The Formation of Stellar Clusters

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We review recent work that investigates the formation of stellar clusters, ranging in scale from globular clusters through open clusters to the small scale aggregates of stars observed in T associations. In all cases, recent advances in understanding have been achieved through the use of state of the art stellar dynamical and gas dynamical calculations, combined with the possibility of intercomparison with an increasingly large dataset on young clusters. Among the subjects that are highlighted are the frequency of cluster-mode star formation, the possible relationship between cluster density and the highest stellar mass, subclustering and the dynamical interactions that occur in compact aggregates, such as binary star formation. We also consider how the spectrum of stellar masses may be shaped by the process of competitive accretion in dense environments and how cluster properties, such as mass segregation and cluster morphology, can be used in conjunction with numerical simulations to investigate the initial conditions for cluster formation. Lastly, we contrast bottom-up and top-down scenarios for cluster formation and discuss their applicability to the formation of clusters on a range of scales.

I. Introduction

Observations indicate that stars frequently form in clustered environments – in rich clusters of many hundreds to many thousands of stars, or in smaller groups and aggregates containing of order ten to a few tens of stars. It is only recently, however, that the properties of young clusters are beginning to be well characterised. Cluster formation is important, therefore, insofar as it is a fundamental unit of star formation. It is also becoming increasingly apparent, given the high stellar densities measured in young clusters and therefore the possible role of encounters, that whether a star forms in a cluster or in isolation may be important in determining its fundamental properties, such as its mass, binarity or possession of planets.

This Chapter will concentrate on the issue of how observed young clusters can be used to deduce the conditions in clusters at birth. In particular, it stresses the interplay between observations and numerical simulations, which allows one to address a number of questions regarding the initial shapes, mass distributions and dynamical states of clusters, as well as exploring how likely it is for clusters to survive as bound structures. Significant observational and computational advances in recent years make this exercise particularly timely. On the observational front, deep wide-field imaging at infrared wavelengths and multi-fibre spectroscopy have brought a wealth of data concerning the state of clusters at increasingly young ages. Numerical simulations have also advanced considerably through the development of hydrodynamic codes that can deal with the highly inhomogeneous conditions in star forming gas. Of particular significance is the recent advent of special purpose 'GRAPE' hardware for the calculation of gravitational forces (Okumura et al. 1993). This innovation has heralded a new era in Nbody calculations, so that it is now straightforward to perform simulations (over tens of dynamical times) in which the number of particles matches the number of stars, even in the case of populous clusters containing many tens of thousands of stars.

The reason it is desirable to derive the basic characteristics of clusters at birth is because of the light such information sheds on *how* clusters form. Observational constraints on the age spread in clusters, the time sequence of star formation as a function of stellar mass, and the degree of subclustering are all important constraints on theoretical models. We defer a fuller discussion of current theoretical ideas until Section VII, but here indicate some of the issues in order to motivate the intervening Sections of the paper.

Historically, cluster formation theories considered the monolithic top-down collapse of Jeans unstable gas, and the main issue therefore concerned the number of fragments ('stars') formed during collapse (Hoyle 1953; Larson 1978). Such studies envisaged rather smooth initial conditions and therefore interest focused on the amplification of initially linear density perturbations and on the efficiency of cooling during collapse. Two facts about the state of star forming gas in molecular clouds however render this picture obsolete. Firstly, the thermal energy content of the gas is negligible compared with the energy density in (assumed MHD) turbulence: hence the question of how pieces of the cloud collapse to form stars does not hinge primarily on cooling but instead on their ability to decouple from the magnetic field. Secondly, molecular clouds are extremely inhomogeneous (e.g. Vazquez Semadeni et al., this volume), consisting of a floculent ensemble of structures within structures (for a hierarchical description of star forming clouds, see Chapter by Elmegreen, Zinnecker, Pudritz and Efremov this volume).

This inhomogeneity of the parent gas has several implications for cluster formation. For one thing, it renders trivial the question: ' Why are stars clustered at birth?', since at some level this reflects the structure of the star forming gas, albeit modified by dynamical effects (see Klessen, Burkert and Bate 1998 for a first attempt to model cluster formation from highly inhomogeneous initial conditions). It should be noted in passing that the fractal dimension characterising the distribution of young stars is *not* equal to that of the gas, implying either that the star formation process engenders tighter clustering or else that stars form from the most tightly clustered component of the molecular gas (Larson 1995).

The complex density structure of star forming clouds also raises questions as to the degree of coordination that is required to form a cluster. It is well known (e.g. Lada et al. 1984; Goodwin 1997; see Section V below) that the formation of a *bound* cluster requires that a high fraction (30-50 %) of the gas must be turned into stars before destructive feedback mechanisms from massive stars come into play: in practice this means a high conversion efficiency within a few cluster dynamical times. Such locally coordinated star formation is a natural expectation in top-down scenarios (i.e. where the structure develops as a result of gravitational instabilities during collapse). It is not however the obvious outcome if star formation is taking place in an already highly structured environment, unless some external agent can synchronise the onset of star formation in a set of discrete, and mutually independent, clumps. Such triggered star formation is therefore an attractive possibility theoretically, and there are clear examples (such as in IC 1396, Patel et al.1998; the Rosette Molecular Cloud, White et al.1997; IC 1805, Heyer et al.1996; Gem OB1, Carpenter et al.1995; and in more isolated "bright rim" regions, Sugitani et al.1991,1994) where the location of young stellar objects – and clusters – in the dense gas swept up by expanding HII regions lends credence to this scenario (Elmegreen and Lada 1977). In other cases, however, the locations of young clusters give no hint of external triggering (e.g. Taurus, NGC 2264). Thus a key question (whether cluster formation is induced or spontaneous) remains unanswered at the present time. Clearly, the derivation of cluster parameters at birth (particularly the age spread of stars within a cluster and the initial degree of sub-clustering) can shed considerable light on this question.

