OBSERVATIONS AND THEORY OF STAR CLUSTER FORMATION

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Young stars form on a wide range of scales, producing aggregates and clusters with various degrees of gravitational self-binding. The loose aggregates have a hierarchical structure in both space and time that resembles interstellar turbulence, suggesting that these stars form in only a few turbulent crossing times with positions that map out the previous gas distribution. Dense clusters, on the other hand, are often well mixed, as if self-gravitational motion has erased the initial fine structure. Nevertheless, some of the youngest dense clusters also show sub-clumping, so it may be that all stellar clustering is related to turbulence. Some of the densest clusters may also be triggered. The evidence for mass segregation of the stars inside clusters is reviewed, along with various explanations for this effect. Other aspects of the theory of cluster formation are reviewed as well, including many specific proposals for cluster formation mechanisms. The conditions for the formation of bound clusters are discussed. Critical star formation efficiencies can be as low as 10% if the gas removal process is slow and the stars are born at sub-virial speeds. Environmental conditions, particularly pressure, may affect the fraction and masses of clusters that end up bound. Globular clusters may form like normal open clusters but in conditions that prevailed during the formation of the halo and bulge, or in interacting and starburst galaxies today. Various theories for the formation of globular clusters are summarized.

I. INTRODUCTION

The advent of large array cameras at visible to infrared wavelengths, and the growing capability to conduct deep surveys with semi-automated searching and analysis techniques, have led to a resurgence in the study of stellar clusters and groupings in the disk and halo of our Galaxy, in nearby galaxies, and in distant galaxies. The complementary aspect of the cluster formation problem, namely the structure of molecular clouds and complexes, is also being realized by submm continuum mapping and comprehensive mm surveys. Here we review various theories about the origin of star clusters and the implications of young stellar clustering in general, and we discuss the requirements for gravitational self-binding in open and globular clusters.

Previous reviews of cluster formation were in Wilking & Lada (1985), Larson (1990), Lada (1993), Lada, Strom, & Myers (1993), and Zinnecker, McCaughrean, & Wilking (1993).

II. STRUCTURE OF YOUNG STELLAR GROUPS

Stellar groupings basically come in two types: bound and unbound. Some of the unbound groups could be loose aggregates of stars that formed in the dense cores of weakly bound or unbound cloud structures, such as the Taurus star-forming complex. Other unbound groups could be dispersed remnants of inefficient star formation in strongly self-gravitating clouds or cloud cores.

This section discusses loose aggregates of young stars first, considering hierarchical structure and a size-time correlation, and then more compact groups of stars, i.e. cluster formation in dense cloud cores, along with the associated process of stellar mass segregation, and the effects (or lack of effects) of high stellar densities on disks, binaries, and the stellar initial mass function.

A. Hierarchical Structure in Clouds and Stellar Groups

1. Gas Structure

Interstellar gas is structured into clouds and clumps on a wide range of scales, from sub-stellar masses (10^{-4} M$_\odot$) that are hundredths of a parsec in size, to giant cloud complexes (10^7 M$_\odot$) that are as large as the thickness of a galaxy. This structure is often characterized as consisting of discrete clumps or clouds with a mass spectrum that is approximately a power law, $n(M)dM \propto M^{-\alpha}dM$, with α in the range from ~ 1.5 to ~ 1.9 (for the smaller scales, see Heithausen et al. 1998 and Kramer et al. 1998, with a review in Blitz 1993; for the larger scales, see Solomon et al. 1987, Dickey & Garwood 1989, and the review in Elmegreen 1993).

Geometrical properties of the gas structure can also be measured from power spectra of emission line intensity maps (Stutzki et al. 1998). The power-law nature of the result implies that the emission intensity is self-similar over a wide range of scales. Self-similar structure has also been found on cloud perimeters, where a fractal dimension of $\sim 1.3\pm0.3$

was determined (Beech 1987; Bazell & Désert 1988; Scalo 1990; Dickman, Horvath, & Margulis 1990; Falgarone, Phillips, & Walker 1991; Zimmermann & Stutzki 1992, 1993; Vogelaar & Wakker 1994). This power-law structure includes gas that is both self-gravitating and non-self-gravitating, so the origin is not purely gravitational fragmentation. The most likely source is some combination of turbulence (see review in Falgarone & Phillips 1991), agglomeration with fragmentation (Carlberg & Pudritz 1990; McLaughlin & Pudritz 1996), and self-gravity (de Vega, Sanchez, & Combes 1996).

Interstellar gas is not always fractal. Shells, filaments, and dense cores are not fractal in their overall shapes, they are regular and have characteristic scales. Generally, the structures that form as a result of specific high pressure events, such as stellar or galactic pressures, have an overall shape that is defined by that event, while the structures that are formed as a result of turbulence are hierarchical and fractal.

2. Stellar Clustering

Stellar clustering occurs on a wide range of scales like most gas structures, with a mass distribution function that is about the same as the clump mass distribution function in the gas. For open clusters, it is a power law with α in the range from ~ 1.5 (van den Bergh & Lafontaine 1984; Elson & Fall 1985; Bhatt, Pandey, & Mahra 1991) to ~ 2 (Battinelli et al. 1994; Elmegreen & Efremov 1997), and for OB associations, it is a power law with $\alpha \sim 1.7-2$, as determined from the luminosity distribution function of HII regions in galaxies (Kennicutt, Edgar, & Hodge 1989; Comeron & Torra 1996; Feinstein 1997; Oey & Clarke 1998).

It is important to recognize that the gas and stars are not just clumped, as in the old plumb-pudding model (Clark 1965), but they are *hierarchically* clumped, meaning that small pieces of gas, and small clusters, are usually contained inside larger pieces of gas and larger clusters, through a wide range of scales. Scalo (1985) reviewed these observations for the gas, and Elmegreen & Efremov (1998) reviewed the corresponding observations for the stars. Figure 1 shows a section of the Large Magellanic Cloud southwest of 30 Dor. Stellar clusterings are present on many scales, and many of the large clusters contain smaller clusters inside of them, down to the limit of resolution.

Stellar clumping on a kiloparsec scale was first studied by Efremov (1978), who identified "complexes" of Cepheid variables, supergiants, and open clusters. Such complexes trace out the recent $\sim 30-50$ million years of star formation in the largest cloud structures, which are the HI "superclouds" (Elmegreen & Elmegreen 1983, 1987; Elmegreen 1995b) and "giant molecular associations" (Rand & Kulkarni 1990) that are commonly found in spiral arms. The sizes of star complexes and the sizes of superclouds or GMA's are about the same in each galaxy, increasing regularly with galaxy size from ~ 300 pc or less in small galaxies like the LMC to ~ 600 pc or more in large galaxies like the Milky Way (Elmegreen et al. 1996). Each star complex typically contains several OB associations in addition to the Cepheids, because star formation continues in each supercloud, first in one center and then in another, for the whole $\sim 30-50$ My. This overall timescale is smaller in smaller galaxies because the complexes are smaller, as Battinelli & Efremov (1999) confirmed for the LMC.

