Dynamical Interactions in Dense Stellar Clusters

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Abstract. This chapter reviews the dynamical processes that occur in young stellar clusters. The formation of a stellar cluster is a complex process whereby hundreds to thousands of stars form near-simultaneously in a bound configuration. We discuss the dynamical processes involved in the formation and early evolution of a stellar cluster.

Young clusters are known to contain significant amounts of mass in gas. The accretion of this gas by individual stars affects the dynamics of the cluster, and the masses of the stars. Accretion rates depend crucially on a star’s position in the cluster, with those nearer the centre having higher accretion rates. This results in a spectrum of stellar masses even if the seeds have equal masses. A by-product of this process is that the most massive stars are formed in the centre of the cluster, as is generally observed. Dynamical mass segregation cannot explain the degree of mass segregation observed in clusters such as the Trapezium Cluster in Orion, implying that the location of the massive stars is an indication of where they formed. This can be explained by the competitive accretion model.

Most field stars are found to be members of binary or multiple systems. Pre-main sequence stars not in clusters have an even higher degree of multiplicity, whereas those in dense groupings such as the Trapezium Cluster have binary frequencies consistent with the field population. This can be understood if most, if not all, stars form in binary systems, but that significant numbers of these systems are destroyed in dense clusters through binary-binary and binary-single interactions. These models make definite predictions for the distribution of binary properties. The early evolution of a cluster sensitively depends on the primordial binary star proportion.

Young stars commonly have circumstellar discs as a remnant of their formation. Close encounters between stars with circumstellar discs have drastic effects on the discs and on the stellar orbits. The discs are trun-
cated at radii comparable to the encounter periastron, limiting their lifetime

times and affecting their potential for planet formation. In small dense
clusters, these interactions can leave two stars bound in a binary system,
whereas in larger clusters, the encounters are too energetic.

Finally, we review the literature on how the removal of residual gas
in the cluster can cause the cluster’s dissolution. If the gas represents a
significant fraction of the total mass, its removal on dynamical timescales

can unbind the cluster allowing the stars to escape and populate the field.

1. Introduction

Recent observations have revealed that most stars do not form singly and in
isolation but rather in groups, from binary systems (e.g., Mathieu 1994; Ghez
1995), to small associations (e.g., Gomez et al. 1993), to clusters containing
hundreds and thousands of stars (e.g., Lada et al. 1991; McCaughrean & Stauffer
1994). In star formation regions such as Orion, it is likely that most stars form
in clusters (Lada, Strom, & Myers 1993; Zinnecker, McCaughrean, & Wilking
1993). These clusters are typically gas rich, with 50–90% of their mass in gas
(e.g., Lada 1991).

Star formation in such systems is necessarily a complex process, involving
significant dynamical interactions between the stars and between the stars and
the gas. Unfortunately, that means that we cannot gain a complete description
of the problem from the commonly used single, isolated star formation scenario
(Shu, Adams, & Lizano 1987). Instead, we must investigate how these interac-
tions affect the dynamics of the cluster and their relevance for explaining the
properties of the individual stars.

The vast amount of recent observational work on young stellar clusters (e.g.,
McCaughrean & Stauffer 1994; Lada & Lada 1995; Meyer 1996; McCaughrean
& O’Dell 1996; Hillenbrand 1997; Hillenbrand & Hartmann 1998) has given an
impetus to the theoretical investigations of their formation and early evolution.
The evolution of young stellar clusters depends on the dynamical processes in-
volved, including competitive gas accretion by the stars, dynamical mass segrega-
tion due to two-body relaxation, binary star interactions, star-disc interactions,
and finally, the effect of gas removal due to its interaction with the constituent
high-mass stars.

2. Preliminaries

There are currently no satisfactory models capable of explaining the initial stages
of cluster formation. Numerical simulations of gravitational collapse and frag-
mentation typically form no more than 10–20 distinct objects (e.g., Bonnell
et al. 1992; Burkert & Bodenheimer 1993; Boss 1996). This maximum num-
ber is due to the collapse proceeding preferentially in some directions, reducing
the dimensionality of the cloud before fragmentation occurs. This aids in the
fragmentation as sheets and lines are inherently more unstable to fragmentation
than are spheroidals, but limits the degree to which fragmentation can occur (see the chapter in this volume by Burkert & Bodenheimer).

There are two possible alternatives which might circumvent this problem. The first is that the initial cloud contains significant substructure at the time of collapse (see, e.g., the chapter by Elmegreen & Efremov in this volume) and that the cloud cools rapidly (or is very gravitationally unstable), so that each "seed" contains a Jeans mass and can thus collapse on its own and more quickly than the overall cloud (e.g., Klessen 1997). Such conditions can result from a dynamical triggering, whereby the cloud is quickly compressed and subsequently cools in the post-shock layer (e.g., Whitworth et al. 1994; Whitworth & Clarke 1997). This is essentially the picture advanced by Fall & Rees (1985) to explain the formation of globular clusters. The second possibility is that the cluster is formed from an agglomeration of smaller clusters. In this case, one would expect some resultant signature of this process in the presence of substructure in the cluster. Although sub-clustering is evident in some embedded clusters (see, e.g., Lada & Lada 1995; Lada, Alves, & Lada 1996; Megeath & Wilson 1997), there appears to be none in the Orion Nebula Cluster (ONC) (Bate, Clarke, & McCaughrean 1998; see also the chapter in this volume by Bate & Clarke), but such sub-clustering could have been removed through evolution.

Subsequent to the initial fragmentation or coagulation event, most clusters are likely to be significantly out of virial equilibrium. This follows from considering the pre-cluster entity as having lost its support (thermal, kinetic, or magnetic) in order to fragment, and thus the resultant cluster will also lack kinetic energy and collapse. The ensuing violent relaxation (Lynden-Bell 1967) revirialises the cluster and produces a large spread in the spectrum of stellar energies. Violent relaxation is mass-independent, such that the resultant stellar orbits depend solely on the stars’ positions 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 does erase many of the initial conditions of the cluster, initial asymmetries in the overall cluster shape can remain, to a lesser degree, after violent relaxation (Aarseth & Binney 1978; Goodwin 1997b). The elongation apparent in the ONC (Hillenbrand & Hartmann 1998) may be an indication of such asymmetric initial conditions. Cluster contraction is expected even if the protostars decouple from the gas in such a way that a cold collapse and thus violent relaxation do not occur, because dynamical friction between the stellar system and the gas causes deceleration of the stars on a timescale probably much shorter than the gas expulsion time (Saiyadpour, Deiss, & Kegel 1997; see also Gorti & Bhatt 1996).

