Revista Mexicana de Astronomía y Astrofísica
ISSN: 0185-1101
rmaa@astroscu.unam.mx
Instituto de Astronomía
México

Bate, Matthew R.
The formation of binary and multiple stars in clusters
Revista Mexicana de Astronomía y Astrofísica, vol. 21, agosto, 2004, pp. 175-183
Instituto de Astronomía
Distrito Federal, México

RevMexAA (Serie de Conferencias), **21**, 175–183 (2004)

THE FORMATION OF BINARY AND MULTIPLE STARS IN CLUSTERS

Matthew R. Bate[1]

RESUMEN

Discutimos aspectos teóricos de la formación de estrellas dobles y múltiples, particularmente en cúmulos estelares. En primer lugar, revisamos los procesos individuales que pueden ocurrir durante la formación de estrellas dobles y múltiples: fragmentación, acreción, interacciones con discos circunestelares e interacciones dinámicas. En segundo, discutimos los resultados recientes del cálculo hidrodinámico a gran escala de la formación de un cúmulo, en el cual todos estos procesos ocurren simultáneamente, y examinamos los mecanismos de formación y las propiedades resultantes de las binarias y múltiples en el cúmulo.

ABSTRACT

We discuss theoretical aspects of binary and multiple star formation, focusing on their formation in stellar clusters. First, we review individual processes that may occur during the formation of binary and multiple stars: fragmentation, accretion, interactions with circumstellar discs, and dynamical interactions. We then discuss the results from a recent large-scale hydrodynamical calculation of cluster formation in which all of these processes occur simultaneously, examining the formation mechanisms and resulting properties of the binary and multiple stars in this cluster.

Key Words: **BINARIES: GENERAL — STARS: FORMATION — STARS: PRE-MAIN SEQUENCE**

1. BINARY AND MULTIPLE STAR FORMATION VIA FRAGMENTATION

The fragmentation of molecular cloud cores as they undergo gravitational collapse is the favoured mechanism for the formation of most binary and multiple stellar systems.There are two main types of fragmentation, prompt fragmentation (e.g., Boss 1986) and disc fragmentation (e.g., Bonnell 1994). ‘Prompt’ (Pringle 1989) fragmentation occurs when gravitationally unstable initial density perturbations grow in amplitude during the overall collapse of a molecular cloud, producing multiple fragments. Fragmentation occurs because the collapse timescale depends on density ρ, as $t_{\rm coll} \propto \rho^{-1/2}$. Thus, initial overdensities tend to collapse faster than the cloud as a whole. Many numerical studies of prompt fragmentation have been performed over the past two decades (e.g., Boss & Bodenheimer 1979; Boss 1986; Bonnell et al. 1991; Bate, Bonnell & Price 1995; Bate & Burkert 1997; Truelove et al. 1998).

Disc fragmentation around a central object can occur in a massive circumstellar disc due to the growth of initially low-amplitude (linear) density perturbations over several dynamical timescales. The ratio of the rotational energy to the magnitude of the gravitational potential energy for the system must be greater than $\beta \approx 0.27$, the value required for the structure to be dynamically unstable to non-axisymmetric perturbations. Various numerical studies have been performed of disc fragmentation (e.g. Bonnell 1994; Whitworth et al. 1995; Bonnell & Bate 1994; Bate & Burkert 1997; Burkert, Bate & Bodenheimer 1997). Bonnell (1994) showed that such disc fragmentation requires a high accretion rate on to the disc from the surrounding cloud. Otherwise, the same non-axisymmetric perturbations that are required for the fragmentation will transport mass and angular momentum within the disc to produce a more stable state without fragmentation occurring. The equation of state of the gas is also critical to its ability to fragment (Pickett et al. 2000) with stiff equations of state resisting fragmentation.

Together, prompt fragmentation and disc fragmentation can produce a wide variety of binary and multiple systems. However, they appear unable to form close binary systems (separations $\lesssim 10$ AU) directly.

1.1. *The Problem with Forming Close Binary Systems by Fragmentation*

Prompt fragmentation can occur during the dynamic collapse of a molecular cloud core because the gas is free to radiate away the gravitational potential energy released during the collapse without the temperature of the gas increasing. However, at some point during the collapse, the rate of heating exceeds the rate at which the gas can cool, the gas

---

[1] School of Physics, U. Exeter, UK.

temperature begins to increase rapidly with density, and a pressure-supported object is formed suppressing further fragmentation (Boss 1986, 1988). This is known as the opacity limit for fragmentation (Low & Lynden-Bell 1976). Initially, the pressure-supported core, known as the first hydrostatic core, has a mass of a few Jupiter-masses and a size of ~ 4 AU (Larson 1969). Thus, the opacity limit for fragmentation sets a minimum stellar mass and also forces the initial separations of binaries to be $\gtrsim 10$ AU, implying that closer binaries can only be formed through subsequent orbital decay (e.g. Boss 1986, Clarke & Pringle 1991b).