Star complexes are well studied in the Milky Way and local galaxies (see reviews in Efremov 1989, 1995). In our Galaxy, they were examined most recently by Berdnikov & Efremov (1989, 1993), and Efremov & Sitnik (1988). The latter showed that *90% of the young (~ 10 My) clusters and associations in the Milky Way are united into the same star complexes that are traced by Cepheids and supergiants.* A similarly high fraction of hierarchical clustering has been found in M31 (Efremov, Ivanov, & Nikolov 1987; Battinelli 1991, 1992; Magnier et al. 1993; Battinelli, Efremov & Magnier 1996), M33 (Ivanov 1992), the LMC (Feitzinger & Braunsfurth 1984), and many other galaxies (Feitzinger & Galinski 1987).

A map showing two levels in the hierarchy of stellar structures along the southwest portion of the western spiral arm in M31 is shown in figure 2 (from Battinelli, Efremov & Magnier 1996). The smaller groups, which are Orion-type OB associations, are shown with faint outlines displaced $0.1°$ to the south of the larger groups for clarity; the smaller groups are also shown as dots with their proper positions inside the larger groups. Evidently *most of the OB associations are within the larger groups.*

The oldest star complexes are sheared by differential galactic rotation, and appear as flocculent spiral arms if there are no strong density waves (Elmegreen & Efremov 1996). When there are density waves, the complexes form in the arm crests, somewhat equally spaced, as a result of gravitational instabilities (Elmegreen & Elmegreen 1983; Elmegreen 1994; Rand 1995; Efremov 1998).

3. Hierarchical Clustering of Stars on Smaller Scales

Hierarchical clustering of stars continues from star complexes to OB associations, down to very small scales. Infrared observations reveal embedded clusters of various sizes and densities in star-forming regions. Many of these, as discussed in the next section, are extremely dense and deeply embedded in self-gravitating molecular cores. Others are more open and clumpy, as if they were simply following the hierarchical gas distribution around them. A good example of the latter is in the Lynds 1641 cloud in the Orion association, which has several aggregates comprised of $10-50$ young stars, plus a dispersed population throughout the cloud (Strom, Strom & Merrill 1993; Hodapp & Deane

1993; Chen & Tokunaga 1994; Allen 1995).

The distribution of young, x-ray active stars around the sky (Guillout et al. 1998) is also irregular and clumpy on a range of scales. The low-mass young stars seen in these x-ray surveys are no longer confined to dense cores. Sterzik et al. (1995), Feigelson (1996), Covino et al. (1997), Neuhäuser (1997), and Frink et al. (1997, 1998) found that the low mass membership in small star-forming regions extends far beyond the previously accepted boundaries. This is consistent with the hierarchical clustering model.

4. Two Examples of Hierarchical Stellar Structure: Orion and W3

There are many observations of individual clusters that are part of a hierarchy on larger scales. The Orion region overall contains at least 5 levels of hierarchical structure. On the largest scale (first level), there is the so-called local arm, or the Orion-Cygnus spur, which has only young stars (Efremov 1997) and is therefore a sheared star formation feature, not a spiral density wave (Elmegreen & Efremov 1996; compare to the Sgr-Car arm, which also has old stars – Efremov 1997). The largest local condensation (second level) in the Orion-Cygnus spur is Gould's Belt, of which Orion OB1 is one of several similar condensations (third level; Pöppel 1997). Inside Orion OB1 are four subgroups (fourth level; Blaauw 1964), and the youngest of them, including the Trapezium cluster, contains substructure too (fifth level): one region is the BN/KL region, perhaps triggered by theta-1c, and another is near OMC-1S (Zinnecker, McCaughrean, & Wilking 1993). The main Trapezium cluster may have no substructure, though (Bate, Clarke, & McCaughrean 1998).

A similar hierarchy with five levels surrounds W3. On the largest scale is the Perseus spiral arm (first level), which contains several giant star formation regions separated by 1–2 kpc; the W3 complex is in one of them, and the NGC 7538 complex is in another. The kpc-scale condensation surrounding W3 (second level) contains associations Cas OB6 and Per OB1 (which is below the galactic plane and includes the double cluster h and χ Per), and these two associations form a stellar complex. The association Cas OB8, which includes a compact group of five clusters (Efremov 1989, Fig. 16 and Table 7 on p. 77) may also be a member of this complex, as suggested by the distances and radial velocities. Cas OB6 is the third level for W3. Cas OB6 consists of the two main star-forming regions W4 (fourth level) and W5, and W4 has three condensations at the edge of the expanded HII region, in the associated molecular cloud (Lada et al. 1978). W3 is one of these three condensations, and therefore represents the fifth level in the hierarchy. The hierarchy may continue further too, since W3 contains two apparently separate sites of star formation, W3A and W3B

(Wynn-Williams, Becklin, & Neugebauer 1972; Normandeau, Taylor, & Dewdney 1997).

Most young, embedded clusters resemble Orion and W3 in this respect. They have some level of current star formation activity, with an age possibly less than 10^5 years, and are also part of an older OB association or other extended star formation up to galactic scales, with other clusters forming in the dense parts here and there for a relatively long time.

5. Cluster Pairs and other Small Scale Structure

Another way this hierarchy appears is in *cluster pairs*. Many clusters in both the Large Magellanic Cloud (Bhatia & Hatzidimitriou 1988; Kontizas et al. 1989; Dieball & Grebel 1998; Vallenari et al. 1998) and Small Magellanic Cloud (Hatzidimitriou & Bhatia 1990) occur in distinct pairs with about the same age. Most of these binary clusters are inside larger groups of clusters and stellar complexes. However, the clumps of clusters and the clumps of Cepheids in the LMC do not usually coincide (Efremov, 1989, p. 205; Battinelli & Efremov, 1999).

Some *embedded* clusters also have more structure *inside* of them. For example, star formation in the cloud G 35.20-1.74 has occurred in several different and independent episodes (Persi et al. 1997), and there is also evidence for non-coeval star formation in NGC 3603, the most massive visible young cluster in the Galaxy (Eisenhauer et al. 1998). W33 contains three separate centers or sub-clusters of star formation *inside* of it that have not yet merged into a single cluster (Beck et al. 1998). The same is true in 30 Dor and the associated cluster NGC 2070 (Seleznev 1995), which appears to have triggered a second generation of star formation in the adjacent molecular clouds (Hyland et al. 1992; Walborn & Blades 1997; Rubio et al. 1998; Walborn et al. 1999). Similarly, NGC 3603 has substructure with an age difference of ~ 10 My, presumably from triggering too (Brandner et al. 1997). Lada & Lada (1995) found eight small subclusters with 10 to 20 stars each in the outer parts of IC 348. Piche (1993) found two levels of hierarchical structure in NGC 2264: two main clusters with two subclusters in one and three in the other. The old stellar cluster M67 still apparently contains clumpy outer structure (Chupina & Vereshchagin 1998). Some subclusters can even have slightly different ages: Strobel (1992) found age substructure in 14 young clusters, and Elson (1991) found spatial substructure in 18 rich clusters in the LMC.

