PRESENT-DAY CLUSTER FORMATION

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ABSTRACT   A review is presented of some of the observed features of cluster formation in our Galaxy and in external galaxies. Evidence is summarized suggesting that star clusters form only in the densest parts of large star-forming complexes, and that the molecular clumps in which they form are compressed in part by the effects of earlier star formation. The formation of massive globular-like clusters apparently requires much larger star-forming complexes than are now found in the Milky Way, and some circumstances in which they may form are noted.

1. INTRODUCTION

While much progress has been made in understanding how stars might form in relative isolation (Shu, Adams, & Lizano 1987), the formation of clusters of stars is necessarily a far more complex process, and is less amenable to theoretical analysis. Therefore, at present, an understanding of how star clusters form must come largely from observations. The formation of globular clusters cannot yet be observed directly, but the circumstances in which clusters are now forming in our Galaxy and the properties of the newly formed clusters can be studied in some detail; in less detail, cluster formation can also be studied in other galaxies as well. As a result of such studies, some apparently general features of present-day cluster formation are beginning to emerge, and they will be reviewed below.

Is the study of present-day cluster formation relevant to understanding the formation of globular clusters, as was suggested by Larson (1987, 1988)? A key question is whether there is any fundamental distinction between the globular and open clusters, or whether, as suggested by Stetson at this conference, clusters form a continuum of objects within which the distinction between globular and open types is somewhat arbitrary. The existence of a continuous range of properties seems likely when all of the clusters in our Galaxy and nearby galaxies are considered, including the oldest Galactic open clusters and the clusters in the Magellanic Clouds and M33, whose properties have been reviewed at this meeting by Friel, Da Costa, and Christian. It has sometimes been emphasized that globular clusters have a more sharply peaked mass distribution than open clusters (van den Bergh 1993), but this does not necessarily make them a distinct class of objects because the classical globular clusters all have ages and therefore lifetimes greater than 10 Gyr, whereas open clusters can have any lifetime; thus globular clusters are strongly selected on the basis of lifetime, and so would be expected to have a narrower range of properties than open clusters. If there is no

really fundamental distinction between the different types of clusters, the study of present-day cluster formation can be regarded as providing information about some part of the parameter space occupied by all clusters. The accessible region of the parameter space may even extend into the mass range of the globular clusters when the massive young clusters in starburst systems are included (see Section 4).

2. OBSERVATIONS OF YOUNG CLUSTERS

Information about the youngest systems of stars has been obtained from classical optical studies of nearby OB and T associations (Blaauw 1964, 1991; Herbig 1962; Cohen & Kuhi 1979; Herbig & Terndrup 1986), and more recently from infrared observations of newly formed stars and clusters that are still embedded in their birth clouds (Lada & Lada 1991; Zinnecker, McCaughrean, & Wilking 1993). From the extensive information now available it is possible to make a relatively complete census of the stellar content of the nearest star-forming regions, and the clustering properties of the newly formed stars in them can be studied. An important finding of recent work with infrared array cameras is that most of the newly formed stars in nearby regions of star formation are located in dense embedded clusters that are partly or largely obscured at optical wavelengths (Lada & Lada 1991).

One of the nearest regions of star formation is the complex of dark clouds in Taurus and Auriga, which contains about $10^4 \, M_\odot$ of molecular gas distributed in a loose system of filaments and clumps. Associated with these clouds are many visible T Tauri stars, which constitute the bulk of the known young stellar population of this region. Although the Taurus clouds are usually regarded as exemplifying an 'isolated' mode of star formation (Lada, Strom, & Myers 1993), most of the young stars in this region are actually not completely isolated but are located in small groupings associated with the most prominent dark clouds (Herbig 1977; Larson 1982; Myers 1987). Truly isolated star formation may therefore be a rare phenomenon, and even in low-density regions, most stars may form in groups or clusters of some sort.

Another well-studied nearby region of star formation is the complex of dark clouds in Ophiuchus and Scorpius, especially the dense cloud near ρ Ophiuchi. Most of the young stars associated with these clouds are observable only at infrared wavelengths, and most of them are located in a concentrated cluster embedded in the ρ Oph cloud; this cloud contains some $500 \, M_\odot$ of molecular gas and more than 100 newly formed stars (Lada et al. 1993), possibly as many as ~ 250 stars according to Greene & Young (1992). The ρ Oph cluster has been studied extensively because of the possibility that it may represent a newly formed open cluster (Wilking & Lada 1985; Wilking, Lada, & Young 1989). However, it is not clear whether this cluster will remain bound after the gas is dispersed, since the formation of a bound cluster requires at least a 30 % efficiency of conversion of gas into stars (Wilking & Lada 1985), while the observed efficiency of star formation in the ρ Oph cluster is only about 20 %, although this latter figure could be an underestimate (Greene & Young 1992).