II. Observations of Young Clusters

Clusters are useful laboratories for star formation studies since they provide stellar samples of constant metallicity at approximately uniform distance. The task of identifying and characterizing clusters so young that they are still embedded in the molecular material from which they formed has been considerably aided within the past decade by near-infrared imaging capabilities. Near-infrared surveys penetrate through an order of magnitude more column density than does visual imaging and allow us to see clusters closer to the epoch of their formation (e.g. Figure 1 shows the infrared H-band image of Mon R2, Carpenter et al. 1997, see also Plate 1).

In what follows we consider only young stellar populations located within 1kpc of the Sun and focus on infrared surveys, as summarized in Table 1. We distinguish between biased surveys or deep imaging of some interesting class of object - e.g. molecular outflows, IRAS point sources, Bok globules, OB or Herbig Ae/Be stars - and the often shallower, unbiased surveys of large regions containing molecular material. We highlight two issues: the relative importance of isolated versus cluster mode star formation, and the apparent association of high mass star formation with the formation of clusters. First, however, we briefly touch on some of the problems involved in the identification and characterisation of clusters.

Clusters are usually identified via enhanced surface density relative to the background. An obvious disadvantage of this method is that since a given cluster subtends a smaller angle at larger distances, distant clusters are more readily identified, although this effect is partially offset by diminishing survey sensitivity at larger distances. Further problems are the correct subtraction of foreground and background sources, and the tendency for patchy absorption to act as a source of spurious clustering. As cluster surveys are extended to regions that are increasingly embedded (i.e. closer to the "$t = 0''$ of star formation), it is becoming increasingly necessary to interpret clustering statistics in conjunction with molecular extinction maps. These not only allow one to distinguish between true clustering and the apparent clustering of sources in windows of low extinction, but also allow more accurate subtraction of foreground and background sources. It should be stressed that in what follows, the term cluster is used to describe apparent groupings of stars in projection; since kinematic data is not usually available, it is not possible to make the conventional distinction between clusters and associations on the basis of whether or not they are gravitationally bound. It should also be noted that the detection of clustering in molecular clouds is strongly affected by the age of the system. With velocity dispersions of 1-2 kms^{-1}, smaller and less dense clusters can disperse quickly, possibly causing us to have over-estimated "typical" cluster membership numbers and projected densities.

The first large scale near-infrared imaging survey of a molecular cloud is the oft-quoted work of Lada et al. 1991b, which covered over 50 pc^2 of the Orion B molecular cloud (see also Li et al. 1997). Subsequently, similar unbiased surveys have been conducted in a number of other star forming regions: the Orion A cloud (Strom,Strom and Merrill 1993; Jones et al. 1994; Ali and DePoy 1995), NGC 2264 (Piche 1993; Lada et al. 1993; Strom et al. 1999), IC 348 (Lada and Lada 1995), NGC 1333 (Aspin and Sandell 1994,1997; Lada, Alves and Lada

1996), the Rosette Molecular Cloud (Phelps and Lada 1997), R CrA (Wilking et al. 1997), Taurus (Itoh et al. 1996), and the most thoroughly studied region, Ophiuchus (Rieke et al. 1989; Barsony et al. 1989; Greene and Young 1992; Comeron et al. 1993; Strom, Kepner and Strom 1995; Barsony et al. 1997). Clusters are found in all cases, and generally there is an accompanying distributed population of young stars as well.

It is obviously of interest to assess what fraction of stars form in clusters. The strong clustering of massive stars has been evident for a long time (e.g. Ambartsumian 1947; Blaauw 1964), but it is the advent of near-infrared imaging (as reviewed by Zinnecker et al. 1993) which has revealed that low mass stars form abundantly in the vicinity of high mass stars and thus share in the cluster environment at birth. The results of unbiased surveys of star forming regions suggest that the fraction of star formation taking place in clusters varies quite strongly from place to place. This is particularly striking in the case of the Orion giant molecular cloud where marked differences are found between the A and B clouds (see Meyer and Lada, 1998 for a fuller discussion). In the Orion B cloud, almost all (96%) of associated infrared sources are thought to be in clusters. In the Orion A cloud, by contrast, there is a significant distributed population with only 50-80% of the stellar population formed in clusters (the range depending on whether one does not or does count the Orion Nebula Cluster (henceforth the ONC)). The Orion A result is more consistent with what has been found in other surveys of molecular clouds, where the fraction of stars located in projected density enhancements ("clusters") is 50-70% (Taurus, Gomez et al. 1993; NGC 2264, Piche et al. 1993; NGC 1333, Lada et al. 1996; IC 348, Lada et al. 1995). We note, however, that while large fractions of the most dense and "active" areas of many clouds have been surveyed in the near-infrared, in no case has the entirety of any giant molecular cloud been mapped. Thus the fraction of stars observed to have formed in and out of clusters and aggregates is still uncertain. Significant progress on characterising the cluster forming properties of different regions is likely to come from analysis of data on star-forming regions contained in the near-infrared all-sky surveys (2MASS,DENIS).

Although it is not clear why the fraction of star formation taking place in dense clusters should vary from cloud to cloud, all of the regions surveyed thus far seem to support a basic picture in which *the majority of star formation at all masses takes place in clusters*.

A similar picture in which clustering is a common, but not ubiquitous, accompaniment to star formation emerges from the biased surveys of localized regions associated with some indicator of very recent star formation. In L1641, 25% of the young IRAS sources surveyed by Chen and Tokunaga (1994) were found to have near-infrared clusters. From the same survey, 63% of the outflow regions contain clusters while in a broader survey Hodapp (1994) found 33% of molecular outflow sources to have clusters. Of 44 bright-rimmed clouds (regions thought to be examples of triggered star formation) containing IRAS sources surveyed by Sugitani et al.(1995) "most" are claimed to harbor small clusters. On the other hand, Carballo and Sahu (1994) found no evidence for clustering around the IRAS sources in their survey and a similar null result was obtained from deep imaging of Bok globules (Yun and Clemens 1994).

