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Dynamics of embedded protostar clusters in clouds

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ABSTRACT

The dynamics of clumps and protostars in a young protocluster system embedded in its parent molecular cloud are studied here through numerical simulations. It is found that the presence of massive clumps and their dynamics strongly affects the motion of the lower mass protostars. Mass segregation of clumps due to dynamical drag by the interclump gas results in the formation of a dense central region, and the lower mass protostars are preferentially ejected out of the cloud via gravitational encounters. The protostellar cluster is found to expand gradually with time, forming a more extended system than the clumps. Thus, embedded protostar clusters are probably dynamically evolved systems with large haloes of low-mass protostars. This explains observations of T Tauri stars, which appear to be isolated from active star-forming sites and are in regions devoid of dense gas. Since multiple star formation sites in clouds are common, outer members are subject to velocity perturbations due to massive clumps and other clusters, possibly leading to a faster removal of objects.

Key words: stars: pre-main-sequence – ISM: clouds – ISM: kinematics and dynamics.

1 INTRODUCTION

Molecular clouds are known to be the sites of star formation in the Galaxy. The warm and massive giant molecular cloud (GMC) complexes and their constituent substructures (e.g. Orion) harbour regions of both low- and high-mass star-forming activity, whereas the relatively cooler and less massive dark cloud complexes (e.g. Taurus-Auriga, ρ Oph) form predominantly low-mass stars. Molecular clouds seem to have structure on all length-scales and are hierarchically organized, with dense regions embedded in less dense gas. These dense regions or clumps have within them highly dense condensations which may again be structured (e.g. Genzel 1992 and references therein). There is increasing evidence (e.g. Lada 1991) that the actual star formation in a cloud proceeds in its densest regions (called cores), which collapse under gravity to form stars.

Observations of star-forming regions indicate that stars form in either clusters of associations (e.g. Trapezium, ρ Oph, etc.), or even in relative isolation (e.g. star formation in Bok globules). Isolated star formation is, however, not as prevalent, with most Galactic molecular clouds forming clusters or loose associations. The cluster mode appears to be dominant – a significant fraction of the high- and low-mass stars in both the warm GMCs and the dark clouds are found in dense compact clusters (e.g. the Trapezium cluster and the ρ Oph cluster). Stars also form in loosely bound groups or associations, such as the OB associations and the T associations of low-mass stars. These groups are perhaps hierarchically organized structures, with subgroups of stars, and are clustered on larger scales (see Larson 1995). Thus the mode of formation is apparently determined by the pre-natal environment of the cloud and it reflects the physical properties of the clouds.

Although most star formation is in an aggregated mode, few such clusters eventually survive the disruption of the molecular cloud to remain bound, as only about 10 per cent of stars in the Galaxy are found in bound open clusters. The early dynamical evolution of a protostellar cluster has been studied in some detail, both analytically and numerically, by various authors. The main emphasis of most of these works was on the gas removal process (e.g. Elmegreen 1983; Mathieu 1983; Lada, Margulis & Dearborn 1984; Verscheuren 1990). The dynamical evolution of an embedded star cluster, as it begins to disperse the molecular material surrounding it, was studied numerically by Lada et al. (1984). They found that the stellar winds from the cluster members, and other disruptive radiative effects of the young stars, serve to weaken the central gravitational potential of the cloud via gas dispersal, which causes a decrease in the binding energy of the cluster. The cluster thus gradually expands and, if the loss in gravitational potential is high enough, the cluster becomes unbound. Therefore the formation of a bound cluster is determined by the amount of mass contained in the stars. The star formation efficiency (SFE) of a cloud (i.e. the fraction of the total core mass converted into stars during the star formation process), for different gas dispersal mechanisms, that is needed to form a bound cluster has hence been found to lie between 30 and 50 per cent. Inclusion of magnetic fields means that a lower SFE is required for the emergence of a bound cluster (Elmegreen & Clemens 1985; Verscheuren 1990).