A potential opportunity to form close binaries directly by fragmentation occurs during a second phase of collapse that occurs within the first hydrostatic core (Larson 1969). When the central temperature of the first core exceeds 2000 K, molecular hydrogen begins to dissociate allowing the gas to absorb energy without its temperature increasing significantly. This triggers a second nearly isothermal collapse during which fragmentation might occur. This possibility has been investigated by Boss (1989), Bonnell & Bate (1994), and Bate (1998,2003). Boss managed to obtain transient fragments that later merged. Bonnell & Bate found that multiple fragments could be obtained via the fragmentation of a massive circumstellar disc. However, in both papers, only the inner regions of the first hydrostatic core were modelled and the calculations began with somewhat arbitrary initial conditions. Bate (1998) followed the collapse of an optically-thin molecular cloud core, through the formation of the first hydrostatic core and the second collapse phases, all the way to stellar densities. He found that fragmentation could not occur due to gravitational torques if the first hydrostatic core was rotationally unstable, and the high thermal pressure if the first hydrostatic core was rotationally stable. Thus, it appears that fragmentation cannot occur during the second collapse phase and that close binary systems cannot form directly via fragmentation.

2. EVOLUTIONARY PROCESSES DURING MULTIPLE STAR FORMATION

Fragmentation is only the first step in the formation of a binary or multiple system. Before the system has attained its final state, three processes can dramatically alter its parameters: accretion, disc interactions, and dynamical interactions.

2.1. *Accretion*

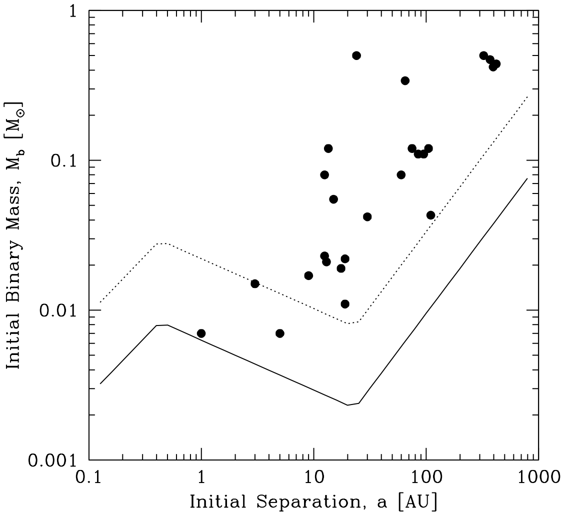

Fig. 1. The dependence of a protobinary's initial mass on its separation (Bate 2000). The points give results from Boss (1986, Figure 13). The solid line gives a simple estimate (Section 2.1) of the minimum mass that a 'seed' protobinary system should have as a function of its separation. The dotted line assumes the binary quickly accretes the gas inside the sphere that encloses it.

In order to determine how a binary evolves due to accretion, we must determine how much mass a typical binary accretes relative to its initial mass. Boss (1986) performed many fragmentation calculations and, for those that formed binaries, he found a linear relationship between the binary's initial mass and its separation in the isothermal collapse regime (Figure 1). This can be understood by a simple Jeans-mass argument (Figure 1, solid line). For fragmentation to occur, the Jeans length at the time of fragmentation must be less than, or similar to, half the separation of the binary which is formed. However, for a fixed temperature, the Jeans mass is proportional to the Jeans length. Thus, we expect that the mass of a newly formed binary should be roughly proportional to its separation in the isothermal regime (separations $\gtrsim 10$ AU). From Figure 1, we see that to obtain binaries with solar-mass primaries, close binaries (separations $\lesssim 10$ AU) should have to accrete ≈ 100 times their initial mass from the cloud in which they form, while wider binaries will have to accrete less (e.g. 100 AU binaries may typically accrete ≈ 10 times their initial mass). Binaries with lower final primary masses will accrete less, while binaries containing massive stars may be expected to have accreted more.

The effects of the accretion of gas from an infalling gaseous envelope on the properties of a pro-

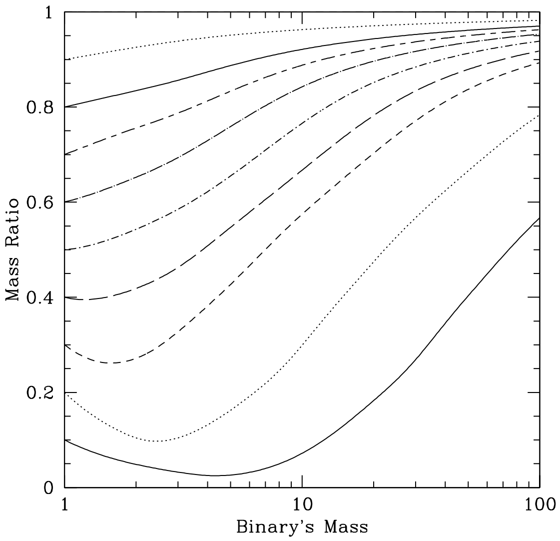

Fig. 2. The evolution of the mass ratio of a binary as it accretes gas from the molecular cloud core in which it formed. The final mass ratio depends on the initial mass ratio from the fragmentation event and how much mass is accreted relative to the binary's initial mass. These evolutionary tracks assume the cloud core initially had a uniform density and was in solid-body rotation.