Regardless of how the cluster initially formed, for the purpose of this discussion we consider a cluster as bound (due either solely to the stars or a combination of stars and gas), and generally spherical in shape, with no significant substructure present. The timescale for processes occurring in the cluster are typically measured in units of the cluster’s dynamical or crossing time:

\[ t_{cross} = \frac{2 \times R_{1/2}}{v_{disp}}, \]

where \( R_{1/2} \) is the cluster half-mass radius and \( v_{disp} \) is the cluster’s one-dimensional velocity dispersion. This is the shortest timescale for global cluster evolution, via
processes such as violent relaxation. Sub-regions of the cluster, such as the central core, can evolve faster and thus independently, on their own crossing time $t_{\text{core}} = 2 \times R_{\text{core}} / v_{\text{disp}}$. Slower processes, such as two-body relaxation which drives the cluster towards equipartition, mass segregation, and core collapse, occur on the cluster’s half-mass relaxation time (Binney & Tremaine 1987; see Equation 10 below),

$$t_{\text{relax}} \approx \frac{N}{8 \ln N} t_{\text{cross}}.$$  (2)

The relaxation time, $t_{\text{relax}}$, is a measure of the time it takes for the kinetic energy, $E_{\text{kin}}$, of a star to change by an amount similar to $E_{\text{kin}}$ through many long-distance (i.e., weak) encounters with individual stars (i.e., two-body relaxation), and thus measures the time it takes for a stellar cluster to lose memory of its initial dynamical configuration. Thus larger clusters will take longer to become fully relaxed. If the initial phase-space distribution of stars in a cluster consisting of single stars is independent of stellar mass, then core collapse occurs typically within $2-3 t_{\text{relax}}$, and the massive stars with mass $m_m$ sink to the cluster centre on the equipartition timescale.

$$t_{\text{eq}} \approx \frac{m}{m_m} t_{\text{relax}},$$  (3)

where $\bar{m}$ is the mean stellar mass (Spitzer 1987, p74; Spurzem & Takahashi 1995, Equation A16). Core contraction occurs because, in a single-star cluster initially in virial equilibrium, the core is hotter (higher velocity dispersion) than the halo. Redistribution of kinetic energy (heat conduction) causes the core to cool and the halo to acquire kinetic energy. A self-gravitating stellar system in which the velocity dispersion is reduced contracts, leading to a temperature increase. It has a negative specific heat capacity (Hachisu & Sugimoto 1978). The star cluster thus evolves to an increasingly compact core with an expanding halo. The result is core collapse (see also Spurzem 1991). Primordial binary stars can, however, completely change the evolution (e.g., Gao et al. 1991, and below).

The maximum lifetime of a cluster depends on its size and environment. Small clusters will dissolve through interactions with a central binary. The timescale for this can be estimated as that required for a binary to absorb the total energy of the cluster (Heggie 1974)

$$t_{\text{diss}} \approx \frac{N^2}{100} t_{\text{cross}}.$$  (4)

In large clusters, the effects of close interactions with binary systems are smaller. Instead, stars are removed as a result of energy transfer from two-body relaxation. The cluster will then dissolve on its evaporation timescale:

$$t_{\text{evap}} \approx 100 t_{\text{relax}},$$  (5)

where $t_{\text{relax}}$ is the median relaxation time during its lifetime. In general, a binary-rich cluster with less than or equal to a few thousand stars will expand due to interactions with binaries that heat the cluster (see Section 6.2), increasing the crossing and relaxation times. Clusters are not isolated but interact with their
surroundings, and can be disrupted by the galactic tidal field (Terlevich 1987) and through encounters with molecular clouds (Terlevich 1987; Theuns 1992). Finally, depending on the shape of the initial mass function, stellar evolution can significantly compromise the lifetime of a cluster (e.g., de la Fuente Marcos 1996a, 1997). Thus, in general, a realistic medium-sized cluster will expand until reaching its tidal radius, at which point it will evaporate by the combined process of evaporation due to stellar interactions and tidal disruption (Kroupa 1995c).

The ONC contains \( \approx 2 \times 10^3 \) stars with a mean age of less than 1 Myr (Hillenbrand & Hartmann 1998), has a one-dimensional velocity dispersion of 2.5 km s\(^{-1}\) (Jones & Walker 1988), and a half-mass radius of \( \approx 0.6 \) pc (Hillenbrand & Hartmann 1998). The relevant timescales are \( t_{\text{cross}} \approx 4.7 \times 10^5 \) years and \( t_{\text{relax}} \approx 30 t_{\text{cross}} \). The cluster age is thus probably 1–3 \( t_{\text{cross}} \). The central core of the ONC, with a radius of \( \approx 0.1 \) pc, has an age of \( \approx 13 \) crossing times. If \( \bar{m} \approx 0.5 \, M_\odot \) and \( m_{\text{in}} \approx 50 \, M_\odot \), then \( t_{\text{eq}} \approx 0.3 \, t_{\text{cross}} \), so that some dynamical mass segregation may have occurred (but see below).

### 3. Gas Accretion

Gas accretion has long been known to play an important role in star formation. Gravitational collapse is a non-homologous process (e.g., Larson 1969), forming a small mass core that subsequently accretes the rest of the surrounding gas. In systems where more than one protostar is formed, the initial collapse and fragmentation results in the majority of the mass still in the form of gas (Boss 1986; Bonnell et al. 1991, 1992; Burkert & Bodenheimer 1993; Bonnell & Bate 1994). Accretion of this gas in binary systems can greatly affect the resultant system properties such as the separation, eccentricity, and stellar masses (Bate, Bonnell, & Price 1995; Bate & Bonnell 1997).