Most of these studies, however, consider the evolution of the embedded protocluster subsequent to star formation as a cluster of stars in a homogeneous medium. Molecular clouds are known to be highly inhomogeneous structures consisting of dense concentrations of gas, and these cores could influence the dynamics of the embedded protostars, even prior to gas dispersal. The dynamics of protostellar cores in molecular clouds was studied by Gorti & Bhatt (1995, hereafter GB95), who found that dynamical drag due to the interclump gas causes a spatial segregation of mass along with a central clustering of the clumps of highest mass. This paper studies the effects of gas drag and the dynamics of the clumps on protostars in a young protocluster through numerical simulations, the main aim being to understand the dynamical evolution of the protostellar system. It is found that the presence of massive clumps and their dynamics in the cluster-forming region strongly affects the motion of the lower mass protostars. The protostar cluster expands in the course of its dynamical evolution and a few of the lowest mass objects are ejected out of the cloud via gravitational encounters. This may explain the observations of the so-called 'isolated' T-Tauri stars seen in maps of star-forming clouds, which appear to be located far from active star-forming sites (Scalo 1990). These stars, apart from their spatial separation, are found to be in low-density regions, contrary to expectations of star formation theories which require association with dense gas (de La Reza et al. 1989). They are also found to be too young to have drifted to their present positions from a neighbouring star cluster, assuming drift velocities of the order of the internal stellar velocity dispersion in the cluster which is typically $\lesssim 1$ km s^{-1}. Here, we propose that these stars have been ejected from their formation sites in dense regions by N-body interactions with other clumps and stars in the cloud. The implications of the results on the apparent SFE of the cloud and further evolution of the protocluster are discussed briefly.

2 EMBEDDED PROTOCLUSTER

2.1 Mathematical model

In our analysis, we adopt a simplified model for the molecular cloud and the embedded protocluster. A molecular cloud is presumed to consist of two distinct components: the high-density clumps and the tenuous interclump medium (hereafter abbreviated as ICM). The clumps are modelled as spherical particles that move through the smoothly distributed ICM. The ICM is treated as a homogeneous substrate of gas distributed according to a Plummer density profile, given by

$$\rho(r) = \rho_0 \left(1 + \frac{r^2}{r_0^2}\right)^{-5/2},$$

Table 1. Cloud parameters.

Cloud mass ($M_\odot$)	10^4	Number of stars	105
Cloud size (pc)	3.2	Number of clumps	105
Average density (cm^{-3})	1600	Maximum mass of clumps ($M_\odot$)	200.0
Total mass in clumps ($M_\odot$)	4612	Minimum mass of clumps ($M_\odot$)	10.0
Total mass in stars ($M_\odot$)	128	Maximum mass of stars ($M_\odot$)	10.0
Mass spectrum index of stars	2.35	Minimum mass of stars ($M_\odot$)	0.5
Mass spectrum index of clumps	1.5		

where r_0 is a scaleheight, chosen here to be equal to one-half of the cloud radius, and r is the distance from the centre of the cloud. The cloud density distribution is truncated beyond the assigned cloud radius. The velocity dispersion of the ICM is equal to the virial velocity of the entire cloud. About ~50 per cent of the total cloud mass is assumed to be contained in the ICM. The quantity ρ_0 is determined from the assigned cloud parameters given in Table 1. The clumps follow a power-law distribution in mass. Thus, $\mathrm{d}N/\mathrm{d}M \propto M^{-x}$, where $\mathrm{d}N$ is the number of objects with mass between M and $M+\mathrm{d}M$, and $x=1.5$ as determined from observations (e.g. Genzel 1992). The cloud also contains the embedded protocluster, which forms a small fraction of the total mass of the cloud. The protostar masses are also distributed according to a power law whose index x has a Salpeter value of 2.35. The details of the mass distribution are again given in Table 1.

