The Formation of Multiple Stars

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Summary. We have undertaken a series of SPH hydrodynamic + N-body simulations in order to explore the multiplicity properties of young stars. We find that binary and multiple stars are a natural outcome of collapsing turbulent flows, with a high incidence of $N > 2$ systems, specially among the higher mass objects. We find a positive correlation of multiplicity with primary mass and a companion frequency that decreases with age, during the first few Myr after formation, in accordance with observations. Binary brown dwarfs are rarely formed, in conflict with observational lower limits of 15%. Brown dwarfs as companions are predominantly found orbiting binaries or triples at large distances; thus we reproduce the so-called brown dwarf desert at short separations. The velocity dispersion for singles is found to be slightly larger, on average, than that of multiples. One caveat of these and previous models, namely the paucity of low mass ratio binaries, has been addressed with additional calculations. We tentatively conclude that their formation is intricately related to an appropriate selection of initial conditions and an accurate modelling of disc accretion and fragmentation.

1 Introduction

Most stars are known to be members of binary or even higher-order multiple systems [21, 19]. Among high-mass stars, the multiplicity fraction (MF) is very close to 100%. For lower mass stars, MF is somewhat lower [21, 24], but still high. The multiplicity properties of brown dwarfs are not so well constrained (see different contributions in this volume), but the lowest bound for MF is believed to be 15% [13, 35]. Thus, any good star formation theory must be a theory of (at least) binary star formation. Currently we can hope to do more theoretically speaking than produce multiple stars by imposing some multi-armed instability on a collapsing core (see [36], and references therein, for a review of different binary formation mechanisms). Turbulent initial conditions, for example, allow star formation to be triggered in a less predictable way, e.g. [9, 27, 28]. In addition, it has become computationally affordable to study the statistics of star pairing beyond pure N-body integration [16]. These two steps forward have made it possible to perform calculations which both resolve the fragmentation and collapse of molecular clouds and produce a statistically significant number of stellar systems, thus opening the door to a direct comparison with observations [9, 17, 18]. In this paper we review the results from the first hydrodynamic calculations to produce a statistically significant number of *stable* multiple systems in the separation range $1 - 1000$ AU. We will concentrate our attention mostly on those aspects pertaining to the multiplicity properties of low-mass stars, and the formation mechanism of low mass ratio binaries.

2 Episode I: The Gas Menace

For some time, numerical models with predictive power about the multiplicity properties of stars (e.g. multiplicity fractions, mass ratio, semi-major axis distributions) had to rely on pure N-body integration [42, 43, 22]. The masses, location and velocities of the stars were selected at the outset, and subsequently the orbital evolution was calculated. This treatment of multiple star 'formation' was necessary, as the computational expense and complexities involved in the modelling of gas fragmentation, collapse and accretion were too demanding. Even today, N-body models still constitute a useful tool to study the dynamical evolution of star clusters, e.g. [32], or to constrain star formation models, [33], either when the gas content is negligible or because it is the only alternative to study large ensembles of protostars.

However, gas is a fundamental ingredient of the star formation process, not only during the fragmentation and collapse stage, but also during the embedded phase of the life of a star. This is so mainly because large amounts of dense gas accumulate in the form of accretion disks around the protostars and due to the larger scale influence of the gas background where the protostar is embedded. Disks provide a mechanism for the accretion of gas with high angular momentum – which can modify substantially the orbital parameters of a protobinary [2, 6, 39] – and a dissipative medium to alleviate the effect of dynamical encounters with other cluster members [37]. Besides, if sufficiently massive and able to cool efficiently [25, 34], disks can fragment, and in doing so, produce a second generation of objects. The background gas also has important effects, since it accounts for a significant fraction of the gravitational potential of a young cluster and, through the action of gravitational drag, can affect the mass evolution and motion of both single and multiple stars (and hence the binary pairing outcomes, cf. [10, 12, 16].

Early star formation models that included the effect of gas did so to study the formation of binary stars from clouds subject to some kind of specific initial instability (rotation beyond a critical limit, multi-armed spiral density perturbations; see review [41]. These models have been of great importance but a caveat remained: they produce a low number of objects in a more or less predictable fashion. Other models tried to take into account large numbers of stars embedded in a big gas cloud [11], e.g. by utilising point masses with the ability to accrete and interact with the gas and other stars ('sink particles', [5]), but once more, with positions and velocities selected at the outset.