Evidence that subclustering did not occur in dense globular clusters was recently given by Goodwin (1998), who noted from numerical simulations that initial substructure in globular clusters would not be completely erased during the short lifetimes of some of the youngest in the LMC. Because these young populous clusters appear very smooth, their initial conditions had to be somewhat smooth and spherical too.

The similarity between the loose clustering properties of many young stellar regions and the clumpy structure of weakly self-gravitating gas appears to be the result of *star formation following the gas in hierarchical clouds that are organized by supersonic turbulence.* Turbulence also implies motion and, therefore, a size-dependent crossing time for the gas. We shall see in the next section that this size-dependent timescale might also apply to the duration of star formation in a region.

B. Star Formation Time Scales

The duration of star formation tends to vary with the size S of the region as something like the crossing time for turbulent motions, i.e., increasing about as $S^{0.5}$. This means that star formation in larger structures takes longer than star formation in sub-regions. A schematic diagram of this time-size pattern is shown in figure 3. The largest scale is taken to be that of a flocculent spiral arm, which is typically ~ 100 My old, as determined from the pitch angle (Efremov & Elmegreen 1998).

This relationship between the duration of star formation and the region size implies that clusters forming together in small regions will usually have about the same age, within perhaps a factor of three of the turbulent crossing time of the small scale, while clusters forming together in larger regions will have a wider range of ages, proportional to the crossing time on the larger scale. Figure 4 shows this relationship for 590 clusters in the LMC (Efremov & Elmegreen 1998). Plotted on the ordinate is the average difference in age between all pairs of clusters whose deprojected spatial separations equal the values on the abscissa. The average age difference between clusters increases with their spatial separation. In the figure, the correlation ranges between $0.02°$ and $1°$ in the LMC, which corresponds to a spatial scale of 15 to 780 pc. The correlation disappears above $1°$, perhaps because the largest scale for star formation equals the Jeans length or the disk thickness. A similar duration-size relation is also observed within the clumps of clusters in the LMC. Larger clumps of clusters have larger age dispersions (Battinelli & Efremov 1999).

The correlations between cluster birth times and spatial scale are reminiscent of the correlation between internal crossing time and size in molecular clouds. The crossing time in a molecular cloud or cloud clump is about the ratio of the radius (half-width at half-maximum size) to the Gaussian velocity dispersion. The data for several molecular cloud surveys are shown in figure 5, with different symbols for each survey. On the top is a plot of the Gaussian linewidth versus size, and on the bottom is the crossing time versus size. Smaller clouds and clumps have smaller crossing times, approximately in proportion to size $S^{0.5}$. Overlayed on this plot, as large crosses, are the age-difference versus separation points for LMC clusters, from figure 4. Evidently, the cluster correlation fits in nicely at the top part of the molecular cloud crossing time-size relation.

These correlations underscore our perception that *both cloud structure, and at least some stellar clusterings, come from interstellar gas turbulence.* The cluster age differences also suggest that *star formation is mostly finished in a cloud within only ~ 2 to 3 turbulent crossing times,* which is very fast. In fact, this time is much faster than the magnetic diffusion time through the bulk of the cloud, which is ~ 10 crossing times in a uniform medium with cosmic ray ionization (Shu et al. 1987), and even longer if uv light can get in (Myers & Khersonsky 1995), and if the clouds are clumpy (Elmegreen & Combes 1992). Thus *magnetic diffusion does not regulate the formation of stellar groups*, it may regulate only the formation of individual stars, which occurs on much smaller scales (Shu et al. 1987; but see Nakano 1998).

Star formation in a cluster may begin when the turbulent energy of the cloud dissipates. This is apparently a rapid process, as indicated by recent numerical simulations of supersonic MHD turbulence, which show a dissipation time of only 1–2 internal crossing times (MacLow et al. 1998; Stone, Ostriker, & Gammie 1998). Most giant molecular clouds have similar turbulent and magnetic energies (Myers & Goodman 1988) and they would be unstable without the turbulent energy (McKee et al. 1993), so the rapid dissipation of turbulence should lead to a similarly rapid onset of star formation (e.g., McLaughlin & Pudritz 1996). The turbulence has to be replenished for the cloud to last more than several crossing times.

The observed age-size correlation is significantly different from what one might expect from simple crossing-time arguments in the absence of turbulence. If the velocity dispersion is independent of scale, as for an isothermal fluid without correlated turbulent motions, then the slope of the age-size correlation would be 1.0, not ~ 0.35. The correlation is also not from stochastic self-propagating star formation, which would imply a diffusion process for the size of a star formation patch, giving a spatial scale that increases as the square root of time. In that case the slope on figure 4 would be 2.

The duration-size relation for stellar groupings implies that OB associations and 10^5 $M_\odot$ GMC's are not physically significant scales for star formation, but just regions that are large enough to have statistically sampled the high mass end of the IMF, and young enough to have these OB stars still present. Regions with such an age tend to have a certain size, ~ 100 pc, from the size-time relation, but the cloud and star formation processes need not be physically distinct.

The time-scale versus size correlations for star formation should not have the same coefficients in front of the power laws for all regions of all galaxies. This coefficient should scale with the total turbulent ISM pressure to the inverse 1/4 power (from the relations $P \sim GM^2/R^4$

and $\Delta v^2 \sim GM/(5R)$ for self-gravitating gas; Chièze 1987; Elmegreen 1989). Thus regions with pressures higher than the local value by a factor of $10^2 - 10^4$ should have durations of star formation shorter than the local regions by a factor of $3 - 10$, for the same spatial scale. This result corresponds to the observation for starburst galaxies that the formation time of very dense clusters, containing the mass equivalent of a whole OB association, is extraordinarily fast, on the order of $\sim 1-3$ My, whereas in our Galaxy, it takes ~ 10 My to form an aggregate of this mass. Similarly, high pressure cores in GMCs (Sect. IIC) should form stars faster than low pressure regions with a similar mass or size.