tobinary system have been studied by Artymowicz (1983), Bate (1997), Bate & Bonnell (1997), and Bate (2000). Generally, accretion of gas with low specific angular momentum enhances the difference in stellar masses and decreases the separation of the binary, while accretion of gas with high specific angular momentum increases the binary's separation and drives the mass ratio toward unity. Bate (2000) considered how the properties of a binary system (i.e., its mass ratio, separation, circumbinary-disc mass, and relative accretion rate on to the circumstellar discs) evolve as a binary accretes and determined how the final properties should depend on the characteristics of the core in which the binary formed (i.e., its radial density and angular momentum profiles). For example, in the long-term, he found that accretion drives the mass ratio towards unity because gas that falls in later tends to have more specific angular momentum (e.g., Figure 2).

2.1.1. *Mass Ratio Distributions for Binaries Formed in Isolated Cores*

As discussed above, to obtain binaries with the same final primary mass, closer systems have to accrete more, relative to their initial fragmentation mass, than wider systems. Thus, closer binaries are more likely to have mass ratios near unity (i.e. similar masses) than wider binaries since, in the long-term, accretion tends to equalise the masses. This is in good agreement with surveys of solar-type stars. Duquennoy & Mayor (1991) find that for binaries of all separations, the mass ratio distribution rises toward low mass ratios (i.e. unequal masses), while Mazeh et al. (1992) and Halbwachs, Mayor & Udry (1998) find that close binaries (periods < 3000 days, or separations $\lesssim 5$ AU) have a uniform mass ratio distribution (i.e. they are biased toward equal masses compared to wider systems).

If the initial mass of a protobinary depends only on its separation, and not the total mass of the cloud, then in order to obtain a more massive primary, the binary must accrete more gas from its envelope. Thus, we expect that massive binaries should have a preference for nearly equal masses when compared to low-mass binaries of similar separation. In fact, recent surveys seem to display the opposite result: massive stars frequently have low-mass companions. The reason for this may be to do with differences in the formation process of low and high-mass stars, namely that high-mass stars are preferentially formed in clusters. This will be discussed in Section 2.1.2.

Since the mass ratios of binaries are expected to become biased toward equal masses for closer binaries or higher-mass primaries, brown dwarf companions are most likely to be found in wide orbits around low-mass stars. For example, consider Figures 1 and 2. To form a brown dwarf companion to a solar-type star with a separation of $\lesssim 10$ AU, the primary would have to accrete ≈ 100 times its initial mass, while the final mass ratio of the binary must be $M_2/M_1 < 0.1$ for the companion to have the mass of a brown dwarf. Thus, such companions are predicted to be extremely unlikely (the initial mass ratio would have to be extremely low or the companion would have to form after the primary had already accreted most of its mass). This result is in good agreement with radial velocity searches for planets around solar-type stars which find a brown-dwarf desert (Halbwachs et al. 2000).

2.1.2. *Accretion in a Clustered Environment*

Thus far, we have assumed that all binaries form in isolated molecular cloud cores. However, many, perhaps most, stars form in dense clusters where they are expected to interact with one another on a similar time-scale to that on which they accrete the bulk of their mass. This is especially important for young intermediate and high-mass stars which are preferentially found in clusters. In this case, stellar motions are generally uncorrelated with those of the gas. Thus, in contrast to the model discussed above where the accretion comes from a rotating molecular cloud core and, therefore, the specific angular momentum of the infalling gas increases as the mass of the binary increases, the gas accreted by a binary in a young cluster would be expected to have very little specific angular momentum throughout the entire accretion phase. The accretion of low angular momentum gas rapidly drives a binary's components to be more unequal in mass. Thus, whereas isolated star formation is expected to produce a trend such that massive binaries are more likely to have equal masses, for binaries in clusters, the trend should be reversed (Bate 2001). This may explain the observation that in open clusters, mass ratio distributions exhibit a steeper rise towards low mass ratios for higher-mass primaries than low-mass primaries (Patience et al. 2002). We note that the trend of more-equal masses for smaller separations should still exist in clusters because the specific angular momentum of the infalling gas, relative to the binary, will still be greater for binaries of smaller separation.

Finally, we note that while young high-mass stars ($M \gtrsim 3\mathrm{M}_\odot$) are preferentially associated with clusters, low-mass stars are formed in isolated star-forming regions (SFRs) as well as in clusters. An obvious implication of this is that the mass ratio distributions of low-mass stars may differ between isolated and clustered SFRs. Indeed, it has been observed that there is a much higher fraction of binaries with components of nearly equal brightness in the Taurus SFR (an isolated SFR) than in the Ophiuchus SFR where the star formation is predominantly in a small cluster (Duchêne 1999).

