REVIEW

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 whether star formation (as traced by binaries, at least) is universal or whether it depends on the environment. In addition, the field population consists of a mixture of systems from different clusters that 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 systems¹ (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 (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 with 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

¹Stars 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.

One contribution of 10 to a Theme Issue ‘Star clusters as tracers of galactic star-formation histories’. 

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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 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 M_⊙) that disperse (are destroyed?) within a few million years (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 (ISF). 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 whether 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 semimajor 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 that are in binaries is usually given by the ‘multiplicity fraction’ (often called just the ‘binary fraction’)

\[
mf = \frac{B + T + Q + \cdots}{S + B + T + Q + \cdots},
\]

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 for 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 a 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 (approx. 100AU) 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 Duchène (1999)).

(a) Binaries in the field

The field provides the canonical binary properties with 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 approximately 0.6, a wide lognormal period/separation distribution with a peak at approximately \( 10^4 \) days/30AU and a mass-ratio distribution which peaks at \( q = 0.2 \) (but the last depends on separation; Mazeh et al. 1992).

However, DM91 probe only a very small mass range around \( 1M_\odot \). 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 approximately 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 Fischer & Marcy 1992, fig. 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 among 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 5–20AU (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 per cent 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 $>1 \, M_\odot$), found 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 per cent 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; Connelley et al. 2008; Lafrenière et al. 2008), but selection 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 astronomical units), 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 with 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 arbitrary (and can vary from author to author), but, as a rough guide, ISF has stellar densities similar to the Galactic field of only a few stars pc$^{-3}$. Low-density star-forming regions (low-density clusters (LDCs) 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 an excess of binaries in Taurus, with almost everything greater than 0.3 $M_\odot$ in a binary system. Ghez et al. (1997) found 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) found an excess of binaries by a factor of 1.6 in Scorpius (Sco)–Centaurus, as did Patience et al. (2002) in $\alpha$ Perseus and Praesepe. Duchène et al. (2004, 2007) and Haisch et al. (2004) also found 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) found an excess of wide (300–1650 AU) binaries in Taurus and Cham I, especially at higher ($>1 \, M_\odot$) masses. Lafrenière et al. (2008) again found 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 fewer than 10 are twice as likely to have a companion than those in groups with more than 10 members. In particular, the Orion Nebula Cluster (ONC) has a binary fraction similar to that of the field (e.g. Petr et al. 1998; Köhler et al. 2006; Reipurth et al. 2007), as do IC 348 (Duchène et al. 1999) and η Cham (Brandeker et al. 2006). Connelley et al. (2008) also found that wide (500–4500 AU) class I binaries are less common in denser regions (at odds with Duchène et al. (2007), who found 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) found evidence for a wide (100–150 AU) low-mass binary population in Upper Sco (USco), as did Konopacky et al. (2007) in Taurus, which are not seen in large numbers in the field.

Kraus & Hillenbrand (2007) found 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 with the field at all masses, possibly greatest at low masses, where approximately 35 ± 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 that 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 found that the binary fractions greater than 1000 AU appear to evolve during the class I phase, even in low-density environments. They argued that this is the result of the decay of higher order systems (§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

*Phil. Trans. R. Soc. A* (2010)
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 semimajor axis \(a\) is given by \(E = -\frac{GM_1 M_2}{2a}\). If the binary is located in an environment in which the average mass of a star is \(m\) and the velocity dispersion \(\sigma\), 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 time scale is very long. Therefore, the environment in which a binary is found is of crucial importance. For example, the hard–soft boundary for a \(1\, M_\odot/1\, M_\odot\) binary in the field, which has a velocity dispersion of several tens of kilometres per second, is a few astronomical units, but the vast majority of binaries are wider than this and perfectly stable because the encounter time scale is many tens of billion years. However, in a typical cluster with a velocity dispersion of a few kilometres per second, the hard–soft boundary is tens of astronomical units, but the encounter time scale is only a few million years, 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 that 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 (1995b) and references therein). However, these processes probably affect only the tightest binaries and do so on a time scale that is short compared with the dynamical time scale 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 ISF, 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,

(i) What are the birth properties of binaries? Do they depend on the environment or are they universal?
(ii) 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 (i) is that we are not certain, but what we do apparently know is very confusing when applied to attempting to answer (ii). Such is science.