2.2 Initial conditions

The clumps are distributed randomly in position within the cloud radius, such that the volume-averaged density of clumps over the cloud is approximately a constant. The velocities of the clumps are randomly drawn from a Gaussian distribution with a mean equal to the virial velocity for the entire cloud. An upper cut-off in velocities is imposed at the escape velocity of the cloud at the cloud radius, so that there is no initial escape of clumps from the cloud. The velocity vector is randomly oriented in space with its magnitude as determined above. The positions and velocities for the stellar components are also determined in a similar manner.

2.3 Forces and softening

The system (clumps and stars) evolves under the influence of the gravitational forces due to the various components and the dynamical friction drag due to the ICM. The ICM is considered static and only provides a source of gravitational potential. The potential arising from the gas is derived from the Plummer density distribution, and the corresponding force obtained. Thus

$$\boldsymbol{F}_{\rm gas}(r) = -\nabla\Phi = -\nabla \frac{\Phi_0}{[1+(r/r_0)^2]^{1/2}},$$

where the symbols have their usual meaning. The force acting on a clump or star due to the other objects is obtained from a simple summing of the individual contributions,

$$F^k_{N\text{-body}} = -Gm_k \sum_{i, i\neq k}^{N} \frac{m_i r_{ik}}{(r_{ik}^2+\epsilon^2)^{3/2}},$$

where the summation is over both clumps and stars, and ϵ is the softening parameter. In order to keep the force evaluation as accurate as possible, the softening parameter is varied according to the nature of the encounter and is different for stars and clumps. A variable softening length is used for the clumps where ϵ is scaled with the clump mass. It is assumed that the clumps all have a constant density ($\sim 10^6$ cm^{-3}) and ϵ_c is set equal to the clump radius. For clump–clump encounters, the smaller of the softening lengths is used. Star–star encounters are modelled with a fixed softening length, ϵ_s, arbitrarily chosen as 10^{-4} pc. Star–clump encounters are treated exactly and the clump is considered as a finite-sized object of radius equal to ϵ_c, and of uniform density. No softening is used for separations larger than ϵ_c. Since the clumps and stars are chosen to have non-overlapping mass spectra, clumps are always more massive than stars and the force acting on the clump due to a star–clump encounter is softened with the constant softening parameter, ϵ_s.

The clumps and stars are also acted upon by a dynamical friction force due to the ICM given by (Chandrasekhar 1943; Binney & Tremaine 1987)

$$\boldsymbol{F}_{\rm drag}(r) = \frac{4\pi \ln\Lambda\, G^2 \rho(r) M^2}{v^3}\left[erf(X) - \frac{2X}{\sqrt{\pi}}\exp(-X^2)\right]\boldsymbol{v}$$

where $\boldsymbol{v}$ is the velocity of the clump, G is the gravitational constant, M is the mass of the clump, ρ is the density of the gas and $\ln\Lambda$ is the Coulomb logarithm, Λ being equal to the ratio of maximum to minimum impact parameters (the maximum impact parameter $b_{\rm max}\sim R$, the radius of the cloud, and the minimum impact parameter $b_{\rm min}=GM/v^2$, so that $\Lambda\sim Rv^2/GM$). The gas velocity is assumed to follow a Maxwellian distribution with a dispersion σ (the virial velocity for the cloud), and X is a dimensionless parameter equal to $v/(\sqrt{2}\sigma)$. The equations are integrated in time using a fourth-order Runge–Kutta method.

For further details and the physical implications of the assumptions involved, refer to GB95. It should be noted that no accretion processes are considered here and the masses of the protostars/clumps do not change with time. This simplification is not expected to affect the results as the mass accreted (within time-scales of interest) here is very low (cf. GB95). Effects of magnetic fields and collisions between clumps are beyond the scope of this work and have not been included.

3 DYNAMICAL EVOLUTION OF PROTOCLUSTERS

We consider three different initial configurations. In the first run, the system consists of the ICM, the clumpy constituent and the protostars, as described earlier. We also study cases in which the gas distribution is smooth with no clumps and cases where there is no drag due to dynamical friction acting on the clumps and the stars.