A stronger candidate for a newly formed bound cluster is found in the more distant and massive complex of molecular clouds in Orion. Most of the T Tauri stars in Orion are located in a single large grouping (Larson 1982) that

coincides with the youngest subgroup 1c of the Orion OB1 association (Blaauw 1964, 1991); there are also many hundreds of fainter stars in this system, which is sometimes called the 'Orion Nebula Cluster' (Jones & Walker 1988). Near its center is a much denser, partly obscured concentration of young stars that appears to form the core of this youngest part of the OB association; this denser system has been called the 'Trapezium Cluster' (Herbig & Terndrup 1986). The full content and extent of the Trapezium cluster have become apparent only with the advent of infrared array photographs, which have shown that it contains more than 500 stars in a highly centrally concentrated and approximately symmetrical distribution centered on the Trapezium (McCaughrean 1989; McCaughrean, Rayner, & Zinnecker 1991a; Zinnecker et al. 1993). The central density of this cluster exceeds 10^4 stars per pc^3, making it the densest known nearby aggregate of stars. The corresponding gas density is about 10^5 molecules per cm^3, which is comparable to the density of the clumps in the associated dense core region of the Orion A molecular cloud in which the Trapezium cluster is still partially embedded. The total mass of stars in the Trapezium cluster is at least comparable to the mass of gas in this region, so that the efficiency of star formation appears to have been high enough in this case to produce a bound cluster.

Many other regions of star formation have recently been observed with infrared array cameras, and most of them have also been found to contain compact clusters embedded in, or closely associated with, dense molecular clumps or cloud cores. The Orion B cloud adjacent to the Orion A cloud contains several such clusters that are somewhat smaller than the Trapezium cluster (E. A. Lada et al. 1991b), and it appears that the clusters that are now known in the Orion A and B clouds contain the majority of the newly formed stars in this region (Lada et al. 1993). An extensive review of the results obtained with infrared cameras, many of which have not yet been published in detail, has been given by Zinnecker et al. (1993). Some embedded clusters for which results have been published include those associated with M17 (C. J. Lada et al. 1991), S106 (Hodapp & Rayner 1991), and LkHα 101 (Barsony, Schombert, & Kis-Halas 1991). Brief reports have also been published for the clusters associated with S255/S257 (McCaughrean et al. 1991b), W3(OH) (Rayner, Hodapp, & Zinnecker 1991), and NGC 3603 (Melnick 1989); the latter object may be the most massive young cluster in our Galaxy, and has a structure resembling that of a globular cluster (Moffat 1983; Moffat, Seggewiss, & Shara 1985).

It is clear from these results that the formation of stars in dense clusters is a very common, if not ubiquitous, mode of star formation in our Galaxy, and it may well account for the formation of most stars. However, most of the embedded clusters that have been found cannot survive for long as bound open clusters, since not enough open clusters are known for most stars to have formed in them; therefore most of these embedded clusters must be dispersed soon after their formation (Lada & Lada 1991). Many cataloged young open clusters may themselves be short-lived objects that are now in the process of dispersing (Battinelli & Capuzzo-Dolcetta 1991). Newly formed clusters almost certainly lose much of their mass soon after they have formed, owing to mass loss from the young stars and also to the escape of stars from the cluster, as is observed to be happening in the Trapezium cluster (van Altena et al. 1988); therefore such clusters will expand considerably, and many of them may be completely dispersed soon after their formation, leaving only the densest and

most massive ones to survive for long as bound open clusters. Evidence that young clusters expand systematically as they age has been presented by Elson (1991, 1992) for a sample of Large Magellanic Cloud clusters.

3. OBSERVED CIRCUMSTANCES OF CLUSTER FORMATION

Understanding the formation of bound clusters of stars evidently requires understanding the origin of the dense molecular clumps that produce them. Some clues concerning the large-scale processes responsible for the formation of these dense clumps and their embedded clusters can be obtained by examining the circumstances in which clusters are observed to form.

