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Binaries in star clusters and the origin of the field stellar population

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Many, possibly most, stars form in binary and higher-order multiple systems. Therefore, the properties and frequency of binary systems provide strong clues to the star-formation process, and constraints on star-formation models. However, the majority of stars also form in star clusters in which the birth binary properties and frequency can be altered rapidly by dynamical processing. Thus, we almost never see the birth population, which makes it very difficult to know if star formation (as traced by binaries, at least) is universal, or if it depends on environment. In addition, the field population consists of a mixture of systems from different clusters which have all been processed in different ways.

Keywords: binaries: general; stars: general; stars: formation; galaxies: star clusters

1. Introduction

Observations suggest that a significant fraction of stars (perhaps most) *in the field* are in binary or multiple systems† (see, e.g., Duquennoy & Mayor 1991; Fischer & Marcy 1992; Lada 2006; Eggleton & Tokovinin 2008). It seems to be impossible to dynamically produce binaries in anywhere near the numbers observed, and so the vast majority of binaries must have formed as binaries (Goodman & Hut 1993).

As we have seen earlier in this volume (see Clarke 2010; de Grijs 2010; Lada 2010), a significant fraction of stars appear to form in star clusters (see also Lada & Lada 2003). Because of their high densities, clusters are regions in which binary systems are likely to be altered (either destroyed or changed) by dynamical processes. Therefore, it is highly likely that far more binaries were formed than are now observed, and even those binaries that survive may have different properties at the present time compared to when they formed.

The field is the sum of all star formation. As much of that star formation was clustered, we expect that the field binary population has undergone some (very probably significant) dynamical processing in their birth clusters. Therefore, it is important to remember that the field binary population is *not* the birth binary population. The field is a mixture of systems from different environments, each of which will have been processed to some degree.

The dynamical processing of binaries in clusters will also alter the numbers and properties of various types of interesting astrophysical systems such as blue

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† Stars appear to have multiplicities from binaries to septuples (e.g., Eggleton & Tokovinin 2008). For brevity we shall use 'binary' to mean systems of any multiplicity, only drawing a distinction when it is required.

stragglers, low- and high-mass X-ray binaries, type Ia supernovae, and intermediate-mass black holes (Hut *et al.* 1992). However, in this review we will concentrate on 'typical' star formation that results in the bulk of the field, i.e., relatively low-mass clusters (10–10^5 $\mathrm{M}_\odot$) that disperse (are destroyed?) within a few Myr (see Lada & Lada 2003). Thus, we will ignore the extremely interesting, but relatively rare cases (at least in the Galaxy) of extremely massive young clusters, or extremely long-lived clusters in which many interesting dynamical processes involving binaries occur.

In this contribution we will review our current understanding of two key astrophysical problems: the universality of star formation and the origin of the field. Binaries are an excellent tool with which to attempt to answer these questions, as binary formation is a fundamental and very common (possibly universal?) outcome of star formation and so similarities and differences between binary populations are indicators of the similarities and differences in the star-formation process in different environments.

First, does star formation care about its environment (see also Clarke 2010; Lada 2010)? Is the outcome of star formation in cores of a particular mass (at the end of the class 0/I phase) always (statistically) the same? The initial mass functions (IMFs) of different regions often appear very similar, but binary properties are probably a far more detailed indicator of the similarity or otherwise of star formation in different regions (Goodwin & Kouwenhoven 2009).

Second, what is the origin of the field-star population? The field is the sum of star formation in high- and low-mass clusters and isolated star formation. Do we understand the origin of the field?

To attempt to answer these questions we will concentrate on local regions and clusters for which we have detailed observations down to low (often substellar) masses. Unfortunately, such clusters are of low mass and often low density and the applicability of extending the conclusions drawn from local star-forming regions to more extreme star formation in massive young clusters and starbursts is debatable.

In §2 we examine the observations of binary systems in the field and in different clusters. In §3 we discuss how binaries can be dynamically processed in clusters and how this alters the birth binary population. In §4 we will investigate what we can infer about the birth binary populations and if they are universal and discuss the origin of the field binary population. We conclude in §5.

2. Observations of binaries

Binary systems can be characterized by three fundamental parameters. The first is the period or separation of the system. Depending on how the binary has been observed, we may have detailed orbital information (such as the semi-major axis and eccentricity) or simply a projected separation. The second is the mass of the primary star. And the third is the mass ratio, which gives the relative masses of the components of the system, $q = M_2/M_1$, where M_1 and M_2 are the masses of the primary and secondary stars, respectively.

The fraction of stars which are in binaries is usually given by the 'multiplicity fraction' (often called just the 'binary fraction')

$$mf = \frac{B + T + Q + ...}{S + B + T + Q + ...}, \tag{2.1}$$

where S, B, T, Q, etc., are the numbers of single, binary, triple, quadruple, etc., *systems* (i.e., a binary system is made of two stars). A number of other methods of quantifying binary fractions are possible (in particular the 'companion-star frequency'; see Reipurth & Zinnecker 1993 for a detailed discussion).

Binaries are usually found in one of three ways: spectroscopic binaries (from radial-velocity variations, biased to close similar-mass companions), photometric binaries (from an 'incorrect' position on an Hertzsprung–Russell diagram, biased towards similar-luminosity or mass companions) and visual binaries (stars too close on the sky to be explained by chance projection, yet again biased towards similar-luminosity or mass companions). Clearly, all of these methods are biased, especially towards missing low-mass (low-q) companions. It is worth keeping in mind throughout that there could be hidden populations of binaries. A recent illustrative example is the discovery of wide (~ 100 au) brown-dwarf companions to stars (e.g., Burgasser *et al.* 2005, 2007).

Given these biases, it is important in any survey of binaries to understand the (primary) masses, separation ranges and mass-ratio distributions that the survey is sensitive to. Often, comparisons of different surveys are far more complex than they first appear (see, for example, the careful comparison by Duchêne 1999).