2.1.3. *Higher-order Multiple Systems*

Until now, we have only discussed the effects of accretion on binary systems. However, accretion can be even more important for the evolution of multiple systems since it can alter their stability by altering the masses of the components or, for a hierarchical system, the ratio of the orbital periods (Smith, Bonnell & Bate 1997). For example, if the ratio of the long orbital period to the short orbital period of a hierarchical triple system decreases, the system may become dynamically unstable and break up into a binary and a single star. Conversely, if an unstable multiple system forms via fragmentation but accretes rapidly, the ratio of the orbital periods may increase to a stable value before the chaotic evolution of the system has resulted in it breaking up.

2.2. *Disc Interactions*

If a binary is surrounded by a circumbinary disc, gravitational torques from the binary transfer angular momentum from the binary's orbit into the disc, causing the binary's components to spiral together (Artymowicz et al. 1991; Bate & Bonnell 1997). Such disc interactions are very efficient; even relatively low-mass discs can have a significant effect over time (Pringle 1991). Thus, although it appears that fragmentation cannot form close binary systems directly (Section 1.1), it is plausible that close binaries may be formed by the spiralling of initially wider binaries. For a triple system surrounded by a circumtriple disc, such evolution may cause the system to evolve from stability to instability.

In groups and clusters of stars, discs may also play a role in the formation of binary and multiple systems through star-disc capture (Larson 1990; Clarke & Pringle 1991a,b; McDonald & Clarke 1995; Hall, Clarke & Pringle 1996). In a star-disc capture, two unbound stars become bound when one star flies through the disc of the other, dissipating enough kinetic energy to form a bound system. Star-disc interactions can plausibly form a significant number of wide binaries in small-N clusters since the cross-section for interactions (disc radii may easily be $100 - 1000$ AU) is much larger than, for example, the tidal capture cross-section. In large-N clusters, however, the velocity dispersion of the stars is usually too large to allow the formation of a bound system and the discs are simply truncated (Clarke & Pringle 1991a).

2.3. *Dynamical Stellar Interactions*

Dynamical interactions between stars can lead to the orbital evolution of a binary in several ways. If the orbital velocity of a binary is greater than the velocity of an incoming object while it is still at a great distance (i.e. the binary is 'hard'), the binary will survive the encounter (Hut & Bahcall 1983). However, several outcomes are possible. The binary may simply be hardened by the encounter, with the single object removing energy and angular momentum. Alternately, if the encounter is sufficiently close, an unstable multiple system will be formed. Its chaotic evolution will usually lead to the ejection of the object with the lowest mass. If the ejected object was a component of the original binary, the net effect is an exchange interaction.

In large-N clusters, dynamical interactions lead to the evolution of the primordial population of multiple systems (e.g., Kroupa 1995). 'Hard' binaries tend to be hardened by encounters, while 'soft' binaries are usually broken up. Potentially, close binaries could be formed by successive hardening of wider binaries. This possibility has been investigated by Kroupa & Burkert (2001) who performed N-body calculations of star clusters (100 to 1000 stars) consisting entirely of binaries with periods $4.5 < \log(P/\text{days}) < 5.5$ to determine the degree to which the binary population could be broadened by dynamical encounters. However, they found that almost no binaries with periods $\log(P/\text{days}) < 4$ were produced. Similarly, the dissolution of small-N clusters typically results in binaries with separations only an order of magnitude smaller than the size of the initial cluster (Sterzik & Durisen 1998).

3. THE FORMATION OF BINARY AND MULTIPLE STARS IN CLUSTERS

Recently, computer power has increased to the point that we are able to perform three-dimensional hydrodynamical simulations of star cluster formation that resolve all of the above processes (Bate et al. 2002a,b; 2003). Thus, we can investigate directly the importance of the above processes in the formation of binary and multiple stars. Although some calculations of star cluster formation have been performed in the past (e.g., Chapman et al. 1992; Klessen, Burkert & Bate 1998; Klessen & Burkert 2000, 2001), either they have not had sufficient resolution to resolve binaries and circumstellar discs, or they have not been evolved long enough for any of the objects to reach their final states.

In the following three sections, we examine the binary and multiple star formation that occurs in the large-scale cluster formation simulation of Bate et al. (2002a,b; 2003). This calculation follows the formation of a cluster of 50 stars and brown dwarfs, resolving the opacity limit for fragmentation (Section 1.1), circumstellar discs with sizes $\gtrsim 10$ AU, and binaries with separations as small as 1 AU.