Accretion also plays an important role in the dynamics of a stellar cluster. Accretion onto individual stars can significantly affect their masses, while the combined effect of mass loading and gas drag decreases the kinetic energy in stars and forces the cluster to contract. Accretion can profoundly affect the cluster, since most clusters contain significant fractions of their total mass in gas, and as the timescale for accretion, probably the gas free-fall time

\[
t_{\text{ff}} \propto \rho_{\text{gas}}^{-1/2}
\]

is of the same order as the cluster crossing time

\[
t_{\text{cross}} \propto \sqrt{R^3_{\text{clust}}/(M_{\text{stars}} + M_{\text{gas}})} \propto (\rho_{\text{gas}} + \rho_{\text{stars}})^{-1/2}
\]

In a previous symposium on the Orion Nebula, Zinnecker (1982) showed how competitive accretion, where the individual accretion rates depend solely on the square of the star’s mass (\( m \propto m^2 \); Equation 8 below), can lead to a spectrum of stellar masses from a small variation in the initial distribution. Although this study neglected the gas dynamics, it did point out the possibilities of explaining the large range in stellar masses through a simple physical process: accretion.
Figure 1. The evolution of a cluster of ten stars undergoing gas accretion. The distance of each star from the centre of the cluster (left panel) and the gas mass fraction accreted by each star (right panel) are given as functions of time, in units where $t_{\text{cross}} = 2.8$. The gas initially comprises 10% of the total mass of the system. Three individual stars are highlighted (see text).

In a recent study (Bonnell et al. 1997), the gas dynamics was included in the competitive accretion model. This was done by modelling the stars and gas in the cluster with a hybrid NBODY-SPH code (Bate et al. 1995). This allows the gas dynamics, the stellar dynamics, the gas accretion by individual stars, and the changing cluster potential to be modelled self-consistently during the evolution.

Accretion affects the stellar dynamics in two ways. Firstly, the accreted mass will have, in general, zero net-momentum compared to the stellar orbits. It will thus decrease the stars' kinetic energies while conserving momentum. Secondly, the stars will excite wakes in the gas, and thus lose kinetic energy via the associated gas drag. Both processes will combine to make the cluster more bound, with the stars that accrete the most (they will also excite larger wakes) sinking more rapidly to the centre.

The primary result of Bonnell et al. (1997) is that the accretion rates depend crucially on the stars’ positions in the cluster. Stars nearer the centre of the cluster are able to accrete significantly more than are those that are in the outer regions of the cluster. This is illustrated in Figure 1, showing the radius in the cluster and the relative mass accretion rate for a cluster of ten stars. The stellar masses are initially uniform and the emerging mass spectrum is solely due to the competitive accretion process. Three stars are highlighted in order to illustrate how the accretion depends on the star’s location.

The stars closest to the centre of the cluster (heavy solid line in Figure 1) 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 funnelled down to the cluster centre, thereby replenishing the gas as it is
The mass range (defined as the maximum over the minimum mass) for a cluster of 100 stars as a function of the total accreted mass in units of the total initial stellar mass (solid line). Also shown is the ratio of maximum to median mass (dashed line) and the half-mass radius (dotted line), in units of the initial half-mass radius. The gas initially comprises 90% of the system mass.

Accretion in a cluster can thus produce a large range in stellar masses from an initially uniform distribution. Figure 2 shows the ratio of maximum to minimum mass and the ratio of the maximum to average mass, as a function of the amount of gas accreted (in units of the total initial stellar mass) for a cluster of 100 stars accreting from gas that initially comprises 90% of the total mass (Bonnell & Bate, in preparation). The range in stellar masses becomes very large ($m_{\text{max}}/m_{\text{min}} \approx 50$), even though the average stellar mass has only increased by a factor two, and the cluster has only accreted $\approx 10\%$ of the gas. The rapid jumps in the mass range are due to collisions between individual stars which are assumed to occur if they pass within 0.1 AU of each other. The cluster is initially contained within 0.1 pc. Thus, the simple physical process of competitive accretion in a stellar cluster can produce a spectrum of stellar masses.
masses and thus possibly account for the observed initial mass function (Scalo 1986; Kroupa, Tout, & Gilmore 1993).

The competitive accretion process results in the most massive stars forming near the centre of the cluster. The stars that happen to be near the centre accrete more than the rest and thus it is these that end up as the most massive. This naturally explains the predominance of massive stars being found near the centre of rich clusters. Other explanations for their being located there pose serious problems (see below).

The resultant spectrum of stellar masses will thus predominantly relate to the initial distribution of stars and gas in a cluster, and then to the competitive accretion process between the massive stars located near the cluster centre. Although it is impossible to calculate the exact form of the resultant stellar mass spectrum without following a sufficient number of evolutions, we can make certain qualitative predictions based on the assumed distributions and the accretion physics assuming near Bondi-Hoyle accretion (e.g., Ruffert 1996)

\[
\dot{m} = 4\pi \rho \frac{(Gm)^2}{(v^2 + c_s^2)^{3/2}}.
\]

First of all, assuming that the overall distribution is that of a globally static (non-collapsing) isothermal sphere (\(\rho \propto r^{-2}\)), that the stars and gas trace the same regions in the same fashion, and that the accretion is completely mass independent, then the resultant mass spectrum would be \(dN/dm \propto m^{-3/2}\). Alternatively, if the accretion depends solely on the star’s mass (Equation 8 with uniform density as in the cluster core), then the resultant spectrum is the same as found by Zinnecker (1982), i.e., \(dN/dm \propto m^{-2}\). Generally, accretion will depend on both the stellar mass and the gas density so that the initial mass function power-law index will be a combination of the above.

4. Dynamical Mass Segregation

An alternative explanation for the location of the massive stars preferentially near the centre of a cluster is that they formed elsewhere in the cluster and subsequently sank to the centre through two-body relaxation. It is well known that this process results in mass segregation, as the encounters redistribute kinetic energy from the more massive to the less massive stars, driving the system towards energy equipartition. The question is, can it occur quickly enough to explain the central location of massive stars such as the Trapezium OB stars in the ONC within its young age (Equation 3)?

Dynamical mass segregation in young stellar clusters has recently been investigated (Bonnell & Davies 1998). Although some degree of mass segregation occurs relatively quickly in most clusters (Equation 3), it requires of order a relaxation time to be fully mass segregated. As most young clusters are significantly younger than a relaxation time (e.g., the ONC is \(< (1/10) t_{relax}\)), we can constrain the initial locations of the massive stars.

