Binary Stars as Critical Tools & Tests in Contemporary Astrophysics
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The Formation of Binary Stars

C.J. Clarke

Institute of Astronomy, Madingley Road, Cambridge, CB3 OHA, U.K.
email: cclarke@ast.cam.ac.uk

Abstract. I argue that binary star statistics offer the best observational constraints on current hydrodynamical simulations of star forming clusters. In these simulations, clusters form hierarchically from the bottom up, and dynamical interactions, mediated by the presence of circumstellar material, play a vital role at the lowest (few body) level of the hierarchy. Such a scenario produces a rich array of complex multiple systems whose properties are in many respects consistent with observations. I however highlight two areas of current disagreement: the simulations over-produce low mass single stars and under-produce binaries with low mass ratios. It is currently unclear to what extent these shortcomings reflect numerical issues and to what extent the omission of relevant physical processes. I conclude with a theorist's wish list for observational diagnostics that would most meaningfully constrain future modeling efforts.

1. Introduction

A decade ago, any review of binary formation mechanisms would have started by setting out a list of possible options (fission, prompt initial fragmentation, disc fragmentation, capture) and would have assessed the feasibility of each, with some speculative attempt to map each of the scenarios onto a set of observational characteristics (see, e.g., Clarke 1995)., We can now say with some confidence that fission is unlikely to be viable (see Tohline & Durisen 2001 for the most authoritative recent investigation of this issue). Binary formation through star-disc capture almost certainly occurs in dense young clusters like the Orion Nebula Cluster, but since such encounters are suffered by less than $\sim$10% of all stars, even in the very densest regions of the cluster core (see Scally & Clarke 2001, Olczak *et al.* 2006), this cannot be a major route for binary production. We are therefore left with fragmentation at various stages of the collapse process, plus star-disc (or dynamical) capture in the very early (deeply embedded) stage of star cluster formation.

The reason why it is not fruitful to try and isolate the observational properties of each of these production routes is that the field has moved on from the situation where simulations started with idealised initial conditions, set up in order to create a binary through one of the aforementioned methods. Instead, we are in era where it is possible to simulate the formation of *entire clusters*. In this case, the creation route of any particular binary is not guided by the prejudices of the simulator, but emerges from the complicated non-linear development of the Jeans instability in a turbulent star forming cloud. Examination, *a posteriori* of how a particular binary came into being shows that a combination of mechanisms is usually involved in the creation of a single system. Thus we are fast abandoning the search for *the* binary formation mechanism and are instead interrogating the simulations, in order to see whether they can reproduce a range of observational statistics on binary stars.

It is not difficult to understand why the subject has advanced in this way. In addition to the obvious advances in the speed of computational hardware, there have been some algorithmic advances which are of particular importance to the binary formation