3.1. *The Formation and Frequency of Binary and Multiple Systems*

As discussed above, although the favoured mechanism for binary and multiple star formation is fragmentation, star-disc capture may also form binaries, especially in small stellar groups. Bate et al. (2003) used their cluster formation calculation to examine which of these formation mechanisms is most prevalent. They found the dominant mechanism for the formation of the binary and multiple systems was fragmentation, occurring both as prompt and disc fragmentation. Although many star-disc encounters occurred during the calculation, most of these served only to truncate the circumstellar discs and did not result in bound stellar systems (c.f. Clarke & Pringle 1991a). Only two star-disc captures occurred. However, it is important to note that, although star-disc encounters do not usually form simple bound systems directly, they do result in dissipation, which is important in the formation both of small-N bound groups and close binary systems (see below).

When the calculation was stopped, there existed 4 multiple systems or stellar groups. They were a close stellar binary system that was ejected from the cloud, an unstable quadruple system, an unstable system consisting of seven objects, and the remains of a small-N group consisting of 11 objects. These systems are depicted in Figure 3. The high-order systems are quite complex, containing 6 close binary systems (separations < 10 AU) and 4 triple systems. These would all undergo further evolution if the simulation were continued. It is likely that most of the close binary systems and some of the triple systems will survive, but it is not possible to determine the eventual binary and multiple frequencies. The best that can be done is to provide an upper limit on the final companion star frequency

$$CSF = \frac{B + 2T + 3Q + ...}{S + B + T + Q + ...}, \tag{1}$$

where S is the number of single stars, B is the number of binaries, T is the number of triples, etc. The 26 single objects, 1 binary, 1 quadruple, 1 septuple and 1 system of 11 objects give a companion star frequency of $20/30 = 67\%$. This high frequency is in broad agreement with the large fractions of binary and multiple systems found in young star-forming regions (e.g., Duchêne 1999).

3.2. *The Formation of Close Binaries*

As discussed in Section 1.1, the opacity limit for fragmentation sets a minimum initial binary separation of ≈ 10 AU. However, at the end of the cluster formation simulation, there exist 7 close binary systems (separations < 10 AU). A full analysis of the mechanisms by which these close binaries form and their properties was performed by Bate et al. (2002b). They found that, rather than forming directly by fragmentation, the 7 close binary systems formed from initially wider multiple systems through a combination of accretion, the interaction of binaries and triples with circumbinary and circumtriple discs, and dynamical interactions.

Accretion onto a binary from a cloud decreases the binary's separation unless the specific angular momentum of the accreted material is significantly