(*a*) *Binaries in the field*

The field provides the canonical binary properties to which other observations are compared, in particular the field G-dwarf distribution investigated by Duquennoy & Mayor (1991; DM91). DM91 found that field G dwarfs have a multiplicity fraction of ~ 0.6, a wide lognormal period/separation distribution with a peak at approximately 10^4 days/30 au and a mass-ratio distribution which peaks at $q = 0.2$ (but the latter depends on separation; see Mazeh *et al.* 1992).

However, DM91 only probe a very small mass range around 1 $M_\odot$. The vast majority of stars are M dwarfs, and the details of M-dwarf multiplicity are far more unclear. Fischer & Marcy (1992) and Reid & Gizis (1997) found a lower multiplicity fraction for M dwarfs, of ~ 0.35–0.4, with a roughly flat mass-ratio distribution (see also Lada 2006 and references therein). Fischer & Marcy (1992) found that the separation distribution is similar to that of DM91 (although it appears to peak at lower separations: see their figure 2). Lada (2006) reviews recent M-dwarf multiplicity surveys and argues that the M-dwarf multiplicity may be even lower, depending on the binary fractions amongst very-low-mass stars.

The binary properties of brown dwarfs are somewhat unclear, but it appears that their multiplicity fraction is very low, at 10–25% (e.g., Basri & Reiners 2006; Law *et al.* 2007), and that they have a far smaller range of separations, usually around 5–20 au (Close *et al.* 2003; Basri & Reiners 2006; Burgasser *et al.* 2007).

Binaries appear to be far more common in stars more massive than 1 $M_\odot$ than below, with a multiplicity fraction approaching 100% above a few $M_\odot$ (e.g., Abt 1983; Shatsky & Tokovinin 2002; Crowther *et al.* 2006; Kouwenhoven *et al.* 2007).

Many field stars are in higher-order multiples than simply binaries. Eggleton & Tokovinin (2008), in a survey of 4558 bright stars (almost all > 1 $M_\odot$), find a raw (uncorrected for selection effects) ratio of multiplicities of 2716 : 1438 : 285 : 86 : 20 : 11 : 2 between one and seven companions. This corresponds to at least 10% of field systems being higher-order multiples and Tokovinin & Smekhov

(2002) suggest that this fraction could be 20–30%. Surveys of young systems also seem to find many higher-order systems (e.g., Leinert *et al.* 1993; Koresko 2002; Brandeker *et al.* 2003; Correia *et al.* 2006; Lafrenière *et al.* 2008; Connelley *et al.* 2008), but selections effects make solid estimates of the higher-order multiplicity fraction difficult.

(*b*) *Young binary systems*

In the last 20 years, there have been many studies of the binary fractions of young (pre-main-sequence: PMS) stars. Note, however, that many of these surveys have concentrated on visual, and therefore relatively wide (hundreds of au), binary systems.

Mathieu (1994 and references therein) summarized the binary fractions and separation distributions of PMS stars and noted that there is a significant excess of binaries with separations around 100 au compared to the (G-dwarf) field (see also Patience *et al.* 2002). This has been confirmed in many young star-forming regions, but it is clear that different regions have different properties (see below).

Star-forming regions can be roughly divided into three categories: isolated, low and high density. Their definitions are somewhat arbitary (and can vary from author to author), but as a rough guide, isolated star formation has stellar densities similar to the Galactic field, of only a few stars pc−3. Low-density star-forming regions (low-density clusters or associations) tend to have densities of 10–100 stars pc−3 (e.g., Taurus), while high-density regions are more like the archetypal 'cluster', with densities of 10^3–10^5 stars pc−3 (e.g., from Orion to Westerlund 1).

Surveys of low-density star-forming regions tend to find an excess binary fraction of a factor of 1.5–2 over the (G-dwarf) field value. Leinert *et al.* (1993) and Ghez *et al.* (1993) found a significant excess of binaries in Taurus, with almost everything $> 0.3\ \mathrm{M}_\odot$ in a binary system. Ghez *et al.* (1997) find twice the field binary fractions in the star-forming clouds Chamaeleon (Cham), Lupus and Corona Australis (see also Köhler *et al.* 2008). Köhler *et al.* (2000) find an excess of binaries by a factor of 1.6 in Scorpius (Sco)–Centaurus, as do Patience *et al.* (2002) in α Perseus and Praesepe. Duchêne *et al.* (2004, 2007) and Haisch *et al.* (2004) also find significant excesses of binaries in very young (flat-spectrum and class I) sources in a number of low-density regions (also found by Connelley *et al.* 2008, but see below). Kraus & Hillenbrand (2007) find an excess of wide (300–1650 au) binaries in Taurus and Cham I, especially at higher ($> 1\ \mathrm{M}_\odot$) masses. Lafrenière *et al.* (2008) again find a significant excess of binaries (and especially triples) in Cham I.

However, studies of higher-density star-forming regions tend to find binary fractions similar to the field. Reipurth & Zinnecker (1993) found that PMS stars in groups of less than ten are twice as likely to have a companion than those in groups with more than ten members. In particular, the Orion Nebula Cluster (ONC) has a binary fraction similar to that of the field (e.g., Petr *et al.* 1998; Kohler *et al.* 2006; Reipurth *et al.* 2007), as do IC 348 (Duchêne *et al.* 1999) and η Cham (Brandeker *et al.* 2006). Connelley *et al.* (2008) also find that wide (500–4500 au) class I binaries are less common in denser regions (at odds with Duchêne *et al.* 2007, who find no environmental dependence).

There are a number of other observations that are worth noting. Studies of very-low-mass objects (brown dwarfs and the smaller M dwarfs) tend to find little or no evolution in the binary fraction between even high-density regions and the field (e.g., Ahmic *et al.* 2007). However, Bouy *et al.* (2006) find evidence for a wide (100–150 au) low-mass binary population in Upper Sco (USco), as do Konopacky *et al.* (2007) in Taurus, which are not seen in large numbers in the field.

