MULTIPLE STELLAR SYSTEMS: FROM BINARIES TO CLUSTERS

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1. Introduction

The study of star formation often concentrates on the easily detectable product of this process: the young stars. These stars are typically not in isolation but are found in groups ranging in sizes from binary systems to clusters containing thousands of stars. In this chapter we discuss the mechanisms for, and implications of, star formation in groups.

Although much theoretical work has gone into understanding the formation of a single star like our sun (e.g. Shu et al. 1987), most solar-type stars are found in binary systems (Duquennoy & Mayor 1992). Furthermore, surveys of pre-main sequence stars have shown that their binary frequency is at least as high as on the main sequence (e.g. Ghez 1995; Mathieu et al.1999). Indeed, there is strong evidence that in some nearby star forming regions such as Taurus and Chameleon, the binary frequency is significantly higher than among the main sequence populations.

A further complication is that star formation in giant molecular clouds (GMCs) such as Orion is predominantly forming clusters of young stars (Lada et al. 1991; Meyer & Lada 1998). Clustering appears to be ubiquitous around young stars more massive than $\approx 5M_\odot$ (Hillenbrand 1995; Testi et al. 1997) with the youngest O-type stars found in rich clusters of a thousand or more stars such as the Orion Nebula Cluster (e.g. Hillenbrand 1997).

The reason why star formation in groups is important is that the dynamical timescales of these systems is of the same order as the stellar formation timescale, the pre-collapse free-fall time. Thus, the stars interact as they are forming, and these interactions necessitate that we study their formation in the group as a whole and not as separate entities. In this chapter, we discuss the formation and early evolution of groups of stars, ranging from binaries to stellar clusters. In Sections 2 through 5 we discuss the formation of binary and multiple systems while in Sections 6 through 8 we discuss the formation of stellar clusters.

2. Observations of Binary Systems

As noted above, binary systems are common both amongst the main sequence (Duquennoy & Mayor 1991; Fisher & Marcy 1992; Mayor et al.; 1992) and amongst the pre-main sequence (PMS) (Simon et al. 1992; Ghez et al. 1993; Reipurth & Zinnecker 1993; Leinert et al. 1993; Mathieu 1994) populations. The fact that the PMS systems have all their discernible properties within 10^6 years implies that the binary pairing has to occur early, on the same timescale that the stars form.

2.1. MAIN SEQUENCE BINARIES

The best statistics on stellar multiplicity and binary properties come from recent volume limited samples. These surveys largely avoid the selection effects which have plagued earlier samples. They found that ≈ 60 % of G-dwarfs (Duquennoy & Mayor 1991), ≈ 45 % of K-dwarfs (Mayor et al. 1992), and ≈ 42 % of M-dwarfs are in binary systems (Fisher & Marcy 1992).

In addition to reproducing the frequency of binary systems, any theory for the formation of binary stars has to take into account the many observed properties of these systems, including their separations, eccentricities and mass ratios. Duquennoy & Mayor (1991), found that binary stars can have separations from a few $R_\odot$ to 10^4 AU. The distribution of separations appears to be unimodal, with a broad peak at ≈ 30 AU. In terms of the eccentricity, only the closest of binary stars have circular orbits, due to tidal circularization. Longer period binaries all have non-zero eccentricities, while the maximum eccentricity at a given period increases with the period. Considering the distribution of mass ratios, Duquennoy & Mayor (1991) show that most binaries do not have equal masses, but that the distribution is slowly increasing for smaller mass ratios. In contrast with the overall mass ratio distribution, the closest systems appear, although with only small number statistics, to have a nearly flat distribution with a possible rise towards equal mass systems (Mazeh et al. 1992).

2.2. PRE-MAIN SEQUENCE BINARIES

Even though a significant fraction of the earliest classified T Tauri stars were known to be binaries, it is only recently that extensive surveys have attempted to quantity the binary frequency of pre-main sequence stars in nearby star forming regions (Mathieu et al. 1989; Simon et al.1992; Ghez et al. 1993; Leinert et al.1993; Reipurth & Zinnecker 1993; Richichi et al. 1994;

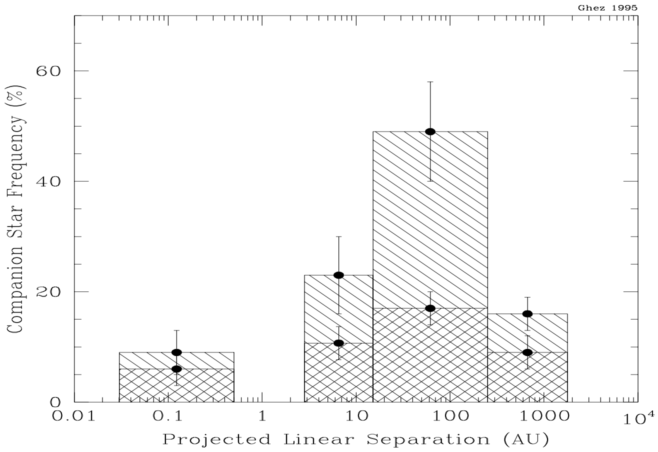

Figure 1. A comparison of companion star frequency for main sequence (cross hatched) and pre-main sequence (hatched) stars (Ghez 1995).

Ghez et al. 1997). The main result of these surveys is that there is an excess (*approx* twice) of pre-main sequence binaries in these regions, compared to the main sequence (Fig. 1; Ghez [1995]; Mathieu et al. [1999]). This unexpected excess is hard to explain if these regions are typical of most youngs stars. Interestingly, surveys of the binary frequency in young stellar clusters yield numbers more similar to the main sequence (e.g. Prosser et al. 1994; Petr et al. 1998) although that may depend on the cluster, and the location in the cluster, considered (Padgett et al. 1997). We will return to this in §8.

3. Binary Formation Theories: Fission and Capture

There have been many theories advanced to explain the origin of binary stars. These theories have generally involved either a dissipative mechanism to join to unbound stars together (capture mechanisms) or a mechanism to separate one body into two. Current thinking is that most binary systems form through some type of a fragmentation scenario, with a possible subsequent reorganisation of the system involving star-disc interactions (or star-disc capture). For the sake of completeness, we begin by discussing the currently discarded theories of fission and traditional capture mechanisms.

3.1. FISSION

Fission, first suggested by Kelvin and Tait in 1883, involves the rotational instability of a contracting, rapidly rotating protostar. It is hypothesised to occur after the initial formation phase has resulted in a quasi-equilibrium pressure-supported protostar. As the contraction proceeds, conservation of angular momentum increases the protostar's spin. The protostar then becomes unstable to non-axisymmetric perturbations once the ratio of rotational to the absolute value of the gravitational energies is greater than 0.27. This instability has the protostar deform into a bar-shape and subsequently separate into two distinct bodies. This process could only explain close binaries, with separations of the order of the protostellar core, so would be unable to form the majority of systems.

Although long an attractive binary formation mechanism, fission has recently been abandoned. This is because numerical simulations have shown that fission does not occur for compressible fluids like stars (e.g. Durisen et al. 1986). Instead, spiral arms form at the ends of the bar which transport angular momentum away from the central object by gravitational torques (e.g. Bonnell 1994). This results in the formation of a disk around a now stable protostar. This disk contains only a small fraction of the total mass but contains the majority of the system's angular momentum. Thus, fission is not a viable mechanism for the formation of any binary stars.

3.2. CAPTURE

Capture, first suggested as a binary formation mechanism by Stoney in 1867 (Tassoul 1978), involves some sort of process that can dissipate excess kinetic energy so that two unbound stars become bound during a close passage. Several variations of this mechanism have been proposed. These include *Tidal Capture*, in which two stars pass close enough together to excite tidal modes in each other which absorb much of their relative kinetic energy (e.g. Fabian, Pringle & Rees 1975; Mardling 1995); *Dynamic Capture*, where three stars pass close together and exchange energy such that one of them is ejected with most of the kinetic energy, leaving the other two bound; and *Star-Disk Capture*, where a circumstellar disk provides the dissipative medium and the relative kinetic energy goes into unbinding some of the disk material. The first two variants require high stellar density and are therefore not likely to contribute a significant fraction of the overall binary population (Hills & Day 1976), although tidal capture is still a leading mechanism for forming X-ray binaries in dense clusters. The last mechanism uses the fact that protostars are observed to have relatively large and massive circumstellar disks which can then act as a dissipative medium, significantly increasing the cross section (e.g. Larson 1990).

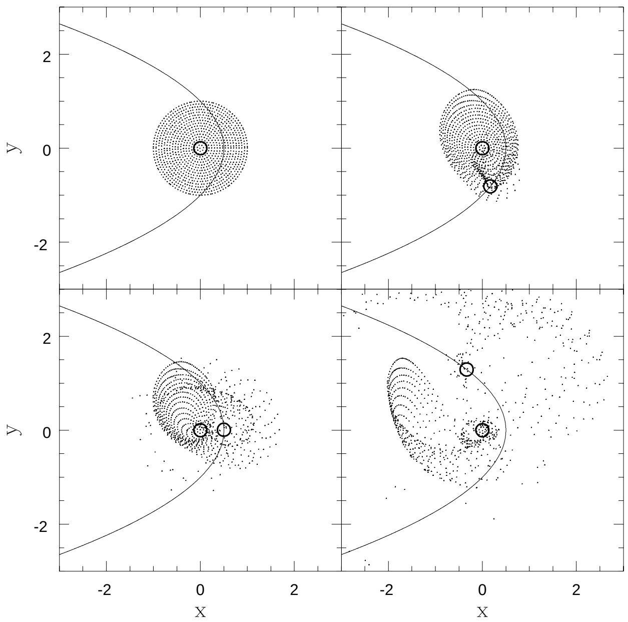

Figure 2. A star-disk interaction where the disk matter exterior to periastron is unbound in tidal tails (Hall, Clarke, & Pringle 1996).