The results of a large-scale CO survey of the molecular clouds in the Ophiuchus region have been presented by de Geus, Bronfman, & Thaddeus (1990). The dense molecular clump containing the ρ Oph cluster is located in the head of a comet-shaped cloud associated with the Upper Scorpius OB association (Blaauw 1991), and the long tail of this cloud points away from the center of the association; several other molecular clouds in the vicinity also have elongated structures that point radially away from the center of the OB association. The windswept appearance and the orientation of these clouds give the strong impression that they have been shaped by outflows from the Upper Scorpius association; such outflows might include expanding ionized flows, stellar winds, supernova explosions, or most probably a combination of all of these effects. The impression that some basically explosive phenomenon is involved is strengthened by the existence of a cavity in the distribution of atomic hydrogen on the high-latitude side of the OB association, bounded by a shell that appears to be expanding away from it (de Geus 1991; Blaauw 1991). The appearance of the molecular clouds and their location on the opposite side of the association suggest that they have been shaped and compressed, and perhaps even formed, by an interaction between this expanding shell and the denser atomic gas at lower Galactic latitudes.

Similar phenomena appear to be occurring on a larger scale in the Orion region of star formation, whose properties have been reviewed by Genzel & Stutzki (1989). The Trapezium cluster is closely associated with, and appears to have formed from, a dense 'ridge' or filament of molecular gas that is the dominant feature in the head of the strikingly comet-like Orion A molecular cloud (Bally et al. 1987, 1991). Just as is the case with the ρ Oph cloud, the long tail of this cloud points away from the center of the OB association; this is well illustrated for example in Fig. 7 of Blaauw (1991), which is based on the large-scale CO map of Maddalena et al. (1986). Again, the observations give the strong impression that the Orion A cloud has been shaped by an energetic outflow from the OB association, which has ablated the cloud into a long cometary shape and perhaps has also compressed some of it into dense filaments, as suggested by Bally et al. (1987, 1991). Similar processes are illustrated by Woodward's (1978) simulation of the deformation of an interstellar cloud swept over by a shock front in the intercloud medium; most of the cloud is ablated into a long cometary structure, but part of it is compressed into a dense elongated clump in the head of the comet.

The molecular ridge in the head of the Orion A cloud runs almost through the middle of the Trapezium cluster, and it contains a string of very dense clumps

(Hasegawa 1987; Sargent & Mundy 1988). The clump nearest the Trapezium is a well-known site of active star formation that contains the Becklin-Neugebauer object and the most luminous infrared source in Orion, IRc2; the two adjacent clumps in the filament are also active sites of star formation. These clumps all lie in projection well within the boundaries of the Trapezium cluster, so it appears that star formation is continuing in this cluster. It is instructive from a theoretical viewpoint to note that the geometry of the star-forming gas in this cluster is very far from spherical, so that models of cluster formation that assume spherical symmetry are unlikely to be relevant; instead, the observations suggest that the formation and fragmentation of dense filaments may play an important role.

The Orion B cloud also borders on the OB association (Blaauw 1991), and it too shows evidence of being structured by outflows or pressures generated by the massive young stars present; the edge of the cloud facing the center of the association is relatively sharply bounded and contains a number of dense clumps (Lada, Bally, & Stark 1991a), giving the impression that it has been compressed, while the opposite edge is more ragged, possibly because of ablation effects. Four of the five dense clumps in the Orion B cloud contain compact infrared clusters similar to, but smaller than, the Trapezium cluster (E. A. Lada et al. 1991b; Lada 1992).

On a still larger scale, the Orion A and B clouds and the entire Orion OB1 association are surrounded by Barnard's Loop, a large gas shell probably created by the combined effects of all of the previous star-forming activity in this region. In the same extended region containing Barnard's Loop, there are also many smaller cometary clouds whose tails all point away from the center of the OB association (Bally et al. 1991). Thus there is convincing evidence that the gas distribution and the structure of the molecular clouds in this region have been strongly influenced by the effects of the earlier episodes of star formation. Additional examples of apparently similar phenomena have been reviewed by Elmegreen (1992). One is in the more distant W3–W4 region, where an extended molecular and atomic cloud is found to contain three massive and dense molecular clumps along the edge adjacent to the W4 H II region (Lada et al. 1978); all three of these clumps appear to have formed clusters of stars, one being associated with the more compact W3 H II region, and one containing the luminous W3(OH) infrared cluster mentioned above.