An even higher incidence of clustering appears in the surveys of regions containing massive stars. For example, the unbiased surveys of Orion B reveal that clusters are associated only with the bright stars exciting the conspicuous nebulae in the region; stated in reverse, each of the high-mass stars in Orion B is accompanied by a cluster. A similar connection is suggested from the biased surveys. The highest incidence of clustering (19/20 cases) occurred in the survey of outer Galaxy IRAS sources radio-selected to contain OB stars (Carpenter et al. 1993). Similarly, the near-infrared surveys of Herbig Ae/Be stars by Hillenbrand (1995) and Testi et al. (1997, 1998) (see also Aspin and Barsony 1994; Wilking et al. 1997), indicate that clusters are present around those Ae/Be stars with masses in excess of $3-5M_{\odot}$, with little evidence of clustering around less massive objects (see also Chapter by Stahler et al.).

One possible correlation in the data is that between stellar density and the mass of the most massive cluster member (Hillenbrand 1995; Testi et al. 1999; see Figure 2). Since clusters exhibit a rather small range of projected radii (see Table 1 and also Fig. 1 in Testi et al. 1999) this also translates into a correlation between the cluster membership number N and most massive star. It is at present unclear whether this correlation represents a genuine physical requirement of high density or N for massive star formation (see, e.g., Bonnell, Bate and Zinnecker 1998), or whether it is merely a consequence of random drawing from an IMF, which would imply that a given cluster is more likely to contain a massive star if it has high N. Distinguishing between these two possibilities will require a significant number of small-N clusters to compare with the mass-distributions in large-N clusters.

A strong association is found between the location of clusters and of dense, massive molecular cloud cores. For example, all the clusters in Orion B are associated with CS cores (Lada et al. 1991a), as are those in Orion A (Strom, Strom and Merrill 1993). Moreover, those CS cores in L1630 which are associated with clusters contain a higher fraction of very dense gas ($\gtrsim 10^5$ cm^{-3}) than the clusterless cores (Lada, Evans and Falgarone 1997). Likewise, in the Rosette molecular cloud, the seven embedded clusters discovered by Phelps and Lada (1997) are all associated with moderately massive molecular cores (as traced by ^{13}CO), although the majority of massive cores do not harbour clusters.

These results may suggest that gas density, as opposed to mass, may be the critical factor in promoting cluster formation, although follow-up studies in a density sensitive tracer such as CS or NH_3 are required in the Rosette region to confirm the hypothesis.

Cluster parameters as summarized in Table 1 are not directly comparable between the various regions due to inconsistencies in the analyses. In particular, we emphasize that the values given for the number of stars, and hence the number density, are in all cases likely to be lower limits. To effect a rigorous comparison of the stellar populations emerging from molecular clouds, we ideally need surveys to uniform completeness in mass (to $< 0.1M_{\odot}$) over a known range in age ($\sim$3 Myr) and through some given value of the extinction (10-20 mag, say). However, if one assumes from current databases that cluster sizes are good to a factor of 2 and cluster densities are good to a factor of $3-5$, intercomparisons can be made.

The sizes of young (ages less than a few $\times 10^6$ years) clusters appear fairly uniform (in the range $0.2 - 0.8$ pc FWHM) and, notably, are a factor of $5 - 10$ times smaller than the typical sizes of Galactic open clusters (with ages a few $\times 10^7$ to 10^9 years; Phelps and Janes 1994; Janes, Tilley and Lynga 1988). Several young clusters within a kiloparsec of the Sun are sufficiently populous to rank as candidate proto-open clusters, although it is uncertain that they will remain bound once their component gas is removed (see Section V). Note that we exclude OB associations from Table 1 and stress that these are considerably bigger (a few tens of pc). Cluster densities have a spread which is larger than the errors, and span a few $\times 10^2$ to a few $\times 10^4$ stars pc^{-3}, the latter value corresponding to the core of the ONC. Such densities correspond to volume averaged values in the range several 10^3 to several 10^5 molecules cm $^{-3}$, consistent with the strong correlation between clusters and concentrations of *dense* molecular gas.

Finally, we turn from a description of the gross parameters of young clusters to a brief mention of recent attempts to characterise their stellar content in detail. This exercise involves combined spectroscopy and photometry in order that stars can be individually de-reddened and placed in theoretical HR diagrams where their location can in principle (i.e. given well determined theoretical tracks) be used to determine stellar masses and ages (cf. Hillenbrand 1997; Herbig 1998; Strom et al. 1999). Recently, this traditionally optical technique has been successfully applied in the near-infrared to study deeply embedded populations – those obscured by 10-50 magnitudes of interstellar and circumstellar extinction (cf. Hodapp and Deane 1993; Greene and Meyer 1995; Carpenter et al.1997; Hanson et al.1997; Luhman and Rieke 1998; Meyer et al.1999). The observationally intensive nature of this exercise means that few clusters have been studied in detail as yet. Clearly, the information yielded on the mass distribution (cf. Meyer et al. 1998, this volume) and age spread of stars in clusters can be expected to have a major impact on cluster formation theories in the next few years. It is notable, for instance, that the relatively old cluster IC 348 appears to show evidence for ongoing star formation over a considerable period (up to 10 Myr; Lada and Lada 1995; Preibisch, Herbig and Zinnecker 1997; Herbig 1998) whereas a high fraction of mass in the ONC would seem to have been converted into stars in less than a million years (Hillenbrand 1997).

III Clusters within clusters?

Images of young clusters often contain substructure that is readily identifiable by eye. Examples occur on a wide range of size scales: at one extreme, the 'Super Star Clusters' (SSCs) observed in interacting galaxies such as the Antennae (Whitmore et al. 1998) comprise ensembles of tens to hundreds of clusters within a couple of hundred pc, while the SSCs themselves appear to be clustered in groups of a few. Nearby star forming regions also contain a wealth of sub-structure (see, for example, Gomez et al. 1993; and Chapter by Elmegreen et al., this volume).