These models focused mostly on the study of the resulting initial mass function (IMF). The purely gas dynamical models had to be refined and taken to a larger scale, while the aim of point-masses-in-gas models had to shift to the study of the properties of multiple stars, if star formation models were to match the predictive power of N-body models. The earliest model to take such step was that by Bate and collaborators [9], who applied more general 'turbulent' initial conditions to a relatively large (for theory standards) 50 $M_\odot$ cloud and followed its fragmentation and collapse down to the opacity limit for fragmentation. For higher densities, pressure-supported objects were replaced by 'sink particles' and, thus, the simulation could be followed well beyond the formation of the first object. This calculation showed the power of the combination of more realistic initial conditions and a refined numerical scheme blending gas with N-body dynamics and, beyond any doubt, it meant a great leap forward in star formation studies; but, obviously, it had some shortcomings too. Among them was the high computational expense involved (even to this day) for just one calculation and the fact that the evolution of the cloud could not be followed for as long as it would be desirable in order to ensure that most multiple systems formed have attained stability. Thus, complementary calculations were necessary. We tried to fill this gap by performing simulations of smaller (5 $M_\odot$) clouds (see Section 3), to be run for longer during the gas-dominated stage, and to be followed as an N-body system until the stability of most of the systems could be guaranteed. These models posed a lower computational demand since each of them dealt with a single star forming 'core', and thus most of the gas within was involved in the star formation process and not 'hanging around' in low density regions as in Bate et al. 'multi-core' calculation. It was possible to perform 10 such calculations and, by applying different initial conditions to each of them, study the dependence of the resulting stellar properties on initial conditions. This aspect of the calculations, however, will not be addressed in this review. Rather, we will focus on the properties of the multiple systems.

2.1 Small-N Clusters

To start with, we will review some simple 'small-N cluster' models, which, though simple, give insight into some of the processes that affect multiple star formation in gas-rich calculations. These models were inspired by the work of Bonnell and collaborators [10, 11] who were the first to use 'sink particles' embedded in a uniform gas cloud as a first approach to study the formation of a large ensemble of stars ($N = 100$). Instead, we have considered systems with $N = 5$ protostars. The details of the numerical scheme (SPH) and initial and boundary conditions can be found in [16] (and in a different context in Sect. 3.1 below). It is enough to say that the 'sink particles' start with the same mass (1/20th of the initial cloud mass each) and are randomly positioned in phase space (with virial velocities on the average), the gas is critically Jeans-unstable and initially static and homogeneous, and remains isothermal throughout the calculation. The simulations are run until all the gas is accreted, then the stellar system is integrated as N-body until stability is attained.

2.2 A Dominant Binary

The 'seed' stars grow in mass by accretion and sink to the cluster centre through gas drag. In doing so, they bind to each other, forming a non-hierarchical multiple. Typically, a central binary comprising most of the mass forms. The other objects are ejected from the cloud or to large distances, where they cannot accrete much. Thus, if the cloud mass is low initially, the ejectae are likely to be substellar (this is one of the proposed formation mechanisms for brown dwarfs [40, 8]). Due to the dynamical decay, most of the binaries are close. The most important feature of the simulation is the *runaway formation of a massive binary*, which then dominates the cluster dynamics. As a result, other binary pairs are very unlikely to form and the other cluster members have comparatively low mass. *Binary pairing is therefore not random for the closest systems.* We will see that this feature is also common in simulations with more realistic initial conditions.

3 Episode II: Attack of the Turbulence

Molecular clouds are seen to display random motions that are typically described as 'turbulent'. Thus, it is a natural choice to impose a turbulent field as initial condition for the gas velocities. Turbulence also provides the seed for the generation of cloud sub-structure, which is subsequently amplified by gravity, leading to the 'dynamic' formation of stellar objects. The chaotic nature of turbulence guarantees that the protostars have an initial spatial distribution that cannot be predicted a priory. This property is welcome, as it decreases the ability of the modeller to pre-determine the outcome. In this section we present the setup and results from a series of 'turbulent' SPH simulations, which constitute the next step in refinement from the 'small-N cluster' simulations discussed before.

