FORMATION OF STAR CLUSTERS

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ABSTRACT. Star clusters are the smallest systems in which the processes that generate a spectrum of stellar masses can be studied, and they may be of particular interest as the birth sites of the most massive stars. Observations suggest that bound clusters form in the densest core regions of giant molecular clouds, the best studied example being the Trapezium cluster in Orion. The efficiency with which giant molecular clouds form bound star clusters is estimated to be approximately 2×10^{-3}, about one-tenth of the overall efficiency of star formation. The high local efficiency of star formation that is necessary to form a bound cluster, as well as the apparent preferential formation of massive stars in such environments, may result from protostellar interactions like tidal effects that cause enhanced accretion from residual circumstellar disks onto forming stars. Another effect of interactions may be the formation of binary systems by captures resulting from the gravitational drag produced by protostellar disks; this mechanism might account for a significant fraction of binaries, and for the observed distribution of mass ratios in binaries. Similar gravitational drag effects acting on larger scales may account for the formation of highly condensed clusters of stars with central subgroups of massive stars.

1. Introduction

Star clusters are of fundamental interest for many reasons, among which are that they are good tracers of stellar populations in galaxies; they serve as fossils that can be used to reconstruct the history of stellar systems; and they provide an observational foundation for our current understanding of stellar evolution. In the context of this meeting, they are of interest as the smallest systems in which the processes that give rise to the stellar Initial Mass Function can be studied. It has often been noted that the mass spectra of stars in open clusters are similar, at least for masses above one solar mass, to the IMF of field stars (e.g., Scalo 1986; Mateo 1988, and this volume). It is therefore important to understand the mechanisms that determine the mass spectra of stars in clusters, since they are probably of quite general importance.

Processes occurring in nascent star clusters may be especially important for the formation of the most massive stars, which appear to form in a more spatially confined fashion than low-mass stars; they may in fact form preferentially in clusters, since it is possible that the IMF for the most massive stars declines less steeply with mass in clusters than in the field (Scalo 1986). There is also suggestive evidence that more massive stars

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tend to form in larger groups and in denser environments than less massive stars; for example, in the Taurus clouds, the T Tauri stars have a median mass of only ~ 0.6 $M_\odot$ and are distributed in scattered small groups, whereas in Orion and NGC 2264, the T Tauri stars are mostly more massive than 1 $M_\odot$ and are mostly located in larger, more condensed clusters (Larson 1982). In the Orion cluster, the more massive T Tauri stars appear to be more centrally concentrated than the less massive ones; most strikingly, the Trapezium, which contains the most massive grouping and the most massive single star in the entire Orion region, is located right at the center of the Orion cluster. Infrared array photographs of other regions of star formation have revealed additional examples of dense groupings of young stars with centrally located massive stars, an example being the S106 cluster (Zinnecker, this volume). Scaled-up versions of the Orion cluster with its central multiple system of massive stars are also found in the Galactic HII region NGC 3603 and in the 30 Doradus nebula of the Large Magellanic Cloud, each of which contains a large, centrally condensed young cluster with a central multiple system of very massive stars (Moffat, Seggewiss, and Shara 1985; Baier, Ladebeck, and Weigelt 1985; Weigelt and Baier 1985).

It is probable that the most direct outcome of the fragmentation of molecular clouds is the formation of low-mass stars, and that they form by the collapse of small clumps or cloud cores of comparable mass (Larson 1985). The formation of massive stars may, on the other hand, be a secondary process resulting from the continuing accretion of residual gas by forming stars in favorable locations, such as the cores of large clusters (Larson 1982, 1986). In the following sections, we consider some of the processes that might contribute to the formation of dense bound clusters of young stars, and to the formation of massive stars and binary and multiple systems in them.

2. Observations of Young Clusters and Their Birthplaces

Nearly all stars form in groups or associations of some kind, but only the densest known systems of young stars, which are actually the cores of larger associations, seem likely to survive as bound clusters. The essential requirement for survival as a bound cluster is a high local efficiency of star formation: at least half of the gas initially present must be turned into stars if the residual gas is removed rapidly, although a somewhat lower star formation efficiency of ~ 30 % will suffice if the gas is removed slowly (Wilking and Lada 1985).