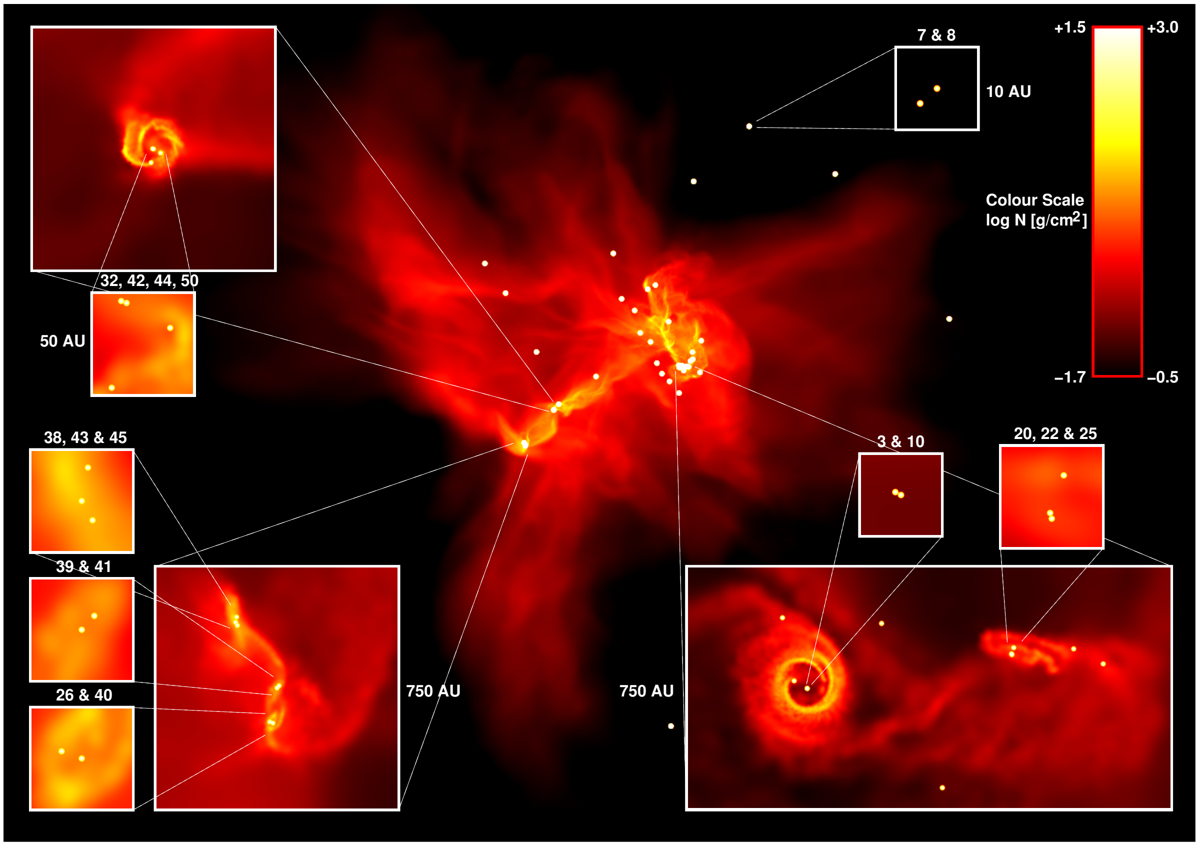

Fig. 3. The multiple stellar systems formed in the large-scale star cluster simulation (Bate et al. 20002a,b; 2003).

greater than that of the binary (Section 2.1). Similarly (Section 2.2), circumbinary discs can tighten the orbit of an embedded binary system via gravitational torques. For hierarchical triples, accretion and/or the interaction with a circumtriple disc can change the relative separations of the triple system, destabilising it and forcing dynamical interactions. However, although these processes all play a role in the formation of close binaries, the most important ingredient is stellar dynamical interaction (Section 2.3). Fly-bys harden existing binaries and closer encounters give exchange interactions, usually ejecting the lowest-mass object.

The main reason that dynamical interactions are able to produce a large number of close binaries in this calculation, while in pure N-body calculations they are not (Section 2.3), is that the presence of gas allows the dynamical interactions to be dissipative and transport angular momentum. When dynamical stellar interactions are combined with accretion, circumbinary/circumtriple disc interactions, star-disc encounters and other tidal interactions, efficient decay of wider systems to form close systems can be achieved. The frequency of close binaries at the end of the calculation is $7/43 \approx 16\%$. This is in good agreement with the observed frequency of close (separation < 10 AU) binaries of $\approx 20\%$ (Duquennoy & Mayor 1991), demonstrating that close binaries need not be created by fragmentation in situ.

The formation mechanisms discussed above lead to several consequences for the properties of close binaries (Bate et al. 2002b). There is a preference for equal masses, with all close binaries in the calculation having mass ratios $q \gtrsim 0.3$ and most having $q > 1/2$. This is due to the mass-equalising effect of long-term gas accretion with increasing angular momentum (Section 2.1) and dynamical exchange interactions that usually result in the ejection of the least massive component. These processes give a natural explanation for the observation that close binaries (periods $\lesssim 10$ years) tend to have higher mass ratios than wider binaries (Mazeh et al. 1992; Halbwachs, Mayor & Udry 1998; Tokovinin 2000). In particular, accretion from a circumbinary disc may be responsible for the formation of close binary systems with 'twin' components (Tokovinin 2004).

Successive dynamical exchanges also lead to a dependence of the close binary fraction on primary mass, since each time a binary encounters a star more massive than the primary, the most massive star will usually become the new primary. Of the ≈ 20 brown dwarfs there is only one close binary brown dwarf system (see below), whereas 5 of the 11 stars with masses > 0.2 M$_\odot$ are members of close binary systems. While it is difficult to extrapolate these results to larger star clusters and more massive stars, this trend of the frequency of close binaries increasing with stellar mass is supported by observational surveys (e.g., Garmany et al. 1980; Mason et al. 1998).

At the end of the calculation, most of the close binaries are still members of unstable multiple systems, with three also being members of hierarchical triple systems. Even allowing for the eventual break up of these systems, it seems likely that some of the hierarchical triple systems will survive. Although the true frequency of wide companions to close binaries is not yet well known, many close binaries do have wider components (e.g. Mayor & Mazeh 1987; Tokovinin 1997, 2000). Indeed, it was this observation that led Tokovinin (1997) to propose that dynamical interactions in multiple systems may play an important role in the formation of close binary systems as, indeed, is found in the cluster simulation.

3.3. *Brown Dwarfs in Binaries*

The formation mechanism and resulting properties of the brown dwarfs in the calculation have been studied in detail by Bate et al. (2002a). The calculation produced 23 stars, 18 definite brown dwarfs that were no longer accreting significantly, and 9 objects that were substellar and but were still accreting at the end of the calculation. All objects, whether they ended up as stars or brown dwarfs, began as opacity-limited fragments containing only a few Jupiter masses (Section 1.1); those that subsequently became stars did so because they managed to accrete enough mass. All 18 definite brown dwarfs formed in dynamically-unstable multiple systems and were ejected from the regions of dense gas in which they formed before they could accrete enough gas to become stars, as recently proposed by Reipurth & Clarke (2001).