3.1 Numerical Scheme and Initial Conditions

We performed 10 calculations of small fragmenting gas clouds, using the SPH technique. Sink particles replace bound blobs after a critical density is reached [5]. We apply standard viscosity with $\alpha = 1$ and $\beta = 2$, and a binary tree to find nearest neighbours and calculate self-gravity. The opacity limit for fragmentation is modelled using an equation of state $p \propto \rho^{\gamma}$, where the gas is isothermal at low densities ($\leq 10^{-13}$ g cm^{-3}) and polytropic with $\gamma = 5/3$ at higher densities.

Each cloud is initially spherical, has radius of $\approx 10^4$ AU, 5 $M_\odot$ and density and temperature of $\approx 10^{-18}$ g cm^{-3} and 10 K respectively. The initial Jeans mass is ≈ 0.5 M$_\odot$. We use 100 SPH particles to resolve the minimum mass of few M$_\mathrm{J}$ that can occur in the calculation [7]), thus resulting in a total of 3.5×10^5 SPH particles.

We impose an initial random 'turbulent' velocity field, defined by a power-law spectrum. The values for the power-law exponent bracket the observed uncertainty in Larson's 'velocity-size' relation. The velocity field is normalised so that there is equipartition of kinetic and gravitational energy initially. We are imposing a parameterised initial velocity field which approximately reproduces observed bulk motions in molecular clouds (often described as 'turbulent' motions) but this term ('turbulence') should not be taken to imply that we are modeling what a fluid dynamicist would recognise as fully developed turbulence.

The hydro-dynamical calculations are run until ≈ 0.5 Myr. Thereafter the remaining gas is removed and the stellar system is evolved as a pure N-body system, using NBODY2 [1]. After 10 Myr we find that 95% of the multiples have decayed into stable configurations (using the criterion by Eggleton & Kiseleva [23]), and we stop the integration. The calculations produce 145 stars and brown dwarfs; 40% of the objects are substellar. The calculations have been performed using the United Kingdom Astrophysical Fluids Facility (UKAFF). Animations are available on request to the first author.

3.2 Triples and higher-order Multiples

Our simulations produce a wealth of multiple systems. The multiplicity fraction at 0.5 Myr after the initiation of star formation is close to 100%. It is apparent that multiple star formation is a major channel for star formation in turbulent flows. The systems can adopt a variety of configurations, like binaries orbiting binaries or triples. Such exotic systems have been observed, and currently, the occurrence of high-order multiples is being revised upwards (15-25% of all systems, [44] and this volume) as large surveys and high-resolution techniques begin to expose the closer and wider companions.

3.3 Multiplicity as a Function of Age

The companion frequency decreases during the first few Myr of N-body evolution, as many of the multiples are unstable. The total companion frequency decays from ≈ 1 to ≈ 0.3. This internal decay affects mostly low-mass outliers, which are released in vast amounts to the field. We expect that in a real cluster the multiplicity would drop even further as star forming cores do not form in isolation but close to one another. Some of our binaries orbiting binaries might not have survived in a more realistic environment. The predicted decrease in the multiplicity frequency has been quantitatively observed by Duchêne et al. [20]. In less dense star forming environments, such as associations or moving groups, we expect that dynamical interactions among different cores should not be that important and that many ejected low-mass objects should have been able to leave the group early on. Therefore the observed companion frequency should, on average, be larger than in dense clusters (notice e.g. the high companion frequencies found among members of the TW Hydrae and MBM 12 associations [14]).