The issue of sub-clustering of stars at birth is a fundamental one because it defines the local potential in which stars form and determines whether or not interactions between adjacent protostars (and associated gas/discs) play an important role in the star formation process. Compact clusters with few members are however short-lived against dynamical dissolution (see Section IV), so that by the age at which clusters are observed in a relatively unobscured state (generally a million years or so) much of the original sub-structure may have been erased, although traces may remain in positional and velocity data. The link between the structure of observed clusters and the structure that they had at birth therefore needs to be mapped out via numerical simulations (see, for example, Goodwin 1997 in the context of the LMC globular clusters).

Apart from these questions of how observed structure relates to structure at birth (which can be addressed by simulations) there is the equally important issue of how the statistical significance of apparent substructure is to be assessed - the eye is notoriously adept at picking out apparent groupings in randomly generated distributions of points. A commonly used statistic is the mean surface density of companions (henceforth the MSDC), first applied to a star forming region (in this case Taurus) by Larson (1995) and subsequently to a number of other star forming regions (Simon 1997; Bate, Clarke and McCaughrean 1998; Nakajima et al. 1998; Gladwin et al. 1999), although incompleteness in some cases limits the utility of this approach. The MSDC is related to the two point correlation function (Peebles 1980) but has the advantage that it is not sensitive to the choice of average density in the surveyed region. It is simply computed, as a function of angular separation, by averaging the surface density of stars in annuli of appropriate radius placed in turn on each of the stars in the sample.

In Taurus, the MSDC can be fitted as a power law (of slope -0.6) for stellar separations in excess of around 0.04 pc (Larson 1995). A uniform stellar distribution gives rise to a flat MSDC (equal surface densities on all scales), so this result is immediate evidence for an inhomogeneous stellar distribution. A power law MSDC over a large dynamic range is moreover evidence for fractal clustering, an interpretation favoured by Larson, although the observed MSDC over the limited dynamic range available in Taurus is also consistent with clustering on a single scale (Bate, Clarke and McCaughrean 1998). The conclusion that Taurus is indeed highly inhomogeneous is readily confirmed by visual inspection of the stellar distribution, which clearly shows the existence of discrete groupings containing around 15 stars in regions of typical size $0.5-1.1$ pc (Herbig 1977; Gomez et al. 1993). Given the velocity dispersion measured in Taurus (e.g. Hartmann et al.1986; Frink et al. 1997), these groups are not bound; this velocity dispersion is however consistent with these groups having expanded from very compact configurations over their assumed lifetimes. Thus the existence of the Gomez groups is consistent with (but does not prove) an origin of stars in compact mini-clusters.

Interpretation of the MSDC in clusters, as opposed to the more diffuse and irregular environment of Taurus, is complicated by the global decline of surface density with radius in this case. It turns out, however, that if the surface density declines with distance from the cluster centre as R^{-1} or less steeply, then for clusters with no substructure, the MSDC should still be approximately flat apart from possible edge effects (Bate, Clarke and McCaughrean 1998). This convenient property means that in the ONC, for example, where the surface density declines with radius approximately as R^{-1} outside the core, the flatness or otherwise of the MSDC can still be used as a diagnostic of clustering.

The result for the ONC is that notwithstanding the fact that the eye can arguably pick out apparent stellar groupings, the MSDC is essentially flat: i.e. the stellar distribution is statistically consistent with a smoothly declining density law with no sub-clustering. This is not to say, however, that sub-clustering is necessarily absent. Through generation of synthetic clusters, Bate, Clarke and McCaughrean showed that over a limited region of parameter space (i.e. for mini-clusters of a few times 10^4 A.U. in size), it was possible to hide a substantial fraction of the stars in mini-clusters and yet produce an MSDC consistent with that observed. The range of size scales that can be hidden in this way shrinks with the membership number of the cluster, so that unless the cluster sizes are very finely tuned, the number of stars contained in each needs to be quite small (a few tens at most).

In summary then, there is no evidence for sub-clustering within the ONC, although there are patterns of sub-clustering that would not be ruled out by the observed MSDC. (Note, however, that the *massive* stars do appear to be clustered in the central regions: see Section VI). Rough estimates suggest that this lack of sub-clustering may not necessarily rule out sub-clustering at birth: although Orion is generally believed to be younger than Taurus (Kenyon and Hartmann 1995), the higher stellar surface density means that sub-clusters would merge and lose their identity more rapidly during the dissolution process. Further modeling, using all the available kinematic and spatial data for the cluster is required in order to rule out the possibility that the ONC was composed of an ensemble of sub-clusters at birth.

IV Dynamical interactions in compact clusters

Mini-clusters comprising N members dissolve due to point mass gravitational interactions on a timescale that is a strong positive function of of N (van Albada 1968; Heggie 1974). Thus point mass gravitational effects are the main agent of dissolution for small N systems, where a central binary can interact and eject the majority of stars, whereas gas expulsion may predominate in larger N systems (see Section V). Compact, small N clusters, therefore, are short-lived even if gas expulsion is neglected: for example, a cluster of 10 stars in a volume of radius 0.1 pc dissolves in less than a million years. This fact underlines the difficulty of assessing the level of sub-clustering at birth in star forming regions, inasmuch as information on the smallest scales is rapidly erased, sometimes before the cluster becomes optically visible.

Cluster dissolution by point mass dynamics results from the formation of a central binary which absorbs the potential energy of the cluster, thereby unbinding the other members. There is an overwhelming tendency for the two most massive stars to constitute the binary (van Albada 1968). Thus *if* binaries form from small N, non-hierarchical ensembles, their pairing statistics are well defined (McDonald and Clarke 1993): the binary fraction is a strongly increasing function of primary mass, and, unless the membership number of the mini-cluster is very small (3 or so), there is a strong tendency for stars to pair with companions of almost equal mass. McDonald and Clarke showed that a hallmark of binaries formed dynamically in such small clusters is that the mass distribution of secondaries does not depend on the primary's mass. This property can be tested for in binary samples with primaries of various masses. It is clear, however, (from the fact that most solar type stars are binary primaries, whereas most OB binaries have high mass secondaries) that this process cannot simultaneously account for both low and high mass binary statistics, unless the IMF is spatially variable.