Using recent observational studies (McCaughrean & Stauffer 1994; Hillenbrand 1997; Hillenbrand & Hartmann 1998) of the Orion Nebula cluster, Bonnell & Davies (1998) showed that the massive stars that constitute the Trapezium,
Figure 3. The probability of observing a Trapezium-like system at the centre of a 1500 member cluster as a function of the time in units of the crossing time. The ONC is probably on the order of three crossing times old or younger. The five lines represent the cases when the 30 most massive stars are placed (from top to bottom): at Lagrangian radii containing 2% (i.e., the 30 massive stars are the centremost stars from the beginning), 10%, 20%, 30%, and 50% of the stars in the cluster.

the central dense core, need to have formed near where they are presently located, and cannot have evolved there due to dynamical mass segregation. The simulations of binary-rich dense clusters lead to the same conclusion (Kroupa, Petr, & McCaughrean, in preparation). If the massive stars originated elsewhere in the cluster, then the mean stellar mass in the core would be significantly lower than that observed ($\approx 5 M_\odot$ for the inner 25–40 stars). Furthermore, the probability of forming a dense grouping containing a significant fraction of the most massive stars (the Trapezium) is very small unless these massive stars originated nearby (Figure 3).

We are left with the conclusion that the most massive stars need to have formed in the centre of the cluster. Furthermore, it is unlikely that they formed from a direct collapse and fragmentation, as the physical conditions in the centre of a cluster would lead to the preferential formation of low-mass stars there (Zinnecker et al. 1993; Bonnell & Davies 1998; Bonnell, Bate, & Zinnecker 1998). Basically, the high stellar density implies a high pre-fragmentation gas density, which in turn implies a low fragment mass. Thus the most probable formation
mechanism for high-mass stars is the competitive accretion process described above, possibly combined with accretion induced collisions (see below).

5. Collisions and the Formation of Massive Stars

Although accretion in young clusters results in a large range of stellar masses, it may not be able to explain the formation of massive ($m > 10 M_\odot$) stars (Yorke 1993). This is because the large radiation pressure from these stars, combined with the opacity of interstellar matter, can result in the halting of any further accretion (see chapter in this volume by Yorke & Zinnecker). An alternative formation mechanism arises due to the dynamics of an accreting cluster.

Accretion onto a rich young cluster will force it to contract significantly, on the timescale of $t_{\text{cross}}$ (see Figure 2). 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 as shown by Bonnell et al. (1998), it will contract with added mass as

$$R_{\text{core}} \propto M_{\text{core}}^{-3}.$$  

(9)

This increases the stellar density dramatically, to the point where collisions become important. Collisions between intermediate mass stars ($2 M_\odot \lesssim m \lesssim 10 M_\odot$), whose mass has been accumulated through accretion in the cluster core, can then result in the formation of massive ($m \gtrsim 50 M_\odot$) 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 θ1 Ori C is significantly younger than $10^8$ years, possibly as young as $\lesssim 10^5$ years. Such a young age has implications for structures that are ionised by θ1 Ori C, e.g., the HII region and the proplyds (see the chapters by Bally, O’Dell, and Johnstone & Bertoldi).

6. Binary Stars

Binary systems in young stellar clusters can play an important role due to their relatively large cross section for interactions. In this way they can both affect the dynamics of clusters and provide insights into the formation environments of most stars. Surveys of main-sequence stars have ascertained that a significant fraction (typically $\gtrsim 50\%$) are in binary systems (e.g., Duquennoy & Mayor 1991). Observations of sparse groups of pre-main sequence stars in Taurus-Auriga imply a significant overabundance of binary systems relative to the main sequence population (e.g., Ghez 1995). An important question that any theory of star formation needs to answer is whether star formation naturally leads to a large binary proportion under all conditions (Clarke 1995), and if so, how this relates to the proportion of binaries found on the main sequence. This has important implications for the origin of the Galactic field population and the fraction of which may have formed in the extreme star-forming environments found in the dense cores of very young clusters.
The best available observational constraints on the abundance of pre-main sequence binary systems in the core of a very dense and very young cluster are those of Petr et al. (1998; see also the chapter by Petr et al. in this volume). They applied near-infrared speckle holography to stellar systems in the core of the Trapezium Cluster, which in turn can be considered the core region of the more massive and extended ONC (Hillenbrand & Hartmann 1998). They found that the binary proportion for low-mass Trapezium Cluster stars is indistinguishable from the binary proportion of low-mass Galactic field main sequence stars over the range of separations 63–225 AU. The binary proportion of low-mass stars within a radius of 0.25 pc of the centre of the Trapezium Cluster was found by Prosser et al. (1994) also to be consistent with the Galactic field value, which is confirmed by an extended study by Petr et al. (this volume). These observations thus indicate that the binary proportion may be independent of the radial distance within 0.25 pc of the centre of the Trapezium Cluster.

It is of considerable interest to investigate where there is a difference between the binary proportions of the Trapezium Cluster and Taurus-Auriga. Such a difference may be a result of star-formation in low-temperature clouds (isolated star formation, e.g., Taurus-Auriga), and higher-temperature clouds (embedded clusters, e.g., the Trapezium Cluster), as has been suggested by Durisen & Sterzik (1994). A temperature sensitivity may be responsible for the difference between Taurus-Auriga and the Galactic field, if most stars form in warm molecular clouds and thus in embedded clusters. However, the dependence on cloud temperature is by no means an established fact at present, owing to the great complexity of the physics of star formation.

Another mechanism that decreases a primordial binary proportion is the disruption of binary systems through binary-binary and binary-single star encounters (Kroupa 1995a, 1995b; de la Fuente Marcos 1996b). The central 0.1 pc diameter core of the Trapezium Cluster has roughly $4.7 \times 10^4$ stars pc$^{-3}$ (McCaughrean & Stauffer 1994), making this region an environment with extraordinarily high stellar density. The inter-stellar distances amount to about 6000 AU. For a binary system with a total mass of 1 $M_{\odot}$, this corresponds to an orbital period, $P$ (in days), of $\log P = 8.2$. Binary systems with orbital periods similar to or larger than this value will be disrupted due to crowding. Furthermore, binary systems with binding energies comparable to the kinetic energy of a perturber will be disrupted. The one-dimensional velocity dispersion within the central radius of 0.41 pc is about 2.5 km s$^{-1}$ (Jones & Walker 1988). A binary system with a system mass of 1 $M_{\odot}$ and with a circular orbital velocity equal to the velocity dispersion, has an orbital period $\log P_{th} = 5.8$, where $P_{th}$ is a “thermal” period corresponding to the “heat” of the cluster’s internal motion. For a binary system with potential energy $E_{pot}$ and orbital kinetic energy $E_{orb}$, the binding energy $E_{bin} = E_{pot}/2 = E_{pot} + E_{orb}$, so that $E_{orb} = -E_{bin}$. Thus, most binary systems with log $P > \log P_{th}$ will be disrupted, because an incoming perturber can transfer enough kinetic energy to the system to make it unbound.