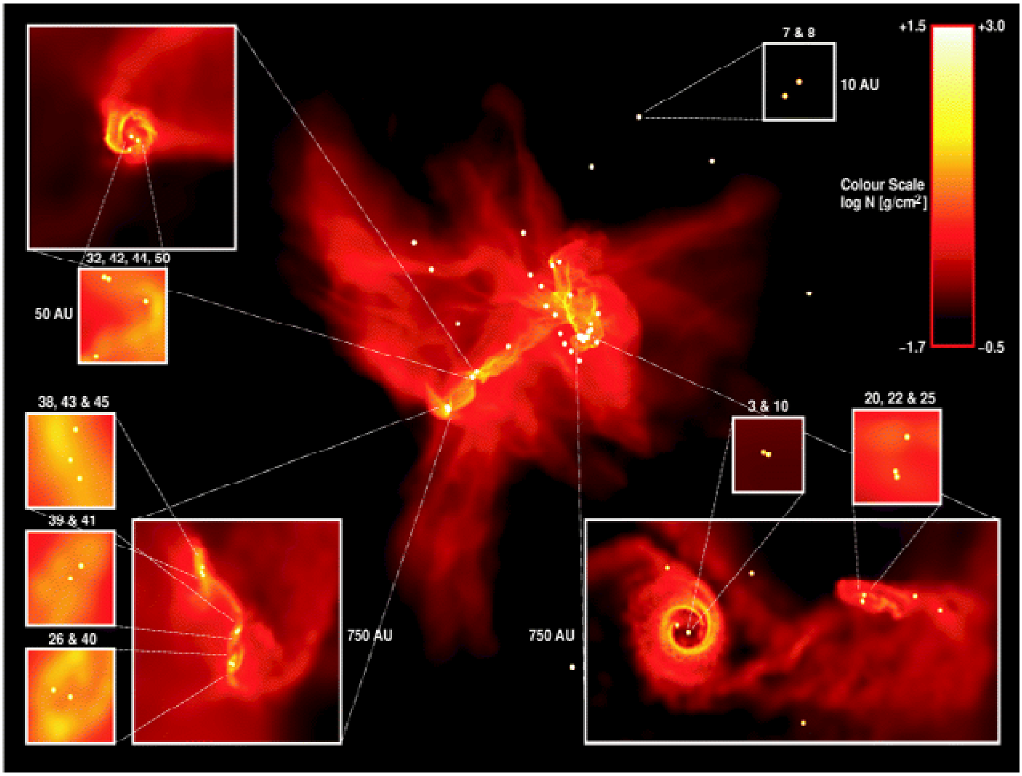

Figure 1. The locations and states of seven close binary systems created after 4×10^5 years in the simulations of Bate *et al.* (2002). The insets (labeled with the dimensions of the binaries in AU) show the variety of multiple systems and distributions of circumstellar material produced.

problem. Chief amongst these is the development of 'sink particles', these being point masses that interact gravitationally and through appropriate hydrodynamical boundary conditions with the rest of the flow but are themselves excised from the domain of detailed computation. This is an essential measure in such simulations, which produce a large number of collapsed regions ('stars') whose internal structure is not itself of interest but which, if not treated in this way, would impose a prohibitive computational load. The implementation of such particles is relatively straightforward in the case of a Lagrangian scheme such as SPH (Bate *et al.* 1995) but has only recently been successfully deployed in Eulerian (grid based) codes (Krumholz *et al.* 2005).

Figure 1 is a snapshot from the simulations of Bate *et al.* (2002) of the fragmentation of a turbulent molecular cloud which singles out some of the binaries and multiple systems created after $\sim 10^5$ years. It is notable that the basic star formation mode is one of small N clusters, so there is plenty of scope for the kind of small N dynamical interactions (exchange, binary hardening, ejection of singles) first explored in the N body context by van Albada (1968). It is, however, also obvious that gas dynamics plays an important role; we see tidal structures in the inset images that evidence disc-disc interactions, as well as massive circumbinary discs which are themselves subject to further fragmentation. The reader is directed to Bate *et al.* (2002, 2003) for a detailed analysis of the creation routes of the multiple systems formed.

Although such simulations generate eye-catching and broadly observationally credible results, it is obviously desirable to check their fidelity through as many routes as possible.

Potential sources of error include the use of incorrect initial conditions or, more likely, the omission of important physical effects such as magnetic fields and a realistic treatment of radiative transfer (see, however, Whitehouse *et al.* 2005, Dale *et al.* 2005, Price & Monaghan 2005 for recent progress in incorporating such effects in SPH codes). Numerical errors are an ever present possibility, so it is encouraging that there is the prospect that Adaptive Mesh Refinement (AMR) codes may develop to the point where they can provide a credible cross-check on results obtained with existing SPH simulations.

The most obvious zeroth order observational check is whether the simulations can reproduce the observed initial mass function (IMF), but this they do easily. In fact the rather featureless form of the IMF makes it too easy to replicate (as evidenced by the plethora of 'successful' IMF theories over the years). Binary statistics are much harder to replicate by any theory, however, on account of the richness of the diagnostic information they contain. It would appear unlikely that any model could accidentally replicate such a sweep of observational diagnostics as the binary and multiplicity fraction, the mass ratio distribution, the eccentricity and period distribution, all as a function of primary mass; indeed, we should be reassured by the fact that current models are conspicuously lacking in several of these areas. *Thus all those engaged in the painstaking task of accumulating binary star statistics should be reassured that, ultimately, their work will provide the most stringent test of star formation theories.*

In this contribution, I will focus on the two properties of binary stars which are set during the main accretion phase of star formation i.e., over the period (< 1 Myr) covered by the simulations: the multiplicity (as a function of primary mass) and distribution of binary mass ratios. Further important information is of course also preserved in the period and eccentricity distributions of binaries. However, these latter quantities can be substantially modified during later pre-main sequence stages. i.e., long after the masses of the constituent bodies have been set. Even at this late stage, it is well known (e.g., Artymowicz *et al.* 1991) that a small quantity of gas in circumbinary orbit can extract significant angular momentum from the binary and hence modify the orbital elements significantly.