In reality, of course, one would not expect interactions in such mini-clusters to result purely from point mass gravity. For few body clusters, the expected radii of circumstellar discs are a significant fraction of the mean interstellar separation (Pringle 1989; Clarke and Pringle 1991) so that hydrodynamic encounters with disc gas are to be expected at closest approach (Larson 1990; Heller 1993; Hall, Clarke and Pringle 1996). Whereas the higher velocity dispersion in large N clusters renders most such encounters disc destroying (rather than binary producing; Clarke and Pringle 1991), the relatively slow encounters within small N mini-clusters can lead to a substantial binary fraction through star-disc capture (McDonald and Clarke 1995). If star-disc capture is the dominant binary production route, the dependence of binary fraction on primary mass is somewhat reduced, whilst the companion mass distribution reflects almost random pairing from the IMF.

In addition to the possible production of binaries, close encounters in mini-clusters can have two further effects. The first is the destructive effect of star-disc encounters. It has been argued for example (Mottmann 1977), that the Sun may have originated in a cluster, so that episodes of intense meteoritic bombardment, as evidenced by the cratering record of the terrestrial planets, would have followed perturbations to the Oort cloud by stellar encounters. Simulations of star-disc encounters indicate that discs are truncated at about one third of the stars' closest approach (Clarke and Pringle 1993), the pruned remnant being left with an exponential radial density profile (Hall 1997) similar to those observed in the 'silhouette discs' in Orion (McCaughrean and O'Dell 1996). Such pruning would not only reduce the strength of disc emission (by reducing the mass and surface area of the disc), but would also shorten the disc lifetime (mainly due to the reduction in the disc's radial extent). It has been noted (e.g. Bouvier, Forestini and Allain 1997; Armitage 1996) that a wide range of disc lifetimes are necessary both to explain the co-existence of Classical and Weak Line T Tauri stars in the same region of the HR diagram and to explain the spread in rotation rates of stars on the ZAMS.

The velocities acquired by stars during the dissolution of small clusters is of order the velocity at pericentre during a three-body encounter. Thus whilst the majority of stars drift apart with a velocity that exceeds the cluster escape velocity by a factor of order unity, stars can be ejected from particularly close encounters with considerably larger velocities. Sterzik and Durisen (1995) have applied this model to the production of the dispersed population of Xray sources detected by ROSAT in the vicinity of star forming regions (Alcala et al. 1996; Neuhauser 1997), arguing that these sources are Weak Line T Tauri stars that were formed in the smaller volume currently occupied by the emission line (Classical T Tauri) stars, but were ejected by dynamical encounters in small clusters (see Feigelson 1996 for an alternative view). The combination of the apparent distance of these stars from their putative birthplaces and their ages derived from the HR diagram implies ejection velocities greater than $\sim$ 3km/s, which requires mini-clusters comprising a few (i.e. $5-10$) stars within a radius of $500-1000$ AU. The close encounters (pericentre of about 0.5 A.U.) that are required to generate such velocities shave the discs to such small radii that the disc depletion timescale is considerably reduced. In the case of discs that are magnetically disrupted in their innermost regions, such tidal pruning in close encounters can lead to the system appearing as a Weak Line T Tauri star even at the young age ($\sim 10^6$ years) inferred for the dispersed population of Xray sources (Armitage and Clarke 1997). It should be noted, however, that many of the dispersed Xray sources may be somewhat older foreground stars - see discussion by Briceno et al. 1997; and Wichmann et al. 1997 - and that proper motion data supports the ejection hypothesis only in some cases (Neuhauser et al. 1998; Frink et al. 1997). Clearly the controversial question of what proportion of the ROSAT sources are indeed runaway T Tauri stars needs to be settled before one can assess the required ejection rates of T Tauri stars from star forming regions and hence the number of compact mini-clusters that are needed to generate this ejection rate.

In summary, then, a number of physical processes occurring in very compact mini-clusters can profoundly affect the properties of the stars and their associated discs. These physical processes rely on small interstellar separations and relatively low velocity dispersions and their role is thus negligible if estimated using the densities and velocity dispersions of large scale star forming regions (such as, for example, the Orion Nebula Cluster or the central regions of Taurus). If the stars in these regions were not considerably sub-clustered at birth, then close encounters would have played an insignificant role and stars would have evolved essentially independently. On the other hand, if stars were tightly clustered at birth, then it may provide solutions to a number of problems (e.g. that of binary formation, of the apparently large dispersion in disc lifetimes or of the generation of runaway T Tauri stars).

V The role of gas in clusters

As discussed in Section II, young stellar clusters are commonly associated with massive cores of molecular gas (e.g. Lada 1992; Lada, Evans and Falgarone 1997). This gas comprises the majority of the cluster mass in the youngest systems (typically 50 to 90 % of their total mass, Lada 1991), but appears to be absent in older systems (eg IC 348 at $\approx 5 \times 10^6$ years, Lada and Lada 1995).

In addition to being a major contributor to the gravitational potential – and hence, by its removal, providing an obvious way to unbind the cluster – the gas can also interact with and be accreted by the stars. As pointed out by several authors (e.g. Zinnecker 1982; Larson 1992), accretion in a clustered environment may play an important role in shaping the observed spectrum, and segregation, of stellar masses. Bonnell et al. (1997) used SPH/accretion particle simulations to study the evolution of clusters initially comprising a few (point mass) stars plus a distributed gas component. The stars excite gravitational wakes in the surrounding gas (cf. Gorti and Bhatt 1996) and gain mass by accretion (in these calculations no gas expulsion is included, so all the gas ultimately ends up on the stars).