Kraus & Hillenbrand (2007) find that wide binaries (330–1650 au) show a strong mass–multiplicity relationship in Taurus, Cham I and USco A, with these three clusters matching the difference between low- and high-density regions well (Taurus and Cham I have an excess while USco A looks like the field). But USco B is very strange, exhibiting an excess of wide companions compared to the field at all masses, possibly greatest at low masses, where approximately $35 \pm 15\%$ of M dwarfs have a wide companion. Köhler *et al.* (2000) also found that the typical separation in USco B was about 30 times greater than in USco A. This may be related to a possible very-low-mass binary population with separations of 100–150 au in USco (Bouy *et al.* 2006).

Connelley *et al.* (2008) also find that the binary fractions > 1000 au appear to evolve during the class I phase, even in low-density environments. They argue that this is the result of the decay of higher-order systems (see §3).

3. Dynamical processing of binaries

A key element in binary evolution in clusters is the dynamical modification of binaries through encounters with single stars and other binary systems (see also Vesperini 2010). This may result in a change in orbital parameters if the encounter is relatively weak or in the destruction (ionization) of one or the other binary system if the encounter is strong. In addition, a binary may swap a single star or component of the other binary for one of its components.

Heggie (1975) and Hills (1975) published seminal papers on dynamical processing of binary systems (for a more gentle introduction to some of these ideas, see the relevant sections of Binney & Tremaine 1987; see also Hut *et al.* 1992).

Binaries can be divided into three categories according to their binding energies relative to their environment. 'Hard' binaries are very strongly bound and are unlikely to suffer disruptive encounters. 'Soft' binaries are very weakly bound and tend to be destroyed by an encounter. 'Intermediate' binaries lie between hard and soft, and can sometimes be destroyed or significantly altered, but sometimes not (these are clearly the most interesting category, but their study requires N-body simulations). The evolution of binaries can be summarized by the Heggie–Hills law: hard binaries get harder, while soft binaries get softer with time.

The binding energy, E, of a binary with two components of mass M_1 and M_2 and semi-major axis a is given by $E = -GM_1M_2/2a$. If the binary is located in an environment in which the average mass of a star is m and the velocity dispersion σ, then a binary is hard if $|E|/m\sigma^2 \gg 1$, and soft if $|E|/m\sigma^2 \ll 1$ (and intermediate if $|E|/m\sigma^2 \sim 1$).

It is important to remember that it is not just the hardness or softness of a binary that is important in understanding whether that binary will survive: the encounter rate also plays a vital role. Even a soft binary may survive for a long time in regions where the encounter timescale is very long. Therefore, the environment in which a binary is found is of crucial importance. For example, the hard–soft boundary for a $1\ \mathrm{M}_\odot/1\ \mathrm{M}_\odot$ binary in the field, which has a velocity dispersion of several tens of km

s^{-1}, is a few au, but the vast majority of binaries are wider than this and perfectly stable because the encounter timescale is many tens of Gyr. However, in a ‘typical’ cluster with a velocity dispersion of a few km s^{-1}, the hard–soft boundary is tens of au, but the encounter timescale is only a few Myr, resulting in rapid dynamical processing.

It is also important to note that it is the *maximum* density a cluster has had, rather than the current density, which is important in setting the maximum size of binaries which we see in a cluster. For example, Parker *et al.* (2009) suggested that to explain the binary population of the ONC it must have been significantly denser in the past and it was during this short-lived dense phase that the binary properties were set (see also Kroupa *et al.* 2001; Scally *et al.* 2005; Moraux *et al.* 2007; Bastian *et al.* 2008; Allison *et al.* 2009).

There are several main effects of encounters between binary systems and single stars or other binary systems. Strong encounters can destroy or heavily modify (e.g., cause a swapping of partners in) binary systems, while even weak encounters can destroy soft systems or change their orbital parameters (e.g., hardening or softening the system, changing the eccentricity or inclination).

Higher-order systems (triples or higher) are often unstable and decay, usually ejecting the lowest-mass member (Anosova 1986), as suggested by Connelley *et al.* (2008) to explain the change of binary properties with age in class I systems (see also Delgado Donate *et al.* 2004; Goodwin *et al.* 2004; Goodwin & Kroupa 2005).

In addition, internal evolution may play a role: the companion may interact with the disc, migrate inwards or outwards, or magnetically brake (see Kroupa 1995*b*; and references therein). However, these processes probably only affect the tightest binaries and do so on a timescale that is short compared to the dynamical timescale of a cluster and so can be considered part of the ‘star-formation process’ (i.e., processes that occur in the class 0/I phase).

4. The initial properties of binaries and the origin of the field

As we have seen, there are a number of ways in which the birth properties of binaries can be altered. In all but the loosest associations and isolated star-forming regions we would expect some dynamical processing by interactions between systems. And even in isolated star formation we would expect decay of higher-order systems or internal evolution to play a role. Thus, in *any* star-forming region we can be almost certain that we are not observing the birth population. And how the birth population has been altered will depend on both the birth population and the local environment and its evolution.

This makes answering the two questions with which we started particularly difficult:

(1) What are the birth properties of binaries? Do they depend on environment or are they universal?

(2) What is the origin of the field? This may be rephrased as: what is the sum of all the processing in all clusters of all (different?) birth populations?

In short, the answer to (1) is that we are not certain, but what we do apparently know is very confusing when applied to attempting to answer (2). Such is science.

(*a*) *The birth properties of binaries*

In §2 *b* we reviewed a number of observations of young binary systems. Two key points are obvious from the observations:
(1) Young stars tend to have an excess of binary companions by a factor of 1.5 to 2 over the field.
(2) Denser star-forming regions tend to look like the field and have few binaries with separations greater than a few thousand au.

These two points can make sense within the context of clustered star formation. Clusters will process binaries and denser clusters will process them more efficiently. Therefore, the conclusion could be drawn that most stars form as binaries with an excess at fairly wide separations (hundreds to thousands of au) and dense clusters will rapidly process this initial population to look like the field. Therefore, most stars form in multiples, many of which are dynamically processed (e.g., Larson 1972, 2002; Mathieu 1994; Kroupa 1995*a*, *b*; Goodwin & Kroupa 2005; Goodwin *et al.* 2007).