Assuming the Trapezium Cluster stars have an age of about $\lesssim 1$ Myr (Prosser et al. 1994; Hillenbrand 1997), a stellar system will have had time to cross a distance of 0.2 pc (the central core) $\approx 13$ times. Thus there will have been many interactions between stellar systems in the cluster core despite its relative youth. Analytic treatment of the outcomes of binary-binary and binary-single star in-
teractions, and of the irregular perturbations acting on the orbit of a binary system in the tidal field of a dense cluster, is non-trivial (Heggie 1975; Heggie & Rasio 1996). In order to estimate the outcomes and their cross-sections, the analytical treatment has to be augmented by a very large number of numerical scattering experiments.

Such investigations show that binary systems with separations greater than that corresponding to the above thermal limit (soft binaries) are disrupted, while those with smaller separations (hard binaries) tend to become more bound. To compensate for the increase in binary-star binding energy, the kinetic energy of the cluster field population increases. Sufficiently bound binaries are thus an energy source in a stellar cluster and cause it to expand. Disruption in binary-single star encounters of binary systems with a period somewhat larger than the thermal limit cools the cluster, because a part of the kinetic energy of a perturber is used to ionise the binary system. This causes cluster contraction. Disruption of a binary in a binary-binary encounter, on the other hand, can lead to the formation of a more bound binary and two ejected single stars. If these do not escape from the cluster then such four-body collisions effectively heat the cluster. Thus there is competition between cooling and heating due to binary star activity, which operates within the first few tens of crossing times, until most soft binaries are disrupted. The probability of stars merging is enhanced significantly in binary-binary collisions (Bacon, Sigurdsson, & Davies 1996), and stellar evolution complicates the stellar interactions in close encounters (e.g., Portegies Zwart 1996; Portegies Zwart et al. 1997).

Exchange reactions near the cluster core lead, on average, to the least-massive star being ejected from the temporary few-body systems. Binary systems will suffer a recoil from interacting with single stars and may even be ejected if the interaction does not force them to merge (Davies, Benz, & Hills 1994). Tightly bound binaries are usually heavier than single stars, and will accumulate in the core through dynamical mass segregation. The energy production through hardening binaries leads to an expanding cluster core, and the innermost cluster region is depleted of low-mass stars. Reviews of these processes can be found in Hut et al. (1992), Davies (1995), Meylan & Heggie (1997), and also Giannone & Molteni (1985).

In general, the binary fraction can be significantly reduced by stellar interactions, with the resultant binary fraction being dependent on the hard/soft binary separation. This limiting separation depends on the velocity dispersion in the cluster and hence its density. Thus, stellar interactions will result in a lower binary fraction in denser clusters (see Figure 4).

The timescales for such processes are too long (many initial relaxation times) to noticeably affect the dynamics of the young ONC on a global scale. For example, it takes about 400 Myr for the mean stellar mass inside the central sphere with a radius of 2 pc to increase by 30%, for a cluster of initially 200 binary stars with an initial half-mass radius of 0.08 pc (Kroupa 1995c). However, it is the core of a stellar cluster where most “action” occurs, and it reacts on a significantly shorter timescale. The timescales for changes of its structure are, however, poorly known, mostly because there have only been a few investigations of clusters that have initially a large proportion of binary stars. A convenient estimate of such a timescale is the half-mass relaxation time, which
for a stellar system in virial equilibrium that consists of \( N \) stars with mean mass \( \overline{m} \), half-mass radius \( R_{1/2} \), and total mass \( M_{\text{cl}} \), is (from Equation 2):

\[
t_{\text{relax}} = \frac{2.1 \times 10^7 \text{ yr}}{\ln(0.4 N)} \left( \frac{M_{\text{cl}}}{100 M_\odot} \right)^{1/2} \left( \frac{1 M_\odot}{\overline{m}} \right) \left( \frac{R_{1/2}}{1 \text{ pc}} \right)^{3/2}.
\] (10)

A stellar system with \( R_{1/2} = 0.1 \text{–} 0.3 \text{ pc} \), \( N = 500 \), and \( M_{\text{cl}} = 300 M_\odot \), has a relaxation time \( t_{\text{relax}} = 0.7 \text{–} 3.7 \text{ Myr} \). These values are characteristic for the Trapezium Cluster, the core of the ONC. Also, for the Trapezium Cluster, \( \sigma \approx 2.5 \text{ km s}^{-1} \), and so \( t_{\text{cross}} = 4 \text{–} 12 \times 10^4 \text{ yr} \). A typical star may thus have crossed the central region many times, as stated above. This implies that collisions between stellar systems will have been frequent in the central few tenths of a parsec of the Trapezium Cluster.

The considerations presented above suggest that the Trapezium Cluster may be old enough to perhaps allow an initial Taurus-Auriga binary population.
to have dynamically evolved to the observed reduced value. Whether this is true can be investigated by numerical simulations. This is the subject of the following sub-sections, further details of which will be available in Kroupa, Petr, & McCAughrean, in preparation.

6.1. A model Trapezium Cluster

The ONC is the presently best studied very young and very dense cluster. Furthermore, the central core, the Trapezium Cluster, is sufficiently small that it may be a dynamically evolved structure. It is thus sensible to take the Trapezium Cluster as a starting point for the study of the dynamical processes involving young binary stars.