In all, the evidence that has been reviewed concerning the circumstances in which star clusters form seems broadly consistent with the concept of 'triggered' or 'self-propagating' star formation proposed by Elmegreen & Lada (1977) and reviewed by Elmegreen (1992). However, the processes involved are evidently quite complex, and many of the details are not yet clear. It seems possible, for example, that the main effect of the earlier episodes of star formation is actually to disperse the residual gas, and that only some fraction of this gas, perhaps that which was already in clumps, is compressed into denser clumps which then form compact clusters of stars. The primary triggering effect of the earlier star formation may then just be to lead to the formation of denser and more tightly bound clusters than would otherwise have formed. The formation of a bound cluster might even represent the culmination of the star-forming activity in a region, occurring only after the residual gas has been pushed around and churned up (and perhaps chemically homogenized) by earlier episodes of star formation until a small part of it has been compressed into a dense enough

clump to form a bound cluster. Once a prominent cluster of stars has formed, the remaining molecular gas in a star-forming cloud is evidently soon dispersed, since observations show that the surrounding gas has already begun to be dispersed from around clusters older than 5 Myr, and very little molecular gas remains around clusters older than 10 Myr (Bash, Green, & Peters 1977; Leisawitz, Bash, & Thaddeus 1989).

There is possible evidence that some even larger-scale dynamical phenomenon has played a role in triggering the formation of the giant molecular clouds and young clusters in some parts of the Galactic disk. Alfaro, Cabrera-Caño, & Delgado (1991) have noted that most of the young clusters in a region about two kiloparsecs across in the third quadrant of galactic longitude are located below the Galactic plane; the Trapezium cluster itself, although not in their sample, is in this same general region and is about 140 parsecs below the Galactic plane. If there is in fact a general depression in the distribution of the gas and young stars in this region, as these authors suggest, then some coherent dynamical phenomenon must presumably have pushed the gas out of the Galactic plane. The same disturbance might then also have triggered the formation of many of the molecular clouds and young star clusters in this region. A possible cause of such effects might be the infall of a high-velocity cloud into the Galactic disk (Franco et al. 1988; Alfaro et al. 1991; Comerón & Torra 1992).

4. EXTRAGALACTIC CLUSTER FORMATION

The Magellanic Clouds are clearly also of great interest as a place to study cluster formation, since they have produced many young clusters that are considerably more massive than the open clusters in the Milky Way, and that have masses approaching those of globular clusters. Some of the properties of these young Magellanic Cloud clusters have been reviewed at this meeting by Olszewski, Richtler, and Mateo. The most luminous young cluster in the Local Group is the 30 Doradus cluster or NGC 2070 in the LMC (Moffat et al. 1985; Walborn 1984, 1991); its mass is at least two orders of magnitude larger than that of the Trapezium cluster, and its central density is also higher and probably exceeds $5 \times 10^4 \, M_\odot/\text{pc}^3$ (Hunter 1992; Campbell et al. 1992). It nevertheless shares some qualitative similarities with the Trapezium cluster in that its most massive stars are concentrated toward the center (Zinnecker et al. 1993), and in that star formation appears to be continuing in its immediate vicinity (Hyland et al. 1992).

The 30 Doradus cluster is located in a large region of active star formation that contains many other young clusters and includes Shapley's Constellation II of bright stars near the end of the LMC bar. It is also centrally located in a spectacular filamentary H II region, the Tarantula Nebula, which exhibits violent turbulent motions apparently caused by a combination of stellar winds and supernova explosions from the many massive young stars in the region (Meaburn 1984). Many authors have suggested that the compression of the residual gas into dense expanding shells by such phenomena, and perhaps also interactions between these shells, may act to trigger further star formation (Tenorio-Tagle & Bodenheimer 1988; Elmegreen 1992). The candidate protostars found by Hyland et al. (1992) in the region of the 30 Dor cluster appear to coincide with dense knots in the H II region that may have been created by interactions between