However, while this scenario is almost certainly correct to some (possibly great) extent, it is not clear if (a) most stars form as binaries or (b) all star-forming regions produce the same population which is then processed to produce different (field or cluster) populations.

(i) *Do most stars form as binaries?*

As pointed out by Lada (2006), most stars (90%) are M dwarfs and most M dwarfs are single. The exact importance of this depends on how binarity is counted, if one third of M dwarfs form in binaries with other M dwarfs then although two thirds of M-dwarf *systems* form single, half of all M-dwarf *stars* form in binaries. However, from the point of view of star formation, if two thirds of low-mass *cores* form single stars, it would be the major mode of star formation.

The importance of binary- versus single-star formation, however, depends on what fraction of the initial M-dwarf binary population is dynamically destroyed. This, in turn, depends on the initial separation distribution of low-mass stars. There is some evidence for a wide (100–150 au) low-mass binary population in low-density regions (Bouy *et al.* 2006; Konopacky *et al.* 2007) which, if common, would be expected to be very susceptible to dynamical destruction (Goodwin & Whitworth 2007). To make binary formation the major mode of star formation, only around 20% of the birth population of M dwarfs would have to be in wide binaries.†

From theory, it might be expected that many low-mass cores only form single stars. If disc fragmentation is the most common mode of binary formation (see Goodwin *et al.* 2007), then very-low-mass cores should not form binary systems. The minimum mass for fragmentation in a disc is probably a few Jupiter masses (say, 0.005 $M_\odot$; Whitworth & Stamatellos 2006). For a disc to fragment, its mass must be significantly greater than this minimum mass to collect enough material to fragment without being sheared apart. Therefore, discs that fragment must probably be > 0.1 $M_\odot$ during the earliest phases of star formation. Most of this disc material will

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† For example, from 100 systems if 70 M dwarfs form as binaries, of which 20 are wide binaries, and 30 form as singles, then the destruction of the wide binaries would produce 50 (of 120) binary systems and 70 (of 120) single stars (as each binary destruction would produce two single M dwarfs).

accrete onto a component of the binary, resulting in a total system mass of > 0.1 M$_\odot$ (in addition to the material that was already in the primary), suggesting a minimum system mass for disc fragmentation as a mode of binary formation of perhaps 0.2 M$_\odot$, i.e., mid-M dwarfs (interestingly close to the point at which Maxted *et al.* 2008 find a dearth of low-mass binaries). However, at least some wide, low-mass binaries do exist, possibly a significant number, which present problems for star-formation models.

On the other hand, to produce the IMF from observed core-mass functions, the efficiency of turning cores into gas must be only around 30% (Alves *et al.* 2007; Goodwin *et al.* 2008). Therefore, 70% of the gas initially in a core must not be accreted onto the stars (why? how?), so possibly much of the material in the disc may not end up on the stars.

In summary, if most low-mass stars form single, then most stars form single. However, it is unclear what the birth separation distribution of low-mass stars is (i.e., are the wide, low-mass populations common or rare at birth?) and without this knowledge it is impossible to assess the degree of dynamical processing of low-mass birth binaries.

(ii) *Is star formation universal?*

Do all stars form the same way? Do cores of a particular mass always produce the same (statistical) outcome, or does this depend on environment? Can the differences between loose associations be explained as the outcome of different levels of processing of the same birth populations?

The simplest null hypothesis is that all star formation is the same in all environments and is then dynamically modified to produce different populations in different environments (Kroupa 1995*a*, *b*). This approach is very successful on a number of counts. The lack of wide binaries (> 1000 au) in dense clusters (like the ONC) compared to loose associations and the field (Scally *et al.* 1999) is explained by the almost complete dynamical destruction of such binaries. The underabundance of intermediate-separation (few hundred au) binaries in clusters and the field compared to T Tauri stars (see §2 *b*) is explained by the partial destruction of such binaries in clusters. Indeed, Kroupa (1995*a*) managed to construct a birth binary population that would produce the field when processed by a 'typical' cluster. There are, however, a number of problems with attempting to produce a universal birth binary population.

Importantly, it is unclear what a 'typical' cluster is. Clusters appear to form with a mass function $\propto M_{\rm cl}^{-2}$ (Lada & Lada 2006), which would imply that an equal mass of stars form in equal logarithmic mass bins. Therefore, 10^5 M$_\odot$ clusters produce as many stars as 10^2 M$_\odot$ clusters.

Also, different star-forming regions appear to form different birth populations. Köhler *et al.* (2000) and Kraus & Hillenbrand (2007) find significant differences between the apparently similar USco A and B associations, with USco B having significantly wider binaries, especially at low masses (see also Bouy *et al.* 2006). Kraus & Hillenbrand (2007) discuss the differences between USco A and B and argue that USco B is a lower-mass association (similar to Taurus or ρ Ophiuchus) and possibly not associated with the more massive Sco OB association.

USco B has probably always been a low-mass association, given its wide binary population. However, Kraus & Hillenbrand (2007) show that USco B is different from the low-mass associations Taurus and Cham I in that it has far more wide (300–1650 au) low-mass binaries than either of these associations (around 30% of 0.1–0.25 $M_\odot$ systems compared to only a few percent in Taurus and Cham I). Did such systems form in Taurus and Cham I only to be broken up? (Such major dynamical evolution seems unlikely unless Taurus and Cham I were significantly denser in the past.)

In addition, to explain the differences between USco A and B from purely dynamical processing, USco A must have been significantly denser in the past. Preibisch *et al.* (2002) suggest that the entire USco region was initially large (~ 25 pc) as it has a large size and low velocity dispersion, which suggests that the entire region was initially of low density. This analysis includes USco A and B as being part of the same star-forming event, while Kraus & Hillenbrand (2007) suggest that USco B should be treated separately. Even with this caveat, it suggests that USco A should not have undergone significant dynamical processing, making the differences difficult to explain by anything other than different birth populations.