The competitive accretion of gas by the various stars leads to an IMF in which the dynamic range of final stellar masses is large, even when the masses of the initial protostellar seeds are all set to the same value. The chief determinant of ultimate stellar mass is in this case the initial position of the protostellar seed in the cluster potential: seeds initially deep in the potential well acquire accreted mass rapidly from the start, and then become hard to nudge from their central position owing to their large masses. Seeds initially at large radii, conversely, accrete mass slowly; being low mass objects, they are more likely to be flung out of the cluster due to interactions with more massive stars, and thus stop accreting altogether. Thus the interplay of hydrodynamic accretion and point mass gravitational interactions is such as to enhance the initial 'advantage' of seeds located near the cluster core, and generates a large dynamic range of stellar masses from arbitrary initial conditions. It is notable in the context of the mass segregation observed in clusters (see Section VI), that competitive accretion provides a natural way of producing the most massive stars in the cluster core, and requires no gradients in the initial conditions.

It has also been argued (Bonnell, Bate and Zinnecker 1998) that massive stars *must* form in the centre of dense clusters. These authors consider systems that become extremely dense (up to 10^8 pc^{-3}) as they shrink due to the effects of continuing accretion of gas. In such high density environments, massive stars can form via collisional build up of protostellar fragments. An episode of vigorous mass loss is then invoked to clear the cluster of gas and cause it to re-expand (since these effects occur on timescales of $\approx 10^4$ years, these clusters are unlikely to be directly observable in their high density phase). The formation of massive stars through collisions is an attractive scenario inasmuch as it avoids the classic problem of forming them by accretion (namely that for stars more massive than around $10 M_\odot$, accretion is halted by the action of radiation pressure on dust grains).

In reality, however, gas is lost from clusters in a variety of ways. Massive stars ($\gtrsim 8 M_\odot$) eject gas by the action of supernovae, photoionisation and stellar winds (Whitworth 1979; Tenorio-Tagle et al. 1986;

Franco, Shore and Tenorio-Tagle 1994). It is also becoming increasingly apparent that low mass stars can provide effective feedback of energy into the surrounding medium through the action of energetic molecular outflows (Eisloeffel et al., this volume). (Note that whereas it is difficult to sustain the case that an *isolated* star can cut off its own accretion supply through the action of outflows – because the outflows are somewhat collimated, whereas accretion occurs over a large solid angle, and preferentially equatorially at small radii – it is obviously the case that a set of randomly orientated outflow sources in a small cluster can inflict significant damage on the residual gas).

The fate of a particular cluster in response to gas loss depends on the initial gas fraction, the removal timescale and the stellar velocity dispersion when the gas is dispersed (Lada, Margulis and Dearborne 1984; Pinto 1987; Verschueren and David 1989; Goodwin 1997b; see also Chapter by Elmegreen et al., this volume). If the gas comprises a significant fraction of the total mass ($\gtrsim$50%) and is removed quickly compared to the cluster crossing time, 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 % can survive with approximately half of the stars if the gas removal occurs over 4 or more crossing times (Lada et al. 1984).

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, the frequency of cluster-mode star formation (see Section II) and the properties of Galactic field binaries (Kroupa 1995) indicate that most stars may form in clusters. The implication is that the life-time of most young clusters is short $\lesssim 10^7$ yr (Battinelli and Capuzzo-Dolcetta 1991), which is a natural consequence of rapid gas expulsion and low local star formation efficiency.

VI. The initial mass distributions and shapes of clusters

A. Mass Segregation

A common observational finding in clusters is that the most massive stars tend to be concentrated in the central core (e.g. Mon R2: Carpenter et al. 1997; ONC: Hillenbrand and Hartmann 1998; NGC 6231: Raboud and Mermilliod 1998; NGC 2157 in the LMC: Fischer et al. 1998; SL666 and NGC 2098 in the LMC: Kontizas et al. 1998). This mass segregation is present even in the youngest clusters, suggesting that it represents the initial conditions of the cluster and is not due to its subsequent evolution. Order of magnitude arguments support this view: the timescale for mass segregation from two-body interactions (which drive the stellar kinetic energies towards equipartition and thus allow the massive stars to sink to the centre) is approximately the relaxation time (Binney and Tremaine 1987; Bonnell and Davies 1998), which is typically very long (many crossing times) compared to the age of the cluster. However, the segregation timescale is inversely proportional to the stellar mass so that the most massive stars will segregate significantly faster than this. It is not therefore clear *a priori* whether the presence of massive subsystems in the cores of clusters (such as the 'Trapezium' of OB stars in the ONC) is attributable to dynamical effects or segregation at birth.

Bonnell and Davies (1998) investigated this issue through N-body simulations of stellar clusters, exploring the timescale for massive stars to sink to the cluster centre as a function of their initial location. Comparing these results with recent observations of the ONC (Hillenbrand 1997; Hillenbrand and Hartmann 1998) shows that the location of the massive stars (and, in particular, the existence of the Trapezium) *cannot* be accounted for by dynamical mass segregation but must reflect the initial conditions. The clearest indication of this result comes from repeated simulations based on different random realisations of the initial conditions. It was found that Trapezium-like systems were generated with significant frequency *only* if the massive stars were initially rather centrally condensed (i.e. within the innermost 10 % of the stars for a 70% probability of Trapezium formation, or within 20 % for a 10% probability. (Note that these simulations did not include gas; it is possible in principle for the observed ONC to have expanded due to previous gas loss, in which case the shorter dynamical timescales in its initially denser configuration may have permitted more effective mass segregation).

As initially discussed by Zinnecker et al. (1993; see also Bonnell et al. 1998), simple Jeans type arguments do not lead to the expectation that the most massive stars should form in the centre of dense clusters. Since these regions have high densities, the associated Jeans mass is *low*, unless the local temperature is anomalously high. Evolutionary effects, involving accretion and protostellar collisions, are probably required to build up massive stars in cluster cores (see Section V).

