Early Evolution of Stellar Clusters

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Abstract. Observations have revealed that most stars are born in clusters. These systems, containing from tens to thousands of stars and typically significant mass in gas in the youngest systems, evolve due to a combination of stellar and star-gas interactions. Simulations of pure stellar systems are used to investigate possible initial configurations including ellipticity, substructure and mass segregation. Simulations of gas-rich clusters investigate the effects of accretion on the cluster dynamics and on the individual masses that result in a stellar mass spectrum. Further stellar interactions, including binary destruction and eventually cluster dissolution are also discussed.

1. Introduction

Although stellar clusters and associations contain but a small fraction of the stellar content of the Galaxy, it is becoming increasingly clear that most stars originate in clusters and that to understand how stars form we have to consider clusters of stars and how such environments can affect their formation. Surveys of nearby star forming regions have found that the majority of pre-main sequence stars are found in clusters (e.g Lada et. al. 1991; Lada, Strom & Myers 1993; see also Clarke, Bonnell & Hillenbrand 2000). The fraction of stars in clusters depends on the molecular cloud considered but generally varies from 50 to ∼90 per cent. This fraction appears to decreases with age.

Young stellar clusters in the solar neighbourhood are found to contain anywhere from tens to thousands of stars with typical numbers of around a hundred (Lada et. al. 1991; Phelps & Lada 1997; Clarke et. al. 2000). Cluster radii are generally a few tenths of a parsec such that mean stellar densities are of the order of ≈ 10^3 stars/pc^3 (c.f. Clarke et. al. 2000) with central stellar densities of the larger clusters (ie the ONC) being ≧10^4 stars/pc^3 (McCaughrean & Stauffer 1994; Hillenbrand & Hartmann 1998; Carpenter et. al. 1997).

These clusters are usually associated with massive clumps of molecular gas. Indeed, the mass in gas is typically much more than that in stars. Gas can thus play an important role in the dynamics of the clusters and possibly affect the final stellar masses through accretion.

Recently, it has become possible to conduct a stellar census in young stellar clusters (e.g. Hillenbrand 1997) by using theoretical pre-main sequence evolutionary tracks to estimate each star’s mass and age. Unfortunately, there is a fair degree of uncertainty in these estimates due to the uncertainty in the tracks themselves (see Hillenbrand 1997 for an example) and due to the possibility of...
ongoing gas accretion affecting the star’s pre-main sequence evolution (Tout, Livio & Bonnell 1999). What is relatively certain in the census is that the cluster stars are generally young (ages \( \approx 10^6 \) years) and contain both low-mass and high-mass stars in proportion as you would expect from a field-star IMF (Hillenbrand 1997). Furthermore, there is a degree of mass segregation present in the clusters with the most massive stars generally found in the cluster cores.

In this paper, I review work that has been done on the evolution of young stellar clusters and how this work can be combined with observations of such clusters to investigate the relevant processes of star formation in clusters.

2. Cluster Morphology

One of the major questions concerning stellar clusters is their formation mechanism. A number of different scenarios can be imagined including a triggering where a shock induces star formation in a group, or a coagulation where a number of smaller groups merge to form one cluster (e.g. Klessen, Burkert & Bate 1998). Such processes can leave traces of their initial conditions in the cluster morphologies. For example, a triggered formation mechanism such as a shock or cloud-cloud collision leads to a flattened structure which then fragments to form a cluster (Whitworth et al. 1994, Bhattal et al. 1998). This flattened morphology should then be in the initial conditions of the stellar cluster.

In order to use the morphology in present-day clusters to constrain possible initial conditions, we have to understand how the early evolution of the stellar cluster can affect its morphology. Boily, Clarke & Murray (1999; see also Goodwin 1997a) have investigated the evolution of a dynamically cold flattened stellar system. Using N-body simulations, they showed how the cluster relaxes through both an initial violent relaxation and subsequent two-body relaxation. As these systems are generally younger than their relaxation time (see below), it is the violent relaxation which will have a greater affect on the cluster mor-
The evolution of a cluster containing subclusters (Scally in preparation). The subclusters dissolve over time into the larger-scale cluster.

Boily et al. found that a flattened system becomes less elliptical, but that the violent relaxation does not completely remove the initial asphericity. For example, a system with an initial axis ratio of 5:1 relaxed to an axis ratio of 2:1. This suggests that the clusters such as the ONC which are significantly elongated (axis ratio of 2:1, Hillenbrand & Hartmann 1998; see also Clarke et al. 2000) were initially very aspherical and thus could have been formed as the result of a triggering mechanism.

Substructure, or subclustering, is another possibility in the cluster’s initial conditions that can constrain the formation mechanism. Bate, Clarke & Mc-Caughrean (1998) used statistical tests for substructure in clusters based on the mean surface density of companions (see also Larson 1995). They found that the ONC is consistent with having no substructure although a narrow window of subclustering is possible. In contrast, IC348 does appear, at least by eye, to have significant substructure (Lada & Lada 1995), but this has not been tested statistically.