It might be expected that (binary) star formation in different regions is different. In dense clusters such as the ONC (which was potentially significantly denser in the past; see above), the average distance between stars is only a few thousand au. At such densities, does it make sense to consider binaries forming with separations approaching the average separation? However, this depends on believing that dense clusters like the ONC *formed* dense, which they may well not have (Allison *et al.* 2009) and that low-density clusters such as Taurus formed at low density rather than in relatively dense low-N clumps (see, e.g., Kroupa & Bouvier 2003).

In summary, it is very unclear if binary star formation is 'universal'. Some observational evidence points to differences between different star-forming regions that cannot be explained by dynamical processing, as we believe that these regions are dynamically young. Unfortunately, the exact form of these differences is difficult to determine, in particular because some dynamical processing must occur in even low-density regions (even if this is almost all internal decay).

(*b*) *The origin of the field binary population*

The field binary population is the sum of all binaries (and single stars) released from all star-forming regions after their dissolution. It is, therefore, the sum of both isolated and clustered star formation and the binaries in clusters will have been dynamically processed to at least some degree.

An important point to make at this point is that *the outcome of star-formation theories/simulations should not and cannot be compared directly to the field.* Even if the models are of isolated star formation, and therefore dynamical processing is not important, in the field, unprocessed and processed binaries are mixed.

As we have seen, star formation does not appear to produce a universal birth population. It is unclear how and why binary properties vary among star-forming environments (or even if 'environment' covers a single parameter such as density, or whether it is a complex mixture of density, turbulence, magnetic field strength, chemistry or a host of other variables; see Klessen *et al.* 2009). Within clustered environments, the birth population is further dynamically modified in a way that depends mainly on density (but the density can and does change significantly on very short timescales).

Given this situation, it seems that attempting to derive the origin of the field population is an impossible task. However, there are a number of interesting constraints which we can apply to the field population. In particular, we can construct a model of universal star formation that explains the field population, differences between clusters and the differences between the M- and G-dwarf binary fractions.

Star-forming regions can be roughly divided into three groups according to how much they will dynamically process their binaries. High-density clusters (HDCs) will significantly process much of their birth binary population. Low-density clusters (LDCs) will process wide systems, but leave fairly close systems unaffected. Isolated star formation (ISF) will probably only suffer decay and internal evolution to modify their birth populations (how important is this?).

Between 75 and 90% of stars form in clusters (Lada & Lada 2003; Lada 2010), and the rest form as ISF. The initial cluster mass function is roughly proportional to $M_{\rm cl}^{-2}$ (Lada & Lada 2003). Clusters appear to form with masses between approximately 10^1 and 10^6 $\mathrm{M}_\odot$, so an equal mass of stars forms in clusters $< 10^{3.5} M_\odot$ as do above. If we take clusters with masses below and above $10^{3.5}$ $\mathrm{M}_\odot$ to be LDCs and HDCs, respectively, then 40% of stars form in HDCs, 40% of stars form in LDCs, and 20% form as ISF (obviously, these numbers are very rough, but they suffice for the following discussion).

Binaries can be divided into four groups according to their separation, a, and so how they will be affected by dynamical processing in these different environments (following Parker *et al.* 2009).

Close binaries ($a < 50$ au) are unaffected by dynamical processing in all but the most extreme environments. Around 50% of G dwarfs and 25% of M dwarfs are in close binaries.

Intermediate binaries ($50 < a/\mathrm{au} < 1000$) are processed to a significant degree in HDCs, and to a much lesser extent in LDCs. Around 20% of G dwarfs and 10% of M dwarfs are in intermediate binaries.

Wide binaries ($10^3 < a/\mathrm{au} < 10^4$) are almost always destroyed in HDCs and are significantly processed in LDCs. They can only survive in ISF. About 15% of G dwarfs and 8% of M dwarfs are in wide binaries.

Very wide binaries ($a > 10^4$ au) cannot survive in any cluster. Indeed, it is difficult to see how they form in even ISF as their separations are larger than the typical size of a core. It is thought that the only way to make significant numbers of very wide binaries may be during the destruction of clusters (M. B. N. Kouwenhoven *et al.* , in prep.). If this is true, then no (or few) stars actually *form* as very wide binaries. About 15% of G dwarfs are in very wide binaries, as are probably a few percent of M dwarfs.

Taking G dwarfs as an example, we can construct a universal birth population which evolves to the observed field distribution. If we assume that G dwarfs form as 30% close, 15% intermediate and 25% wide binaries, and 30% single stars, then dynamical processing will destroy a few percent of intermediate binaries (i.e., half of the intermediate binaries in HDCs), most of the wide binaries (all in the HDCs, half in LDCs). If wide binaries then form later (a big 'if'), then this will produce a field population with 30% close, 12% intermediate and 10% wide binaries, and nearly 50% single stars, of which a fifth must somehow form very wide binaries (taking the single-star fraction from 50 to 40%).

The assumption has been made that G dwarfs are not in binaries with other G dwarfs so the destruction of a G-dwarf binary will not dilute the G-dwarf binary fraction other than by creating a single G dwarf where there was once a binary with a G-dwarf primary. This is probably fairly reasonable for G dwarfs where only very-high-mass-ratio systems are both G dwarfs. However, for M dwarfs, most are in binaries with other M dwarfs and so every binary destruction will add two single M dwarfs, rather than one. This would dilute the total M-dwarf binary fraction to a lower value of only 40–45%, only slightly higher than observed.

This model also ignores the decay of higher-order multiple systems (see above) which will dilute the binary fraction even further (Goodwin & Kroupa 2005), especially at low masses as ejected stars will generally be of low mass (Anosova 1986; Reipurth & Clark 2001).

Therefore, we have a model in which all stars of whatever mass form with the same birth binary fractions and separation distributions, which explains why (a) denser clusters look like the field, but with few wide binaries, (b) low-density clusters have more wide binaries and (c) there are more single M dwarfs than G dwarfs.

In summary, it is possible to construct a universal model of star formation. However, this apparently contradicts the previous section in which we saw that there appear to be different populations in clusters which are difficult to explain by anything other than different birth populations. Of course, star formation would never be expected to be completely universal, but how common and how significant are the differences between different regions? Also, can our understanding of local, generally low-mass, cluster formation be extended to more massive and extreme events at all, or are they completely different again (see also de Grijs 2010)?