3.1 Clumpy gas distribution

The system was evolved numerically for a few cloud crossing times and it is found that there is an overall expansion of the protostar/clump system with the formation of a centrally dense region. There is a mass segregation established in the cloud with the more massive objects concentrated towards the centre of the cloud and the lower mass objects moving on orbits which take them far from the cloud centre. Fig. 1 shows spatial plots of the system at different times, where protostars are denoted by asterisks and clumps by open circles. The large circle is drawn at twice the cloud radius. The protostar system continuously expands with time and a few objects move in large orbits which take them out of the cloud system. In approximately 5 Myr, about 10 per cent of the protostars are at distances greater than twice the cloud radius. It is also seen that a few clumps (two out of 105 in number) also lie outside this boundary. The average positions of clumps and stars at different times are plotted in Fig. 2(a), where open circles and asterisks denote the average radial distance from the cloud centre, $\langle r\rangle$, of clumps and stars, respectively. Thus, the protostar system expands considerably with time, as can be seen from the figure, as compared with the clump system.

3.2 Clumpy gas distribution with no gas drag

The system was evolved under only gravitational forces, excluding the gas drag. The clumps and stars thus move under the influence of the gas potential and the N-body forces. The plot of average position of the two components against time is shown in Fig. 2(b). There is no significant difference in the evolution of stars and clumps, and both systems expand slightly with time.

3.3 Smooth gas distribution

Although molecular clouds are known to be clumpy in nature, with a large fraction of their mass in high-density clumps, we study here a hypothetical case where the gas is smoothly distributed throughout the cloud. This is done so that the dynamical influence of clumps on an embedded protocluster can be studied, by comparison with the earlier simulation. In order to study the effect of the gas distribution on the dynamics of the protocluster, a mass of gas equivalent to that contained in the clumps was distributed uniformly over the cloud. Thus the cloud gas consists of the ICM, distributed according to a Plummer density profile, and some gas, distributed uniformly through the cloud. This is done so that the overall potential as seen by the stars remains unaltered and the time-scales of the system do not change. The averaged position of the stars is plotted against time in Fig. 2(c) and, on comparing with Fig. 2(a), it is evident that there is relatively little expansion of the protocluster system.

4 DISCUSSION

Embedded protoclusters in molecular clouds are dynamically influenced by the presence of clumps in the cloud cores. The formation of a star cluster involves the gravitational collapse and subsequent fragmentation of a dense core