3.3. STAR-DISC CAPTURE

The dynamics of star-disc captures have been investigated by Clarke & Pringle (1991; 1993), Heller (1993) and Hall, Clarke & Pringle (1996). During an encounter, where the minimum separation of the two stars is less than the disk radius, the disk matter exterior to this distance is unbound, removing the necessary energy from the two stars (see Fig. 2). The energy exchange is from perturbing star to disk as long as the periastron separation is $R_{\rm peri} \leq 1.5 R_{\rm disk}$. The actual energy liberated by this encounter is estimated to be between 2 and 5 times the binding energy of the material exterior to periastron, depending on the exact geometry of the encounter (Hall, Clarke & Pringle 1996).

Although this process will not form many binaries in the field stars where interactions are too rare, It can be a significant process in small stellar clusters (Clarke & Pringle 1991). These clusters are more appropriate than larger clusters (> 100 stars) as the higher velocity dispersion in dense stellar clusters tend to destroy the disk at the first encounter. The dynamics of these small clusters has been investigated for stars without (McDonald & Clarke 1993) and with star-disk interactions (McDonald & Clarke 1995). Without disks, interactions in a small cluster results in the formation of a single binary containing the two most massive stars. This dynamical biasing results in mass ratios consistent with that observed if the cluster contains

$\lesssim$4 stars. Otherwise, the mass ratios peak towards equal masses. When star-disk interactions are included, the binary frequency is increased such that it is consistent with those observed for main sequence solar type binaries. Furthermore, the star-disk interactions remove the dynamical biasing so that the secondary mass function is compatible with random picking from the IMF. This happens as the star-disk interactions cause the binaries to be harder and thus are less likely to be disrupted by subsequent encounters, independent of the secondary mass (McDonald & Clarke 1995). In terms of the separation, the interactions are most likely to occur with periastron of order the disk radius. Thus, it is unclear at present if you can form very close systems from this mechanism.

An important point in this argument is that small clusters are necessary for this mechanism to work. Their formation would require some sort of "Prompt Fragmentation" as set out by Pringle (1989). An example of this is the fragmentation of a cooled shock layer in cloud-cloud collisions (Chapman et al. 1992). Star-disk capture has been found to occur among fragments formed in this layer (Turner et al. 1995).

4. Binary Formation through Fragmentation

Fragmentation as a mechanism for the formation of binary systems was first proposed by Hoyle (1953). He noted that if the collapse is isothermal, then as the density of a cloud is increased, the Jeans mass, the minimum mass for an object to be gravitationally bound decreases and smaller parts of the cloud become gravitationally unstable. He envisioned a repetitive process known as "hierarchical fragmentation". Although, in general, this does not occur due to the non-homologous nature of gravitational collapse with pressure (see below), the idea of fragmentation due to a decreasing Jeans mass does occur and can be thought of as "Thermally Driven Fragmentation". This generally occurs during the collapse process. Alternatively, fragmentation can occur with a near constant Jeans mass when the total mass available is increased. An example of this type of process is when rotation halts collapse at a certain stage (e.g a circumstellar disc) and mass is added through the continuing infall.

4.1. GRAVITATIONAL COLLAPSE AND FRAGMENTATION

In order to see when fragmentation may occur in the star formation process, it is useful to consider the Jeans mass, M_J and the Jeans radius, R_J the minimum mass and radius, respectively, for a cloud of given density, ρ and

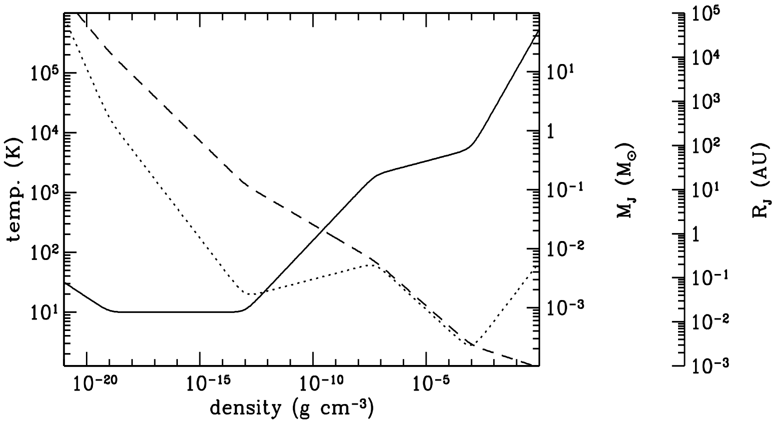

Figure 3. The temperature (solid line), Jeans mass (dotted line), and Jeans radius (dashed line) of interstellar gas as a function of density, showing the different phases the gas passes through during collapse (adapted from Tohline 1982).

temperature, T to be gravitationally bound:

$$R_J = \left(\frac{5R_gT}{2G\mu}\right)^{1/2}\left(\frac{4}{3}\pi\rho\right)^{-1/2}, \tag{1}$$

and

$$M_J = \left(\frac{5R_gT}{2G\mu}\right)^{3/2}\left(\frac{4}{3}\pi\rho\right)^{-1/2}, \tag{2}$$

where R_g is the gas constant, G is the gravitational constant, and μ is the mean molecular weight.

Once collapse is initiated, there are four main phases that the collapsing cloud passes through. Figure 3 shows a schematic of the temperature as a function of the density for a protostellar collapse (adapted from Tohline 1982). The collapse is parameterised by a polytropic equation of state $P = K\rho^\gamma$ ($T \propto \rho^{\gamma-1}$) where γ depends on the collapse phase. In the first phase, the collapse proceeds isothermally ($\gamma = 1$) until densities of the order of 10^{-14} to 10^{-13} g cm^{-3} are reached. At this point, the gas is no longer optically thin, and the trapped radiation increases the temperature (phase 2; $\gamma = 7/5$). This forms a first protostellar core which contracts quasistatically with increasing mass. Once the temperature has reached 2000 K, the molecular hydrogen starts to dissociate, absorbing some of the thermal energy and allowing for a second collapse stage (phase 3; $\gamma \approx 1.1$). Finally, once all the gas is in atomic form, a second protostellar core is formed which continues to contract quasistatically as it grows in mass (phase 4; $\gamma = 5/3$).

In order for fragmentation to occur, the total mass available for fragmentation has to be $M_{\rm tot} \gtrsim 2M_J$, otherwise each object cannot be independently gravitationally bound. This occurs most readily when the Jeans mass decreases as the density increases during the collapse. Figure 3 show the evolution of the Jeans mass during the four phases of collapse. It decreases throughout the isothermal collapse phase where $\gamma = 1$, increases when the fist core is formed ($\gamma = 7/5$), decreasing again during the second collapse phase where $\gamma \approx 1.1$, and increasing once more when all the hydrogen has dissociated ($\gamma = 5/3$). Thus fragmentation is most likely to occur during or slightly after the two collapse phases.

The scale at which fragmentation is likely to occur can be understood in terms of the Jeans radius, the minimum radius for an object to be bound, and its evolution throughout the collapse (Fig. 3). The Jeans radius gives an indication of the minimal initial separation as objects with smaller separations would not be separately bound. Thus, in order for fragmentation to produce binaries with separations less than 1 AU, densities greater than 10^{-10} g cm^{-3} are required. This in turn implies fragment masses on the order of the Jeans mass being $M_{\rm frag} \lesssim 0.01 M_\odot$. Any close binary formed from a straight fragmentation will thus have to accrete most of its final mass in order to achieve stellar status.

A limitation on thermally driven fragmentation is that collapse proceeds non-homologously, limiting the mass available for fragmentation. From near-uniform density initial conditions, pressure gradients develop near the outer edge of the cloud and propagate inwards at the speed of sound. These pressure gradients act to slow down the collapse, allowing the inner regions to fall away from the outer part of the cloud. The central region of the cloud collapses with nearly uniform density while the outer part of the cloud has a steep density gradient (e.g. Larson 1969). Only in the central regions, where the dynamical timescale, the free-fall time,

$$t_{ff} = \left(\frac{3\pi}{32 G\rho}\right)^{1/2}, \tag{3}$$

is approximately constant, can fragmentation occur. In the outer regions, the dynamical timescale increases with radius, so that mass at a given radius can never catch up with the mass interior to it, and can never be caught by matter exterior to it. Thus, due to tidal shearing, fragmentation can never occur in a region of a dynamically collapsing cloud with a steep density gradient. In an isothermal collapse, for example, the density profile approaches $\rho \propto R^{-2}$ (Larson 1969), so that the central mass decreases as $M_{\rm cent} \propto \rho^{-1/2}$, exactly as does the Jeans mass. This limitation is increased if the cloud is initially dominated by a steep density profile. Fragmentation from such initial conditions cannot occur during the dynamical collapse phase due to the tidal shearing from inner regions.