5. Conclusions

We initially asked two fundamental questions related to star formation:
1. Is star formation (as probed by binary properties, at least) universal, or does it depend on environment?
2. What is the origin of the field binary population?

As we have seen, the properties of binaries in different environments *are* different. In particular, dense clusters have fewer binaries and those that they have tend to be close or intermediate binaries (< 1000 au). However, this difference can be explained by dynamical processing of the initial binary population in a cluster. If a cluster such as the ONC did form a significant wide binary population, it would have been destroyed by now. Low-density star-forming regions may provide a clue to the birth properties of stars, but only if one believes that star formation is universal. The difference between Taurus and the ONC is striking, but can be explained by both a different birth population or dynamical processing, or a mixture of both (dynamical processing *must* have occured in the ONC). Of particular interest in this regard are observations of USco, especially the differences between USco A and B, both of which are thought to have formed at low density but have very different binary properties. This may indicate differences in the initial conditions of the cloud. Could this be due to triggered star formation (see Preibisch *et al.* 2002)?

It is crucial to remember that we will *never* see an intact birth population, even in a young cluster. The only way to see a potentially intact birth system is to examine the deeply embedded phases of star formation. But even then, significant accretion and fragmentation to form binaries is ongoing during the class 0 phase, so that we will see 'unfinished' systems. However, by the class I phase, dynamical decay can have occurred. Does this mean that the 'birth population' is a meaningless phrase?

One of the few statements that we can make without argument is that *the field is not the birth population.* The field is a mixture of potentially different birth populations which have been processed to different degrees in their birth clusters and then mixed. Dynamical processing destroys binary systems. Therefore, there *must* have been more binaries formed than we see in the field (of course, if star formation is not universal, then some regions may form like the field, but not all).

Without an understanding of the universality or otherwise of star formation in different environments, it is impossible to constrain the origin of the field population. As we have seen, it is possible to explain the field binary population as the result of a universal mode of star formation that has been processed differently in different-density environments. Equally, it is possible to explain it as the sum of many different modes of star formation, each of which was then processed in different ways (if this is the case, then we have a vast parameter space of possible answers). For simplicity, we would probably prefer that (binary) star formation is universal. However, this might well not be the case.

References

Abt, H. A. 1983 Normal and abnormal binary frequencies. *Annu. Rev. Astron. Astrophys.* **21**, 343–372.

Ahmic, M., Jayawardhana, R., Brandeker, A., Scholz, A., van Kerkwijk, M. H., Delgado–Donate, E. & Froebrich, D. 2007 Multiplicity among young brown dwarfs and very low mass stars. *Astrophys. J.* **671**, 2074–2081.

Allison, R. J., Goodwin, S. P., Parker, R. J., de Grijs, R., Portegies Zwart, S. F. & Kouwenhoven, M. B. N. 2009 Dynamical mass segregation on a very short timescale. *Astrophys. J.* **700**, L99–L103.

Alves, J., Lombardi, M. & Lada, C. J. 2007 The mass function of dense molecular cores and the origin of the IMF. *Astron. Astrophys.* **462**, L17–L21.

Anosova, J. P. 1986 Dynamical evolution of triple systems. *Astrophys. Space Sci.* **124**, 217–241.

Basri, G. & Reiners, A. 2006 A survey for spectroscopic binaries among very low mass stars. *Astron. J.* **132**, 663–675.

Bastian, N., Gieles, M., Goodwin, S. P., Trancho, G., Smith, L. J., Konstantopoulos, I. & Efremov, Yu. 2008 The early expansion of cluster cores. *Mon. Not. R. Astron. Soc.* **389**, 223–230.

Binney, J. & Tremaine, S. 1987 *Galactic Dynamics.* Princeton, USA: Princeton University Press.

Bouy, H., Martín, E. L., Brandner, W., Zapatero–Osorio, M. R., Béjar, V. J. S., Schirmer, M., Huélamo, N. & Ghez, A. M. 2006 Multiplicity of very low-mass objects in the Upper Scorpius OB association: a possible wide binary population. *Astron. Astrophys.* **451**, 177–186.

Brandeker, A., Jayawardhana, R. & Najita, J. 2003 Keck adaptive optics imaging of nearby young stars: detection of close multiple systems. *Astron. J.* **126**, 2009–2014.

Brandeker, A., Jayawardhana, R., Khavari, P., Haisch Jr, K. E. & Mardones, D. 2006 Deficit of wide binaries in the η Chamaeleontis young cluster. *Astrophys. J.* , **652**, 1572–1584.

Burgasser, A. J., Kirkpatrick, J. D. & Lowrance, P. J. 2005 Multiplicity among widely separated brown dwarf companions to nearby stars: Gliese 337CD. *Astron. J.* **129**, 2849–2855.

Burgasser, A. J., Reid, I. N., Siegler, N., Close, L., Allen, P., Lowrance, P. & Gizis, J. 2007 Not alone: tracing the origins of very-low-mass stars and brown dwarfs through multiplicity studies. In *Protostars and Planets V* (eds B. Reipurth, D. Jewitt & K. Keil) pp. 427–441. Tuscon, USA: University of Arizona Press.

Clarke, C. 2010 The physics and modes of star cluster formation: simulations. *Phil. Trans. R. Soc. A*, this volume.

Close, L. M., Siegler, N., Freed, M. & Biller, B. 2003 Detection of nine M8.0–L0.5 binaries: the very low mass binary population and its implications for brown dwarf and very low mass star formation. *Astrophys. J.* **587**, 407–422.

Connelley, M. S., Reipurth, B. & Tokunaga, A. T. 2008 The evolution of the multiplicity of embedded protostars. II. Binary separation distribution and analysis. *Astron. J.* **135**, 2526–2536.

Correia, S., Zinnecker, H., Ratzka, Th. & Sterzik, M. F. 2006 A *VLT*/NACO survey for triple and quadruple systems among visual pre-main sequence binaries. *Astron. Astrophys.* **459**, 909–926.