2. Multiplicity as a function of stellar mass

Figure 2 provides a schematic illustration of the sorts of 'system architectures' commonly produced by turbulent fragmentation calculations at the end of the accretion phase. These derive from the study of Delgado *et al.* (2004), which simulated multiple realisations of turbulent $5M_\odot$ cores. This focus on small scale cores implies that of course one misses the interactions on larger scales that are captured by simulations such as Bate *et al.* (2002), which model a $50M_\odot$ cloud (see Figure 1). Nevertheless, the computational savings afforded by such small scale simulations means that it is possible, at the same numerical resolution as used by Bate *et al.*, to obtain a statistically meaningful set of multiple star systems. In contrast to the Bate *et al.* calculations, these multiples can then be integrated to the point where a large fraction of the gas has accreted on to the stars and are thereafter integrated to the point of dynamical stability as a pure N-body system.

From Figure 2, it is immediately obvious that the initial star formation process involves the creation of high order quasi-hierarchical multiples. The 13 multiples generated in the simulations have membership numbers roughly uniformly distributed in the range $N = 2 - 7$, where the membership number excludes 'outliers' (see below). A remarkable feature of the multiples shown in Figure 2 is the tendency for each constituent subsystem to apportion its mass roughly equally between components (for example, the

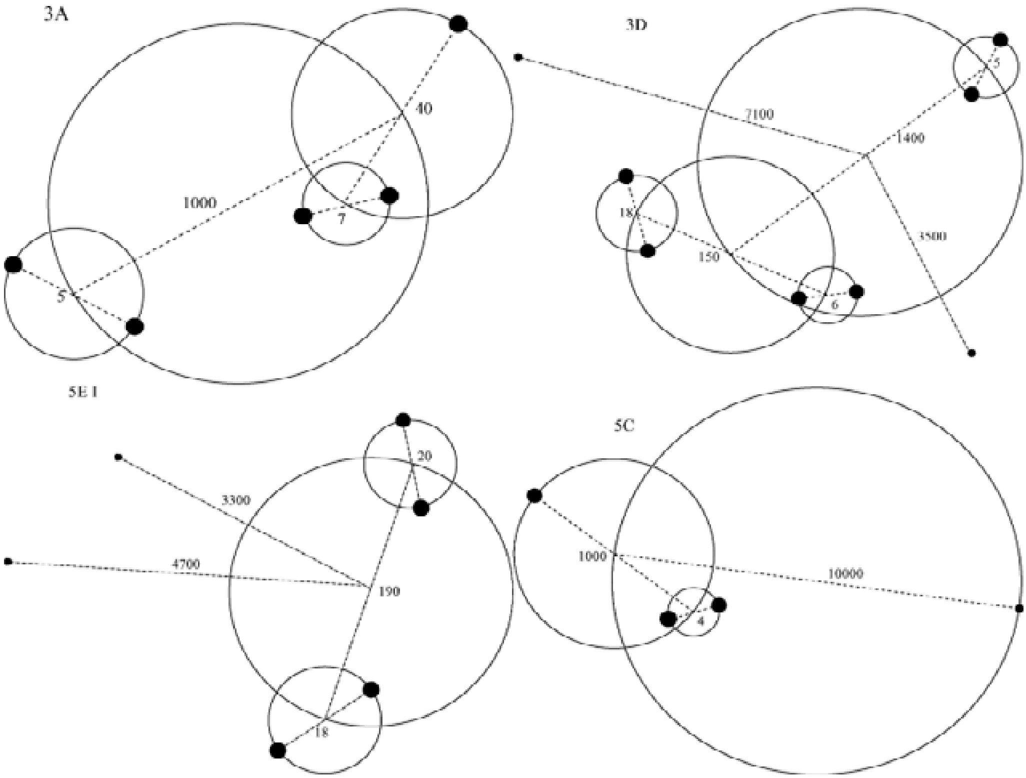

Figure 2. Schematic diagrams (not to scale) of some common system architectures produced in the simulations of Delgado *et al.* (2004) after ~ 1 Myr. The numbers refer to separations in AU.

system shown in the upper left consists of a nearly equal mass 7 AU binary with total mass nearly equal to its triple companion at 40 AU, whilst the total mass of the triple is roughly the same as the total mass of the (roughly equal mass ratio) 5 AU binary at 1000 AU). Evidently, some process (see Section 3) is ensuring a roughly equitable mass distribution at every level of the hierarchy.