There are many observations of the duration of star formation in various regions, both active and inactive. In the Orion Trapezium cluster, the age spread for 80% of the stars is very short, less than 1 My (Prosser et al. 1994), as it is in L1641 (Hodapp & Deane 1993). It might be even shorter for a large number (but not necessarily a large fraction) of stars in NGC 1333 because of the large number of jets and Herbig-Haro objects that are present today (Bally et al. 1996). In NGC 6531 as well, the age spread is immeasurably small (Forbes 1996). Other clusters have larger age spreads. Hillenbrand et al. (1993) found that, while the most massive stars (80 $M_\odot$) in NGC 6611 (=M16) have a 1 My age spread around a mean age of ~ 2 My, there are also pre-main sequence stars and a star of 30 $M_\odot$ with an age of 6 My. The cluster NGC 1850 in the LMC has an age spread of 2 to 10 My (Caloi & Cassatella 1998), and in NGC 2004, there are evolved low mass stars in the midst of less evolved high mass stars (Caloi & Cassatella 1995). In NGC 4755, the age spread is 6 to 7 My, based on the simultaneous presence of both high and low mass star formation (Sagar & Cannon 1995). One of the best studied clusters for an age spread is the Pleiades, where features in the luminosity function (Belikov et al. 1998) and synthetic HR diagrams (Siess et al. 1997) suggest continuous star formation over ~ 30 My when it formed (~ 100 My ago). This is much longer than the other age spreads for small clusters, and may have another explanation, including the possibility that the Pleiades primordial cloud captured some stars from a neighboring, slightly older, star-forming region (e.g., Bhatt 1989). Recall that the age spreads are much larger than several My for whole OB associations and star complexes, as discussed above.

C. Clusters in Dense Molecular Cores

1. Cluster Densities

Infrared, x-ray, and radio continuum maps reveal dense clusters of young stars in many nearby GMC cores. Reviews of embedded infrared clusters, including 3-color JHK images, were written by Lada, Strom & Myers (1993) and Zinnecker, McCaughrean & Wilking (1993).

Most observations of embedded young clusters have been made with JHK imagery. A list of some of the regions studied is in Table 1. These clusters typically have radii of ~ 0.1 pc to several tenths of a pc, and contain several hundred catalogued stars, making the stellar densities on the order of several times 10^3 pc^{-3} or larger. For example, in the Trapezium cluster, the stellar density is ~ 5000 stars pc^{-3} (Prosser et al. 1994) or higher (McCaughrean & Stauffer 1994), and in Mon R2 it is ~ 9000 stars pc^{-3} (Carpenter et al. 1997). Perhaps the more distant clusters in this list are slightly larger, as a result of selection effects.

Some clusters, like W3, NGC 6334, Mon R2, M17, CMa OB1, S106, and the maser clusters, contain massive stars, even O-type stars in the pre-UCHII phase or with HII regions. Others, like rho Oph, contain primarily low mass stars. Although the mass functions vary a little from region to region, there is no reason to think at this time that the spatially averaged IMFs in these clusters are significantly different from the Salpeter (1955), Scalo (1986), or Kroupa, Tout, & Gilmore (1993) functions. Thus the clusters with high mass stars also tend to have low mass stars (Zinnecker, McCaughrean, & Wilking 1993), although not all of the low-mass stars are seen yet, and clusters with primarily low mass stars are not populous enough to contain a relatively rare massive star (see review of the IMF in Elmegreen 1998a).

Embedded x-ray clusters have been found in NGC 2024 (Freyberg & Schmitt 1995), IC348 (Preibisch, Zinnecker, & Herbig 1996), IC1396 (Schulz, Berghöfer, & Zinnecker 1997), and the Mon R2 and Rosette molecular clouds (Gregorio-Hetem et al. 1998). These show x-ray point sources that are probably T Tauri stars, some of which are seen optically. The presence of strong x-rays in dense regions of star formation increases the ionization fraction over previous estimates based only on cosmic ray fluxes. At higher ionization fractions, magnetic diffusion takes longer and this may slow the star formation process. For this reason, Casanova et al. (1995) and Preibisch et al. (1996) suggested that x-rays from T Tauri stars lead to self-regulation of the star formation rate in dense clusters. On the other hand, Nakano (1998) suggests that star formation occurs quickly, by direct collapse, without any delay from magnetic diffusion. X-rays can also affect the final accretion phase from the disk. The X-ray irradiation of protostellar disks can lead to better coupling between the gas and the magnetic fields, and more efficient angular momentum losses through hydromagnetic winds (cf. Königl & Pudritz 1999). Such a process might increase the efficiency of star formation. The full implications of x-ray radiation in the cluster environment are not understood yet.

A stellar density of 10^3 $M_\odot$ pc^{-3} corresponds to an H_2 density of $\sim 10^4$ cm^{-3}. Molecular cores with densities of 10^5 cm^{-3} or higher (e.g., Lada 1992) can easily make clusters this dense. Measured star formation efficiencies are typically 10%-40% (e.g., see Greene & Young 1992; Megeath et al. 1996; Tapia et al. 1996). Gas densities of $\sim 10^5$ cm^{-3} also imply extinctions of $A_V \sim 40$ mag on scales of ~ 0.2 pc, which are commonly seen in these regions, and they imply masses of ~ 200 M$_\odot$ and virial velocities of ~ 1 km s^{-1}, which is the typical order of magnitude of the gas velocity dispersion of cold star-forming clouds in the solar neighborhood. There should be larger and smaller dense clusters too, of course, not a *characteristic* cluster size that is simply the average value seen locally, because unbiased surveys, as in the LMC (Bica et al. 1996), show a wide range of cluster masses with power-law mass functions, i.e., no characteristic scale (cf. Sect. IIA).

2. Cluster Effects on Binary Stars and Disks

The protostellar binary fraction is lower in the Trapezium cluster than the Tau-Aur region by a factor of ~ 3 (Petr et al. 1998), and lower in the Pleiades cluster than in Tau-Aur as well (Bouvier et al. 1997). Yet the binary frequency in the Trapezium and Pleiades clusters are comparable to that in the field (Prosser et al. 1994). This observation suggests that most stars form in dense clusters, and that these clusters reduce an initially high binary fraction at starbirth (e.g., Kroupa 1995a; Bouvier et al. 1997).

The cluster environment should indeed affect binaries. The density of $n_{star} = 10^3$ stars pc^{-3} in a cloud core of size $R_{core} \sim 0.2$ pc implies that objects with this density will collide with each other in one crossing time if their cross section is $\sigma \sim (n_{star} R_{core})^{-1} \sim 0.005$ pc^2, which corresponds to a physical size of $10^3 - 10^4 \left(R_{core}(pc) n_{star}/10^3\right)^{-1/2}$ AU. This is the scale for long-period binary stars.