In the Taurus clouds, the stellar density is low, and the efficiency of star formation is only a few percent (Jones and Herbig 1979; Myers 1982); therefore the groups of young stars that are observed in the Taurus clouds are very unlikely to survive as bound clusters after the gas is removed. A more promising candidate for a young open cluster is the much denser system of ~ 80 young stars embedded in the core of the ρ Ophiuchus cloud (Wilking, Lada, and Young 1989); however, even in this case the efficiency of star formation is only about 20 %, so it is not clear whether a bound open cluster will survive. The best known candidate for a very young (and still forming) open cluster is probably the exceedingly dense and partly obscured cluster of several hundred young stars around the Trapezium, which forms the core of the much larger Orion association (Herbig and Terndrup 1986). Infrared array photographs have greatly increased the number of known stars in the Trapezium cluster, many of which are invisible optically; this strengthens the conclusion of Herbig and Terndrup that this is the densest known system of young stars (McCaughrean 1989; Zinnecker, this volume). About 500 stars are now known within about 0.4 pc of the Trapezium, and the density of stars in the core region within 0.1 pc of the Trapezium may exceed 10^4 stars per pc^3. The total mass of the stars in the Trapezium cluster is comparable to or larger than the mass of gas in the same region, which is a few hundred $M_\odot$; therefore this cluster has a good chance of surviving as a bound open cluster. The velocity dispersion of about 1.5 km/s measured for the stars near the Trapezium (van Altena et al. 1988) is consistent with this cluster (including gas) already being in virial equilibrium, and implies a total mass of ~ 500 $M_\odot$ within a radius of 0.4 pc. The Trapezium cluster is presently exceptionally compact, but after losing its gas and some massive stars which appear to be escaping from it (van Altena et al. 1988), it will probably expand considerably to become a more typical open cluster.

Infrared array photographs show that the more massive and distant M17 molecular cloud also contains an embedded cluster, larger and even more heavily obscured than the Trapezium cluster (Gatley, De Poy, and Fowler 1988). These examples and others (E.A. Lada, this volume) suggest that the birthplaces of open clusters are the dense core regions of massive molecular clouds like the Orion cloud and the M17 cloud. The most outstanding characteristic of these cores, and the one that seems to be essential for the formation of a bound star cluster, is their combination of high mass and high density: in the OMC1 core region of the Orion cloud, more than 10^3 $M_\odot$ of gas is contained in a region whose average density exceeds 10^4 molecules per cm^3, while in the M17SW core region of the M17 cloud, 10^4 $M_\odot$ of gas is contained in a region of similarly high average density (Larson 1981). A related property of OMC1 and M17SW is that they both have unusually large internal velocities for their sizes (Larson 1981).

How are such massive and dense cloud cores formed? Almost certainly, strong dissipation of the internal motions in at least part of a giant molecular cloud is required; also, loss of some of the magnetic energy contributing to the support of the cloud may be required. The observed cometary shapes of both the ρ Ophiuchus cloud and the Orion A cloud suggest that interaction with a surrounding medium is another effect that exerts an important influence on the structure and evolution of these clouds. In both cases, the dense core containing the cluster of newly formed stars constitutes the head of the "comet", and long filamentary streamers emanate from it in one direction to form the tail. Detailed CO maps of the Orion A cloud give the strong impression that hydrodynamic interaction with a wind or expanding superbubble blowing past the cloud has played a role in generating its intricately filamentary structure, and may also have laterally compressed the filaments (Bally et al. 1987). As noted by these authors, a likely source for such a wind would be the older part of the Orion OB association which lies just beyond the head of the comet. Similar cometary shapes were obtained in a numerical simulation by Woodward (1978) of an interstellar cloud swept over by a shock in the intercloud medium; in this calculation, a dense clump of gas was formed at the head of the cloud, partly by lateral compression.

The Trapezium cluster is located at the center of the most massive and prominent filament in the Orion cloud, a narrow ʃ-shaped structure forming the head of the comet, which also contains a string of dense clumps (Batrla et al. 1983; Wilson and Johnston 1989). The large velocity gradient along this filament suggests that rotation is important in it (Bally et al. 1987), and the spiral shape of the filament suggests that gravitational torques may help to redistribute angular momentum within it and thus allow gas to collect at its center and form a cluster of stars there; indeed, the entire structure bears some resemblance to a barred spiral galaxy.