(a) The birth properties of binaries

In §2b we reviewed a number of observations of young binary systems. Two key points are obvious from the observations,

(i) Young stars tend to have an excess of binary companions by a factor of 1.5–2 over the field.
(ii) Denser star-forming regions tend to look like the field and have few binaries with separations greater than a few thousand astronomical units.

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 astronomical units), 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 1995a,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 whether (i) most stars form as binaries or (ii) 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 per cent of the birth population of M dwarfs would have to be in wide binaries.\(^2\)

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 greater than 0.1 M\(_\odot\) during the earliest phases of star formation. Most of this disc material will accrete onto a component of the binary, resulting in a total system mass of greater than 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) found 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 per cent (Alves et al. 2007; Goodwin et al. 2008). Therefore, 70 per cent 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 the 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 (greater than 1000 AU) in dense clusters (like the ONC) compared with 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

\(^2\)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).
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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 ISF 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 juncture is that the outcome of star-formation theories/simulations should not and cannot be compared directly with the field. Even if the models are of ISF, 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; 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 time scales).

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 that 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: (i) high-density clusters (HDCs) will significantly process much of their birth binary population, (ii) LDCs will process wide systems, but leave fairly close systems unaffected, and (iii) ISF will probably only suffer decay and internal evolution to modify their birth populations (how important is this?).

Between 75 and 90 per cent 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 $M^{-2}_{\text{cl}}$ (Lada & Lada 2003). Clusters appear to form with masses between approximately $10^1$ and $10^6 M_\odot$, so an equal mass of stars forms in clusters less than $10^{3.5} M_\odot$ as above. If we take clusters with masses below and above $10^{3.5} M_\odot$ to be LDCs and HDCs, respectively, then 40 per cent of stars form in HDCs, 40 per cent of stars form in LDCs and 20 per cent 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).

(i) Close binaries ($a < 50$ AU) are unaffected by dynamical processing in all but the most extreme environments. Around 50 per cent of G dwarfs and 25 per cent of M dwarfs are in close binaries.
(ii) **Intermediate binaries** \((50 < a/\text{AU} < 1000)\) are processed to a significant degree in HDCs and to a much lesser extent in LDCs. Around 20 per cent of G dwarfs and 10 per cent of M dwarfs are in intermediate binaries.

(iii) **Wide binaries** \((10^3 < a/\text{AU} < 10^4)\) are almost always destroyed in HDCs and are significantly processed in LDCs. They can survive only in ISF. About 15 per cent of G dwarfs and 8 per cent of M dwarfs are in wide binaries.

(iv) **Very wide binaries** \((a > 10^4 \text{AU})\) 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 (Kouwenhoven *et al.* submitted). If this is true, then no (or few) stars actually form as very wide binaries. About 15 per cent of G dwarfs are in very wide binaries, as are probably a few per cent of M dwarfs.

Taking G dwarfs as an example, we can construct a universal birth population that evolves to the observed field distribution. If we assume that G dwarfs form as 30 per cent close, 15 per cent intermediate and 25 per cent wide binaries, and 30 per cent single stars, then dynamical processing will destroy a few per cent of intermediate binaries (i.e. half of the intermediate binaries in HDCs), and 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 per cent close, 12 per cent intermediate and 10 per cent wide binaries, and nearly 50 per cent 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 (i) denser clusters look like the field, but with few wide binaries, (ii) low-density clusters have more wide binaries, and (iii) 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 that 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,

(i) Is star formation (as probed by binary properties, at least) universal, or does it depend on the environment?
(ii) 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 (less than 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 a different birth population or dynamical processing or a mixture of both (dynamical processing must have occurred 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 (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 that 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


*Phil. Trans. R. Soc. A* (2010)


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