The exception to this rule lies in the most distant members of the hierarchy, i.e., the so-called 'outliers' which are single stars located at $\sim 3000-10000$ AU from the centre of mass of the multiple. There are typically $2-3$ such outliers per multiple at the end of the accretion stage, and these outliers are always of very low mass (usually in the brown dwarf regime). Their creation is easily understood in terms of the dynamics of small N multiple systems: low mass objects acquire high kinetic energy at the expense of high mass stars in bound subsystems and are often ejected from their natal cores (Reipurth & Clarke 2001). Sometimes such interactions however impart insufficient energy to unbind the low mass object completely and they thus end up in weakly bound orbits with apocentres at many times the typical size of the parent multiple.

The above description refers to the end of the hydrodynamical evolution stage (i.e., after about a Myr) and is thus applicable to the predicted multiplicity statistics of the youngest pre-main sequence stars. After a further ~ 10 Myr of purely N-body integration, the situation looks very different: although there are still some high order multiples (up to $N = 6$) which are apparently dynamically stable hierarchies (according to the criteria of Eggleton & Kiseleva 1995), the majority of systems have been broken up into their

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constituent binary stars. It is also notable that only 10% of the 'outliers' present at ~ 1 Myr remain bound at 10 Myr: as expected, such low mass and weakly bound objects are liable to escape during the orbital reconfiguration of the parent multiples.

In terms of commonly used descriptors of multiple star properties, Delgado *et al.* (2004) found that the multiplicity fraction (defined as the number of multiples divided by the number of multiples plus singles) remains roughly constant (at $\sim$0.2) during the phase of dynamical break up (i.e., between $\sim 1 - 10$ Myr). The reason that this is the case — despite the drastic reconfiguration of the multiples over that period — is that the breaking down of multiples into (mainly) singles and binaries increases the number of multiples and singles by about the same factor. The companion fraction, on the other hand, (i.e., the mean number of companions per system) changes strongly (from about 1 to about 0.3) through the same reconfiguration. This illustrates the care that is needed when interpreting these quantities: although the companion fraction better captures the fact that high order multiples are being broken up, the values are misleading unless one thinks carefully about what is involved (i.e., a companion frequency of 1, which might suggest that most systems contain two stars, in this case represents the situation where the majority of stars are either in high order multiples or are singles).

The general outcome of these models, therefore, is that higher order multiple systems are abundant among young stars, but that these tend to break up as a result of dynamical interactions on timescales of ~ 10 Myr. This is in broad qualitative agreement with the recent multiplicity studies of young stars by Correia *et al.* (2006), which find some evidence that higher order systems are favoured in pre-main sequence, compared with main sequence, binaries. Correia *et al.* however point out that their observed abundances of higher order systems (compared with binaries) are somewhat lower than predicted by the simulations.

An obvious discrepancy, as pointed out by Goodwin & Kroupa (2005) is that the multiplicity fraction produced by the simulations is much lower than that observed, i.e., about 0.2 compared with values of $0.5 - 0.6$ in the observational literature (see Duquennoy & Mayor 1991, Tokovinin & Smekhov 2002). This relatively low multiplicity fraction is a consequence of the large numbers of stars produced per core (typically > 3). [Note, however, that early estimates (McDonald & Clarke 1993) relating number of stars per core to multiplicity fraction were overly pessimistic, since they assumed, as is the case for purely N-body interactions, that only one binary is formed per cluster. In the hydrodynamic simulations, we have seen that the creation of high order multiples, which then decay dynamically, actually produces several binaries per star forming core].