Clearly, many complex processes must have played a role in the formation of the Trapezium cluster, and little is yet understood about how such clusters are formed. One effect that may often be involved is that external compression of a molecular cloud may indirectly trigger the formation of a star cluster by helping to dissipate the turbulent and magnetic energy that support the cloud against collapse (Elmegreen 1989). The filaments in the Orion cloud may represent regions in which such dissipation has been particularly effective.

3. Efficiency of Cluster Formation

Given the complexities involved, an understanding of cluster formation is probably best approached empirically rather than theoretically at present. Accordingly, it is important to try to establish from the available data some of the systematic characteristics of cluster formation, such as the efficiency with which molecular clouds form bound clusters.

The total amount of molecular gas in the Orion A cloud containing the Trapezium cluster is about 10^5 $M_\odot$, and another 10^5 $M_\odot$ of molecular gas is located in the associated Orion B cloud, which contains a number of smaller embedded clusters (E. A. Lada, this volume). Of these clusters, only the Trapezium cluster seems likely to survive for a long time as a bound open cluster, so the surviving cluster mass will probably be a few hundred $M_\odot$. Thus in the Orion region, the efficiency of conversion of molecular gas into bound clusters appears to be of the order of $(1 - 2) \times 10^{-3}$. The M17 cloud is somewhat more massive than the Orion complex, and it may also be forming a somewhat more massive cluster; this would be consistent with its having a similar efficiency of cluster formation. On a much larger scale, the efficiency of cluster formation in the 30 Doradus region may also be of the order of 10^{-3}, since both the total mass of gas in this region and the estimated cluster mass are about two orders of magnitude larger than in Orion (Larson 1988).

We can also use estimates of the cluster formation rate in the solar neighborhood to derive the cluster formation efficiency. According to Elmegreen and Clemens (1985), the mass spectrum of open clusters is approximately a power law with the same slope as the mass spectrum of molecular clouds; this fact is consistent with the hypothesis that, on the average, molecular clouds with different masses convert the same fraction of their mass into bound clusters. Most molecular clouds probably do not form more than one cluster large enough to contain O stars, since the formation of such a cluster rapidly leads to the destruction of the cloud: observations show that molecular clouds are largely dispersed within $\sim 5 - 10$ Myr after forming a typical open cluster (Leisawitz, Bash, and Thaddeus 1989). The rate of formation of open clusters in the local Galactic disk has been estimated to be roughly 0.4 clusters per kpc^2 per Myr (e.g. Miller and Scalo 1978; Elmegreen and Clemens 1985; Battinelli and Capuzzo-Dolcetta, this volume). This is about equal to the rate of formation of molecular clouds with masses greater than 10^5 $M_\odot$, assuming a typical cloud lifetime of 20 Myr (Larson 1981). Since a typical open cluster mass is a few hundred $M_\odot$, this result suggests a typical cluster formation efficiency of a few times 10^{-3}. As noted by Battinelli and Capuzzo-Dolcetta, however, some of the clusters included in this estimate are likely to be unbound and may not survive for a long time.

Thus, on the basis of somewhat limited evidence, we estimate that the efficiency of formation of bound clusters in molecular clouds is of the order of 2×10^{-3}. This is an order of magnitude smaller than the overall efficiency of star formation, which is typically estimated to be about 0.02 (e.g., Myers et al. 1986). This difference is consistent with earlier estimates that about 10 percent of all stars are formed in open clusters (e.g., von Hoerner 1968; Miller and Scalo 1978). An important implication of this result for the conditions under which stars form is that at least 10 percent of stars must form in regions where the local efficiency of star formation is quite high, i.e. of order 1/2 or more; as we have seen, observations suggest that such efficiencies are achieved only in the very densest parts of giant molecular clouds.

The above considerations apply to open clusters forming in giant molecular clouds like those observed nearby, but they may also apply more generally to massive clusters such as those in the Magellanic Clouds (including the 30 Doradus cluster), and even to globular clusters. In fact, our current knowledge of cluster systems in galaxies does not indicate any sharp distinction between globular and open clusters, so there is no reason to suppose that globular clusters form in a fundamentally different way from open clusters. If a low efficiency of cluster formation such as that inferred above also applies to globular clusters, this would imply that the globular clusters in our Galaxy formed as parts of much larger star-forming systems with masses of 10^8 $M_\odot$ or more, which may have resembled dwarf galaxies and which may have constituted the building blocks of the Galactic halo (Larson 1988).