The following parameters are chosen to specify a model Trapezium Cluster at birth, i.e., at the time when stellar dynamics starts dominating over gas dynamics:

- \( N = 1600 \) stars
- An initial mass function deduced from star-count data in the Galactic field by Kroupa, Tout, & Gilmore (1993), based on Scalo’s (1986) determination for \( m > 1 M_{\odot} \).
- Lower and upper stellar mass limits, \( m_l \) and \( m_u \), of 0.08 and 30 \( M_{\odot} \) respectively
- A Plummer density distribution in virial equilibrium with \( R_{1/2} = 0.1 \) pc
- Initial position vectors and velocity dispersion independent of stellar mass
- An isotropic velocity distribution for the binary centres-of-mass

The resulting cluster mass is \( M_{\text{cl}} = 700 M_{\odot} \). The initial number of stars is guided by the detection in the near-infrared of 500 probable Trapezium Cluster members within a radius of about 0.65 pc (Zinnecker et al. 1993). Probably not all Trapezium Cluster stars will have been detected, and most binary systems would have not been resolved in that study. Also, allowance must be made for the dynamical evolution during the first Myr. The initial half-mass radius is guided by the modelling of McCAughrean & Stauffer (1994). These parameters are a compromise, in that they give a central density that is larger by an order of magnitude than the observed value, and a velocity dispersion that is somewhat smaller than the observed value. The relaxation and crossing times are \( t_{\text{relax}} = 0.62 \) Myr and \( t_{\text{cross}} = 0.1 \) Myr, respectively. The central number density will decrease and the half-mass radius will increase within 1 Myr owing to the heating through binary stars. The assumption that the velocity and position vectors are not correlated with the stellar mass is contradicted by the observations, which show that the massive stars are concentrated in the cluster core. However, the present assumption allows investigation of whether dynamical mass-segregation in young binary-rich clusters can lead to the observed mass-segregation on timescales of 1 Myr or less (see above). For the primordial binary star population two models are investigated:
• Model A: All stars are in $N_{\text{bin}} = 800$ binary systems; the initial period distribution is taken from Kroupa (1995b), with $\log P_{\text{min}} \approx 0$ (0.02 AU for a $1 M_\odot$ system) and $\log P_{\text{max}} = 8.43$ (8200 AU for a $1 M_\odot$ system).

• Model B: 1200 stars are in $N_{\text{bin}} = 600$ binary systems, and $N_{\text{sing}} = 400$ stars are single; a Duquennoy & Mayor (1991) initial log-period distribution, with $\log P_{\text{min}} = 0$ and $\log P_{\text{max}} = 11$ ($4.2 \times 10^5$ AU for a $1 M_\odot$ system).

In Model A, the binary fraction, $f_{\text{tot}}$, is 1, consistent with the pre-main sequence binary proportion in Taurus-Auriga. In Model B, $f_{\text{tot}} = 0.6$, consistent with the binary proportion for Galactic field main sequence stars. Here, $f = N_{\text{bin}} / (N_{\text{bin}} + N_{\text{sing}})$, and the subscript “tot” implies that all periods are counted. The initial model period distributions are compared with the observational data in Figure 5. In addition, the following assumptions are made: the initial mass-ratio distribution is random and the initial eccentricity distribution is thermally relaxed (Kroupa 1995a, 1995b). All results quoted here are averages of three equivalent simulations per model.

Computer simulations of stellar clusters are problematic because the forces have to be computed for each pair of stars, so that the computational time scales as $N^2$. Binary stars, some of which have to be integrated with very small time-steps, cause additional serious delays. An $N$–body programme must allow the simulation of dynamical processes that have timescales ranging from days to many $10^8$ yr. For this purpose, the best available code for the realistic simulation of stellar clusters, $N_{\text{BODY5}}$, was used (Aarseth 1985, 1994). It incorporates many special algorithms to ensure computational speed and efficiency without compromising accuracy. Short descriptions of the code may be found in Hut et al. (1992) and Meylan & Heggie (1997).

6.2. A model Trapezium Cluster: overall evolution

From ground-based near-infrared images of the Trapezium Cluster core, McCaughrean & Stauffer (1994) estimate that 29 systems are within the central spherical volume with a radius of 0.053 pc.

Figure 6 compares the evolution of the number of systems within the central region of the model clusters with the above observational constraint. The models are initially over-dense by an order of magnitude, but agree with the observational constraint after 2.5 Myr (Model B) and 4.2 Myr (Model A). The cluster expands mostly through three- and four-body interactions. In a cluster consisting initially of single stars, on the other hand, the central number density increases continuously (e.g., Spurzem & Takahashi 1995), until the core collapses at $\approx 2-3t_{\text{relax}}$ (Spitzer 1987). That the number of systems is consistently higher in Model A than in Model B is due to enhanced binary destruction in Model A, which liberates new single stars. The disruption of wide binaries also cools the cluster which slows the expansion for Model A relative to Model B, leading to a larger density in the core.

The one-dimensional tangential velocity dispersion within 0.41 pc of the centre of the Trapezium Cluster, is estimated by Jones & Walker (1988) to be $2.54 \pm 0.27$ km/s from their proper-motion survey. The data indicate no anisotropy, but these authors, van Altena et al. (1988), and Tian et al. (1996)
Figure 5. Distribution of orbits, $f_P$, for main sequence multiple systems (solid dots, Duquennoy & Mayor 1991) and pre-main sequence systems in Taurus-Auriga (open squares: log $P > 4$, Köhler & Leinert 1998; log $P = 3.5$, Richichi et al. 1994; log $P < 2$, Mathieu 1994). Main sequence G-, K- and M-dwarf binaries have essentially the same period distribution (cf. Figure 1 of Kroupa 1995a). The dotted histogram is the initial period distribution from Kroupa (1995b, Figure 7). Crowding in the model Trapezium Cluster changes this distribution to the long-dashed one, which is Model A. A Gaussian log-period birth distribution that fits the solid dots, changes through crowding in the model Trapezium Cluster to the distribution shown as the short-dashed line. This is Model B.

note that the plate-reduction algorithms used eliminate any signature due to rotation, expansion, or contraction. Thus, it is presently unknown if the Trapezium Cluster is expanding or contracting.

The evolution of the one-dimensional velocity dispersion within 0.41 pc of the density maximum of the model clusters is shown in Figure 6. The velocity dispersion increases slightly during the first few $10^5$ yr because the numerical model contracts slightly during adjustment to viral equilibrium, which is never perfectly achieved in a discrete rendition of a dynamical system. The velocity dispersion is similar to the observed value during these times, but then decreases substantially. The velocity dispersion is inconsistent with the observational constraint when the central number density agrees with the observations.
Figure 6. Upper panel: The time evolution of the number of stellar systems within 0.053 pc of the density maximum of the model cluster. The thick curves assume no binary systems are resolved, and the thin curves count all stars. The observational constraint with the Poisson error range is indicated by the dotted lines. Lower panel: The time evolution of the one-dimensional velocity dispersion of centres-of-mass within a projected distance of 0.41 pc from the density maximum of the model cluster. The observational one-sigma uncertainty range is indicated by the dotted lines. In both panels, the solid curves are for Model A and the dot-dashed curves for Model B.