If we scrutinise the simulations more closely (Figure 3) we see that the discrepancy is entirely at the low mass end (indeed, the simulations somewhat over-produce binaries at the high mass end (around $1M_\odot$), although this would be remedied by modeling larger cores so that higher mass stars would be able to disrupt some of the solar mass binaries). However, the model results that best fit the binary fraction in the stellar domain (those where 60% of the core mass is accreted onto the stars before the multiples are evolved as N-body systems), produce *no* binaries in the brown dwarf regime. The observational value is however in the range $10 - 20\%$ (Martin *et al.* 2003). Since stars and brown dwarfs are formed in roughly equal numbers, one can understand why the simulations can match the stellar binary data and yet produce a global multiplicity fraction which is so low.

The reason for the over-production of single brown dwarfs in the simulations is probably due to the fact that the discs in the simulations can fragment too easily. Despite some unpublished claims that such fragmentation was a result of under-resolution in the SPH calculations, further convergence tests have not supported this assertion (Bonnell & Bate,

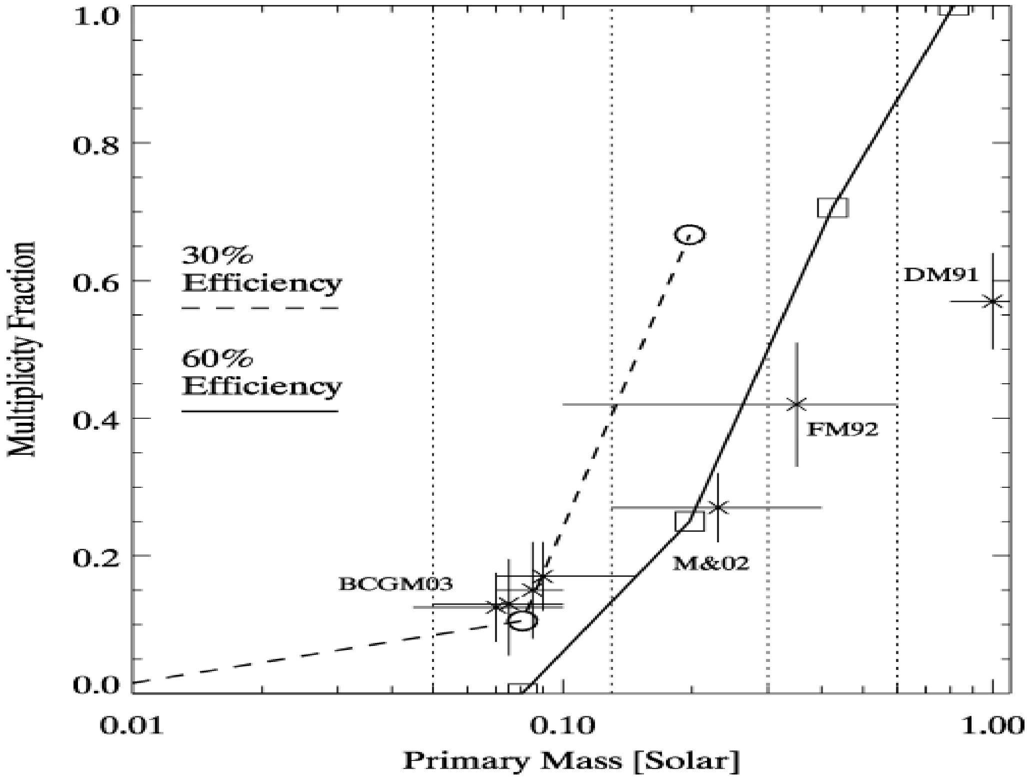

Figure 3. Multiplicity fraction as a function of primary mass produced by the simulations of Delgado *et al.* (2004). Observational data is labeled according to its source, i.e., DM91 = Duquennoy & Mayor (1991), FM92 = Fischer & Marcy (1992), M&02 = Marchal *et al.* (2003), BCGM03 = Bouy *et al.* (2003), Close *et al.* (2003), Gizis *et al.* (2003), Martin *et al.* (2003).

private communication). Instead, it is more likely that excessive disc fragmentation is a result of the unrealistic treatment of the thermal physics. Following Gammie (2001) is it well known that discs should only fragment if the local cooling timescale is less than around three times the local dynamical timescale. Given the cooling rates to be expected in circumstellar discs when radiative cooling with a realistic opacity law is assumed, this criterion is only expected to be met at large radii in the disc (i.e., at $>$ 100 AU; Rafikov 2002) †. The binary formation simulations discussed here (i.e., those of Bate *et al.* 2002 and Delgado *et al.* 2004; see also Wadsley *et al.* 2006) instead employ an isothermal equation of state, until the gas has collapsed to very high densities. An isothermal equation of state however implies an effectively *zero* cooling timescale, since pdV work can be radiated away instantly; thus it is unsurprising that the discs in these simulations are able to fragment at essentially all radii. In future, it will be desirable to explore binary formation in simulations which, instead of using an isothermal equation of state, treat cooling of the disc gas via radiative diffusion (see Whitehouse *et al.* 2005).