4. Protostellar Interactions in Dense Clusters

What physical mechanisms might produce a very high efficiency of star formation in dense environments? And how might we understand the apparent preferential formation of massive stars in dense regions? A high efficiency of star formation and larger typical stellar masses could both be explained if the efficiency with which residual cloud gas is accreted by forming stars were strongly enhanced in dense environments. This could result, for example, from the effect of protostellar interactions in redistributing angular momentum in flattened protostellar envelopes or disks, thus causing enhanced accretion onto the central stellar cores (Larson 1982). For example, hydrodynamic interactions might create turbulence in protostellar disks and thereby provide a source of viscosity to drive accretion. Another possibility is that tidal perturbations may trigger episodes of enhanced accretion from such disks (Larson 1982). Tidal effects are, in fact, known to play an important role in driving gas inflows in the disks of spiral galaxies and in triggering bursts of star formation near their centers.

Considerable evidence now exists that at least low-mass young stars often possess residual circumstellar disks with radii of order 100 AU or more and masses of order 10^{-2} to 10^{-1} $M_\odot$ (Strom, Edwards, and Strom 1989; Sargent 1989). Many of the unusual characteristics of the more extreme T Tauri stars may be caused by accretion from such disks, and in fact accretion is the most plausible energy source for the bipolar outflows that are almost ubiquitously present around young stellar objects. Disk accretion would then be an important part of the star formation process itself, adding a significant fraction of the final mass to a forming star. The evidence indicates that gaseous protostellar disks are largely accreted or otherwise removed from around young stars over a time interval that is typically between 10^6 and 10^7 years.

In binary systems containing disks, a possible mechanism for driving an accretion flow is the tidal excitation of spiral shock waves in the disk (Sawada et al. 1987; Spruit et al. 1987; Rozyczka and Spruit 1989). In a forming binary system, this mechanism should be very effective in causing accretion or dispersal of any residual disk gas that experiences strong tidal effects. However, even for a single star with a remnant circumstellar disk, tidal encounters with passing stars can disturb the disk and generate spiral acoustic waves in it, possibly with shocks, just as tidal interactions between galaxies can generate spiral density waves in galactic disks (e.g. Byrd, Saarinen, and Valtonen 1986). For a steady two-armed spiral shock pattern in a disk, the accretion rate has been calculated numerically by Spruit (1987) and from wave theory by Larson (1989); for a typical protostellar disk, the resulting accretion timescale is about 10^6 years at a radius of 1 AU and 10^7 years at a radius of 40 AU. Therefore tidally induced spiral waves of sufficient strength and duration can, at least in principle, disperse protostellar disks in the timescales inferred from observations.

In order to drive an accretion flow, a tidally generated acoustic wave must be strong enough to contain a shock, and this requires that its velocity amplitude exceed about 0.14 times the sound speed (Larson 1989). For a protostellar disk heated by the central star, it can be shown that in order to generate tidal disturbances of this amplitude, a perturbing star of comparable mass must pass within about 5 disk radii. In a dense environment like the Trapezium cluster, such close encounters will be frequent (Herbig 1983; Herbig and Terndrup 1986), especially if some disks have radii exceeding 1000 AU like the disk of HL Tau (Sargent and Beckwith 1987). For example, in the core of the Trapezium cluster, most of the stars will pass within 300 AU of another star at least once during the cluster age of ~ 1 Myr, and about 30 % of the stars will pass within 100 AU of another star; this is close enough to strongly disturb a disk of solar-system size. Thus in such an environment, encounters may well be sufficiently close and frequent to play an important role in the evolution of protostellar disks, and so to increase the rate at which gas is accreted by forming stars. This would increase both the efficiency of star formation and the typical stellar mass, in accordance with the evidence discussed in Sections 1 and 2.

Possible evidence that tidal effects can result in the removal of protostellar disks is provided by the fact that, while the frequency of binaries is normal among the weak-lined T Tauri stars, few close binaries have been found among the strong-lined T Tauri stars whose properties may reflect the presence of disks (Herbig 1989; Mathieu, Walter, and Myers 1989). Thus there may be an anticorrelation between binarity and the presence of disks around young stars, as would be expected if tidal effects in binaries act to disperse disks. Herbig and Terndrup (1986) have also noted that the low-mass stars in the Trapezium cluster appear to be as young as typical T Tauri stars, but few of them actually show strong T Tauri characteristics; a possible explanation would be that circumstellar disks have already been largely removed from these stars by tidal interactions with neighboring stars.