Crowther, P. A., Hadfield, L. J., Clark, J. S., Negueruela, I. & Vacca, W. D. 2006 A census of the Wolf–Rayet content in Westerlund 1 from near-infrared imaging and spectroscopy. *Mon. Not. R. Astron. Soc.* **372**, 1407–1424.

de Grijs, R. 2010 A revolution in star cluster research: setting the scene. *Phil. Trans. R. Soc. A*, this volume.

Delgado Donate, E. J., Clarke, C. J., Bate, M. R. & Hodgkin, S. T. 2004 On the properties of young multiple stars. *Mon. Not. R. Astron. Soc.* **351**, 617–629.

Duchêne, G. 1999 Binary fraction in low-mass star forming regions: a re-examination of the possible excesses and implications. *Astron. Astrophys.* **341**, 547–552.

Duchêne, G., Bouvier, J., Bontemps, S., André, P. & Motte, F. 2004 Multiple protostellar systems. I. A deep near-infrared survey of Taurus and Ophiuchus protostellar objects. *Astron. Astrophys.* **427**, 651–665.

Duchêne, G., Bontemps, S., Bouvier, J., André, P., Djupvik, A. A. & Ghez, A. M. 2007 Multiple protostellar systems. II. A high resolution near-infrared imaging survey in nearby star-forming regions. *Astron. Astrophys.* **476**, 229–242.

Duquennoy, A. & Mayor, M. 1991 Multiplicity among solar-type stars in the solar neighbourhood. II. Distribution of the orbital elements in an unbiased sample. *Astron. Astrophys.* **248**, 485–524.

Eggleton, P. P. & Tokovinin, A. A. 2008 A catalogue of multiplicity among bright stellar systems. *Mon. Not. R. Astron. Soc.* **389**, 869–879.

Fischer, D. A. & Marcy, G. W. 1992 Multiplicity among M dwarfs. *Astron. J.* **396**, 178–194.

Ghez, A. M., Neugebauer, G. & Matthews, K. 1993 The multiplicity of T Tauri stars in the star forming regions Taurus–Auriga and Ophiuchus–Scorpius: A 2.2 micron speckle imaging survey. *Astron. J.* **106**, 2005–2023.

Ghez, A. M., McCarthy, D. W., Patience, J. L. & Beck, T. L. 1997 The multiplicity of pre-main-sequence stars in southern star-forming regions. *Astrophys. J.* **481**, 378–385.

Goodman, J. & Hut, P. 1993 Binary–single-star scattering. V. Steady state binary distribution in a homogeneous static background of single stars. *Astrophys. J.* **403**, 271–277.

Goodwin, S. P. & Kouwenhoven, M. B. N. 2009 What does a universal initial mass function imply about star formation? *Mon. Not. R. Astron. Soc.* **397**, L36–L40.

Goodwin, S. P. & Kroupa, P. 2005 Limits on the primordial stellar multiplicity. *Astron. Astrophys.* **439**, 565–569.

Goodwin, S. P. & Whitworth, A. P. 2007 Brown dwarf formation by binary disruption. *Astron. Astrophys.* **466**, 943–948.

Goodwin, S. P., Whitworth, A. P. & Ward–Thompson, D. 2004 Simulating star formation in molecular cloud cores. I. The influence of low levels of turbulence on fragmentation and multiplicity. *Astron. Astrophys.* **414**, 633–650.

Goodwin, S. P., Kroupa, P., Goodman, A. & Burkert, A. 2007 The fragmentation of cores and the initial binary population. In *Protostars and Planets V* (eds B. Reipurth, D. Jewitt & K. Keil) pp. 133–147. Tuscon, USA: University of Arizona Press.

Goodwin, S. P., Nutter, D., Kroupa, P., Ward–Thompson, D. & Whitworth, A. P. 2008 The relationship between the prestellar core mass function and the stellar initial mass function. *Astron. Astrophys.* **477**, 823–827.

Haisch Jr, K. E., Greene, T. P., Barsony, M. & Stahler, S. W. 2004 A near-infrared multiplicity survey of class I/flat-spectrum systems in six nearby molecular clouds. *Astrophys. J.* **127**, 1747–1754.

Heggie, D. C. 1975 Binary evolution in stellar dynamics. *Mon. Not. R. Astron. Soc.* **173**, 729–787.

Hills, J. G. 1975 Encounters between binary and single stars and their effect on the dynamical evolution of stellar systems. *Astron. J.* **80**, 809–825.

Hut, P., McMillan, S., Goodman, J., Mateo, M., Phinney, E. S., Pryor, C., Richer, H. B., Verbunt, F. & Weinberg, M. 1992 Binaries in globular clusters. *Publ. Astron. Soc. Pac.* **104**, 981–1034.

Klessen, R. S., Krumholz, M. R. & Heitsch, F. 2009 Numerical star-formation studies: a status report. *Adv. Sci. Lett.*, in press (arXiv:0906.4452).

Köhler, R., Kunkel, M., Leinert, C. & Zinnecker, H. 2000 Multiplicity of X-ray selected T Tauri stars in the Scorpius–Centaurus OB association. *Astron. Astrophys.* **356**, 541–558.

Köhler, R., Petr–Gotzens, M. G., McCaughrean, M. J., Bouvier, J., Duchêne, G., Quirrenbach, A. & Zinnecker, H. 2006 Binary stars in the Orion Nebula cluster. *Astron. Astrophys.* **458**, 461–476.

Köhler, R., Neuhäuser, R., Krämer, S., Leinert, C., Ott, T. & Eckart, A. 2008 Multiplicity of young stars in and around R Coronae Australis. *Astron. Astrophys.* **488**, 997–1006.

Konopacky, Q. M., Ghez, A. M., Rice, E. L. & Duchêne, G. 2007 New very low mass binaries in the Taurus star-forming region. *Astrophys. J.* **663**, 394–399.

Koresko, C. D. 2002 Imaging the circumstellar environments of young binaries in southern star-forming regions. *Astron. J.* **124**, 1082–1088.