Another indication that a cluster environment affects binary stars is that the peak in the separation distribution for binaries is smaller (90 AU) in the part of the Sco-Cen association that contains early type stars than it is (215 AU) in the part of the Sco-Cen association that contains no early type stars (Brandner & Köhler 1998). This observation suggests that dissipative interactions leading to tighter binaries, or perhaps interactions leading to the destruction of loose binaries, are more important where massive stars form.

Computer simulations of protostellar interactions in dense cluster environments reproduce some of these observations. Kroupa (1995a) got the observed period and mass-ratio distributions for field binaries by following the interactions between 200 binaries in a cluster with an initial radius of 0.8 pc. Kroupa (1995b) also got the observed correlations between eccentricity, mass ratio, and period for field binaries using the same initial conditions. Kroupa (1995c) predicted further that interactions will cause stars to be ejected from clusters, and the binary fraction among these ejected stars will be lower than in the remaining cluster stars (see also Kroupa 1998). These simulations assume that all stars begin as binary members and interactions destroy some of these binaries over time.

Another point of view is that the protostars begin as single objects and capture each other to form binaries. In this scenario, McDonald & Clarke (1995) found that disks around stars aid with the capture process, and they reproduced the field binary fraction in model clusters with 4 to 10 stars (see review by Clarke 1996). According to this simulation, the cluster environment should affect disks too. There are indeed observations of this nature. Mundy et al. (1995) suggested that massive disks are relatively rare in the Trapezium cluster, and Nürnberger et al. (1997) found that protostellar disk mass decreases with stellar age in the Lupus young cluster, but not in the Tau-Aug region, which is less dense. When massive stars are present, as in the Trapezium cluster, uv radiation can photoionize the neighboring disks, and this is a type of interaction as well (Johnstone et al. 1998).

3. Cluster Effects on the IMF?

The best examples of cluster environmental effects on star formation have been limited, so far, to binaries and disks. Nevertheless, there are similar suggestions that the cluster environment can affect the stellar mass as well, and, in doing so, affect the initial stellar mass function (e.g. Zinnecker 1986). For example, computer simulations have been able to reproduce the IMF for a long time using clump (Silk & Takahashi 1979; Murray & Lin 1996) or protostellar (Price & Podsiadlowski 1995; Bonnell et al. 1997) interaction models of various types.

There is no direct evidence for IMF variations with cluster density, however (e.g., see Massey & Hunter 1998; Luhman & Rieke 1998). Even in extremely dense globular clusters, the IMF seems normal at low mass (Cool 1998). This may not be surprising because protostellar condensations are very small compared to the interstar separations, even in globular clusters (Aarseth et al. 1988), but the suggestion that massive stars are made by coalescence of smaller protostellar clumps continues to surface (see Zinnecker et al. 1993; Stahler, Palla, & Ho 1999).

Another indication that cluster interactions do not affect the stellar mass comes from the observation by Bouvier et al. (1997) that the rotation rates of stars in the Pleiades cluster are independent of the presence of a binary companion. These authors suggest that the rotation rate is the result of accretion from a disk, and so the observation implies that disk accretion is not significantly affected by companions. Presumably this accretion would be even less affected by other cluster members, which are more distant than the binary companions. Along these lines, Heller (1995) found in computer simulations that interactions do not destroy protostellar disks, although they may remove ~half of their mass.

There is a way that could have gone unnoticed in which the cluster environment may affect the IMF. This is in the reduction of the thermal Jeans mass at the high pressure of a cluster-forming core. A lower Jeans mass might shift the turnover mass in the IMF to a lower value in dense clusters than in loose groups (Elmegreen 1997, 1999).

D. Mass Segregation in Clusters

One of the more perplexing observations of dense star clusters is the generally centralized location of the most massive stars. This has been observed for a long time and is usually obvious to the eye. For young clusters, it cannot be the result of "thermalization" because the time scale for that process is longer than the age of the cluster (e.g., Bonnell & Davies 1998). Thus it is an indication of some peculiar feature of starbirth.

The observation has been quantified using color gradients in 12 clusters (Sagar & Bhatt 1989), and by the steepening of the IMF with radius in several clusters (Pandey, Mahra, & Sagar 1992), including Tr 14 (Vazquez et al. 1996), the Trapezium in Orion (Jones & Walker 1988; Hillenbrand 1997; Hillenbrand & Hartmann 1998), and, in the LMC, NGC 2157 (Fischer et al. 1998), SL 666, and NGC 2098 (Kontizas et al. 1998). On the other hand, Carpenter et al. (1997) found no evidence from the IMF for mass segregation in Mon R2 at $M < 2\mathrm{M}_\odot$, but noted that the most massive star (10 $\mathrm{M}_\odot$) is near the center nevertheless. Raboud & Mermilliod (1998) found a segregation of the binary stars and single stars in the Pleiades, with the binaries closer to the center, presumably because of their greater mass. A related observation is that intermediate mass stars always seem to have clusters of low mass stars around them (Testi, Palla, & Natta 1998), as if they needed these low mass stars to form by coalescence, as suggested by these authors.

There are many possible explanations for these effects. The stars near the center could accrete gas at a higher rate and end up more massive (Larson 1978, 1982; Zinnecker 1982; Bonnell et al. 1997); they (or their predecessor clumps) could coalesce more (Larson 1990; Zinnecker et al. 1993; Stahler, Palla, & Ho 1999; Bonnell, Bate, & Zinnecker 1998), or the most massive stars and clumps forming anywhere could migrate to the center faster because of a greater gas drag (Larson 1990, 1991; Gorti & Bhatt 1995, 1996; Saiyadpour, Deiss, & Kegel 1997). A central location for the most massive pieces is also expected in a hierarchical cloud (Elmegreen 1999). The centralized location of binaries could be the result of something different: the preferential ejection of single stars that have interacted with other cluster stars (Kroupa 1995c). The presence of low-mass stars around high-mass stars could have a different explanation too: high-mass stars are rare so low-mass stars are likely to form before a high-mass star appears, whatever the origin of the IMF.

III. CLUSTER FORMATION MODELS

A. Bound Clusters as Examples of Triggered Star Formation?

Section IIA considered loose stellar groupings as a possible reflection of hierarchical cloud structure, possibly derived from turbulent motions, and it considered dense cluster formation in cloud cores separately, as if this process were different. In fact the two types of clusters and the processes that lead to them could be related. Even the bound clusters, which presumably formed in dense cloud cores, have a power law mass distribution, and it is very much like the power law for the associations that make HII regions, so perhaps both loose and dense clusters get their mass from cloud hierarchical structure. The difference might be simply that dense clusters form in cloud pieces that get compressed by an external agent.