5. Formation of Binaries by Capture

The passage of a star close to or through a protostellar disk surrounding another star will also generate a gravitational drag effect that can cause it to be captured into a bound binary orbit. In effect, the presence of residual disks around young stars greatly increases the cross section for the capture formation of binaries, and may make this an important mechanism of binary formation. To the extent that binary and multiple systems may be viewed as the smallest "star clusters", similar processes may also play a role in the formation of larger condensed stellar systems as well (see Section 6).

The detailed calculations of Shima et al. (1985) show that the deceleration experienced by a body of mass M moving with supersonic velocity V through a uniform medium of density ρ is given to within about 30 percent by

$$dV/dt \sim -12\pi G^2 M\rho / V^2.$$

The resulting decrease in velocity is proportional to the column density of matter traversed; for example, an object passing perpendicularly through a disk of surface density μ has its velocity changed by an amount

$$\Delta V \sim -12\pi G^2 M\mu / V^3.$$

The disk surface density μ can be estimated if we adopt a model for the disk, for example a marginally self-gravitating disk with $Q = 2$, as considered by Larson (1983, 1984). Such a disk contains about one-third of the mass of the central star in a region the size of our Solar System; since this is more mass than is typically observed in protostellar disks, we take as a more representative example a disk with the same radial structure but with only one-tenth the mass of the central star in a region of this size. If a star of mass M_2 passes on a nearly parabolic orbit through such a disk at a distance r from a central star of mass $M_1 > M_2$, its velocity is changed by

$$\Delta V \sim -(M_2/M_1)\, c(r),$$

where $c(r)$ is the sound speed at radius r in the disk. For a disk heated by the central star, as assumed by Larson (1983, 1984), it can then be shown that capture into a bound orbit will occur if the two stars pass within a capture radius that is given approximately, and almost independently of M_1, by

$$r_{\text{cap}}(\text{AU}) \sim 350\, M_2(\text{M}_\odot)^{4/3}\, V(\text{km/s})^{-8/3},$$

where V here denotes the relative velocity at infinity. This result shows that if V is not too large, capture will often occur when a star passes through a protostellar disk around another star. For disks with the same radial structure but different masses, the capture radius scales as the 4/3 power of disk mass.

The total cross section for captures is dominated for close encounters by the gravitational focusing effect, and is approximately

$$\sigma \sim 2\pi\, GM_1\, r_{\text{cap}} / V^2.$$

The capture rate Γ per star, allowing that two stars are involved in each capture, is

$$\Gamma = 2 \int N(V)\sigma(V) V dV$$

where $N(V)$ is the number density of stars as a function of relative velocity V. For a Maxwellian velocity distribution, this integral diverges weakly for small relative velocities and large capture radii, but if we assume a maximum capture radius of order 500 AU, the result is

$$\Gamma \sim 21\, GM_1 N\, r_{\text{cap}}(V_0) / V_0$$

where N is the total number density of stars and V_0 is the one-dimensional stellar velocity dispersion. As an example, if we assume that $M_1 = M_2 = \text{M}_\odot$ and adopt $N \sim 10^4$ pc^{-3} and $V_0 = 1.5$ km/s, as appropriate for the core of the Trapezium cluster, we obtain a capture rate per star of

$$\Gamma \sim 0.4\ \text{Myr}^{-1}.$$

This result must be regarded as only an order-of-magnitude estimate, but it does suggest that within the ~ 1 Myr age of the Trapezium cluster, an appreciable fraction (of order 40%) of the stars in the core of this cluster may be captured into binaries. Because of the many uncertainties involved in such an estimate, including the lack of any specific information about disks in dense environments and the lack of a proper treatment of the hydrodynamics of protostellar interactions, it remains unclear whether capture with disks is an important mechanism of binary formation, but this possibility at least seems worth further attention.

Binary systems formed by random captures such as those considered above would typically be quite wide and eccentric, with separations of the order of tens or hundreds of AU; close binaries with separations < 1 AU would not be formed directly in significant numbers by such a process. However, if disks are not immediately destroyed by the encounters and if significant disk material remains present for several orbital periods following a capture, continuing gravitational drag will shrink the orbits of binaries formed by capture; detailed numerical simulations will be needed to study this effect. Another likely possibility is that the stars in a young cluster do not form with random positions and velocities, but in compact subgroups that have relatively small internal motions; such subgroups would provide an especially favorable environment for close encounters and captures, and if the initial stellar velocities are sufficiently small, very close binaries could be formed. Subclustering is, in fact, almost ubiquitously observed in regions of star formation, but a more detailed knowledge of its properties will be needed to evaluate its possible importance for the formation of binary and multiple systems.