6.3. A model Trapezium Cluster: binary stars

The observations in the core of the Trapezium Cluster by Petr et al. (1998; this volume) resolve binary systems with separations over the range 63–225 AU. Of the 42 systems that appear projected within the central radius of 0.041 pc, six are OB stars and four are binary systems. The apparent binary proportion of
Figure 7. The time evolution of the apparent binary proportion in the model Trapezium Clusters. Models A and B are the solid and dot-dashed lines respectively. Upper panel: observational constraints from Prosser et al. (1994) are shown as dotted lines. Lower panel: observational constraints from Petr et al. (1998) are shown as the horizontal lines. Here, the central dotted line is $f_{\text{app}}$ for all systems in their sample, and the central dashed line is $f_{\text{app}}$ for the low-mass systems only. Poisson uncertainties are indicated by the upper and lower horizontal lines.

the entire sample is $f_{\text{app}} = 0.095 \pm 0.05$, and the binary proportion for low-mass ($m < 1.5 \, M_\odot$) stars is $f_{\text{app, lms}} = 0.06 \pm 0.04$. The subscript “app” means that the observed $f$ is the apparent binary proportion that an observer deduces from projected star positions within some range of separations to which the observational apparatus is sensitive. The binary proportion of low-mass stars within a radius of 0.25 pc of the centre of the Trapezium cluster was found by Prosser et al. (1994) to be $f_{\text{app}} = 0.12 \pm 0.02$ for separations over the range 26–440 AU.

Observations and theory are compared in Figure 7. Significant evolution of the model binary population occurs within the first 1 Myr, and $f_{\text{Model A}} >$
in the upper panel, suggesting that the initial binary proportion and period distribution can, in principle, be constrained. The above inequality is violated for times $t > 1$ Myr in the much smaller sample in the cluster core, and information on the initial binary proportion is lost. The model results show that the observational constraints are still too weak to allow a distinction between Models A and B. Both are consistent with the data for dynamical cluster ages $t > 0.3$ Myr.

The observations by Petr et al. (1998; this volume) and Prosser et al. (1994) suggest that $f$ is roughly independent of radial distance. As is evident from Figure 8, initially there are fewer binaries near the centre. This is a result of disruption from crowding, and is much more pronounced for Model A, which is more abundant in long-period binaries than Model B. After 1 Myr, there remains a slight radial dependence, with $f_{\text{tot}}$ increasing slightly with increasing $r < 1.3$ pc in Model A. The decay for larger $r$ is a result of primarily low-mass stars being expelled to large radii after three- and four-body interactions near the cluster core. The radial dependence has vanished at $t = 5$ Myr, and $f_{\text{tot}} \approx 0.35$. In Model B, $f_{\text{tot}} \approx 0.3$ for $t > 1$ Myr and all $r$, and little further evolution is apparent until $t = 5$ Myr.

The models confirm that $f_{\text{tot}}$ should be independent of $r$ for $t > 1$ Myr, by which time the stellar population is well mixed. If observations find $f(r \approx 1.3 \text{ pc}) > f(r > 1.3 \text{ pc})$ and/or $f(r \approx 1.3 \text{ pc}) > f(r < 0.3 \text{ pc})$, then this would be evidence for $f_{\text{tot}} \approx 1$ at birth, and that the Trapezium Cluster is merely on the order of one crossing time old.

### 6.4. A model Trapezium Cluster: eccentricity-period diagram

The dynamical interactions between stellar systems near the core of a cluster have a rich variety of outcomes. Binary systems that survive such an encounter will have their orbital properties significantly affected. The relative change in eccentricity is usually much larger than the relative change in binding energy (Heggie 1975). A binary system emanating from an interaction will often have an eccentric orbit, and may be identified in the eccentricity-period diagram if it lies outside the observed envelope (see Figure 9).

The eccentricity-period diagram after 1 Myr is shown for Model A in Figure 9. The region to the left of the envelope has been populated. Those binaries with a very large eccentricity would lead to physical collisions between the companion pre-main sequence stars. However, it is noteworthy that the two orbits furthest away from the envelope, (a) $e = 0.39$, $\log P = 0.72$ and (b) $e = 0.94$, $\log P = 2.29$, are systems that have been ejected from the cluster. System (a) consists of two stars each with a mass of $2.79 M_\odot$, at a distance of 8.4 pc from the model cluster and receding with 50.3 km s$^{-1}$ from it. System (b) is located at a distance of 13.1 pc from the cluster, is receding from it with a velocity of 22.8 km s$^{-1}$, and consists of a 0.51 $M_\odot$ and a 0.35 $M_\odot$ star. Real systems with such large eccentricities and short orbital periods will undergo significant orbital evolution within probably 10–1000 orbital periods, i.e., within less than a few thousand years. How fast tidal circularisation proceeds remains uncertain (see Mathieu 1994; Kroupa 1995b and references therein; Verbunt & Phinney 1995), given that the distended internal structure of the pre-main sequence stars is an important ingredient of tidal circularisation theory, but it is likely to slow down
as circularisation progresses. An observer is therefore most likely to capture such systems towards the end of the circularisation phase, when the eccentricity has decayed considerably. Possible observational counterparts to such systems are found in Table A2 in Mathieu (1994): P2486 has spectral class G5, has $e = 0.161$ and $\log P = 0.72$, and is located in the Trapezium Cluster; OriNTT 429 is a K3 system with $e = 0.27$ and $\log P = 0.87$, but does not appear to be in a young cluster.

7. Circumstellar Discs

Stellar encounters involving single stars and their circumstellar discs are also an important dynamical process in stellar clusters as their large sizes (100–1000 AU) result in significant cross sections for interactions. Circumstellar discs are a ubiquitous by-product of the star formation process due to the presence of even small amounts of angular momentum in the pre-collapse molecular clouds.
Figure 9. The eccentricity-period diagram for Model A at time $t = 1\,\text{Myr}$. All surviving orbits of the three simulations are plotted. The distribution for Model B is very similar. The thick dashed line represents the observed envelope for main-sequence binary stars with a G-dwarf primary (Duquennoy & Mayor 1991). The initial model data are distributed to the right of the envelope (see Figure 5 of Kroupa 1995b). Systems with eccentricities above this line with $e$ of order 0.2 or greater are therefore evidence for stellar encounters.