† Indeed, according to the recent simulations of Lodato *et al.* (2006), discs with longer cooling timescales do not fragment even when subject to large amplitude impulsive interactions with passing stars.

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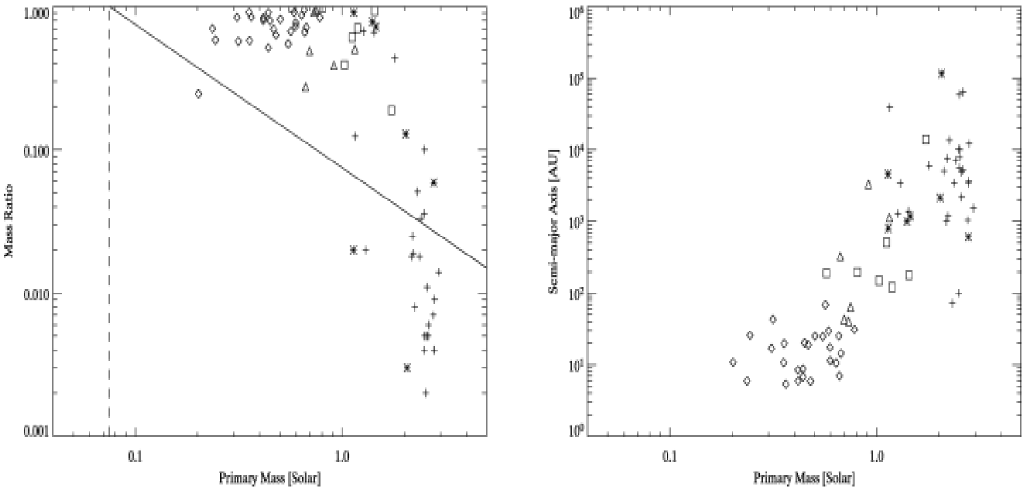

Figure 4. Mass ratios and separations of multiples as a function of 'primary' mass, from the simulations of Delgado *et al.* (2004). Here mass ratio q is the ratio of the mass of the outermost object of the subsystem under consideration to the total mass of all the objects interior to it (i.e., for a triple [(1-2)-3], q=m3/(m1 +m2)). Primary mass refers to the total mass of all the objects interior to that for which the mass ratio is being calculated. Diamonds correspond to binaries (either independent or bound to larger structures), triangles denote triples, squares quadruples, asterisks quintuples and crosses higher-order multiples.

3. The binary mass ratio distribution.

Figure 4 illustrates an obvious deficiency of all hydrodynamical models to date - the tendency not to produce binaries with low mass ratios. This tendency is shown at every level of the clustering hierarchy, as was noted in Section 2 above. Figure 4 shows that binaries are almost never produced in the simulations with $q = M_2/M_1 < 0.5$, with the exception of the very low mass 'outliers' which remain in wide orbits ($\sim$ 5000 AU) for about 10 Myr or so, before being dynamically ejected from the system. The under-production of low q pairs appears to be a generic property of turbulent fragmentation calculations (see also Goodwin *et al.* 2004) and appears to be a consequence of accretion of gas upon the proto-binary. For any plausible history of binary assembly, the material falling in upon a newly formed binary is generally of high specific angular momentum compared with the binary itself, and in these circumstances it is widely claimed (Artymowicz 1983, Bate & Bonnell 1997) that such gas will preferentially accrete upon the secondary. In this case, binaries evolve rapidly towards unit mass ratio, regardless of their initial mass ratio (Bate 2000). In the SPH simulations, this certainly appears to be the case and implies that any solution to the problem should relate to this accretion phase rather than to the creation of the binary.