There are many young clusters embedded in cores at the compressed interfaces between molecular clouds and expanded HII regions, including many of those listed in Table 1 here, as reviewed in Elmegreen (1998b). For example, Megeath & Wilson (1997) recently proposed that the embedded cluster in NGC 281 was triggered by the HII region from an adjacent, older, Trapezium-like cluster, and Sugitani et al. (1995) found embedded clusters inside bright rimmed clouds. Compressive triggering of a cluster can also occur at the interface between colliding clouds, as shown by Usami et al. (1995). A case in point is the S255 embedded cluster (Zinnecker et al. 1993; Howard et al. 1997; Whitworth & Clarke 1997).

Outside compression aids the formation of clusters in several ways. It brings the gas together so the stars end up in a dense cluster, and it also speeds up the star formation processes by increasing the density. These processes can be independent of the compression, and the same as in other dense regions that were not rapidly compressed; the only point is that they operate faster in compressed gas than in lower density gas. The external pressure may also prevent or delay the cloud disruption by newborn stars, allowing a large fraction of the gas to be converted into stars, and thereby improving the chances that the cluster will end up self-bound (cf. Sect IV; Elmegreen & Efremov 1997; Lefloch et al. 1997).

Cloud cores should also be able to achieve high densities on their own, without direct compression. This might take longer, but the usual processes of energy dissipation and gravitational contraction can lead to the same overall core structure as the high pressure from an external HII region. Heyer, Snell & Carpenter (1997) discussed the morphology of dense molecular cores and cluster formation in the outer Galaxy, showing that new star clusters tend to form primarily in the self-gravitating, high-pressure knots that occur here and there amid the more loosely connected network of lower pressure material. Many of these knots presumably reached their high densities spontaneously.

B. Spontaneous Models and Large Scale Triggering

The most recent development in cluster formation models is the direct computer simulation of interacting protostars and clumps leading to clump and stellar mass spectra (Klessen et al. 1998). Earlier versions of this type of problem covered protostellar envelope stripping by clump collisions (Price & Podsiadlowski 1995), the general stirring and cloud support by moving protostars with their winds (Tenorio-Tagle et al. 1993), and gas removal from protoclusters (Theuns 1990).

The core collapse problem was also considered by Boss (1996) who simulated the collapse of an oblate cloud, forming a cluster with ~ 10 stars. A detailed model of thermal instabilities in a cloud core, followed by a collapse of the dense fragments into the core center and their subsequent coalescence, was given by Murray & Lin (1996). Patel & Pudritz (1994) considered core instability with stars and gas treated as separate fluids, showing that the colder stellar fluid destabilized the gaseous fluid.

Myers (1998) considered magnetic processes in dense cores, and showed that stellar-mass kernels could exist at about the right spacing for stars in a cluster and not be severely disrupted by magnetic waves. Whitworth et al. (1998) discussed a similar characteristic core size at the threshold between strong gravitational heating and grain cooling on smaller scales, and turbulence heating and molecular line cooling on larger scales.

Some cluster formation models proposed that molecular clouds are made when high velocity clouds impact the Galactic disk (Tenorio-Tagle 1981). Edvardsson et al. (1995) based this result on abundance anomalies in the ζ Sculptoris cluster. Lepine & Duvert (1994) considered the collision model because of the distribution of gas and star formation in local clusters and OB associations, while Phelps (1993) referred to the spatial distribution, ages, velocities, and proper motions of 23 clusters in the Perseus arm. Comeron et al. (1992) considered the same origin for stars in Gould's Belt based on local stellar kinematics. For other studies of Gould's Belt kinematics, see Lindblad et al. (1997) and De Zeeuw et al. (1999).

Other origins for stellar clustering on a large scale include triggering by spiral density waves, which is reviewed in Elmegreen (1994, 1995a). According to this model, Gould's Belt was a self-gravitating condensation in the Sgr-Carina spiral arm when it passed us ~ 60 My ago, and is now in the process of large-scale dispersal as it enters the interarm region, even though there is continuing star formation in the Lindblad ring and other disturbed gas from this condensation (see Elmegreen 1993).

The evolution of a dense molecular core during the formation of its embedded cluster is unknown. The core could collapse dynamically while the cluster stars form, giving it a total lifetime comparable to the core crossing time, or it could be somewhat stable as the stars form on smaller scales inside of it. Indeed there is direct evidence for gas collapse onto individual stars in cloud cores (Mardones et al. 1997; Motte, Andre & Neri 1998), but not much evidence for the collapse of whole cores (except perhaps in W49 – see Welch et al. 1987; De Pree, Mehringer, & Goss 1997).

IV. CONDITIONS FOR THE FORMATION OF BOUND CLUSTERS

A. Critical Efficiencies

The final state of an embedded cluster of young stars depends on the efficiency, ϵ, of star formation in that region: i.e., on the ratio of the final stellar mass to the total mass (stars + gas) in that part of the cloud. When this ratio is high, the stars have enough mass to remain gravitationally bound when the residual gas leaves, forming a bound cluster. When this ratio is low, random stellar motions from the time of birth disperse the cluster in a few crossing times, following the expulsion of residual gas. The threshold for self-binding occurs at a local efficiency of about 50% (von Hoerner 1968). This result is most easily seen from the virial theorem $2T + \Omega = 0$ and total energy $E = T + \Omega$ for stellar kinetic and potential energies, T and Ω. Before the gas expulsion, $E = \Omega_{before}/2 < 0$ from these two equations. In the instant after *rapid* gas expulsion, the kinetic energy and radius of the cluster are approximately unchanged because the stellar motions are at first unaffected, but the potential energy changes because of the sudden loss of mass (rapid gas expulsion occurs when the outflowing gas moves significantly faster than the virial speed of the cloud). To remain bound thereafter, E must remain less than zero, which means that during the expulsion, the potential energy can increase by no more than the addition of $|\Omega_{before}|/2$. Thus immediately after the expulsion of gas, the potential energy of the cluster, Ω_{after}, has to be less than half the potential energy before, $\Omega_{before}/2$. Writing $\Omega_{before} = -\alpha G M_{stars} M_{total}/R$ and $\Omega_{after} = -\alpha G M_{stars}^2/R$ for the same α and R, we see that this constraint requires $M_{stars} > M_{total}/2$ for self-binding. Thus the efficiency for star formation, M_{stars}/M_{total}, has to exceed about 1/2 for a cluster to be self-bound (see also Mathieu 1983; Elmegreen 1983).

Another way to write this is in terms of the expansion factor for radius, R_{final}/R_{before}, where R_{final} is the cluster radius after the gas-free cluster readjusts its virial equilibrium. A cluster is bound if R_{final} does not become infinite. Hills (1980) derived $R_{final}/R_{initial} = \epsilon/(2\epsilon - 1)$, from which we again obtain $\epsilon > 0.5$ for final self-binding with efficiency ϵ. Danilov (1987) derived a critical efficiency in terms of the ratio of cluster radius to cloud radius; this ratio has to be < 0.2 for a bound cluster to form.