Fragmentation of a spherically-symmetric collapsing cloud is inherently difficult due to the arguments stated above. Furthermore, unless there ex-

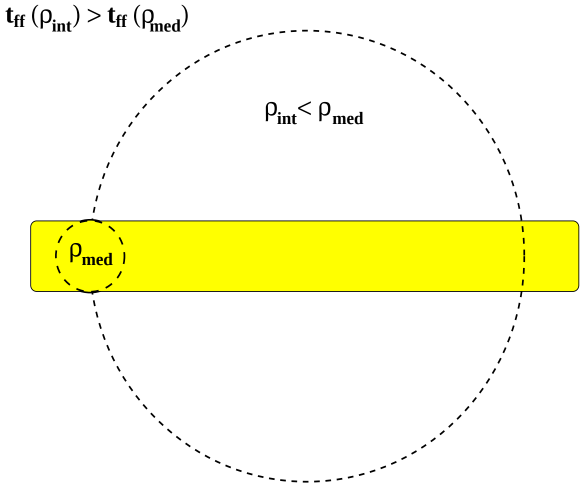

Figure 4. Non-spherical structures are easier to fragment. The local density at a point inside a slab of gas is higher than the mean density interior to it. Thus, the local free-fall time is shorter than the free-fall time for the matter at this point to fall to the centre of the slab.

ists a significant off-centre density enhancement such as a shell, the uniform free-fall time implies that any small perturbation cannot grow before merging with the rest of the collapsing cloud. Fortunately, few non-stellar structures are perfectly spherical, including molecular clouds and their cores which exhibit predominantly elongated geometries (eg Myers et al. 1991). Such clouds, being either prolate or oblate are more susceptible to fragmentation due to their configurations. This occurs as subregions of the cloud are then more likely to collapse on themselves before merging with the rest of the cloud. This can be seen by considering the free-fall time for these regions and for the cloud as a whole (Fig. 4). A subregion in the slab has a density that is higher than the mean density of the material interior to it, as much of the interior region is empty. Thus, it's free-fall time is less than the mean free-fall time of the cloud at that radius. The subregion can thus collapse on itself, if it contains more than a Jeans mass, faster than the cloud as a whole collapses. This amplifies the asphericity of the cloud (e.g. Lin Mestel & Shu 1965), making it even more susceptible to fragmentation. Fragmentation is thus much easier in clouds which have significant non-spherical geometries, be it either initial (prolate or oblate) or generated during the collapse from smaller perturbations or rotation.

The last point we need to consider before discussing the fragmentation scenarios is the effect of rotation. Angular momentum perturbs the collapse, introducing a flattening into the cloud and eventually halting the collapse. The end-points for a collapse including rotation can be estimated as (e.g.

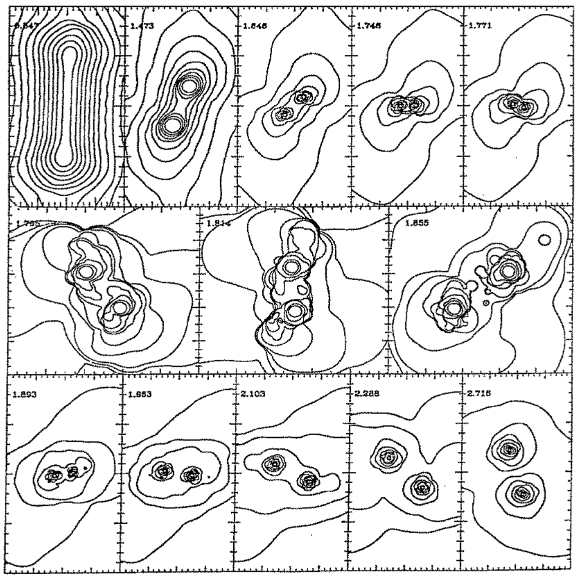

Figure 5. The fragmentation of a cylindrical prolate cloud and the formation of a binary system (Bonnell et al. 1991).

Tohline 1981)

$$R_{\rm final} \approx \beta R_{\rm initial}, \tag{4}$$

where $\beta = E_{\rm rot}/|E_{\rm grav}|$. Determinations of β in molecular cloud cores have yielded values of $\beta \lesssim 0.1$, with a mean value of $\beta \approx 0.02$ (Goodman et al. 1993). Thus for initial cloud radii of $R_{\rm initial} \approx 0.05$ pc, rotationally supported objects should have sizes on the order of 200 AU.

4.2. FRAGMENTATION DURING COLLAPSE

The earliest three-dimensional simulations of gravitational collapse and fragmentation were of initially spherical clouds with several Jeans masses, and significant rotation. (e.g. Boss & Bodenheimer 1979; Bodenheimer et al 1980; Miyama et al. 1984; Monaghan & Lattanzio 1986; Boss 1986). In these simulations, fragmentation was due to large initial non-axisymmetric perturbations which grew during the collapse (e.g. Boss & Bodenheimer 1979), or due to significant initial rotation that halted the collapse allowing smaller perturbations to grow (e.g. Miyama et al. 1984).

Since then, observations have shown that molecular cloud cores deviate significantly from spherically symmetry, often having elongated (and probably prolate) shapes (Myers et al. 1991). Furthermore, their typically small rotation rates (Goodman et al. 1993), imply that rotation is generally not

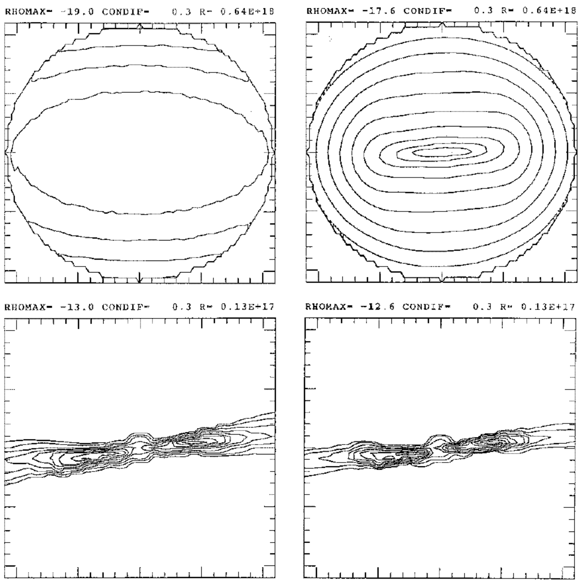

Figure 6. The fragmentation of a Gaussian density prolate cloud and the formation of a binary system (Boss 1993).

an important factor in driving fragmentation on scales greater than 200 AU.

This has driven the simulations towards the collapse of prolate clouds with little rotation. Simulations have been performed for uniform-density cylindrical clouds (Fig. 5 Bonnell et al. 1991, 1992), uniform-density prolate spheroidals (Nelson & Papaloizou 1993; Monaghan 1994; Nelson 1998) and Gaussian-density-profile prolate clouds (Fig. 6 Boss 1993, 1998; Sigalotti & Klapp 1997). All of these can result in the formation of binary systems. The fragmentation arises when collapse occurs preferentially towards the major axis such that the two sides of the cloud collapse on themselves before collapsing together. This occurs if the Jeans radius (see above) is less than the minor axis, or if the cloud has $M \gtrsim 2M_J$. The binary systems that result are highly eccentric and can have a variety of mass ratios (Bonnell & Bastien 1992a).

For prolate clouds that have many Jeans masses such that the Jeans radius is much less than the cloud's minor axis, then the collapse forms a narrow bar (Bastien 1983). This bar is unstable to fragmentation and can thus form many self-gravitating clumps (Bastien et al. 1991; Bonnell et al. 1991; Burkert & Bodenheimer 1993; Bate & Burkert 1997). A cautionary note on this bar-mode fragmentation is that it requires either significant initial perturbations (e.g. Bastien et al. 1991) which is not unlikely in molecular clouds, or else a mechanism that halts the bar's collapse (e.g. heating in the optically thick phase), at which the fragmentation can then proceed (e.g. Bate & Burkert 1997; Nelson 1998). The collapse of oblate clouds with many Jeans masses is also susceptible to fragmentation in an analogous manner (Boss 1996; Klapp & Sigalotti 1998). In this case, collapse occurs initially towards a sheet which can then fragment due to perturbations in the cloud.

According to the criteria of a decreasing Jeans mass, thermally driven fragmentation should, in principle, be possible during the second collapse phase (Fig. 3). Complications in this case are that before the second collapse phase commences, the matter is part of a pressure-supported outer protostellar core which can only contract quasistatically. Thus it should be near equilibrium and any perturbations should be removed before the collapse is initiated. Simulations of this collapse phase have not found any thermally driven fragmentation (Boss 1989).

Fragmentation during the collapse phase can also be driven by cooling (i.e. $\gamma_{eff} < 1$). The removal of thermal support is an efficient way of destabilising a cloud that would otherwise not fragment in the isothermal regime. Monaghan & Lattanzio (1991) have found that for spherical clouds that would normally collapse without fragmenting, the inclusion of molecular cooling can drive the fragmentation process. Chapman et al. (1992) have also invoked cooling to aid fragmentation. They modelled the collision of two stable clouds with cooling occurring in the shocked region. This resulted in a rapid decrease in the Jeans mass with resulting fragmentation into many protostellar fragments. In both cases, the fragmentation does not occur in a spherical cloud but rather in oblate slabs caused either by rotation (Monaghan & Lattanzio 1991) or the shock in the cloud-cloud collision (Chapman et al. 1992).

4.3. DISC FRAGMENTATION

Although early fragmentation simulations were performed with large amounts of rotational energy ($\beta \approx 0.2$) in which rotation soon impeded the collapse allowing for quick fragmentation, it is now clear that any rotationally driven fragmentation will generally only occur after the cloud has collapsed to a fraction of it's initial size (see above). Fragmentation at this stage requires either pre-existing non-axisymmetric perturbations or the generation of new non-axisymmetric structures. Any initial perturbation present in this object needs to have survived the collapse phase without growing non-linear and thus fragmenting at an earlier stage, and without being washed away in the earlier stages of the collapse where they could not have contained a Jeans mass.