Of the 18 definite brown dwarfs, none are in binaries. However, there is a close binary brown dwarf (semimajor axis 6 AU) within an unstable multiple system consisting of 7 objects. Also in this system is a close binary (semimajor axis 7 AU) consisting of a low-mass star (0.13 M$_\odot$) and a brown dwarf. This septuple system will undergo further dynamical evolution, and it is still accreting. However, because these subsystems are close, it is possible they will survive the dissolution of the multiple system, in which case the calculation would produce one binary brown dwarf system, one star/brown dwarf system, and ≈ 20 single brown dwarfs. Thus, the formation of close binary brown dwarfs is possible, but the fraction of brown dwarfs with a brown dwarf companion should be low ($\sim 5\%$).

This low frequency is primarily due to the closeness of the dynamical encounters that eject the brown dwarfs from the dense gas in which they form before they can accrete to stellar masses. The minimum separations during the encounters are usually less than 20 AU, so any wide systems are usually disrupted. However, another type of dynamical interaction also plays a role. Several binary brown dwarf systems that form during the calculation are destroyed by exchange interactions where one or both of the brown dwarfs are replaced by stars.

Observationally, the frequency of brown dwarf binaries is not yet clear. Both Reid et al. (2001) and Close et al. (2002) observed 20 brown dwarf or very low-mass primaries and found that 4 have companions giving binary frequencies of $\approx 20\%$. However, as discussed by Close et al., these surveys are magnitude limited rather than volume limited and may therefore overestimate the true frequency of brown dwarf binaries. The cluster calculation favours a lower frequency, but due to the small number of objects, a frequency of 20% cannot be excluded (there would be a probability of $\approx 6\%$ of finding 1 binary out of 20 systems). It is important to note that none of the binary brown dwarf systems currently known have projected separations > 15 AU (Reid et al. 2001; Close et al. 2002), consistent with their having survived dynamical ejection from unstable multiple systems.

Some of the computations reported here were performed using the UK Astrophysical Fluids Facility (UKAFF).

REFERENCES

Artymowicz, P. 1983, Acta Astronomica, 33, 223
Artymowicz, P., Clarke, C. J., Lubow, S. H., & Pringle, J. E. 1991, ApJ, 370, L35
Bate, M. R. 1997, MNRAS, 285, 16
Bate, M. R. 1998, ApJ, 508, L95
Bate, M. R. 2000, MNRAS, 314, 33

Bate, M. R. 2001, in The Formation of Binary Stars, IAU Symposium Vol. 200, eds. H. Zinnecker, R.D. Mathieu, (Astron. Soc. Pacific; Chelsea, MI), p. 429

Bate, M. R. 2003, in preparation

Bate, M. R., & Bonnell, I. A. 1997, MNRAS, 285, 33

Bate, M. R., Bonnell, I. A., & Bromm, V. 2002a, MNRAS, 332, L65

Bate, M. R., Bonnell, I. A., & Bromm, V. 2002b, MNRAS, 336, 705

Bate, M. R., Bonnell, I. A., & Bromm, V. 2003, MNRAS, 339, 577

Bate, M. R., Bonnell, I. A., & Price, N. M. 1995, MNRAS, 277, 362

Bate, M. R., & Burkert, A. 1997, MNRAS, 288, 1060

Bonnell, I. A. 1994, MNRAS, 269, 837

Bonnell, I. A., & Bate, M. R. 1994, MNRAS, 271, 999

Bonnell, I., Martel, H., Bastien, P., Arcoragi, J.-P., & Benz W. 1991, ApJ, 377, 553

Boss, A. P. 1986, ApJS, 62, 519

Boss, A. P. 1988, ApJ, 331, 370

Boss, A. P. 1989, ApJ, 346, 336

Boss, A. P., & Bodenheimer, P. 1979, ApJ, 234, 289

Burkert, A., Bate, M. R., & Bodenheimer, P. 1997, MNRAS, 289, 497

Chapman, S., Pongracic, H., Disney, M., Nelson, A., Turner, J., & Whitworth, A. 1992, Nature, 359, 207

Clarke, C. J., & Pringle, J. E. 1991a, MNRAS, 249, 584

Clarke, C. J., & Pringle, J. E. 1991b, MNRAS, 249, 588

Close, L. M., Siegler, N., Potter, D., Brandner, W., & Liebert, J. 2002, ApJ, 567, L53

Duchêne, G. 1999, A&A, 341, 547

Duquennoy, A., & Mayor M. 1991, A&A, 248, 485

Garmany, C. D., Conti, P. S., & Massey, P. 1980, ApJ, 242, 1063

Halbwachs, J. L., Mayor, M., & Udry, S. 1998, in Rebolo R., Martin E. L., Zapatero Osorio M.R., eds., Brown Dwarfs and Extrasolar Planets (ASP Conf. Ser. 134). Brigham Young University, Provo, p. 308

Halbwachs, J. L., Arenou, F., Mayor, M., Udry, S., Queloz, D. 2000, A&A, 355, 581