Before examining possible solutions, it is important to be clear that there is indeed an observational problem. It is often cited that among the closer binaries (i.e., those with a period of less than 2000 days), the q distribution rises gently towards unit mass ratio (Mazeh *et al.* 1992) and is therefore not grossly inconsistent with the output of the simulations. However, these systems represent a small fraction of all binaries (recall that the median binary period is $\sim$ 200 years) and *for the binary population as a whole* it is clear that the mass ratio distribution rises quite steeply towards low q (Duquennoy & Mayor 1991, Evans 1995, Woitas *et al.* 2001, Prato *et al.* 2002, Halbwachs *et al.* 2003). Given that in the case of wider pairs, this dataset consists of binaries culled from the literature, and which can therefore be expected to be selectively incomplete at *low* q, it is hard to escape the conclusion that low q pairs are abundant in nature.

It has recently been suggested, however, that the lack of low q binaries in the simulations might be an artifact of the SPH calculations. Ochi *et al.* (2005) used a grid-based code to re-examine the (SPH) calculations of Bate & Bonnell (1997), which modeled gaseous accretion onto a protobinary. Both codes agree that in the case of accretion of gas whose specific angular momentum is larger than that of the protobinary, the accreted gas falls preferentially into the Roche lobe of the *secondary*, which is to be expected, given the larger displacement of the secondary from the system centre of mass. In the SPH calculations, this gas is retained in the secondary's Roche lobe and then accretes onto the secondary star. In the grid-based calculation, however, gas that enters the secondary's Roche lobe near the L2 point then circulates half an orbit around the secondary and then passes through the L1 point into the primary's Roche lobe, where it is then accreted. Thus in these latter calculations, the mass ratio of the binary can decline even when the inflowing material has high specific angular momentum.

It is not easy to assess which of these simulations is correct. Proponents of the grid-based code can legitimately question whether it is not the large viscosity in the SPH calculations which artificially shrinks the orbits of gas in the secondary's Roche lobe and thus prevents the transfer of material into the primary's Roche lobe. On the other hand, it can also be reasonably pointed out that the grid-based code models rather warm gas which can be deflected too readily by pressure gradients in the low gravity environs of the L1 point. Detailed follow up of these issues is under way, but is not currently pointing to an obvious resolution. If the lack of low q systems turns out *not* to be a numerical artifact, it will be necessary to take a harder look at the assumptions (initial conditions, physics modeled) behind the simulations.

4. Summary

Binary star statistics offer the best opportunities to check the veracity of star formation simulations. Current simulations, in which star formation proceeds in a highly interactive small N cluster mode, provide the right ingredients for generating a wealth of binaries and higher order multiple systems, in broad agreement with observations. This allows one to focus on areas of disagreement, and here we have highlighted the over-production of low mass single stars and the under-production of binaries with low mass ratios.

There are also a number of areas where current observational datasets are too incomplete to test the simulations. A theorist's wish list in this regard would run as follows.

i) The assembly of the sort of binary statistics that are currently available for G dwarfs to a range of lower mass bins,

ii) A better collation of the high order multiplicity statistics and of how mass is distributed at each level of the hierarchy, and

iii) An understanding of how the latter properties vary as a function of age. According to the models, the pre-main sequence stage should involve significant reconfiguration (breaking up) of high order multiple systems. In particular, it is predicted that rich young multiple systems should be accompanied by low mass outliers in weakly bound orbits. Evidently, deep imaging of the environs of pre-main sequence multiple systems is required to check out this prediction.

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Discussion

Andrei Tokovinin: What is the influence of high angular momentum (high beta) on the stability of resulting multiples and ejections? Did you model accretion of matter with different $\vec{J}$ during formation of a multiple system?

Clarke: The simulations do not impose any net rotation in the star forming core, but the initial gas has non-zero vorticity and thus has some degree of rotational support. From the size scales of the resulting multiples (Figure 1) one can judge that, since the initial core size is $\sim 10^4$ AU, $\beta \sim 0.1$. We have not attempted to *impose* a range of β values on our initial conditions, so cannot comment on any systematic dependence of the multiple star properties on β. Likewise, the accretion of material with different $\vec{J}$ is a natural outcome of the simulations. As we discuss, there is a tendency for late arriving material to have high $\vec{J}$ and, in these SPH simulations, for the mass ratios to increase at every level of the hierarchy as a result.