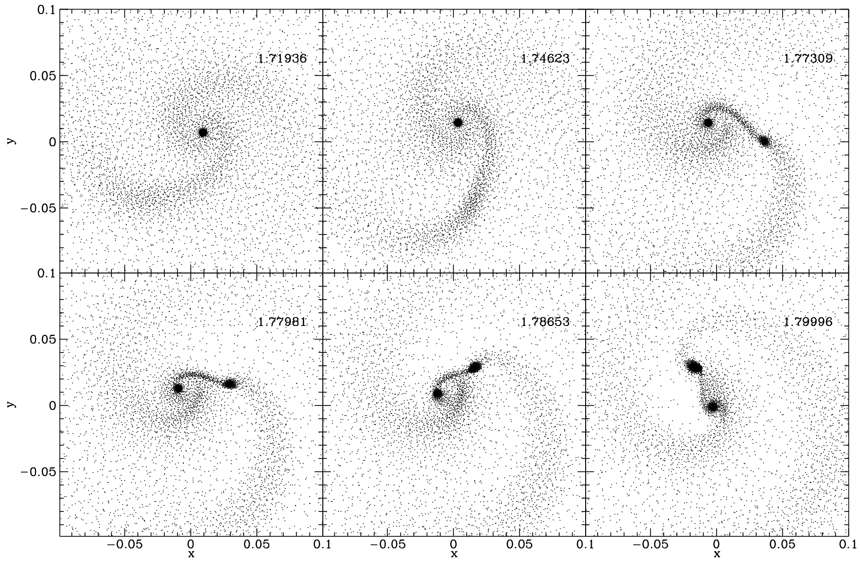

Figure 7. Protostellar disk fragmentation due to a rotational instability (Bonnell & Bate 1994a).

Alternatively, non-axisymmetric structure can be driven into the disk due to a dynamical rotational instability (Bonnell 1994). In the absence of pre-existing perturbations, the rotationally supported post-collapse object will evolve towards a single central fragment and a surrounding disk. In order to do this, it undergoes a rotational instability which generates an $m = 2$ bar-mode and accompanying spiral arms which ultimately drives the disk fragmentation (Bonnell 1994). This instability occurs due to the necessary redistribution of angular momentum to form a stable pressure-supported protostellar core and surrounding disk. This rotationally-driven bar-mode instability is equivalent to that invoked in the fission mechanism. The primary difference is that in this case the bar is surrounded by a disk and interacts with the continuing infall. As this process occurs at the end of the collapse phase, material is continually being added to the disk on a dynamical timescale (equivalent to that of the disk). This material is necessary to continually drive the instability and provide the mass-reservoir for the subsequent fragmentation.

The outward transport of angular momentum from the bar-mode and spiral arms drive an $m = 1$ mode into the system (Bonnell 1994; Bonnell & Bate 1994a). Small asymmetries in the rate of angular momentum transport between the two ends of the bar, coupled with the dynamic nature of the instability, then propel the central object from the centre of mass. The combination of the two ($m = 1$ and $m = 2$) modes allow the spiral arms to gather matter together, and even collide, such that a Jeans mass condensation is formed which can then collapse to form a secondary (Fig. 7). The angular momentum transport by way of the spiral arms removes the rotational support inherent in the disk, thus allowing the fragment to collapse. It should be noted that the continued infall onto the system is a necessary condition, without which no fragmentation occurs (Bonnell 1994). A similar mode of fragmentation has been found to occur where the disk is fed by an accretion flow (Whitworth et al. 1995). In this case, subsequent accretion from a shearing sheet formed in a cloud-cloud collision continually spins up the disk until the bar-mode instability develops.

Disk fragmentation can also occur at the end of the second collapse phase and in so doing, form a close binary system with separation of order 10 $R_\odot$ (Bonnell & Bate 1994a). A related study by Boss (1989) found that an initial $m = 2$ perturbation grew during the second collapse phase but that was forced to merge due to the gravitational torques. It is these torques that cause the disk fragmentation in the Bonnell & Bate study, which was able to resolve the fragmentation due to the Lagrangian nature of the code and the longer periods over which the evolution was followed. Due to the small value of the Jeans mass, the binary has a very small mass ($M_{\mathrm{binary}} < 0.01$ $M_\odot$), and thus will have to accrete the majority of its final mass. A limitation on fragmenting a disk around the second core is that if significant non-axisymmetric structure develops around the first core due to a similar instability, then sufficient angular momentum is transferred outwards ensuring that the second core and disk are rotationally stable (Bate 1998a).

Massive circumbinary disks have also been shown to fragment due to the interaction with the inner binary (Bonnell & Bate 1994; Burkert & Bodenheimer 1996). In this case, the binary takes the role of the $m = 2$ bar-mode. The fragmentation follows the same evolution as above with the binary driving an $m = 1$ mode into the system, forcing the binary to spiral away from the system's centre of mass (see Fig. 8). The interaction of the spiral arms then forms the additional fragment.

In all of these calculations, the role of the continued infall is of prime importance as it adds mass to the disk helping to drive the instabilities. This implies that this disk fragmentation process occurs only at the end of a collapse phase as it is then that infall will be at its strongest.

An alternative method to fragment a disk can occur where the spiral arms are triggered by a passing star (Watkins et al. 1998; see also Bonnell et al. 1992). In clusters or binary systems, the passage of a star near the disk can induce spiral arms which removes the rotational support and increases the local density, resulting in the disk fragmentation. Studies of isolated, nearly stable circumstellar disks without infall have hypothesised

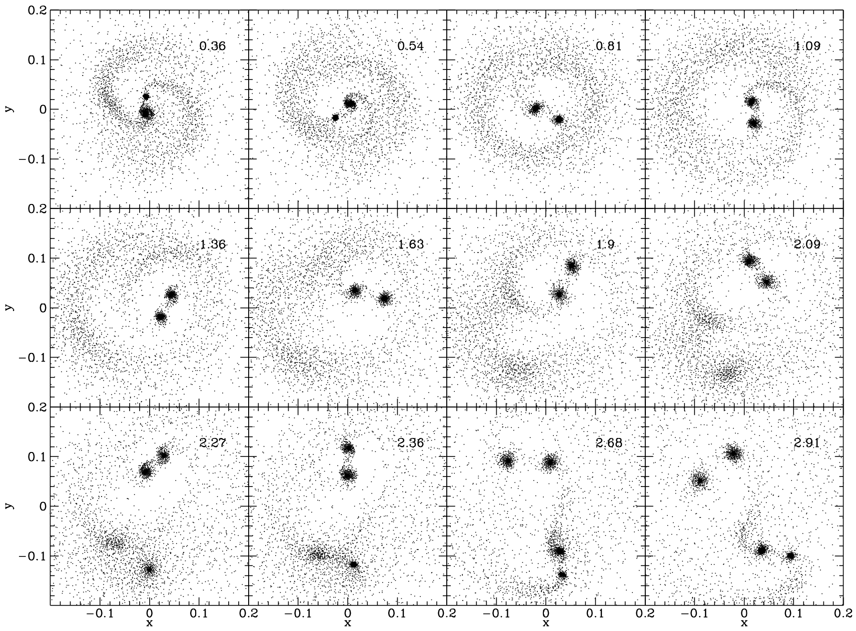

Figure 8. The fragmentation of a massive circumbinary disk due to the interaction with the central binary (Bonnell & Bate 1994b).

that fragmentation could result from the complicated interplay of waves in the disk that drive the $m = 1$ motion (Adams et al. 1989; Shu et al. 1990). To date this mechanism has not been found in simulations (eg Laughlin & Bodenheimer 1994) which may be due to questions as to the original boundary conditions (Heemskerk et al. 1992).

5. Early Evolution of Binary Systems

Once a young binary system has formed through one of the above processes, it can still be expected to undergo significant evolution before either component reaches the main sequence. This is because there will almost certainly be residual matter which will interact with the system. The fragmentation process is essentially inefficient in that most of the cloud mass has not ended up in one of the protostars by the time the system has formed. Instead, this matter infalls over longer periods, to be accreted or form surrounding disks. The disks themselves can further complicate the picture by removing angular momentum and energy from the system as in the star-disk interactions. Furthermore, gravitational interactions between the fragments in a multiple system will occur, forcing it to evolve into a more hierarchical and thus stable configuration (e.g. Burkert & Bodenheimer 1996).

5.1. ACCRETION IN BINARY SYSTEMS

Accretion on to a young binary system is likely to be one of the most important contributors to the final parameters of the system. This is especially true when the system is formed via fragmentation as it then contains but a fraction of the total mass available. In general, the mass of a protobinary soon after fragmentation is dependent on its separation such that closer systems have smaller initial masses and will subsequently have to accrete a larger percentage of their final masses (e.g. Boss 1986). In particular, systems that originate through fragmentation with separations of a few $R_\odot$ need to accrete $> 99\%$ of their final mass, without merging, to form a main sequence close binary (Bonnell & Bate 1994a).

To determine the final state of a binary formed through fragmentation, it is necessary to be able to follow the evolution until all of the infalling material has been accreted (Bate, Bonnell & Price 1995). Numerical simulations of accretion onto a binary system have found that the main dependencies are on the binary's mass ratio and the relative specific angular momentum, j, of the infalling material (Bate 1997; Bate & Bonnell 1997). For unequal masses, low j material is accreted by the primary or its disk. For higher j, the infall can also be accreted by the secondary or its disk. When $j >> j_{\rm binary}$ the infall is then accreted by neither component but forms a circumbinary disk (Fig. 9). Accretion can significantly alter the mass ratio and separation of the binary and is probably a main factor in determining the final binary properties. Probable final binary properties can be evaluated using these results under the assumption of various initial conditions (Bate 1998b). Thus, close binaries which formed from a disk fragmentation are likely to have near-equal masses if they accrete predominantly high j matter while if they accrete mostly low j matter, they would have been forced to merge.