At present, most young clusters do not display significant substructure, but it is possible that the initial conditions did contain subclustering that has since been removed through its evolution (Bate et al. 1998). This can be
investigated through N-Body simulations (Scally, in preparation), investigating how the subclusters relax and dissolve into the surrounding larger-scale cluster. This occurs due to a combination of the tidal forces acting on the subcluster and its internal relaxation which leads it to dissolve on a timescale proportional to the number of stars it contains.

3. Mass Segregation

Young stellar clusters are commonly found to have their most massive stars in or near the centre (Hillenbrand 1997; Carpenter et al. 1997). This mass segregation is similar to that found in older clusters but the young dynamical age of these systems offers the chance to test whether the mass segregation is an initial condition or due to the subsequent evolution. 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. 3).

Numerical simulations of two-body relaxation have shown that while some degree of mass segregation can occur over the short lifetimes of these young clusters, it is not sufficient to explain the observations (Bonnell & Davies 1998). Thus the observed positions of the massive stars near the centre of clusters
like the ONC reflects the initial conditions of the cluster and of massive star formation that occurs preferentially in the centre of rich clusters.

Forming massive stars in the centre of clusters is not straightforward due to the high stellar density. For a star to fragment out of the general cloud requires that the Jeans radius, the minimum radius for the fragment to be gravitationally bound,

$$R_J \propto T^{1/2} \rho^{-1/2},$$

be less than the stellar separation. This implies that the gas density has to be high, as you would expect at the centre of the cluster potential. The difficulty arises in that the high gas density implies that the fragment mass, being approximately the Jeans mass,

$$M_J \propto T^{3/2} \rho^{-1/2},$$

is quite low. Thus, unless the temperature is unreasonably high in the centre of the cluster before fragmentation, the initial stellar mass is quite low. Equation (2) implies that the stars in the centre of the cluster should have the lowest masses, in direct contradiction with the observations. Therefore, we need a better explanation for the origin of massive stars in the centre of clusters.

4. 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). This gas can interact with, and be accreted by, the stars as both move in 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. 4) with those in the centre accreting more gas than those near the outside. This process is termed “competitive accretion” (Zinnecker 1982) each star competes for the available gas reservoir with the advantage going to those in the cluster centre that benefit from the overall cluster potential.

Accretion in stellar clusters naturally leads to both a mass spectrum and mass segregation. Even from initially equal stellar masses, the competitive accretion results in a wide range of masses with the most massive stars located in or near the centre of the cluster. Furthermore, 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.

5. Formation of Massive Stars

The formation of massive stars is problematic not only for their special location in the cluster centre, but also due to the fact that the radiation pressure from massive stars is sufficient to halt the infall and accretion (Yorke & Krugel 1977; Yorke 1993). This occurs for stars of mass $\gtrsim 10 M_\odot$.

A secondary effect of accretion in clusters is that it can force it to contract significantly. 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 the core, initially at $n \approx 10^4$ stars pc$^{-3}$, can contract to the point where, at $n \approx 10^8$ stars pc$^{-3}$, stellar collisions are significant (Bonnell, Bate & Zinnecker 1998). Collisions between intermediate mass stars ($2M_\odot \lesssim m \lesssim 10M_\odot$), whose mass has been accumulated through accretion in the cluster...
Figure 6. Binary frequency (heavy line) versus log separation (in au) for clusters with a stellar density of $n = 10^3$ stars pc$^{-3}$, velocity dispersion of $v_{\text{disp}} = 2$ km s$^{-1}$ for 10$^6$ years (top left panel), $n = 10^4$ stars pc$^{-3}$, $v_{\text{disp}} = 2$ km s$^{-1}$ for 10$^6$ years (top right panel), $n = 10^6$ stars pc$^{-3}$, $v_{\text{disp}} = 5$ km s$^{-1}$ for 10$^5$ years (bottom left panel) and $n = 10^8$ stars pc$^{-3}$, $v_{\text{disp}} = 10$ km s$^{-1}$ for 10$^4$ years (bottom right panel). The binary frequency is initially flat and the light line indicates the number of systems destroyed versus separation (Smith & Bonnell, in preparation).

core, can then result in the formation of massive ($m \gtrsim 50M_\odot$) stars. This model for the formation of massive stars predicts that the massive stars have to be significantly younger than the mean stellar age due to the time required for the core to contract (Bonnell et al. 1998).