such expanding shells. It has also been suggested that the 30 Dor cluster itself is located at a point where several large shells intersect, and that the resulting accumulation and compression of gas was responsible for the formation of the cluster in this location (Cantó et al. 1980; Meaburn 1981; McGregor & Hyland 1981). In support of such a picture, Bruhweiler, Fitzurka, & Gull (1991) have noted the existence of a very large dust ring about 2 kpc across that encloses most of the star-forming region associated with 30 Dor and Shapley II, and they point out that the 30 Dor cluster lies just inside this ring at a point where it overlaps with the luminous supershell LMC 2 (Meaburn 1980). The most massive complex of molecular clouds in the LMC is also located in this same region (Cohen et al. 1988), and therefore another possibility is that interactions between the expanding shells and these massive molecular clouds have triggered the formation of the 30 Dor cluster, perhaps by processes similar to but larger in scale than those that appear to have occurred in the Ophiuchus and Orion regions.

The large mass of the 30 Dor cluster in comparison with Galactic open clusters is almost certainly a consequence of the exceptionally large size and mass of the 30 Dor – Shapley II star-forming complex, which has a diameter of about 2 kpc and a total gas mass of the order of $10^8 \, M_\odot$; this is at least an order of magnitude more mass than is found in typical star-forming regions in the Milky Way and other spiral galaxies. A possible reason for the large mass of the 30 Dor – Shapley II complex is that it is located just off the end of the LMC bar, which is a region where gas flows in barred galaxies tend to converge and where large complexes of gas and young stars are often seen; the barred Sc spiral M83, for example, has a star-forming region of roughly similar size and mass near the end of its bar (Kenney & Lord 1991).

Also of interest as systems in which to study the formation of massive clusters are the 'blue compact dwarf' or 'H II' galaxies (Thuan 1987; Kunth 1989; Melnick 1987, 1992). The appearance of these galaxies is dominated by starburst regions associated with massive gas concentrations usually located near their centers. Examples include the well-known compact galaxy I Zw 18 = Mkn 116 (Viallefond, Lequeux, & Comte 1987) and the relatively nearby starburst dwarf NGC 1705 (Melnick, Moles, & Terlevich 1985; Meurer et al. 1992), both of which contain massive young star clusters near their centers. The most massive young cluster known may be the 'super star cluster' in NGC 1705, which has an estimated mass of about $1.5 \times 10^6 \, M_\odot$, assuming a normal IMF (Meurer et al. 1992). Like the 30 Dor cluster, this luminous cluster is not isolated but is located in a region containing many young massive stars and clusters, and it is also centrally located in an extended filamentary H II region. NGC 1705 shows no evidence for barred structure or for interactions with other galaxies that might have been responsible for the accumulation of $10^8 \, M_\odot$ of gas near its center, but another effect that may cause gas to concentrate at the centers of dwarf galaxies like NGC 1705 is that these galaxies are gravitationally dominated by dark matter that has a very high central density (Kormendy 1990; Pryor 1992), and this dark matter provides a potential well within which the gas may become highly condensed before forming stars (Larson 1992b).

The luminous clusters in the starburst dwarf galaxies mentioned above have masses and sizes similar to those that might be expected for young globular clusters. Dwarf galaxies are also metal-poor systems, and I Zw 18 in particular has a metal abundance that is only about 1/40 of the solar value, typical of the

globular clusters in the Galactic halo. All of the evidence thus seems consistent with the possibility that the globular clusters in the Galactic halo were formed in protogalactic subsystems with properties similar to those of dwarf galaxies, as suggested by Searle and Zinn (1978) and as discussed further by Freeman and Zinn at this meeting (see also Larson 1990b, 1992b). To the extent that similarities exist in the properties of the various star-forming regions that have been discussed in this review, the formation of globular clusters might then be expected to share some similarities with the formation of clusters whose formation can be more directly observed. Some features of observed cluster formation that may be of general significance are summarized in the next section.

5. GENERAL FEATURES OF CLUSTER FORMATION

Although only a few regions of cluster formation have yet been studied in much detail, making generalizations hazardous, it may nevertheless be useful to summarize some possibly general features that are suggested by the evidence reviewed above. Accordingly, the following tentative conclusions are offered as hypotheses to be tested by further observations:

(1) *Star clusters form only in the dense cores of much larger star-forming complexes.* This conclusion is suggested by the fact that in all cases where sufficient information is available, newly formed clusters of stars are found to be embedded in, or closely associated with, the densest core regions of much larger molecular clouds or complexes. A local efficiency of star formation high enough to ensure the formation of a bound cluster appears to be attained only in regions where the gas density exceeds about 10^4 molecules per cm^3. Thus, understanding cluster formation requires understanding how a sufficiently large amount of gas can be compressed into a clump with at least this density.