3.4 Multiplicity as a Function of Primary Mass

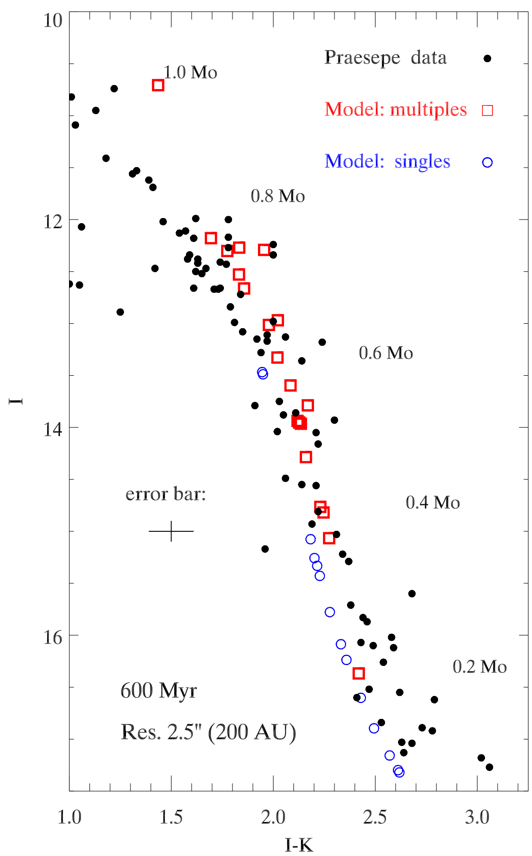

Fig. 1. Colour-magnitude diagram (I vs $I-K$) for the Praesepe cluster, with our results superimposed. Binaries closer than 200 AU are considered as unresolved.

We find a positive dependence of the multiplicity fraction on primary mass (see Fig. 3 in [17]), in qualitative agreement with observations. This dependence can also be illustrated by a direct comparison with the infrared colour-magnitude diagram of the 600 Myr old Praesepe cluster (Fig. 1). The cluster was observed by Hodgkin et al. [30]; the masses of simulated stars were converted to magnitudes using the tracks by Baraffe et al. [3]. Binaries with less than 200 AU separation are considered as unresolved.

Two features from Fig. 1 are worth noting: first, the simulated cluster shows a binary sequence whose width is comparable to that of the Praesepe, except for systems redder than $I - K = 2.5$. This seems to suggest that the formation of a significant number of triples, quadruples, etc. may indeed be common in real clusters. Second, although our binary fraction for G stars is in agreement with observations, our models fail to produce as many low-mass binaries as observed. For example, a binary fraction of at least 15% is seen among brown dwarfs, e.g. [13, 35], although values as high as $30 - 40\%$ have been predicted [38] (but see [31]).

3.5 Bound Brown Dwarfs

During the first few $\times 10^5$ yr most brown dwarfs are locked in multiple systems, often orbiting a binary or triple in eccentric orbits at large separations. Most of these systems are unstable and decay in a few Myr, releasing individual brown dwarfs to the field. Only a few substellar objects survive as bound to stars. Of these, the majority orbit a binary or triple at distances greater than 100 AU. One case out of 4 consists of a brown dwarf orbiting an M star at 10 AU. Our results are in agreement with the observed brown dwarf desert at very small separations. However, more than a dozen substellar companions to stars at wide separations are known [26]. According to our results, we would expect that a large fraction of the primaries in these wide systems should turn out, in closer examination, to be $N \geq 2$ multiples.

3.6 Velocity Dispersion

Single and binary stars attain comparable velocities in the range $1{-}10\ \mathrm{km\ s^{-1}}$. Higher-order multiples display lower velocity dispersions (Fig. 2). This kinematic segregation as a function of N is the expected outcome of the break-up of unstable multiples, whereby the ejected objects (typically singles, or less often binaries) acquire large velocities whereas the remaining more massive multiple recoils with a lower speed. Therefore, we would expect low-mass star-forming regions like Taurus, where a local kinematic segregation may survive against the influence of large scale dynamics, to display an overabundance of multiple systems in the densest regions, from where the low mass singles can escape more easily. This prediction was made by Delgado-Donate et al. [17, 18], and has been recently supported by the simulations [4]. On the observational side, it must be noted that the most recent survey of Taurus [29], covering several times the area of previous surveys, has found that the