5.2. STAR-DISC INTERACTIONS IN BINARY SYSTEMS

Star-disk interactions can be important even after a binary system has formed. In addition to the the penetrating circumstellar disk encounters which dissipate orbital motion and possibly binding initially unbound stars (e.g. Clarke & Pringle 1991, 1993 see §3.3 above), there are less dynamic interactions that occur over longer timescales. These include gap-clearing between circumstellar and circumbinary disks (e.g. Artymowicz & Lubow 1994,1996), the removal of angular momentum by a circumbinary disk (Pringle 1991; Artymowicz et al.1991) and the generation of disk-warps in non-aligned binary systems (e.g. Terquem & Bertout 1993, Larwood et

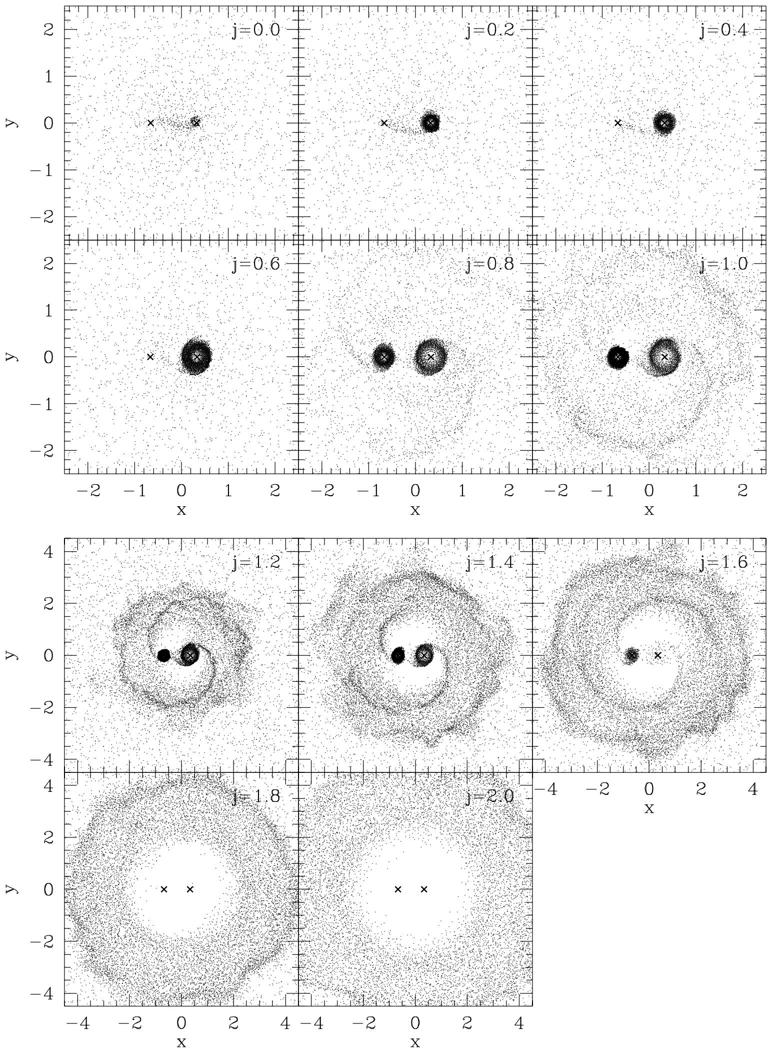

Figure 9. Accretion onto, and disk formation in, a binary system of mass ratio $m_2/m_1 = 0.5$. Each panel is for a different value of the specific angular momentum of the infalling gas in units of the binaries specific angular momentum. (Bate & Bonnell 1997).

al. 1996). Of particular interest in terms of the eventual binary properties is the possibility of the circumbinary disk driving the binary's orbital evolution towards lower separations and higher eccentricities (e.g. Artymowicz & Lubow 1994) and continued accretion through the gaps in the disks (Artymowicz & Lubow 1996).

6. Implications of Binary Star Formation

We now have many pieces to the puzzle of binary star formation. We can use them to draw some implications as to how star the formation process works. First of all, the existence of binary stars has significant implications as to the initial conditions when gravitational collapse is initiated. The fragmentation mechanisms discussed above all require a relatively flat density profile in the region where fragmentation occurs. Thus uniform initial conditions are the easiest (eg Bonnell et al. 1991) to fragment with Gaussian density profiles also being susceptible to fragmentation (Boss 1993; Burkert & Bodenheimer 1996), although only in the flat inner regions. Exceptions to this include having differential rotation in the initial conditions which helps drive a rotationally supported object to fragment (Myhill & Kaula 1992; Boss & Myhill 1995). Another possible except is the disk fragmentation of a $1/r$ density profile cloud (Burkert, Bate & Bodenheimer 1997) although such initial conditions are not in equilibrium such that the central regions expand while the rest of the cloud collapses.

All of the above exclude strongly centrally (e.g. $\rho \propto r^{-\alpha}, \alpha > 1$) condensed profiles with solid-body rotation such as is expected if the precollapse core forms through ambipolar diffusion. Furthermore, the requisite two Jeans masses in a near uniform density region mean that the core could not have formed through any quasistatic process. Instead, the core needs to have formed through a dynamical event such as originally discussed by Pringle (1989). Such initial conditions are unlikely to be smooth and will have much density structure that can aid the fragmentation process. Furthermore, the vast diversity in binary properties including non-aligned disks (Stapelfeldt et al. 1998) and non-coplanar multiple systems (Fekel 1981) imply that any angular momentum is independent of the structure of the core (e.g. Bonnell et al. 1992), again implying non-relaxed initial conditions.

There are many observational properties of PMS (and main sequence) binaries which should be used to constrain their formation. These include IR companions (e.g. Koresko, Herbst & Leinert 1997), circumbinary disks (e.g. Dutrey et al. 1994), spin-orbit alignment (Hale 1994), and relative disk evolution and accretion (e.g. Simon & Prato 1995).

7. Stellar Clusters

Star formation is a considerably more complex process than envisioned when considering the formation of single isolated objects. Not only are most stars in binary and multiple systems, it is also becoming apparent that most stars form in clusters containing from ten to thousands of stars (see chapter by E. Lada). Such clusters are best observed in the IR allowing us to peer through the surrounding gas (e.g. Fig. 10).

Figure 10. The Orion Nebula Cluster seen in the IR H-band (McCaughrean et al. 1996).

The question as to how clusters form is still very open. In this section we address some of the key processes that most likely play significant roles in the formation and early evolution of stellar clusters. Observations of young clusters are now beginning to yield the information necessary to constrain any cluster formation model. The knowledge of the gas content in clusters (e.g. chapter by E. Lada), the ability to peer through this gas using IR observations (e.g. McCaughrean & Stauffer 1994) in order to characterise the stellar content (e.g. Hillenbrand 1997) are crucial ingredients in constructing any cluster formation model.

7.1. FORMATION MECHANISM

The formation of stellar clusters is a significant unsolved problem in the field of star formation and for astronomy in general. There are currently no models that can adequately explain how hundreds to thousands of stars can form in a mutually bound environment. The problem involves both our lack of understanding of the initial conditions for cluster formation and the inherent difficulties in the fragmentation process to form the required number of fragments.

In order for a cluster of stars to form, the initial conditions must contain many (as many as stars) Jeans masses, yet are most likely supported against gravity for significant time periods before collapse is initiated. This is a requirement as otherwise the individual stars would form before the cluster is assembled. The initial support is unlikely to be thermal as the thermal energy content in molecular clouds is negligible on such length scales. Instead, molecular clouds are most likely supported by a combination of turbulent and possibly magnetic energies. Their removal is a key ingredient in the initial conditions for fragmentation and thus cluster formation. Whatever process removes the supporting energy needs to be dynamical 1) to avoid a relaxed pre-collapse cloud which will not fragment and 2) so that the stars thus formed are approximately coeval. Candidates for this process involve an external triggering such as a collision or shock wave (e.g. Chapman et al. 1992) or an internal dissipation of the supporting energy on a dynamical timescale. What is clear is that processes such as ambipolar diffusion cannot be the dominant removal mechanism.

Another key ingredient to the cluster formation puzzle is that the pre-collapse configuration must contain significant structure to allow for the fragmentation. This structure could either be on small scales such as kernels in a MHD turbulent medium (Myers 1998; see chapter by P. Myers) or on large scales (e.g. Klessen, Burkert & Bate 1998). The difficulty with the small-scale structure is that a triggering mechanism is required to initiate collapse in all the kernels near-synchronously.

The collapse and fragmentation of a cloud with large-scale structure has recently been investigated by Klessen et al. (1998). Simulating a piece of a molecular cloud, containing 200 Jeans masses and significant structure on larger scales, Klessen et al. (1998) showed that the collapse formed filamentary structures which fragmented into a significant number of stars. These stars then fall together to form a cluster (see Fig. 11).

In order to develop a model for the cluster fragmentation, we need to use the results of such simulations and determine some observational consequences that can be used to descriminate between the different scenarios. For example, the gas fraction in clusters can tell us about the relative strengths of large and small-scale structures, or stellar ages relative to the cluster's dynamical timescale can tell us about how coeval the population is, and thus from how far away the individual stars could have formed.