B. Cluster morphology

Simulations of cluster dynamics are often undertaken in spherical geometry, motivated in part by the shapes of globular clusters in the Galaxy. It is however well known that some clusters are significantly flattened, the best studied examples being the globular clusters in the LMC. Since some of these systems are both young (with ages, at less than 20 Myr, of order 10 crossing times) and significantly elliptical (projected axis ratio on the sky $\gtrsim 0.7$), it would seem likely that they would have originated from aspherical initial conditions. Analysis of the projected axis ratio distribution in these clusters suggests that their intrinsic shapes are triaxial (Han and Ryden 1994), indicating that velocity anisotropy, rather than rotational flattening, is responsible. Further examples of flattened young clusters are found among the SSCs ('super star clusters') that are conspicuous in images of some interacting galaxies (O'Connell et al. 1994). Here the strongly disturbed gas flows that are to be expected in galactic encounters make cluster formation from cloud-cloud collisions an attractive possibility (Murray and Lin 1992, Kimura and Tosa 1996), so that flattened clusters are a natural expectation in these environments. In the Galaxy, obvious examples of flattened young clusters are the ONC, MonR2, and NGC 2024, where isophotal fitting of the outer regions yields a projected axis ratio of about 2:1 (Hillenbrand and Hartmann 1998, Carpenter et al. 1997, Lada et al.1991).

The interest in examining the shapes of young clusters derives from the clues that these might give as to the mechanism for cluster formation. Indeed, it is hard to think of an external trigger for cluster formation - be it cloud-cloud collisions or the sweeping up of gas by supernova blast waves or powerful stellar winds - that does not induce star formation in sheet/slab-like geometry. At first sight, it might appear most obvious to examine the shapes of the youngest embedded clusters in nearby star forming regions, which are still associated with molecular material (see Table 1). This exercise is however complicated by the problem of patchy extinction, plus the difficulty of isophotal fitting in clusters comprising relatively few stars. Therefore the young globular clusters in the LMC are the best laboratories for studying this problem, since they are relatively populous and devoid of gas.

Clusters in which star formation is externally triggered, e.g. by a shock wave, are however unlikely to form in virial equilibrium, so that even the youngest of the LMC globular clusters would already have undergone a phase of violent relaxation. Numerical simulations are therefore required in order to relate the morphologies of observed clusters to the initial (i.e. pre-violent relaxation) configuration of the star forming gas. This exercise (Boily, Clarke and Murray 1999; see also Aarseth and Binney 1978; Goodwin 1997) yields the answer that apart from the thinnest initial configurations (i.e. sheets of scale height less than the mean interstellar separation, which are subject to two-body scattering on a dynamical timescale) the system retains a strong memory of its initial geometry during the violent relaxation process. The relation between 'initial' and 'final' (i.e. relaxed) morphologies is set by the principle of adiabatic invariance, and yields the prediction that the initial geometry is substantially more flattened than that of the relaxed cluster. When applied to the LMC globulars, initial conditions that are flattened in the ratio of about 1:5 are required.

Although the degree of flattening that is required is quite substantial, it can be generated by gas swept up in shocks of relatively low Mach number. Since the density contrast induced in strong shocks is of order the square of the Mach number, one sees that far flatter configurations (axis ratio of order 10^{-4}) would be produced, for example, by colliding cold, thermally supported *homogeneous* clouds at relative velocities typical of the LMC. In the case of collisions between inhomogeneous clouds, density peaks carry momentum across the net symmetry plane and generate a buckled, and thus effectively, thicker, geometry. The initial morphologies deduced for the LMC globulars may thus be compatible with externally triggered cluster formation in clouds containing substantial pre-existing density structure.

VII. Theoretical considerations

In this Section we we lay out a very idealised conceptual framework for cluster formation and indicate where recent theoretical work can be slotted into this framework.

In order to keep an open mind as to whether cluster formation is primarily a bottom-up or top-down process, we set up a general scenario in which the cluster progenitor gas, mass M_{clus}, consists prior to cluster formation of an ensemble of dense lumps, mass M_J. Since molecular clouds are hierarchically structured, we define the mass scale M_J as being the mass of *thermally* supported lumps that are marginally Jeans stable. Substructure within such lumps is not gravitationally bound, whereas larger scale structures are supported by superthermal random motions. We now suppose that some external trigger over-runs the proto-cluster region, which destabilises lumps of mass M_J. Each lump then collapses to form a member of the eventual cluster (e.g. Klessen et al. 1998). If this destabilisation promotes sub-fragmentation of the lumps, down to a mass scale M_*, then the initial state of the cluster is one of an ensemble of mini-clusters (mass M_J).

Stated in this general manner, one can consider cluster formation as occupying some position on a spectrum of possibilities. The extreme positions are top-down fragmentation (as envisaged, for example, in many models for globular cluster formation, e.g. Fall and Rees 1979; Murray and Lin 1989), in which case $M_J = M_{clus}$, and bottom-up scenarios, in which case $M_J = M_*$. We note that top-down fragmentation engenders structures that are coeval (to within a crossing time), whereas the age spread in bottom-up scenarios depends on the timescale on which discrete lumps are destabilised, and is affected, for example, by the speed with which an external trigger over-runs the region.

Before proceeding further, we here introduce some numbers that will motivate the following discussion. Hierarchical structures in molecular clouds obey a mass-radius ('Larson') relation of the form $M \propto R^2$, which corresponds to a hierarchy of self-gravitating structures that share the same kinetic pressure. As one descends such a hierarchy, structures of increasing density are characterised by a decreasing velocity dispersion, until eventually the scale is reached at which this velocity dispersion becomes subthermal. This scale represents the minimum mass of a self-gravitating structure within a cloud of given kinetic pressure (or, equivalently, M/R^2 for the parent GMC) and temperature, and is thus equal to M_J in the above nomenclature. Employing canonical values for the temperature and mass-radius relation in GMCs (respectively $T = 10K$ and $(M/1M_\odot) \sim (R/0.1pc)^2$; Chieze 1987) one finds that M_J is of order of a solar mass.