Meanwhile, we note that the distribution of mass ratios of binaries formed by capture can be predicted if the radial distribution of surface density in the capturing disks is known. The above approximate equations imply that for any primary mass M_1, the capture rate for stars of mass $M_2 < M_1$ is proportional to the capture radius $r_{\rm cap}$, which in turn is proportional to $M_2^{4/3}$; in fact, a detailed calculation shows that a capture rate more nearly proportional to M_2 is found if a maximum capture radius of order 500 AU is assumed, as before. If stars are captured randomly from a Salpeter mass spectrum with $N(M_2) \propto M_2^{-7/3}$, the total capture rate per unit M_2 is then proportional to $M_2^{-4/3}$. This implies a distribution of mass ratios $q = M_2/M_1$ of the form

$$N(q) \propto q^{-4/3}.$$

This result is valid if the radial distribution of surface density in the disk is $\mu \propto r^{-7/4}$, as appropriate for a marginally self-gravitating disk; if instead we adopt $\mu \propto r^{-3/2}$, as assumed in some models of the solar nebula (e.g. Nakano 1987), the capture rate becomes approximately proportional to $M_2^{3/2}$, and the predicted distribution of mass ratios becomes

$$N(q) \propto q^{-5/6}.$$

Both of these predictions are consistent with a recent analysis of the data for a large sample of spectroscopic binaries by Trimble (1989), which yields approximately $N(q) \propto q^{-1}$. Qualitatively, the essential prediction is that the distribution of mass ratios should be flatter than the stellar initial mass spectrum, since the gravitational capture cross section increases with stellar mass.

If gravitational capture is an important mechanism of binary formation, then the fact that the capture rate per star Γ is proportional to both the primary mass M_1 and the density of stars N suggests, assuming similar disk properties, that binary formation should occur most frequently among the most massive stars and in the densest environments. The presence of Trapezium-like multiple systems of massive stars, several of which themselves may be close binaries, at the centers of several young clusters may exemplify both of these effects. It has long been recognized that the most massive stars are rarely found in isolation (e.g. Blaauw 1964), which suggests that they form almost exclusively in binary and multiple systems, although Abt (1983) notes that the frequency of binaries is not a strong function of stellar mass. At present there does not seem to be any evidence that the frequency of binaries depends on environment, but this possibility may be worth further investigation. If no strong dependences are found, a possible reason might be that the binary formation process tends to saturate with the eventual destruction of the capturing protostellar disks.

6. Evolution of Protoclusters

Gravitational drag effects similar to those discussed above may also play a role in the formation of larger condensed systems of stars, including open clusters and even globular clusters. The essential effect of gravitational drag in a system of forming stars is to dissipate orbital kinetic energy, and thus to cause the system to shrink. The capture formation of binaries will itself cause some dynamical cooling and contraction of a forming cluster, since the kinetic energy of relative motion of the encountering pairs is removed from the cluster when binaries form. Moreover, even if capture does not occur, encounters between stars with disks will still be "sticky" and will dissipate some of the kinetic energy of relative motion, causing the whole system to contract. The residual gas need not even be in disks to have this effect, since the gravitational drag experienced by a star depends only on the column density of matter traversed, and not on its spatial distribution.

The gravitational gas drag effect discussed above is essentially similar to the "dynamical friction" effect of stellar dynamics, by which the more massive stars in a cluster are slowed down via gravitational interaction with a background of less massive stars. Both dynamical friction and gas drag result in a deceleration that is proportional to the stellar mass and to the average density of the material causing the drag. Gas drag and dynamical friction will in fact operate together in a forming cluster of stars, and just as in stellar dynamics, the net effect will be strongest for the most massive stars, which as a result will rapidly lose energy and sink toward the center of the cluster. However, unlike dynamical friction, gas drag removes energy from the orbital motions of all of the stars and not just the more massive ones, and this will tend to make the whole system contract. Since the drag effect increases with increasing matter density, the result may be the runaway development of a compact, very dense core (or cores), just as happens in a dynamical collapse. It would then seem almost inescapable that the end result of the processes that have been discussed will be the formation of a highly condensed cluster dominated by a compact central subgroup of massive stars, as is observed in the young clusters mentioned in Section 1.