6. Binaries in clusters

Binary stars can play an important role in young stellar clusters as well as in older, evolved clusters. Their importance stems not from their influence on the dynamics of the cluster, but rather from how the cluster dynamics affect, and destroys, some of the binaries. The high binary frequency in nearby, non-clustered star-forming regions (e.g. Mathieu 1994; Ghez 1995, Mathieu et al. 2000) compared to the main sequence (Duquennoy & Mayor 1991) and to that in clustered...
star forming regions (Padgett, Strom & Ghez 1997; Petr et al. 1998; Mathieu et al. 2000) suggest that as most stars are formed in clusters, the cluster environment plays an important role in setting the binary frequency. This can happen in one of two ways, either the cluster environment impedes binary formation or it subsequently destroys them.

Kroupa (1995) has shown how a 100% binary frequency can be reduced through stellar encounters in clusters and how the final binary frequency depends on the stellar density in the cluster. Binary systems wider than the hard-soft limit (basically where the orbital velocity is equal to the cluster velocity dispersion) are destroyed in encounters. Thus denser systems with higher velocity dispersions disrupt more binaries.

This binary destruction in clusters can also be used as a tracer of the cluster evolution (Smith & Bonnell, in preparation). Figure 6 shows the resultant binary frequency versus separation for clusters of various stellar densities. Clusters with stellar densities of the order of $10^3$ stars pc$^{-3}$ only have a significant effect on systems wider than $>10^3$ au whereas clusters with higher densities destroy closer systems. Thus, if a cluster does go through a very dense phase in order for collisions to occur (see above) then no binaries wider than 100 au should survive with significant depletion extending down to 10 au (Fig. 6).

7. Cluster Dissolution

The majority of young stellar clusters dissolve before their low-mass stars reach the main sequence. This can happen either through a sudden removal of the majority of the binding mass, the gas contained in the cluster, or through the dynamical interactions that put all of the cluster’s binding energy into a central binary.

Gas removal is most important for large stellar clusters that are more likely to contain massive stars. These stars can ionise the intracluster gas which can then escape (unless the velocity dispersion is $v_{\text{disp}} \gtrsim 10$ km s$^{-1}$). Gas removal on timescales less than the dynamical time is catastrophic for the cluster if gas is the major mass component (Lada, Margulis & Dearborn 1984; Goodwin 1997b). Gas removal over many dynamical times will leave a remnant cluster containing a fraction of the initial cluster stars.

The second possibility for cluster dissolution is that two-body relaxation takes the cluster’s binding energy and puts it into one central binary, typically containing the most massive stars (Sterzik & Durisen 1998; Bonnell in preparation). This occurs on a timescale similar to the relaxation time of the cluster as a whole (the difference in that it involves only the central binary as the energy source and that the binary shrinks during the energy exchange),

$$t_{\text{diss}} \approx N t_{\text{cross}}. \quad (3)$$

Thus, small clusters will dissolve readily through two-body relaxation whilst large clusters dissolve through the interaction of their massive stars with the gas. It should only therefore be the intermediate clusters which have long dissolution times but that do not contain very massive stars which survive long enough to be considered as open or Galactic clusters.
8. Summary

The early evolution of stellar clusters involves many interactions which affect the clusters' and the individual stellar properties. Understanding these interactions, and their possible consequences, allows us to investigate probable cluster initial conditions and how they relate to observations of young stellar clusters.

The dynamical interactions are of two types, pure stellar interactions and star-gas interactions. The first type are investigated through N-Body simulations and include violent relaxation and two-body relaxation. Both of these decrease initial structure, including ellipticity and substructure, although some degree of structure is likely to remain long enough to be observable. The ellipticity in the ONC could thus indicate an initially highly aspherical initial condition. Two-body relaxation also drives mass segregation although this occurs over many dynamical times in large clusters such that the position of the massive stars in the ONC reflects their initial location and thus constrains how massive stars form.

Star-gas interactions include accretion of the gas onto the stars and the feedback (especially from massive stars) from the stars onto the gas. Although feedback has not yet been studied in this context, we are starting to understand the process of accretion in clusters. Gas accretion in a stellar cluster is highly competitive and uneven. Stars near the centre of the cluster accrete at significantly higher rates due to their position where they are aided in attracting the gas by the overall cluster potential. This competitive accretion naturally results in both a spectrum of stellar masses, and an initial mass segregation even if all the stars originate with equal masses. Accretion in stellar clusters can also force the core of the cluster to contract sufficiently to allow for stellar collisions to occur. Such a collisional model for the formation of massive stars evades the problem of accreting onto massive stars.

Wide binary systems in clusters are destroyed by stellar encounters in clusters. The maximum separation which survives such interactions depends primarily on the cluster density and velocity dispersion. Wide systems are more likely to survive less dense clusters than in the core of dense clusters. Binaries can thus be used as a tracer of the cluster evolution.

Finally, clusters dissolve through either gas removal (generally larger clusters) or through dynamical interactions which transfer all the clusters binding energy to a central binary (small-N clusters). Thus, clusters surviving to the main sequence and Galactic cluster status represent a small subset of the initial population of stellar clusters.

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