (and unprocessed) binaries in nearby low-density star-forming regions compared to the field must be explained. In terms of dynamical destruction through encounters, so-called super star clusters, such as the Galactic Arches, Trumpler 14 and Westerlund 1, or R136 in the LMC, may be dense enough to affect binaries with separations <100 au. If these regions do process such close systems, and they all evaporate into the field, then the underabundance of close binaries in the field compared to low-mass star-forming regions could be reconciled.

We have data on <100 au binaries only for regions with total masses of a few  $\times 10^2 M_{\odot}$ . Naked clusters appear to have a cluster mass function of the form  $N(M_{cl}) \propto M_{cl}^{-2}$  (Lada & Lada 2003). If this mass function extends to embedded clusters, it suggests that an equal mass of stars forms in each decade of cluster mass. Therefore, an equal mass of stars forms in super star clusters ( $\sim 10^5 M_{\odot}$ ) as in our low-mass regions ( $\sim 10^2 M_{\odot}$ ). At first sight this may appear to solve the overabundance of close binaries; however, in a universal star formation model *all* stars must form with the low-density, unprocessable overabundance we see in the  $\sim 10^2 M_{\odot}$  regions. However, close binaries can only be processed in very high density regions with masses  $> 10^4 M_{\odot}$ , thus requiring a bi-modal density distribution in regions forming half of stars in low-density environments and half in very high density environments.

Finally, we note a recently proposed mechanism for the destruction of close binaries. Kornreich, Kaczmarek & Palfzner (2012) suggest that binaries form with a log-flat separation distribution. The wide binaries are processed dynamically in the cluster environment, whereas the close binaries decay due to dynamical friction with gas in the cluster, thereby sculpting the log-flat distribution into the log-normal observed in the field. For the orbital decay mechanism to be effective, a high gas density is required ( $10^4$ – $10^6 \text{ cm}^{-3}$ ), which presumably may be present in very massive clusters. However, we note that this mechanism is most effective at low separations (<10 au), and it is difficult to see how this could destroy or alter the required proportion of binary systems in our sample, which have separations in the range 19–100 au.

## 6 CONCLUSIONS

By collating and analysing binary statistics for seven nearby young regions we have created comparable samples of companions to stars with similar masses, separations from 19 to 774 au and contrasts of  $\Delta K \leq 2.5$ . We compare all seven regions with each other and with the field in the 62–620 au separation range. For the wider 19–774 au range we cannot include our densest regions (IC 348 and the ONC), nor can we for a restricted 19–100 au range in which dynamical processing should be unimportant.

Our results can be summarized as follows.

(i) There is either a weak trend or no trend of decreasing MF with density in all separation ranges, including the unprocessed 19–100 au range.

(ii) The separation distributions of all regions are statistically indistinguishable from one another, except in the 19–100 au separation range.

(iii) The MFs and separation distributions of the young regions are very different to the field in all but the 62–620 au separation range. Specifically, there is an excess of close binaries (<100 au) in these nearby regions compared to the field.

Our conclusion from these results is that binary formation is not universal and consequently *the star formation process is not universal*. The 19–100 au range in the low-density regions has not been, and will not be, dynamically processed, yet it is inconsistent with the separation distribution and multiplicity of comparable field stars. Only the densest Galactic clusters could process some of their sub-100 au binaries, but to explain the discrepancy half of all field binaries must originate in very massive clusters. This excess of close binaries in low-density regions compared to the field must mean that other regions underproduce close binaries, or that the regions we have analysed are atypical in some way.

To confirm these intriguing results, more observations, especially probing smaller separations, are required. CrA may be a particularly fruitful target as it is a relatively nearby region ( $\sim 130$  pc) with a Taurus-like multiplicity, but at significantly higher density. A more complete membership census would allow a firmer determination of its density and could demonstrate that denser regions do not necessarily have fewer multiple systems. However, it must be emphasized that care must be taken in ensuring that comparisons apply the same selection effects (separation range, primary mass and sensitivity to companions), in particular between different regions, but also between regions and the field.

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