7.2. CLUSTER DYNAMICS

As soon as the stars form in a cluster, they start to interact gravitationally with each other. These interactions can remove or relax the initial conditions so have to be considered if we want to use the present cluster conditions to constrain the formation process. There are two types of in-

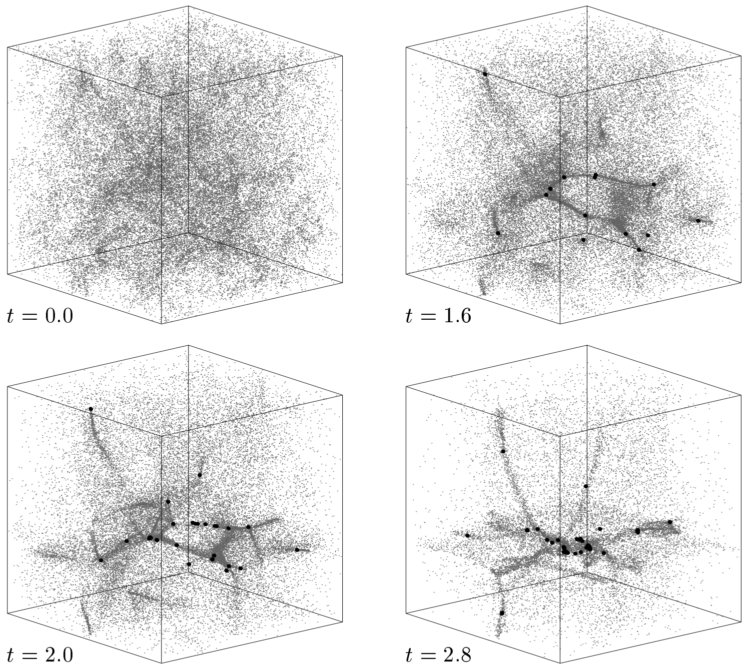

Figure 11. The collapse and fragmentation of a piece of a molecular cloud, leading to the formation of a stellar cluster (Kelssen et al. 1998).

teractions that we consider here. The first, *violent relaxation*, involves the global change of the cluster's potential due to a cold collapse. It occurs on the dynamical timescale of the cluster, the crossing time:

$$t_{\rm cross} = \frac{2 \times R_{1/2}}{v_{\rm disp}}, \tag{5}$$

where $\mathrm{R}_{1/2}$ is the cluster half-mass radius and $v_{\rm disp}$ is the cluster's one-dimensional velocity dispersion, which, in a virialised cluster is

$$v_{\rm disp} = \sqrt{\frac{GM_{\rm clust}}{R_{1/2}}} \tag{6}$$

This is the shortest timescale for global cluster evolution. The second process, *two-body relaxation*, involves the gravitational interaction between individual stars. Two-body relaxation transfers kinetic energy to the lower-mass stars, driving the system towards equipartition and mass segregation. This process requires many interactions and thus occurs on longer

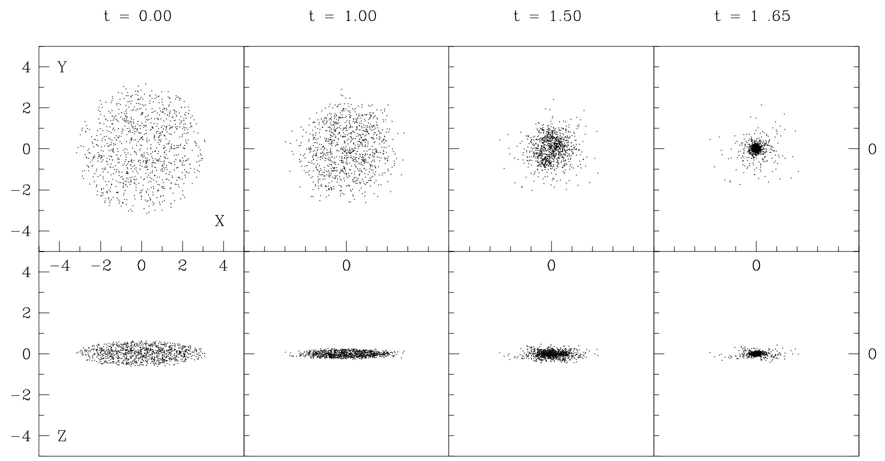

Figure 12. The cold collapse and violent relaxation of an initially flattened cluster (Boily et al. 1998). The post violent-relaxation cluster remains flattened, although less so than the original cluster.

timescales, called the relaxation time (Binney & Tremaine 1987):

$$t_{\rm relax} \approx \frac{N}{8 \ln N} t_{\rm cross}, \tag{7}$$

where N is the niumber of stars in the cluster. The relaxation time, $t_{\rm relax}$, is a measure of the time it takes for the kinetic energy, $E_{\rm kin}$, of a star to change by an amount similar to $E_{\rm kin}$, and thus measures the time it takes for a stellar cluster to lose memory of its initial dynamical configuration.

It should be noted that sub-regions of the cluster, such as the central core, can evolve faster and thus independently of the rest of the cluster. The timescale for this is the crossing time of the sub-region or core, e.g., $t_{\rm core} = 2 \times R_{\rm core}/v_{\rm disp}$. The same follows for the relaxation timescale.

7.2.1. *Violent Relaxation*

Violent relaxation involves the global collapse of a stellar system when it forms with sub-virial kinetic energy (Lynden-Bell 1967). This is likely to occur in the initial stages of a cluster as the the pre-cluster entity must have lost its support (thermal, kinetic or magnetic) in order to fragment. Unless it only loses this support on small, stellar scales, then it follows that the cluster should initially be "cold" and collapse.

The changing gravitational potential during the collapse introduces a large scatter into the distribution of stellar energies. Basically, the potential of the cluster during collapse and reexpansion are not the same so that individual stars "see" different potentials and thus react differently. Stars that fall in to the centre early see a low density core when they fall in but a high density core when they emerge on the other side, thus decreasing their energy. In contrast, stars that fall in later see a high density core and get accelerated towards the centre. By the time they pass through the centre the core has reexpanded and they thus suffer less deceleration and emerge with a higher energy.

Violent relaxation is mass-independent, such that the resultant stellar orbits depend solely on the stars' position in the cluster during the event. As it is mass independent, it results in a near uniform and mass-independent velocity dispersion, and a centrally condensed configuration (see Binney & Tremaine 1987).

Although violent relaxation tends to remove the initial conditions of the cluster, it does not completely erase large-scale non-spherical morphologies. This is important as most triggering mechanisms (shocks, cloud-cloud collisions) result in flattened systems and thus cluster morphology can be used as a constraint on the cluster formation mechanism. Boily, Clarke & Murray (1998; see also Goodwin 1997) have explored the relationship between the initial cluster morphology and the post violent relaxation configuration. They find that although the flattening decreases during the collapse and violent relaxation, it remains significant in the cluster morphology (Fig. 12). Thus, the apparent 2:1 elongation in the Orion Nebula Cluster (Hillenbrand & Hartmann 1998) would imply a pre-violent relaxation morphology that was significantly more aspherical with a 5:1 axis ratio (Boily et al. 1998). These calculations do not include any gas which could be a major contributor to the cluster potential. Still, the gas should collapse as do the stars, and even though it will not reexpand, the gas should not negate the violent relaxation process or the result that the stellar kinematics reflect to some degree the "cold" initial conditions.

7.2.2. *Mass Segregation*

Stellar clusters are commonly found to have their most massive stars in or near the centre (e.g. Raboud & Mermilliod 1998). This mass segregation is also found in the youngest clusters (e.g. Carpenter et al. 1997; Hillenbrand & Hartmann 1998). In the ONC, mass segregation appears to extend down to stars of a few solar masses (Hillenbrand & Hartmann 1998). This preference to have the massive stars near the centre of clusters is either due to the initial conditions of stellar clusters, in which case it is telling us something about the formation process and how massive stars form, or it could be due to dynamical mass segregation in the cluster.

We know that two-body relaxation drives a stellar system towards equipartition of kinetic energy and thus towards mass segregation. In gravitational interactions, the massive stars tend to lose some of their kinetic energies to lower-mass stars and thus sink to the centre of the cluster (see Fig. 13).

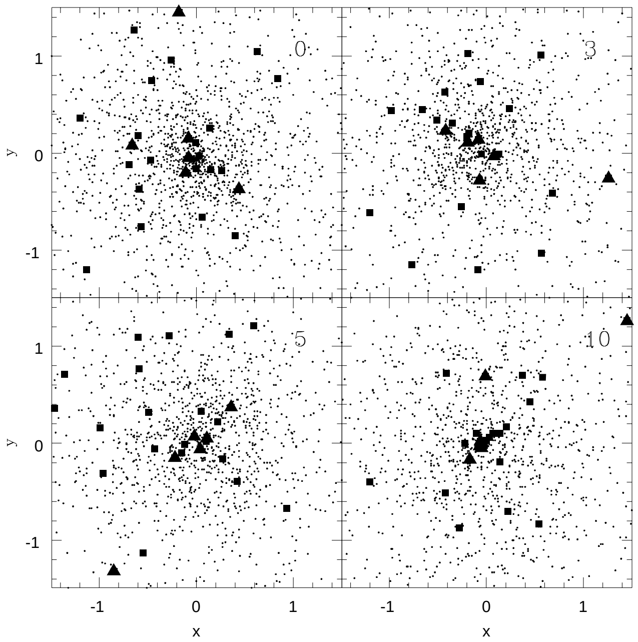

Figure 13. The dynamical mass segregation of the massive stars in a cluster containing 1500 stars (Bonnell & Davies 1998). The six most massive stars are indicated by triangles while the next 24 most massive stars are indicated by squares. The time is given in units of the crossing time.

The question is whether this process can occur quickly enough to explain the observations of mass segregation in young clusters. In order to test this possibility, we need to characterise the contents (masses, positions, ages) of young clusters which has only been accomplished for a few systems (e.g the ONC; Hillenbrand 1997; Hillenbrand & Hartmann 1998).