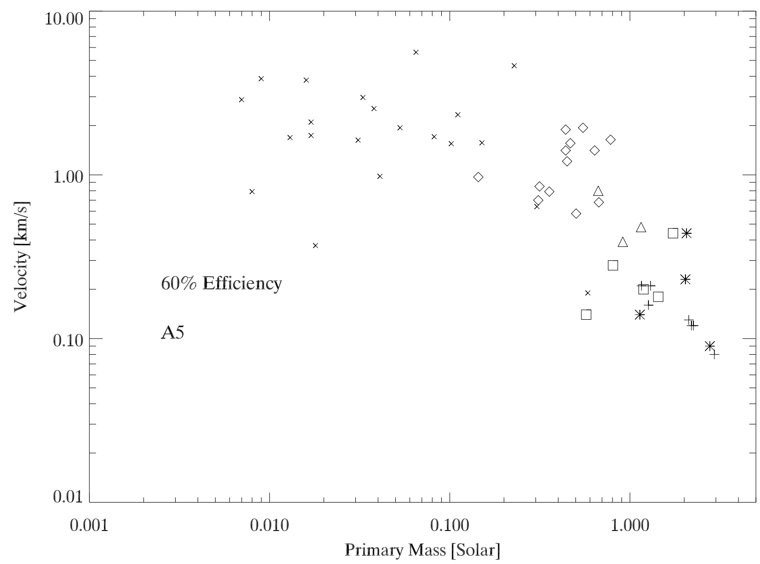

Fig. 2. Velocity (in km s^{-1}) versus primary mass (in $M_{\odot}$), after the end of the hydro calculations (60% efficiency). Small crosses represent singles and the other symbols refer to $N > 1$ multiples. A5 is a simulation label.

fraction of brown dwarfs increases as one moves away from the densest cores, known before to be over-abundant in binaries. This seems to be an indication for an average larger speed of the lower-mass single objects, as predicted.

4 Episode III: Revenge of the Binaries

We have shown that 'turbulent' calculations are able to form a large fraction of multiples systems. For a significant range of primary masses, we reproduce the observed multiplicity fractions and the basic features of the IMF, and provide a viable formation mechanism for brown dwarfs. This is a substantial achivement. However, we must look more closely at the distribution of binary parameters, which is the most exacting area in which star formation theories can be compared with observations, and check critically against solid empirical results. Presently we have focused on low mass ratio binaries, i.e. those whose component masses differ by at least a factor of 2–3 – these are known to comprise roughly half of the population of binaries. We will argue that the high occurrence of this type of binary cannot be explained within current and past star formation models.

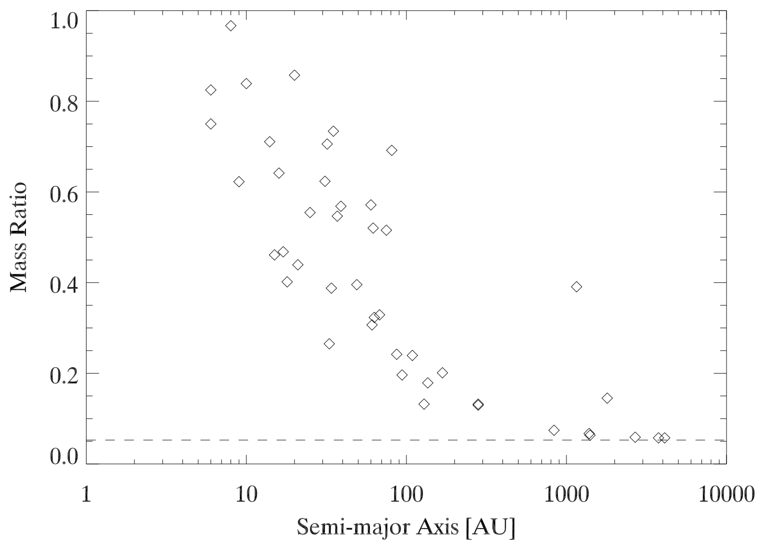

Fig. 3. Mass ratio q versus semi-major axis a [in AU] for different values of the initial specific angular momentum of the two-body system in the 'toy models'. The dashed horizontal line marks the minimum value the mass ratio can have, given the initial setup of the models.

4.1 Where are the Low Mass Ratio Binaries?

Binaries with a relatively low binding energy (wide, low mass ratio q or low-mass binaries) are seen to be under-produced by all star formation calculations to date. N-body models, e.g. [43, 22], and hydrodynamic simulations, e.g. [12, 17, 18], run into difficulties to produce systems of this type, as dynamical interactions – which play a vital role in the formation of multiples and the ejection of low-mass objects – also act to disrupt systems with a low binding energy, low-q binaries among them. Even 'turbulent' calculations with subsonic Mach numbers [27, 28] also fail to produce enough low binding energy binaries despite the lower mean number of objects formed per cloud.