There can be many modifications to this result, depending on the specific model of star formation. One important change is to consider initial stellar motions that are less than their virial speeds in the potential of the cloud because the cloud is supported by both magnetic and kinematic energies, whereas the star cluster is supported only by kinematic energy. This modification was considered by Lada, Margulis, & Dearborn (1984), Elmegreen & Clemens (1985), Pinto (1987), and Verschueren (1990), who derived a critical efficiency for isothermal clouds that may be approximated by the expression,

$$2\,(1-\epsilon)\ln\left(\frac{\epsilon}{1-\epsilon}\right) + 1 + \epsilon = 1.5t^2$$

where $t = a_s/a_{VT} < 1$ is the ratio of the stellar velocity dispersion to the virial. This expression gives ϵ between 0.29 at $t = 0$ and 0.5 at $t = 1$. Other cloud structures gave a similar range for ϵ. This result is the critical star formation efficiency for the whole cloud; it assumes that the stars fall to the center after birth, and have a critical efficiency for binding in the center equal to the standard value of 0.5.

A related issue is the question of purely gravitational effects that arise in a cluster-forming core once the stars comprise more than $\sim$ 30% of the gas. In this situation, the stars may be regarded as a separate (collisionless) "fluid" from the gas. The stability of such two fluid systems was considered by Jog & Solomon (1984) and Fridman & Polyachenko (1984). The Jeans length for a two-component fluid is smaller than that for either fluid separately. Dense stellar clusters might therefore fragment into sub-groups, perhaps accounting for some of the sub-structure that is observed in young embedded star clusters (Patel & Pudritz 1994).

Lada, Margulis & Dearborn (1984) also considered the implications of slow gas removal on cluster self-binding. They found that gas removal on timescales of several cloud crossing times lowers the required efficiency by about a factor of 2, and when combined with the effect of slow starbirth velocities, lowers the efficiency by a combined factor of ~ 4. For clouds in which stars are born at about half the virial speed, and in which gas removal takes ~ 4 crossing times, the critical efficiency for the formation of a bound cluster may be only $\sim 10\%$.

Another way to lower the critical efficiency is to consider gas drag on the stars that form. Gas drag removes stellar kinetic energy and causes the stars to sink to the bottom of the cloud potential well, just like a low birth velocity. Saiyadpour et al. (1997) found that the critical efficiency can be only 0.1 in this case. Gas accretion also slows down protostars and causes them to sink to the center (Bonnell & Davies 1998).

It follows from these examples that the critical efficiency for self-binding can be between ~ 0.1 and 0.5, depending on the details of the star formation process.

B. Bound Clusters versus Unbound OB Associations

The onset of massive star formation should mark the beginning of rapid cloud dispersal because ionizing radiation is much more destructive per unit stellar mass than short-lived winds from low-mass stars. (e.g., see Whitworth 1979). According to Vacca, Garmany & Shull (1996), the ionizing photon luminosity scales with stellar mass approximately as M^4. In that case, the total Lyman continuum luminosity from stars with luminosities in the range $\log L$ to $\log L + d\log L$ increases approximately as $L^{0.66}$ for a Salpeter IMF (a Salpeter IMF has a number of stars in a logarithmic interval, $n\left[M_{star}\right] d\log M_{star}$, proportional to $M_{star}^{-1.35} d\log M_{star}$). Thus the total ionizing luminosity increases with cluster mass more rapidly than the total cloud mass, and cloud destruction by ionization follows the onset of massive star formation.

If massive stars effectively destroy clouds, then the overall efficiency is likely to be low wherever a lot of massive stars form (unless they form *preferentially* late, as suggested by Herbig (1962), and not just randomly late). Thus we can explain both the low efficiency and the unboundedness of an OB association: the destructive nature of O-star ionization causes both. We can also explain why all open clusters in normal galaxy disks have small masses, generally less than several times 10^3 $M_\odot$ in the catalog of Lynga (1987; e.g., see Battinelli et al. 1994): low mass star-forming regions are statistically unlikely to produce massive stars. Discussions of this point are in Elmegreen (1983), Henning & Stecklum (1986), and Pandey et al. (1990).

The idea that massive stars form late in the development of a cluster goes back to Herbig (1962) and Iben & Talbot (1966), with more recent work by Herbst & Miller (1982) and Adams, Strom & Strom (1983). However, Stahler (1985) suggested the observations have a different explanation, and the rare massive stars should be later than the more common low-mass star anyway, for statistical reasons (Schroeder & Comins 1988; Elmegreen 1999).

The efficiency of star formation has been estimated for several embedded clusters, giving values such as 25% for NGC 6334 (Tapia et al. 1996), 6-18% for W3 IRS5 (Megeath et al. 1996), 2.5% for Serpens (White et al. 1995), 19% for NGC 3576 (Persi et al. 1994), and 23% for rho Oph (Greene & Young 1992), to name a few.

C. Variation in Efficiency with Ambient Pressure

Variations in the efficiency from region to region could have important consequences because it might affect the fraction of star formation going into bound clusters (in addition to the overall star formation rate per unit gas mass). One consideration is that the efficiency may increase in regions of high pressure (Elmegreen, Kaufman & Thomasson 1993; Elmegreen & Efremov 1997). This is because the virial velocity of a gravitationally-bound cloud increases with pressure and mass as $V_{VT} \sim (PM^2)^{1/8}$, as may be determined from the relationships $V_{VT}^2 \sim GM/(5R)$ and $P \sim GM^2/R^4$ for radius R. If the pressure increases and the virial velocity follows, then clouds of a given mass are harder to destroy with HII regions, which push on material with a fixed velocity of about 10 km s^{-1}. In fact, a high fraction of star formation in starburst galaxies, which generally have a high pressure, could be in the form of bound clusters (Meurer et al. 1995).

The lack of expansion of HII regions in virialized clouds with high velocity dispersions also means that the massive stars will not ionize much. They will only ionize the relatively small mass of high density gas initially around them.

We can determine the average pressures in today's globular clusters from their masses and sizes using the relationship $P \sim GM^2/R^4$. This gives $P \sim 10^6 - 10^8$ k$_{\rm B}$ (Harris & Pudritz 1994; Elmegreen & Efremov 1997), which is $10^2 - 10^4$ times the local total ISM pressure. If the pressures of star-forming regions in the Galactic halo were this high when the globular clusters formed, and the globular cluster cloud masses were higher than those near OB associations by a factor of ~ 10, to account for the higher globular cluster masses, then the velocity dispersions in globular cluster cores had to be larger than the velocity dispersion in a local GMC by a factor $\left(M^2P\right)^{1/8} = \left(10^2 \times 10^4\right)^{1/8} \sim 5.6$. This puts the dispersion close to 10 km s^{-1}, making the globular cluster clouds difficult to disrupt by HII regions.