Two-body relaxation occurs on the relaxation timescale which for the ONC is about 25 $t_{\rm cross}$ whereas it appears to be only 3 $t_{\rm cross}$ old. Although this implies that the ONC cannot be fully relaxed, the relaxation timescale depends inversely on mass such that the most massive stars sink more quickly to the centre of the cluster. For this reason, Bonnell & Davies (1998) performed numerical N-body simulations of the cluster considering possible initial locations of the massive stars. Using initial conditions with uniform specific kinetic energies as is expected after cluster formation and violent relaxation, Bonnell & Davies showed that initially unsegregated clusters are not able to relax quickly enough to reproduce the observations. The only possibility for uniformly spatially distributed stellar masses is if the massive stars are initially in equipartition such that they are already energy segregated and only have to sink to the centre of the cluster (on the

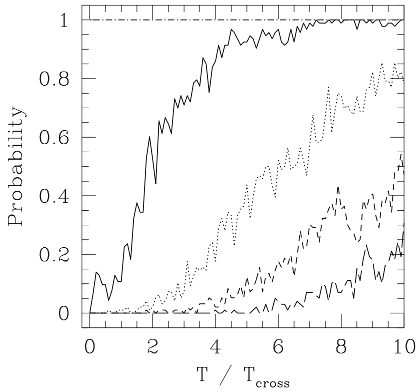

Figure 14. The probability of observing a trapezium-like system at the centre of the cluster as a function of the time in units of the crossing time. The ONC is probably $\lesssim 3t_{\rm cross}$ old. The five lines represent the cases when the 30 most massive stars are placed (from top to bottom): at Lagrangian radii containing 2 per cent (the 30 massive stars), 10 per cent, 20 per cent, 30 per cent, and 50 per cent of the stars in the cluster (from Bonnell & Davies 1998).

timescale of $\approx t_{\rm cross}$) in order to be spatially segregated. As stated above, such initial conditions are not expected for stellar clusters.

The best indication that the massive stars formed near the centre of the cluster comes from the probability to form a Trapezium-like system in the centre of the ONC. This dense knot consisting of a sizable fraction of the most massive stars requires that the massive stars are initially within the central 10 % (for a 50 % probability of having a Trapezium) to 20 % ($\approx$ 10 % probability) of all stars (see Fig. 14).

7.3. ACCRETION AND STELLAR MASSES

Young stellar clusters are commonly found to be gas-rich with typically 50 to 90 % of their total mass in the form of gas (e.g. Lada 1991; see also chapter by E. Lada). This gas can interact with, and be accreted by, the stars as they both move in the cluster. The timescale for accretion can be estimated as the gas free-fall time which, for systems where the gas is a significant contributor to the cluster potential, is of the same order as the cluster's crossing time:

$$\begin{aligned} t_{\rm ff} &\propto \rho_{\rm gas}^{-1/2}, \\ t_{\rm cross} \propto \frac{R_{\rm clust}}{v_{\rm disp}} &\propto \sqrt{\frac{R_{\rm clust}^3}{(M_{\rm stars}+M_{\rm gas})}} \\ &\propto (\rho_{\rm gas}+\rho_{\rm stars})^{-1/2}. \end{aligned} \tag{8}$$

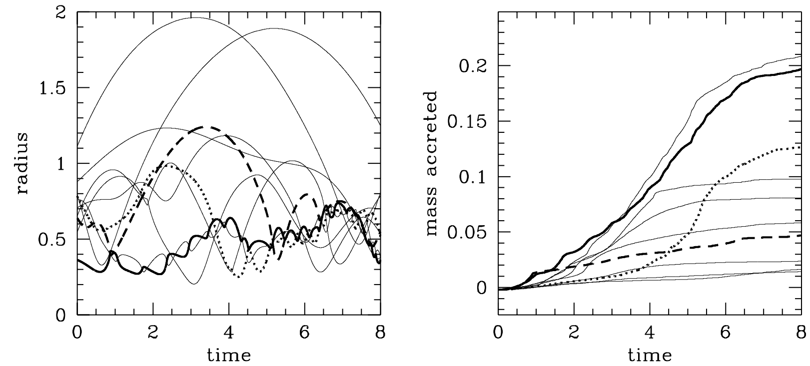

Figure 15. The evolution of a cluster of 10 stars undergoing gas accretion is shown. The distance of each star from the centre of the cluster (left) and the gas mass fraction accreted by each star (right) are given as functions of time, in units where t_{cross}=2.8. The gas initially comprises 10 % of the total mass of the system. Three individual stars are highlighted (see text).

Thus, we expect that significant accretion can occur on the dynamical timescale of the cluster. If significant accretion occurs, it can affect both the dynamics and the masses of the individual stars (e.g. Larson 1992).

Simulations of accretion in clusters using a combination SPH and N-body code have found that accretion is a highly non-uniform process where a few stars accrete significantly more than the rest (Bonnell et al. 1997). Individual stars' accretion rates depend largely on their position in the cluster (see Fig. 15) with those in the centre accreting more gas than those near the outside. This process is termed "competitive accretion" (Zinnecker 1982) as the accretion depends on being in a favourable location and in having significant gravitational attraction to overcome that of the nearby stars.

The stars closest to the centre of the cluster (heavy-solid line in Fig. 15) accrete more than do the other stars because of the increased gas density near the centre. The density is greater because the gas preferentially falls into the deepest part of the cluster's gravitational potential. Furthermore, gas is efficiently funneled down to the cluster centre, thereby replenishing the gas as it is accreted. Stars that spend most of their time in the outer regions of the cluster do not have this benefit so they do not accrete nearly as much gas. Stars eject from the centre of the cluster also suffer a marked decrease in their accretion rates.

This competitive accretion process naturally results in a spectrum of stellar masses even if they are initially all equal (Bonnell et al. 1997). A large range of stellar masses is produced (factor 10) even though the median stellar mass increases by less than a factor 2. This occurs as the competitive

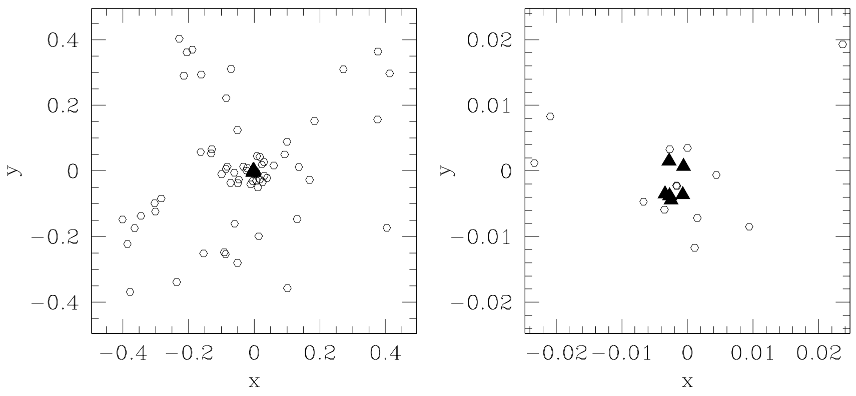

Figure 16. The position of the 6 most massive stars (with $M_\star \gtrsim 4M_{\rm med}$, filled triangles) in a cluster of 100 stars. The right-hand panel is a blow-up of the cluster core. The masses of the most massive stars are due to the competitive accretion process.

accretion is a runaway process where the few stars near the centre accrete more and are thus able to attract even more gas. Thus, if the initial gas mass-fraction in clusters is generally equal, then larger clusters will produce higher-mass stars and a larger range of stellar masses as the competitive accretion process will have more gas to feed the few stars that accrete the most gas. Finally, accretion in clusters also naturally results in a mass segregated cluster (see Fig. 16) where the most massive stars are formed near the centre of the cluster due to the accretion.

7.4. FORMATION OF MASSIVE STARS

The formation of massive stars is one of the most important unsolved problems in star formation. We know that they cannot form in an analogous manner to low-mass star-formation as their radiation pressure will reverse the infall process once they attain $\approx 10\ M_\odot$ (Yorke & Krugel 1977; Yorke 1993). Disk accretion is a possibility but the disks would have to 1) be thin enough to survive the radiation field and 2) extend far enough to be replenished without the infall being affected by the radiation pressure (Jijina & Adams 1996). The fact that young massive stars are generally found in the centre clusters suggests that their formation is linked to their special environment. They are unlikely to have formed elsewhere and evolved to the centre by the time we observe them (Bonnell & Davies 1998; and see above). Furthermore, a simple Jeans mass argument would imply that due to the crowded conditions in the centre of clusters, the gas density would have had to have been very high which implies a low Jeans (or fragment)

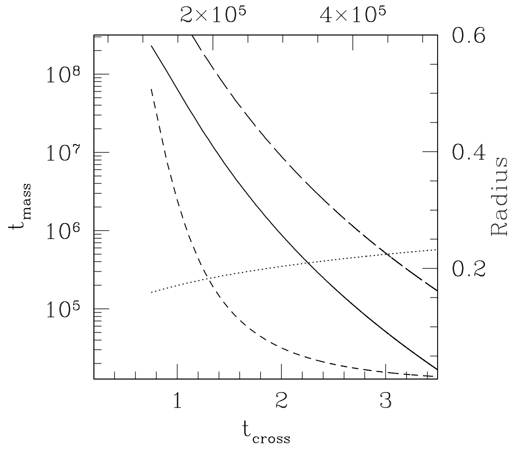

Figure 17. The timescale to double a star's mass either by collisions (solid and long-dashed lines) or through accretion (dotted line) is plotted versus time in units of $t_{\rm cross}$ (and in years) for a 0.1 pc cluster of 100 stars (Bonnell et al. 1998). The accretion rate is 2×10^{-6} $\rm M_{\odot} yr^{-1}$ and the merger radius is either 0.1 (solid line) or 0.01 au (long-dashed line). The half-mass radius is also plotted (short-dashed line).

mass at the time of formation (c.f. Zinnecker et al. 1993; Bonnell, Bate & Zinnecker 1998). Subsequent accretion (see above) can increase their mass to near $10M_{\odot}$ but beyond that something further is required.