We have studied this problem by reviewing the existing literature and performing simple 'toy models' of $N = 2$ embedded stars [15]. We find that most models to date fail to produce low-q binaries due to the production and mutual interaction of several binary pairs (which promotes the exchange of higher-mass components as binary companions) and due to the fact that the first binary, which goes on to accrete rapidly and thus dominate the dynamics of the system, forms with a rather high mass ratio initially. These problems are hard to avoid as the components form in collapsing filaments and are thus pre-destined to interact shortly after formation, decreasing the chances of attaining different masses before a bound pair is formed. In addition, for a bound system, the accretion of high angular momentum material is seen to increase q, as matter is preferentially accreted onto the secondary. This result has tentatively been called into question by Ochi et al. [39].

4.2 Possible Solutions to the Riddle

In order to investigate possible solutions to the puzzle of low-q binary formation, we have performed simple 'toy models' of the evolution of an embedded protobinary, where the relative specific angular momentum of the binary is chosen as a free parameter. The models are very similar to those described in Section 2, except that now $N = 2$. These simulations show that, provided that the specific angular momentum of the protobinary is weakly coupled to the specific angular momentum of the gas it accretes, a binary with initially nearly equal mass components can end up with a very low mass ratio. From these models it is possible to obtain a relation between semi-major axis and mass ratio (Fig. 3) which is in close agreement to that observed among wide binaries. Thus, it seems that the condition of weak angular momentum coupling may be of relevance to the formation of wide low-q pairs. It remains unclear, however, how such binaries can form under more realistic initial conditions.

From our study, we tentatively conclude that low-q systems can either form in cores where the proto-binary has lower specific angular momentum than its gas reservoir or else where a low-mass companion forms through *delayed* disk fragmentation. In both situations, the system has to form in relative isolation, to survive disrupting encounters with other binaries. It is unclear, however, how any of these conditions can be met in practice. We thus flag the creation of extreme mass ratio and brown dwarf binaries as an unsolved problem and challenge to theorists.

5 Conclusions

Gas is a very important actor in the theatre of star formation. Even after the fragmentation and collapse phase, gas plays a vital role through the dissipation of energy during encounters, accretion, disk fragmentation and drag in the more diffuse background. We have presented simple models of small clouds with a few accreting point masses, that represent a first step towards the investigation of the role of gas in star formation. From them, we can see that the formation of a dominant binary, with lower mass objects orbiting at large separations or ejected from the cloud, is a typical outcome of the break-up of an accreting multiple.

On a more realistic ground, we have undertaken the first hydrodynamical + N-body simulations of multiple star formation to produce a statistically significant number of stable hierarchical multiple systems, with components separations in the range $1-1000$ AU. We have shown that a high multiplicity fraction is typical of the very early stages, a few $\times 10^5$ yr after star formation begins, with many different possible multiple configurations. At later stages (a few Myr), many systems have decayed, ejecting brown dwarfs to the field and decreasing the companion frequency. Both the high initial multiplicity and its dependence on age seem to be in accord with recent observations.

We find a positive dependence of multiplicity on primary mass, with few low-mass stars being primaries. The paucity of brown dwarf binaries in our simulations indicate that the models need finer tuning. Brown dwarfs are found, however, orbiting binaries or triples at large distances, and thus we suggest that a good test of our models is to look into the primaries of wide brown dwarf companions in search of multiplicity. The velocity dispersion among multiples is seen to be, on average, somewhat lower than for the singles, and thus we would expect this weak kinematic segregation to show up in regions where the large scale dynamics are not very relevant (low-mass star forming regions, associations).

We have also shown that hydrodynamic simulations of binary formation fail to produce extreme mass ratio binaries with anything like the frequency with which they are observed. Too efficient fragmentation, intersecting flows, the formation of a dominant binary and the accretion of high angular momentum material from a circumbinary disk are key factors that reduce the formation and survival probability of low-q binaries. Possible solutions to this riddle have been identified – weak coupling of the specific angular momentum of a protobinary with its surrounding material, initial conditions less prone to fragmentation – but it remains unclear how they may occur naturally under realistic initial conditions.

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