Kouwenhoven, M. B. N., Brown, A. G. A., Portegies Zwart, S. F. & Kaper, L. 2007 The primordial binary population. II. Recovering the binary population for intermediate mass stars in Scorpius OB2. *Astron. Astrophys.* **474**, 77–104.

Kraus, A. L. & Hillenbrand, L. A. 2007 The role of mass and environment in multiple-star formation: a 2MASS survey of wide multiplicity in three young associations. *Astrophys. J.* **662**, 413–430.

Kroupa, P. 1995*a* Inverse dynamical population synthesis and star formation. *Mon. Not. R. Astron. Soc.* **277**, 1491–1506.

Kroupa, P. 1995*b* The dynamical properties of stellar systems in the Galactic disc. *Mon. Not. R. Astron. Soc.* **277**, 1507–1521.

Kroupa, P., Aarseth, S. & Hurley, J. 2001 The formation of a bound star cluster: from the Orion Nebula cluster to the Pleiades. *Mon. Not. R. Astron. Soc.* **321**, 699–712.

Kroupa, P. & Bouvier, J. 2003 The dynamical evolution of Taurus–Auriga-type aggregates. *Mon. Not. R. Astron. Soc.* **346**, 343–353.

Lada, C. J. 2010 The physics and modes of star cluster formation: observations. *Phil. Trans. R. Soc. A*, this volume.

Lada, C. J. & Lada, E. A. 2003 Embedded clusters in molecular clouds. *Annu. Rev. Astron. Astrophys.* **41**, 57–115.

Lada, C. J. 2006 Stellar multiplicity and the initial mass function: most stars are single. *Astrophys. J.* **640**, L63–L66.

Lafrenière, D., Jayawardhana, R., Brandeker, A., Ahmic, M. & van Kerkwijk, M. H. 2008 A multiplicity census of young stars in Chamaeleon I. *Astrophys. J.* **683**, 844–861.

Larson, R. B. 1972 The collapse of a rotating cloud. *Mon. Not. R. Astron. Soc.* **156**, 437–458.

Larson, R. B. 2002 The role of tidal interactions in star formation. *Mon. Not. R. Astron. Soc.* **332**, 155–164.

Law, N. M., Hodgkin, S. T. & Mackay, C. D. 2007 Discovery of five very low mass close binaries, resolved in the visible with lucky imaging. *Mon. Not. R. Astron. Soc.* **368**, 1917–1924.

Leinert, C., Zinnecker, H., Weitzel, N., Christou, J., Ridgway, S. T., Jameson, R., Haas, M. & Lenzen, R. 1993 A systematic approach for young binaries in Taurus. *Astron. Astrophys.* **278**, 129–149.

Mathieu, R. D. 1994 Pre-main-sequence binary stars. *Annu. Rev. Astron. Astrophys.* **32**, 465–530.

Maxted, P. F. L., Jeffries, R. D., Oliveira, J. M., Naylor, T. & Jackson, R. J. 2008 A survey for low-mass spectroscopic binary stars in the young clusters around σ Orionis and λ Orionis. *Mon. Not. R. Astron. Soc.* **385**, 2210–2224.

Mazeh, T., Goldberg, D., Duquennoy, A. & Mayor, M. 1992 On the mass-ratio distribution of spectroscopic binaries with solar-type primaries. *Astrophys. J.* **401**, 265–268.

Moraux, E., Lawson, W. A. & Clarke, C. J. 2007 η Chamaeleontis: abnormal initial mass function or dynamical evolution? *Astron. Astrophys.* **473**, 163–170.

Parker, R. J., Goodwin, S. P., Kroupa, P. & Kouwenhoven, M. B. N. 2009 Do binaries in clusters form in the same way as in the field? *Mon. Not. R. Astron. Soc.* **397**, 1577–1586.

Patience, J., Ghez, A. M., Reid, I. N. & Matthews, K. 2002 A high angular resolution multiplicity survey of the open clusters α Persei and Praesepe. *Astron. J.* **123**, 1570–1602.

Petr, M. G., Coude Du Foresto, V., Beckwith, S. V. W., Richichi, A. & McCaughrean, M. J. 1998 Binary stars in the Orion Trapezium cluster core. *Astrophys. J.* **500**, 825–837.

Preibisch, T., Brown, A. G. A., Bridges, T., Guenther, E. & Zinnecker, H. 2002 Exploring the full stellar population of the Upper Scorpius OB association. *Astron. J.* **124**, 404–416.

Reid, I. N. & Gizis, J. E. 1997 Low-mass binaries and the stellar luminosity function. *Astron. J.* **113**, 2246–2269.

Reipurth, B. & Clarke, C. J. 2001 The formation of brown dwarfs as ejected stellar embryos. *Astron. J.* **122**, 432–439.

Reipurth, B. & Zinnecker, H. 1993 Visual binaries among pre-main sequence stars. *Astron. Astrophys.* **278**, 81–108.

Reipurth, B., Guimarães, M. M., Connelley, M. S. & Bally, J. 2007 Visual binaries in the Orion Nebula cluster. *Astron. J.* **134**, 2272–2285.

Scally, A., Clarke, C. J. & McCaughrean, M. J. 1999 Wide binaries in the Orion Nebula cluster. *Mon. Not. R. Astron. Soc.* **306**, 253–256.

Scally, A., Clarke, C. J. & McCaughrean, M. J. 2005 Dynamical evolution of the Orion Nebula cluster. *Mon. Not. R. Astron. Soc.* **358**, 742–754.

Shatsky, N. & Tokovinin, A. A. 2002 The mass ratio distribution of B-type visual binaries in the Sco OB2 association. *Astron. Astrophys.* **382**, 92–103.

Tokovinin, A. A. & Smekhov, M. G. 2002 Statistics of spectroscopic sub-systems in visual multiple stars. *Astron. Astrophys.* **382**, 118–123.

Vesperini, E. 2010 Star cluster dynamics. *Phil. Trans. R. Soc. A*, this volume.

Whitworth, A. P. & Stamatellos, D. 2006 The minimum mass for star formation and the origin of binary brown dwarfs. *Astron. Astrophys.* **458**, 817–829.