A secondary affect of accretion in clusters is that it can force it to contract significantly. If the gas has little net rotation, then its motions will generally be disconnected from the motions of individual stars, and have zero net momentum. The added mass increases the binding energy of the cluster while accretion of basically zero momentum matter will remove kinetic energy. If the core is sufficiently small that its crossing time is relatively short compared to the accretion timescale, then it will contract with added mass as (Bonnell, Bate & Zinnecker 1998)

$$R_{\rm core} \propto M_{\rm core}^{-3}. \tag{9}$$

This increases the stellar density dramatically, to the point where collisions become important (see Fig. 17). Collisions between intermediate mass stars ($2M_{\odot} \lesssim m \lesssim 10M_{\odot}$), whose mass has been accumulated through accretion in the cluster core, can then result in the formation of massive ($m \gtrsim 50M_{\odot}$) stars (Bonnell et al. 1998). In this model, the massive stars that are found in the centre of rich young clusters are significantly younger than the mean stellar age. If this is how the massive stars in the Trapezium formed, then we would predict that θ^1C is significantly younger than 10^6 years, possible as young as $\lesssim 10^5$ years.

7.5. CLUSTER DISSOLUTION

Although most stars appear to form in clusters, the vast majority of stars in the Galaxy are not in clusters. This implies that at some point the young clusters must dissolve to populate the galactic field population. Clusters can dissolve in one of two ways, they can be unbound either through stellar interactions with a central binary or if a significant percentage of their mass (residual gas) is removed.

In small clusters ($N \lesssim 100$), a central binary forms that can interact and eject other cluster members. Essentially, the binary absorbs the total potential energy of the cluster, unbinding all the other members. Estimates of the timescale for this process tell us that it is a strong function of the number of cluster members (Heggie 1974):

$$t_{\rm diss} \approx \frac{N^2}{100} t_{\rm cross}. \tag{10}$$

Thus clusters with $N \approx 100$ will dissolve on time scales of order 100 $\rm t_{cross}$. This corresponds to lifetimes of several $\times 10^7$ years. Smaller clusters will dissolve on shorter timescales such that small clusters of order 10 stars will only last a few crossing times at most. These dissolved clusters then correspond to the Gomez groups in taurus (Gomez et al. 1993). The probability of seeing a cluster increases with the number of stars that it contains, and thus (for random picking from a universal IMF) with the expectation value of the mass of the most massive star. If we assume an age of a few million years as a median age of the young stellar population in the nearby star formation regions, then for an average crossing time of $t_{\rm cross} \approx 3 \times 10^5$ years, we should only see clusters with at least 25 stars. This also implies that we should only see clustering around stars of at least $m \gtrsim 3 M_{\odot}$. Hillenbrand (1995) and Testi et al. (1997) both found that clustering around Herbig AeBe stars is evident only for stars with masses greater than 3 to 5 $\rm M_{\odot}$.

Larger clusters will not dissolve through interactions with a central binary as the timescale becomes too long for stars with greater than a few hundred members. Instead, these clusters are large enough that they are likely to contain a massive star ($m \gtrsim 8 M_{\odot}$) that can eject any residual gas from the cluster. Young clusters contain significant amounts of gas, typically comprising a majority of the total cluster mass (Lada 1991). This gas is therefore a major contributor in making the cluster gravitationally bound and its removal can unbind the cluster, dispersing the stars into the galaxy.

Gas removal in clusters occurs due to the energetics of the component massive stars (Whitworth 1979; Tenorio-Tagle et al. 1986; Franco, Shore & Tenorio-Tagle 1994). The photo-ionization and winds from these stars is capable of removing any residual gas from the cluster. The fate of a particular cluster depends on the gas fraction, the removal timescale and stellar velocity dispersion when the gas is dispersed (Lada, Margulis, & Dearborne 1984; Pinto 1987; Verschueren & David 1989; Goodwin 1997b). If the gas comprises a significant fraction of the total mass ($\gtrsim$50%) and is removed quickly compared to the cluster crossing time, $t_{\rm cross}$, then the dramatic reduction in the binding energy, without affecting the stellar kinetic energy, results in an unbound cluster. Alternatively, if the gas is removed over several crossing times, then the cluster can adapt to the new potential and can survive with a significant fraction of its initial stars. For example, clusters with gas fractions as high as 80 per cent can survive with approximately half of the stars if the gas removal occurs over 4 or more crossing times (Lada et al. 1984).

8. Binary Stars in Clusters

In this last section, we address the overlap between binary systems and stellar clusters, namely the question of binaries in clusters. The finding that the PMS binary frequency in nearby clouds is higher than that found on the main sequence (Ghez 1995, and see above) is, at first, disturbing as it implies a decrease in binarity with age, Recently, binary surveys in clusters such as the ONC have found that the binary frequency in these dense regions is generally more typical of the field stars (Prosser et al. 1994; Petr et al. 1998; Padgett et al. 1997; Patience et al. 1998). We can thus explain the difference between the binary frequency in young and old systems by the hypothesis that most stars form in clusters such as Orion where the binary frequency is lower than in nearby dark clouds. The question remains why there is a difference between these two regions.

One possibility is that binary systems are intrinsically harder to form in rich dense clusters. For example, the fragmentation of a collapsing cloud could be inhibited by its environment. This hypothesis has not as yet been fully explored but the only relevant collapse calculations done to date indicate that fragmentation is easier in the presence of tidal fields (Boss 1981; Felice & Sigalotti 1991)).

Another possibility is that clusters have an initially high binary frequency but that a significant fraction of these binaries are destroyed through binary-binary interactions. Interactions involving binaries tend to disrupt wide (soft) ones and harden closer (hard) ones. The border between the two possibilities, the hard/soft limit is given by binary systems with orbital velocities similar to the velocity dispersion in the cluster. Thus, denser clusters will be able to disrupt closer binaries than can less dense clusters. Kroupa (1995) has investigated this scenario using N-body simulations and

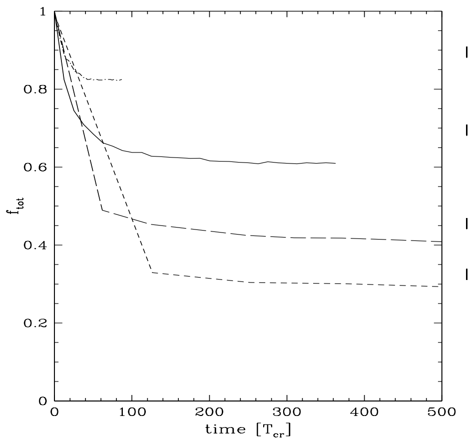

Figure 18. The binary fraction in clusters containing initially 100 % binaries is plotted as a function of time in units of the initial crossing time. The clusters considered have $R_{1/2} = 0.08$ pc (short-dashed line), $R_{1/2} = 0.25$ pc (long-dashed line), $R_{1/2} = 0.8$ pc (solid line), and $R_{1/2} = 2.5$ pc (dot-dashed line). Adapted from Kroupa 1995.

assuming a 100 % binary frequency. He found that the resultant binary frequency depends primarily on the cluster density (see Fig. 18), with preferentially the wider systems being disrupted. Figure 18 also shows that it takes several tens of crossing times before the soft binaries are all disrupted. Presumably, the wider systems are disrupted more quickly as their collisional cross section is larger, while closer systems have longer collisional timescales.

The binary fraction detected in the core of the ONC (Petr et al. 1998) is consistent with the above picture of binary disruptions as the core is $\approx 30t_{\rm cross}$ old. It does imply that the binary fraction in the outer parts of the cluster should reflect the initial population as the cluster as a whole is only $\approx 3t_{\rm cross}$ old. This may be a problem as there appears to be a lack of wide binaries even in the outer parts of the cluster (Scally, Clarke & McCaughrean 1998) where the collisional timescale is significantly longer than the local $t_{\rm cross}$.

9. Summary

The formation of multiple systems and stellar clusters is a complex dynamical process where individual stars interact on the same timescale as they form. There are two main phases that have to be considered, 1) the gravitational collapse and fragmentation where the number of objects is decided and the subsequent 2) accretion of residual gas and interactions between individual stars where the eventual stellar and system parameters are fixed.

Fragmentation requires initial conditions for collapse that are far from equilibrium in that they must contain several Jeans masses, with generally elongated (prolate or oblate) structure, and not be very centrally condensed. Such initial conditions cannot have been formed from a quasistatic evolution but require a dynamic formation mechanism (e.g. Pringle 1989).

Binary and multiple systems can form through the fragmentation of a collapsing cloud or through the fragmentation of a circumstellar disk at the end of the collapse phase. Subsequent star-disk interactions can also form bound systems in small clusters. Binary systems formed through fragmentation can have a wide range of mass ratios and eccentricities, with separations from 10^4 AU down to a few $R_\odot$. Closer systems need to accrete the majority of their eventual mass and this accretion will be the determining factor of their system properties. Observations of the diverse properties ofyoung binary systems need to be used to constrain their formation and early evolution.

The formation of stellar clusters is a more difficult problem in that the cloud has to fragment into hundreds to thousands of self-gravitating objects. The first attempts at modelling this fragmentation are being made, but significant observational constraints are necessary in order to progress. Subsequent dynamics, including violent relaxation and mass segregation need to be considered in order to extrapolate backwards from the present-state of young stellar clusters to their initial post-fragmentation configuration. Using N-body simulations, it appears likely that the initial state of clusters is somewhat flattened and that mass segregation is initial and not due to two-body relaxation. These properties can then be used to constrain the cluster formation process.

Accretion in clusters can generate both a mass spectrum and mass segregation in a young cluster. It is a competitive process where a few stars, located near the cluster centre, accrete the majority of the gas. These stars benefit from the overall cluster potential that funnels gas down to the core. Accretion in clusters also tends to shrink the cluster. If sufficient accretion occurs in a dense cluster, the core may shrink sufficiently to allow stellar collisions to occur. Massive stars may then form by this process, alleviating the problem of accreting onto stars with $M_\star \gtrsim 10 M_\odot$.

Lastly, the binary frequency in different regions may reflect the stellar density when they were formed. Assuming a 100 % initial binary frequency, binary interactions in clusters can destroy binaries down to the hard/soft limit of the cluster such that denser clusters should have fewer binaries.

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