Thermally supported, self-gravitating clumps of around solar mass are indeed observed, in nearby star forming clouds such as Taurus, as the dense cores traced by NH_3 (Benson and Myers 1989). The low masses of these cores implies that one would expect top-down fragmentation to be operative only in the generation of mini-clusters - i.e. those comprising a small number of stars. More populous clusters must result from a bottom-up process, i.e. the coordinated collapse of a number of such units. Cores that are currently forming clusters (such as those in Orion) have superthermal line widths and are thus presumed to be supported by Alfvenic turbulence (Harju, Walmsley and Wouterloot 1993). Myers (1998) has however suggested that these cores should contain pockets of thermally supported gas from which Alfvenic turbulence is excluded, arguing that regions can decouple from the turbulence on size-scales less than the minimum turbulent wavelength (this being set by the requirement that the inverse frequency equals the ion-neutral collision time). We will return below to the issue of how such thermally supported pockets might be destabilised.

If one considers instead the environment in which the Galactic globular clusters would have formed, with kinetic pressures characteristic of the proto-galaxy and temperatures of 10^4K (this marking the steep decline of the cooling function for primordial gas), one obtains a mass scale M_J of around $10^5 - 10^6 M_\odot$ (Fall and Rees 1979). This mass is comparable to that of globular clusters, suggesting that star formation in globular clusters may well have been a top-down process.

The issue of hierarchical fragmentation in the top-down collapse of Jeans unstable gas has however a controversial history (see for example Hoyle 1953; Hunter 1962; Layzer 1963 for early analytical arguments for and against opacity limited fragmentation). Larson (1978) studied the problem numerically using a crude Lagrangian hydrodynamic code and concluded that fragmentation does not proceed down to the opacity limit, but instead reflects the number of Jeans masses in the gas at the initiation of collapse.

The production of clusters by top-down fragmentation thus requires that a clump initially containing one Jeans mass makes a rapid (i.e. less than dynamical timescale) transition, so that it contains a large number of Jeans masses as it enters its collapse. This reduction in Jeans mass may be achieved either via cooling or compression, if the system remains spherically symmetric. Most plausible compression mechanisms however result in the system becoming approximately planar: the 2D Jeans mass then depends only on the temperature and column density, so that the fragmentation of clouds that are swept up in shocks, for example, demands that such shocks cool to *less than* the original temperature (Lubow and Pringle 1993; Whitworth et al. 1994). In the context of globular cluster formation at primordial epochs, it has been suggested (e.g. Palla and Zinnecker 1987; Murray and Lin 1989) that protogalactic shocks activate non-equilibrium cooling (i.e. cooling by molecular hydrogen whose formation is catalysed by a non-equilibrium concentration of electrons in rapidly cooling gas) and that this can effectively cool proto-globular clouds from 10^4 K to 100 K.

In the context of current star forming clouds, no such dramatic cooling is required, since M_J is already in the stellar regime and thus sub-fragmentation, if it occurs, will only involve a small number of pieces. Whitworth and Clarke (1997) considered the response of Jeans stable clumps to the mildly supersonic shocks induced by clump-clump collisions, and concluded that cooling by dust in the dense gas behind the shock imposes close thermal coupling between the gas and dust: whether or not this represents a 'better than isothermal' shock (as required to promote sub-fragmentation) of course depends on the relation between the dust and gas temperature in the unshocked clump, which is uncertain.

Bottom-up cluster formation places less stringent requirements on the interaction between clumps and external trigger (since the trigger only has to destabilise the clumps rather than initiate sub-fragmentation). Whitworth et al. (1998) have shown that the densities and temperatures of thermally supported clumps in molecular clouds place them close to, but somewhat outside, a regime in which dust cooling can dispose of the compressional heating generated by collapse on a free-fall time. It is interesting to note that if the mass-radius relation for molecular clouds was somewhat different, so that thermally supported clumps lay within this regime, then gas would not 'hang up' at this scale but would instead collapse to a star on a free fall time. If, conversely, thermally supported clumps lay far from this regime, then they would be extremely hard to destabilise and the star formation rate would be correspondingly low. The proximity of observed dense cores to the dust cooling regime instead allows a situation where such cores are stable, but may be destabilised by fairly modest perturbations (see, for example, the suggestion of Clarke and Pringle 1997 that cores may be destabilised by external stirring, which widens the bandpass for cooling in optically thick lines). Clearly, a situation where Jeans mass clumps are fairly stable (and hence may accumulate in a given region) but are then fairly easy to destabilise is an optimum one for producing clusters. Considerably more work is required, however, before the feasibility of such ideas can be established.

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Figure Captions

Figure 1. The Mon R2 cluster imaged in the near-infrared H-band (from Carpenter et al. 1997). The field of view is $\sim 3.2 \times 3.2$ arcmin^2 corresponding to $\sim 0.8 \times 0.8$ pc^2 for a distance of 830 pc. The central cluster is completely embedded and contains >300 stars within a 0.4 pc diameter.

Figure 2. Quantification of clustering around Herbig Ae/Be stars. In the left panel, stellar surface density (pc^{-2}) is plotted against mass ($M_\odot$) of the most massive star (from Hillenbrand 1995); random errors of 10% in mass and $\sqrt{N}$ in star counts at K-band are shown, along with a least-squares fit. In the right panel, stellar volume density (pc^{-3}) is plotted against spectral type of the Ae/Be star (from Testi et al. 1998); counting statistics in the I-band source counts are shown. For scaling reference only the innermost region of the Orion Nebula Cluster is plotted in the upper right of panel (a) and the upper left of panel (b). Regions containing more than one Ae/Be star do not occupy any preferred location in these diagrams.

Plate 1. The Mon R2 cluster imaged in the near-infrared (from Carpenter et al. 1997). The field of view is $\sim 9 \times 6$ arcmin^2 corresponding to $\sim 2.2 \times 1.4$ pc^2 for a distance of 830 pc. The bright nebulous stars near the image periphery are part of a larger chain of reflection nebulae. The central cluster is completely embedded and contains >300 stars within a 0.4 pc diameter.