(2) *The clouds in which clusters form appear to have been shaped and compressed by earlier episodes of star formation.* The evidence for this is clearest in the nearest and best studied regions of cluster formation, the Ophiuchus and Orion clouds, but similar phenomena may also have occurred elsewhere, for example in the W3–W4 region. The situation is less clear in extragalactic star-forming regions where the available information about cloud structure is much less detailed, but the strong dynamical effects of the earlier episodes of star formation are nevertheless evident from the filamentary distribution and the kinematics of the ionized gas in these regions. The compression of the residual gas into dense shells by such effects may play an important role in triggering the formation of massive clusters in these regions.

(3) *The formation of a dense bound cluster may be the culminating event in a region of star formation.* This suggestion, which is more speculative, is based on the fact that the earlier episodes of star formation in Ophiuchus and Orion have not left any bound clusters; the only candidates for young bound clusters in these regions are the most recently formed subsystems. The stars in the expanding associations produced by the earlier episodes of star formation cannot have originated in very small volumes of space (Blaauw 1991), and therefore they cannot have formed in clusters, even if unbound. Thus, dense bound clusters are apparently not the first things to form in a region of star formation, and

they may appear only after several previous episodes of star formation have already occurred. Such a delay would be consistent with the possibility that cluster formation occurs as a consequence of the effects of earlier episodes of star formation.

(4) *The efficiency of formation of bound clusters in star-forming clouds is very low, typically of the order of 10^{-3} to 10^{-2}.* For example, the Ophiuchus clouds contain about $10^4 \, M_\odot$ of gas, but the mass of the ρ Oph cluster is only of the order of $100 \, M_\odot$; since it is doubtful whether even this much mass will remain bound after the gas is dispersed, the efficiency of cluster formation in this region is probably less than 10^{-2}. In the Orion region, the total mass of molecular gas is about $2 \times 10^5 \, M_\odot$ while the mass of the Trapezium cluster is perhaps $\sim 400 \, M_\odot$, implying an efficiency of cluster formation of about 2×10^{-3}; in the 30 Doradus region, a similar efficiency is suggested by the fact that a cluster with a mass of the order of $10^5 \, M_\odot$ is forming in a complex containing about $10^8 \, M_\odot$ of gas (Larson 1988, 1990a). In the dwarf galaxies I Zw 18 and NGC 1705, the total mass of gas present is about $10^8 \, M_\odot$ while the mass of the central massive star cluster is about $10^6 \, M_\odot$, implying an efficiency of cluster formation of the order of 10^{-2}. The typical efficiency of $\sim 2 \times 10^{-3}$ estimated by Larson (1990a) for the formation of open clusters in our Galaxy is consistent with earlier estimates that only about 10% of all stars are formed in such clusters, since the overall efficiency of star formation is about ten times higher than this, or $\sim 2\%$.

There is a weak suggestion in these results that the efficiency of cluster formation may be higher in dwarf galaxies like NGC 1705 than in our Galaxy, i.e. $\sim 10^{-2}$ as compared with 2×10^{-3}, although this difference may not be significant, given the uncertainties. It may be relevant in this context that the Fornax dwarf spheroidal galaxy has an unusually high abundance of globular clusters. If globular clusters were formed in systems resembling dwarf galaxies, they may thus have formed with higher efficiencies than present-day open clusters. A relatively high efficiency of cluster formation is in any case required at early times to account for the evidence that the globular clusters in galaxies formed before most of the field stars, as was noted by Harris (1991) and again at this meeting.

(5) Even allowing for a higher formation efficiency, the evidence suggests that *the formation of massive globular-like clusters requires much larger gas complexes than are found in our Galaxy,* perhaps ones having masses of the order of $10^8 \, M_\odot$ or more. Some ways in which such very massive gas complexes might be formed have been mentioned above, and others have been suggested previously in the literature. They include:

(a) the dynamical effect of a bar in causing the gas in a galaxy to pile up at the ends or at the center of the bar (Kenney & Lord 1991), as may occur in the LMC and NGC 1569 (Meurer et al. 1992);

(b) the gravitational effect of the dark matter in dwarf galaxies in causing the gas to concentrate at the center (Larson 1992b), which might be important in non-barred isolated dwarfs like NGC 1705;

(c) galaxy mergers, as suggested by Schweizer (1987, 1992) and discussed at this meeting by Ashman, an example of which may be provided by NGC 1275 (Holtzman et al. 1992; Faber, this meeting); and

(d) gravitational instabilities in massive young gas disks, as suggested by Larson (1987, 1988) to account for the origin of the disk globular clusters in our Galaxy.