V GLOBULAR CLUSTER FORMATION

Globular clusters in the halos of galaxies are denser, smoother, and more massive than open clusters in galactic disks, and the globulars are also much older, but they have about the same power law mass distribution function as open clusters at the high mass end, and of course both are gravitationally bound systems. We are therefore faced with the challenging question of whether the similarities between these two types of clusters are more important than their differences. If so, then they may have nearly the same formation mechanisms, modified in the case of the globulars by the peculiar conditions in the early Universe. If the differences are too great for a unified model, then we need a unique formation theory for globular clusters.

The history of the theory on this topic is almost entirely weighted toward the latter point of view, because the full mass distribution function for globular clusters is essentially a Gaussian (when plotted as linear in number versus logarithm in mass or luminosity; e.g., Harris & Racine 1979; Abraham & van den Bergh 1995), with a *characteristic mass* of several $\times 10^5$ $M_\odot$. Nearly all of the early models have attempted to explain this mass. For example, Peebles & Dicke (1968), Peebles (1984), Rosenblatt et al. (1988) and Padoan et al. (1997) regarded globular clusters as primordial objects produced by density fluctuations in the expanding Universe. Peebles & Dickey (1968) thought the characteristic mass was a Jeans mass. Other models viewed globulars as secondary objects, formed by thermal instabilities in cooling halo gas (Fall & Rees 1985; Murray & Lin 1992; Vietri & Pesce 1995) or gravitational instabilities in giant bubbles (Brown et al. 1995) or the shocked layers between colliding clouds (Zinnecker & Palla 1987; Shapiro, Clocchiatti, & Kang (1992); Kumai et al. 1993; Murray & Lin 1992). Schweizer (1987) and Ashman & Zepf (1992) suggested many globulars formed during galaxy mergers. This could explain the high specific frequency of globular clusters (number per unit galaxy luminosity; Harris & van den Bergh 1981) in ellipticals compared to spirals if the ellipticals formed in mergers. However, Forbes et al. (1997) found that galaxies with high specific frequencies of globular clusters have lower cluster metallicities, whereas the opposite might be expected in the merger model. Also, McLaughlin (1999) has suggested that the specific frequency of globular cluster is the same everywhere when x-ray halo gas and stellar evolution are included.

There is another point of view if the globular cluster mass function is not primordial but evolved from an initial power law. This is a reasonable hypothesis because low mass globulars evaporate and get dispersed first, depressing an initial power law at low mass to resemble a Gaussian after a Hubble time (Surdin 1979; Okazaki & Tosa 1995; Elmegreen & Efremov 1997). Observations of young globular clusters, forming in starburst regions, also show a power law luminosity function with a mixture of ages (Holtzman et al. 1992; Whitmore & Schweizer 1995; Meurer et al. 1995; Maoz et al. 1996; Carlson et al. 1998), and the high mass end of the old globular systems is nearly a power law too (Harris & Pudritz 1994; McLaughlin & Pudritz 1996; Durrell et al. 1996).

In that case, there is a good possibility that old globular clusters formed in much the same way as young open clusters, i.e., in dense cores that are part of a large-scale hierarchical gas structure derived from cloud collisions (Harris & Pudritz 1994; McLaughlin & Pudritz 1996) or turbulent motions (Elmegreen & Efremov 1997). Direct observations of globular cluster luminosity functions at cosmological distances should be able to tell the difference between formation models with a characteristic mass and those that are scale free.

Another model for globular cluster formation suggests they are the cores of former dwarf galaxies (Zinnecker et al. 1988; Freeman 1993), "eaten" by the large galaxy during dissipative collisions. The globulars NGC 6715, Terzan 7, Terzan 8, and Arp 2 that are comoving with the Sgr dwarf galaxy are possible examples (Ibata et al. 1995; Da Costa & Armandroff 1995). Other dwarf galaxies have globular cluster systems too (Durrell et al. 1996), so the globulars around large galaxies may not come from the cores of the dwarfs, but from the dwarf globulars themselves. It remains to be seen whether this formation mechanism can account for the globular cluster luminosity function.

VI CONCLUSIONS

1. Loose hierarchical clusters form when the associated gas is only weakly self-gravitating and clumped in this fashion before the star formation begins. Dense clusters come from strongly self-gravitating gas, which may be triggered, and which also may be gravitationally unstable to bulk collapse.

2. Cluster formation is often quite rapid, requiring only a few internal crossing times to make most of the stars. This follows from the relatively small age differences between nearby clusters and from the hierarchical structure of embedded and young stellar groups. Such structure would presumably get destroyed by orbital mixing if the region were much older than a crossing time.

3. Dense cluster environments seem to affect the formation or destruction of protostellar disks and binary stars, but not the stellar initial mass function.

4. Bound clusters require a relatively high star formation efficiency. This is not a problem for typically low mass open clusters, but it requires something special, like a high pressure, for a massive globular cluster.

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FIGURE CAPTIONS

Figure 1. Star field southwest of 30 Dor in the Large Magellanic Clouds, showing hierarchical structure in the stellar groupings. Image from Efremov (1989).

Figure 2. OB associations and star complexes along the western spiral arm of M31. The black dots show the positions of the OB associations inside the outlines of the star complexes. The faint outlines to the lower left of this show the actual OB associations in relation to each other, shifted to the southeast by the length of the diagonal line for clarity (from Battinelli et al. 1996).

Figure 3. Schematic diagram of the relationship between the duration of star formation and the region size, from Efremov & Elmegreen (1998). Larger regions of star formation form stars for a longer total time.

Figure 4. The average age differences between clusters in the LMC are plotted versus their deprojected angular separations, for clusters in the age interval from 10 to 100 My, from Efremov & Elmegreen (1998). Clusters that are close together in space have similar ages. The line is a fit to the data given by $\log \Delta t(\mathrm{yrs}) = 7.49 + 0.38 \log S(\mathrm{deg})$.

Figure 5. The molecular cloud size-linewidth relation for the Milky Way is shown at the top, considering many different surveys, as indicated by the symbol types, and the ratio of half of the size to the Gaussian linewidth is shown at the bottom. This latter ratio is the crossing time in the cloud; it scales about as the square root of the cloud size. Superposed on this crossing time-size relation is the age-difference versus size relation shown in the previous figure, using clusters from the LMC. If the size-linewidth relations for the two galaxies are comparable, to within a factor of two, then this diagram suggests that the duration of star formation in a region is approximately equal to the turbulent crossing time, at least on the large scales considered here (from Efremov & Elmegreen 1998).