Hall, S. M., Clarke, C. J., & Pringle, J. E. 1996, MNRAS, 278, 303

Hut, P., & Bahcall, J. N. 1983, ApJ, 268, 319

Klessen, R. S., & Burkert A. 2000, ApJS, 128, 287

Klessen, R. S., & Burkert A. 2001, ApJ, 549, 386

Klessen, R. S., Burkert, A., & Bate, M. R. 1998, ApJ, 501, L205

Kroupa, P. 1995, MNRAS, 277, 1522

Kroupa, P., & Burkert, A. 2001, ApJ, 555, 945

Larson, R. B. 1969, MNRAS, 145, 271

Larson, R. B. 1990, in Capuzzo-Dolcetta R., Chiosi C., di Fazio A., eds, Physical Processes in Fragmentation and Star Formation. Kluwer, Dordrecht, p. 389

Low, C., & Lynden-Bell, D. 1976, MNRAS, 176, 367

Mason, B. D., Gies, D. R., Hartkopf, W. I., Bagnuolo, W. G. Jr., Brummelaar, T. T., & McAlister, H. A. 1998, AJ, 115, 821

Mayor, M., & Mazeh, T. 1987, A&A, 171, 157

Mazeh, T., Goldberg, D., Duquennoy, A., & Mayor, M. 1992, ApJ, 401, 265

McDonald, J. M., Clarke, C. J. 1995, MNRAS, 275, 671

Patience, J., Ghez, A. M., Reid, I. N., & Matthews, K. 2002, AJ, 123, 1570

Pickett, B. K., Durisen, R. H., Cassen, P., & Mejia, A. C. 2000, ApJ, 540, L95

Pringle, J. E. 1989, MNRAS, 239, 361

Pringle, J. E. 1991, MNRAS, 248, 754

Reipurth, B., & Clarke, C. J. 2001, AJ, 122, 432

Reid, I. N., Gizis, J. E., Kirkpatrick, J. D., & Koerner, D. W. 2001, AJ, 121, 489

Smith, K. W., Bonnell, I. A., & Bate, M. R. 1997, MNRAS, 288, 1041

Sterzik, M F., & Durisen, R. H. 1998, A&A, 339, 95

Tokovinin, A. A. 1997, AstL, 23, 727

Tokovinin, A. A. 2000, A&A, 360, 997

Tokovinin, A. A. 2004, this volume

Truelove, J. K., Klein, R. I., McKee, C. F., Holliman, J. H.II, Howell, L. H., Greenough, J. A., & Woods, D. T. 1998, ApJ, 495, 821

Whitworth, A. P., Chapman, S. J., Bhattal, A. S., Disney, M. J., Pongracic, H., & Turner, J. A. 1995, MNRAS, 277, 727

Matthew Bate: School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL, UK (mbate@astro.ex.ac.uk).

DISCUSSION

Kaper – Your calculations end after about 200,000 yr. When do you expect the first stars to settle on the main sequence? From an observational point of view: how much time should we add to the age derived for a cluster to take the "star formation duration" properly into account?

Bate – These simulations form low mass stars, so they will take $\sim 10^7$ years to settle onto the main sequence. The duration of the star formation process is short compared to this time $\sim 10^5$ years, although low-mass objects can be ejected very quickly, in $\sim 10^4$ years.

Hanawa – I would like to know the origin of IMF obtained in your simulation. Do higher mass stars have higher accretion rates or larger duration of accretion?

Bate – Higher mass stars accrete for longer rather than accreting more rapidly, but it is important to note that we only form stars of masses $\lesssim 1\ M_\odot$ in these calculations.

Hanawa – Can you comment on a paper which claims that the abundance of equal-mass close binaries is due to observational selection effects?

Bate – Early papers that looked at mass ratios of close binaries used magnitude-limited surveys and were therefore biased towards finding equal mass systems. More recent surveys (e.g., Mazeh et al. 1992) and Halbwachs' work) use volume-limited surveys and should not suffer this bias.

Hummel – I noticed that in the two simulations running side by side the elapsed time was different. Why is this so?

Bate – The two calculations were each run for 1.40 initial free-fall times of the clouds. Because the second cloud is smaller and denser, its free-fall time in years is shorter.

Mathieu – How would you relate your simulations to regions like Taurus-Auriga, where the binary frequency is very high and where protostars (binaries?) are invariably located near the centers of isolated molecular cores? This does not seem to be a region of extensive stellar dynamical activity, yet there is a rich and varied binary population.

Bate – The calculations I have shown are of denser systems, such as Ophiuchus and the Trapezium cluster. However, as shown by the differences between my two calculations with different densities, lower density clouds do result in less disc truncation, and fewer dynamical interactions. So I think the trend is in the right direction. With such a low-density environment as Taurus, I expect larger discs, fewer interactions and a quieter environment, as observed. Also, it is interesting to note that Taurus has a lot of nearly equal mass binaries, which would be consistent with accretion from isolated cores rather than a cluster environment.