These discs are commonly found around young stars of ages $\lesssim\text{few Myr}$ (Strom, Edwards, & Strutskie 1993). Interactions between stars and discs in a clustered environment can play an important role in the dynamics of the stars and of the discs.

Star-disc interactions have been proposed as a mechanism to form binary systems (Larson 1990; Clarke & Pringle 1991; see Clarke 1995), by way of removing kinetic energy from the stellar motions and leaving the system bound. The necessary encounter is a violent one, with the perturber’s orbit passing through the other star’s disc, unbinding the matter initially outside of the periastron passage. Star-disc interactions can be effective in small clusters where the velocity dispersion is low (Clarke & Pringle 1991; McDonald & Clarke 1995; Clarke 1995; Hall, Clarke, & Pringle 1996), and can help explain the high incidence of binary systems amongst pre-main sequence stars such as is found in Taurus (Ghez, Neugebauer, & Matthews 1993; Leinert et al. 1993). This mechanism
may also lead to a high binary proportion in dense clusters if fragmentation initially produces sub-clumps, each of which is a small cluster.

In larger clusters and after the possible initial sub-clumping is erased, the velocity dispersion is higher and the chance of a destructive high velocity encounter before a low velocity, and hence capturing, encounter is large (Clarke 1995). Thus, in clusters such as the ONC, the primary effect of star-disc interactions is the disruption they inflict on the discs and thus on the disc’s evolution. The encounter will generally remove all disc material exterior to the periastron separation (Figure 10). This paring down of the disc results in a smaller disc mass and a disc radius of $\approx 1/3$ of the original periastron radius (Clarke & Pringle 1993; Heller 1995; Hall et al. 1996; Larwood 1997). Additionally, the disc displays an exponential outer edge similar that observed for several of the silhouette disks in the Trapezium Cluster (Hall 1997; McCaughrean & O’Dell 1996; see also the chapter by McCaughrean et al. in this volume).

If the original periastron radius is not too small, the disc compression caused by the encounter can decrease the formation timescale of outermost planets. This may lessen the discrepancy between the excessively long formation timescale of Neptune and empirical proto-stellar disc life-times if the Sun formed in an embedded cluster (Eggers et al. 1997), which is also corroborated by the obliquity of the planetary system (Heller 1993).
8. Gas Expulsion

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 to the cluster potential 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, & Dearborn 1984; Pinto 1987; Verschueren & David 1989; Goodwin 1997b; Saiyadpour et al. 1997). If the gas is removed quickly compared to the cluster crossing time, $t_{\text{cross}}$, then the dramatic reduction in the binding energy, without affecting the stellar kinetic energy, results in an unbound cluster for any reasonable gas mass fraction, unless the stellar cluster was in a state of collapse prior to gas removal. 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% can survive with approximately half of the stars if the gas removal occurs over four or more crossing times (Lada et al. 1984). Clusters with larger central concentrations survive preferentially as the cluster core with a high stellar density is less affected by the removal of gas from the rest of the cluster (Lada et al. 1984; Goodwin 1997b). However, violent gas expulsion through massive outflows from the massive central stars (Churchwell 1997) is likely to be an important process governing core evolution.

The number and age distribution of Galactic clusters suggests that only a few percent of all Galactic field stars can have originated in bound clusters (Wielen 1971). However, star counts in molecular clouds (Lada & Lada 1991) and the properties of Galactic field binaries (Kroupa 1995a) indicate that most stars may form in clusters. The implication is that the life-time of the typical embedded cluster is $\lesssim 10$ Myr (Battinelli & Capuzzo-Dolcetta 1991), which is a natural consequence of rapid gas expulsion and low local star formation efficiency.

9. Summary

The formation of a stellar cluster involves many dynamical processes that need to be understood. The least understood of these is the initial formation mechanism from which hundreds to thousands of stars form nearly simultaneously in a bound grouping. Subsequent evolution depends to a large extent on interactions with, and accretion of, the gas by the stars. Competitive accretion in a cluster potential results in a large range of stellar masses, comparable to that observed in the Orion Nebula Cluster. It is thus a strong candidate process to explain the observed distribution of stellar masses. This process naturally results in forming the most massive objects near the cluster centre whereas their location there cannot be due to dynamical mass segregation. Accretion also shrinks the
stellar distribution, such that with sufficient accretion, it is possible for collisions to occur in the cluster core, thereby aiding in the formation of massive stars.

Stellar interactions in young clusters are significant, as they commonly have circumstellar discs, and are often in binary and multiple systems, thereby increasing their cross section for such interactions. Binary-single and binary-binary interactions in young clusters are generally destructive, unbinding the wider systems and reducing the binary fraction. Assuming that the normal mode of star formation is that of binary stars (as is found in Taurus-Auriga), then the observed binary fraction in different stellar populations is an indication of the subsequent dynamical interactions and thus the degree to which the star formed in a clustered environment. The observed binary fraction in the Trapezium Cluster is consistent with having originally been as high as that found in Taurus-Auriga, and having subsequently been reduced through stellar interactions. If this is the case, then the binary fraction in the outer, less evolved part of the cluster, should be as high as that in Taurus-Auriga.

Interactions between multiple- and single-star systems in an initially binary-rich cluster significantly affect the early evolution of the cluster. The core expands with a rate depending on the number ratio of hard to soft binaries. In single-star clusters, on the other hand, the core will contract.

Star-disc interactions in small clusters and sub-clusters can aid in the formation of binary systems by transferring kinetic energy from the stars’ orbits to unbinding parts of the disc. In larger clusters, these interactions are more violent and will rarely form binary systems but will significantly affect the discs, removing that fraction of their mass located beyond periastron. Disc compression during less-destructive star-disc encounters can induce planet formation and decrease the timescale for assembly of outer planets.

The majority of young clusters will not form bound open clusters but will instead disperse their stars into the field. This must be the case if most stars are formed in clusters but spend the majority of their lifetime as field stars. The cluster dispersal will generally occur when either—for small clusters—an evaporation time has been reached or—for larger clusters—when a massive star has removed all remaining gas and thus unbinds the cluster.

Acknowledgments. We thank the editors and the organisers of the Ringberg conference on the Orion star formation complex for having invited us to a stimulating meeting. Sverre Aarseth is thanked warmly for readily providing his Nbody5 code.

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