From the equations given in Section 5, it can be estimated that the timescale for loss of orbital energy due to gravitational drag in the core of the Trapezium cluster is roughly 0.5 Myr for a one-solar-mass star; for more massive stars, this timescale varies inversely with stellar mass. Thus there appears to have been time within the ~ 1 Myr age of the Trapezium cluster for gravitational drag to have produced a much more centrally concentrated mass distribution, especially for the more massive stars.

If star formation typically begins in small dense subclusters, then gravitational drag could also play a role in causing these subsystems to merge into a single larger and more condensed system of stars, much as mergers of small galaxies can play a role in the formation of larger galaxies. Gravitational drag would in fact be much more effective for groups or subsystems of stars than for single stars, because of their much larger masses. It is also possible that such processes could lead to the formation of a hierarchy of subsystems of different sizes; results suggestive of such a hierarchy of subsystems, sometimes dominated by central massive objects, were found in some of the simulations of collapse and fragmentation of Larson (1978). Although these calculations were intended to follow gas dynamics, the formation of condensed objects soon caused gravitational drag effects to become important for the evolution of the system, and to play a significant role in the formation of the binary and multiple systems that frequently resulted.

Although no simulation of the formation of a large cluster of stars has yet been attempted, some of the qualitative features of such a process might resemble the formation of a cluster of galaxies as simulated using standard N-body techniques by West and Richstone (1988). In these calculations, the galaxies are represented by massive particles and the dominant dark matter is represented by a much larger number of low-mass particles; the massive particles then experience a strong dynamical friction effect. Starting from random initial conditions, the calculations show the formation first of a number of subclusters with massive particles concentrated toward their centers; subsequently these subclusters merge into a single relatively symmetrical and highly centrally condensed system in which the more massive particles are strongly concentrated at the center. These results bear a strong resemblance to the distribution of young stars in regions of star formation: as in the simulations, subgroups like the NGC 1999 group in Orion are often seen, and large clusters tend to have compact central subsystems of massive stars and extended halos of low-mass stars, like the flare stars in Orion (Larson 1982). Gas drag would of course further accentuate the formation of compact subsystems beyond what is found in such purely stellar-dynamical simulations. However, continuum hydrodynamics alone, without assistance from the gravitational drag effect that becomes important when stars or groups of stars begin to form, may not suffice to generate such extremely condensed structures. One may then speculate that the interplay between gas dynamics and particle dynamics that results in the sticky stellar dynamics discussed above may be the essential effect responsible for the formation of very dense stellar systems ranging all the way from binary systems through open and globular clusters to the dense cores of large galaxies.

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DISCUSSION

Zinnecker: I wonder whether the criterion for the formation of bound clusters is as stringent as you indicated, i.e. a star formation efficiency greater than 50%. I am thinking of expanding OB associations whose cores nevertheless appear bound.

Larson: A star formation efficiency of 50% is not a strict requirement, since an efficiency of ~ 30% will suffice if gas removal is gradual, as I indicated in the written version of my talk. This is still much higher than the observed *overall* efficiency of star formation in most associations, so that they cannot remain bound. However, a dense core can survive as a bound cluster if the *local* efficiency of star formation in the core is sufficiently high.

Mouschovias: Even in a dense cluster like the Trapezium cluster, can captures result in anything but very wide binaries? How short a binary period can captures explain, according to your estimate?

Larson: Random captures in an environment like the Trapezium cluster will yield mostly wide binaries with typical separations of the order of 100 AU, assuming that protostellar disks of this size are present. Since the capture cross section is proportional to the distance of closest approach, I would guess that only ~ 1% of directly formed capture binaries would have separations as small as 1 AU. However, if the disk material is not immediately removed, continuing gravitational drag could shrink the orbits of binaries formed by capture. Another, perhaps more promising, way to make close binaries might be in fragmenting clumps or filaments whose angular momentum is small (perhaps because of magnetic braking).

Mateo: What if already existing binaries interact with a third star – will this provide a way to form closer binaries?

Larson: I have not looked into this, but it seems entirely possible. In a star cluster, such effects will tend to shrink the orbits of binaries that are more tightly bound than the cluster; this would in fact be the case for many capture binaries.