Clearly, much further work will be required to establish to what extent these mechanisms or others may be involved in the formation of massive globular-like clusters. Probably several different mechanisms are required to account for the formation of the globular clusters, since it seems clear from the large range of properties discussed at this meeting that they cannot all have formed in the same way.

6. SMALLER-SCALE PROCESSES

Little is yet known about the details of how clusters of stars form in dense molecular cloud cores, but this will be an important subject of study in the coming years. One reason for its importance is that some results of the star formation process, such as the occurrence and detailed properties of binary and planetary systems, are probably determined or influenced by the effects of protostellar interactions in dense environments (Larson 1990a; Pringle 1991; Heller 1991, 1993). Another very important result of star formation processes that is apparently established in forming systems of stars is the stellar initial mass function (Larson 1989, 1991, 1992a). Current evidence suggests that, at least for masses above one solar mass, the IMF has a universal power-law form that holds even on the scale of individual star clusters (Scalo 1986; Larson 1991; Mateo, this meeting). Since most star formation appears to occur in groups or clusters of some kind, an understanding of the origin of the IMF requires an understanding of the detailed processes that occur in forming clusters of stars.

Both individual stars and clusters appear to form only in parts of molecular clouds where the gas density is at least 10^4 molecules per cm^3. In the nearby dark clouds, the regions that collapse to form stars can be identified with the 'ammonia cores', which have average densities of $\sim 3 \times 10^4$ molecules/cm^3 or more (Myers 1987). In Taurus, this dense gas is mostly distributed in scattered small clumps, whereas in Ophiuchus it is mostly concentrated in the ρ Oph cloud. A physical distinction appears to exist between the star-forming ammonia cores and the surrounding diffuse envelopes in that in the cores, gravity is resisted mainly by thermal pressure, whereas in the envelopes 'non-thermal' effects such as turbulence and magnetic fields predominate (Fuller & Myers 1992; Myers & Fuller 1992). The loss of turbulent energy by dissipation and the loss of magnetic energy by ambipolar diffusion may be crucial in allowing the cores to collapse into stars (Shu et al. 1987), but the collapse of the surrounding envelopes may be inhibited because ambipolar diffusion is much slower at the lower densities of the envelopes (Mouschovias 1990). Thus, star formation probably involves the segregation of the gas in molecular clouds into dense, quiescent, weakly magnetized cores that collapse into stars, and diffuse, turbulent, strongly magnetized envelopes that remain behind (Mouschovias & Morton 1992). The formation of the dense star-forming cores may occur spontaneously, or it may be triggered or accelerated by external compression (Elmegreen 1992).

In such a picture, clusters of stars will form if the dense star-forming cores are themselves strongly clustered. This might occur if cores that were originally

formed in a more dispersed fashion are somehow aggregated (Myers 1991), or if a dense molecular clump is somehow built up and then fragments into star-forming cores. In either case, analogies might exist with other kinds of aggregation or growth processes in nature, which often produce complex fractal-like structures (Meakin 1986). There is in fact evidence that molecular clouds possess self-similar or fractal structures over a wide range of scales (Scalo 1990; Falgarone & Phillips 1991; Falgarone, Phillips, & Walker 1991), so it is possible that the dense regions in which clusters form also have fractal structures, possibly filamentary in nature. If stars and groupings of stars form from such fractal cloud structures, for example if they from the filaments of a fractal network, this self-similarity of the initial conditions might result in a scale-free or power-law form for the stellar initial mass function. With simple assumptions, the observed universal slope of the upper IMF can in fact be accounted for in this way (Larson 1992a).

It seems clear, in any case, that processes occurring in forming clusters of stars are important in determining some of the basic properties of stars, and therefore a better understanding of the details of cluster formation should eventually lead to a better understanding of how these basic properties of stars, such as the stellar mass spectrum and the occurrence of binaries, are related to the properties of the larger systems in which they form.

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