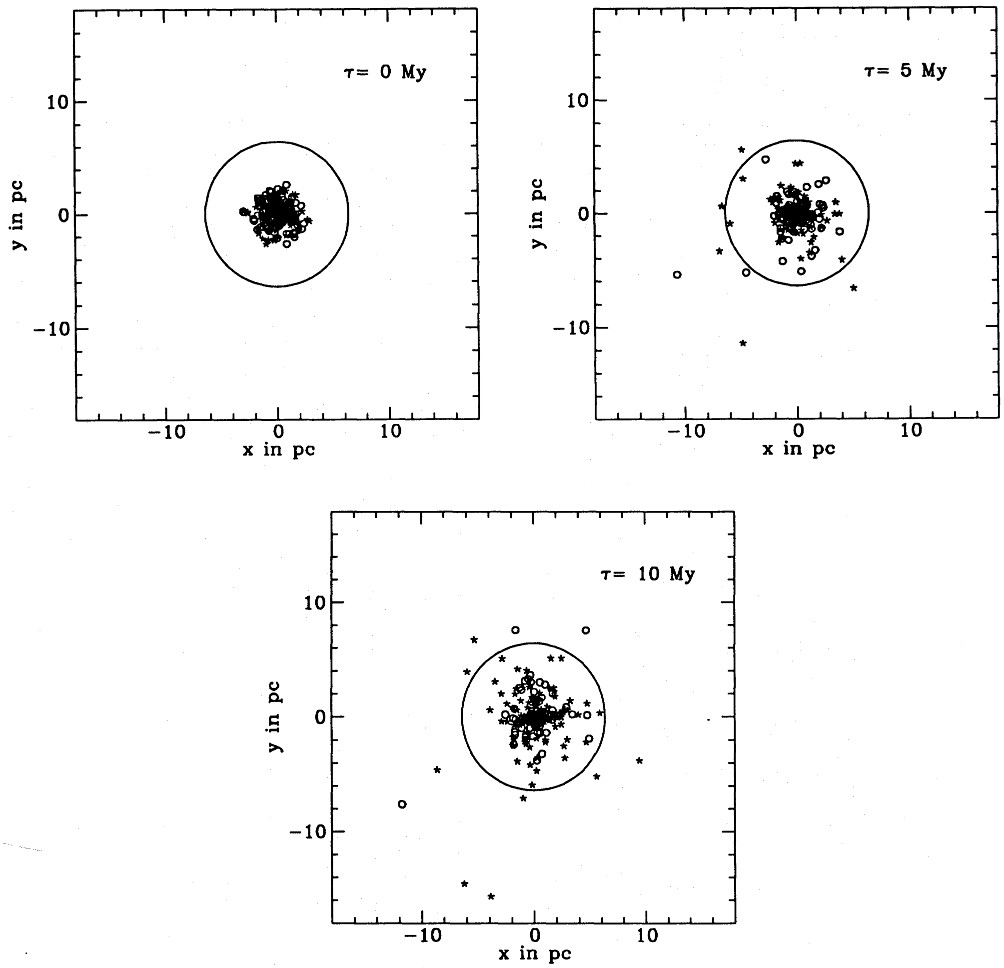

Figure 1. The plots show the projected spatial positions of the clumps (denoted by open circles) and stars (denoted by asterisks) at three different epochs. The large circle is drawn at twice the assigned cloud radius.

region in a molecular cloud. Since star formation is not a very efficient process, with a relatively small fraction of the cloud's mass being converted into stars (e.g. Lada 1992), the collapse phase culminates in a young star cluster embedded in gas and those clumps that do not undergo collapse to form stars. Alternatively, stars may drift out of their parent core fragments, and the dynamics of the protocluster is also affected by these remnant clumps (e.g. the spatial offset of *IRAS* sources from the CS peak intensity positions in star-forming regions; McCaughrean 1991). Since clumps are more massive than the stars they form, they are expected significantly to influence the motion of stars through gravitational encounters. The dynamics of the clumps themselves influences the initial stages of the evolution of a protocluster. It is thus important to study the evolution of the clumps, to assess their role in the early dynamical evolution of the protostar cluster (GB95). The effect of dynamical friction on clumps is to cause a spatial mass segregation in the cloud. As the frictional force is mass-dependent, the more massive clumps are dragged down preferentially with respect to the low-mass objects and settle towards the centre of the cloud. This deepening of the gravitational potential well at the centre of the cloud affects the dynamics of the lower mass protostars/clumps, which gain kinetic energy via three(few)-body encounters during the passage through the cloud interior. The formation of a dense nucleus in the system also causes scattering of the halo orbits and results in an exchange of energy. This causes low-mass protostars/clumps to move in larger and larger orbits with successive interactions, and therefore a gradual expansion of the halo. Both dynamical friction due to the gas and an equipartition of energy lead to a mass segregation in the system. A few of the low-mass objects acquire high velocities and some even manage to escape the system. Dynamical friction, however, is more pronounced on the higher mass clumps that are dragged down by the gas and settle at the centre of the cloud. The gas drag does not affect the motion of the low-mass objects directly but causes an 'accelerated relaxation' of the system in relatively short time-scales. (The time-scale is dependent to some extent on the initial conditions, especially the initial velocity distribution. If the stars that form after fragmentation have a velocity distribution that is subvirial, the cluster goes through a collapse phase and stabilizes after a few oscillations. In such a case, violent relaxation causes an

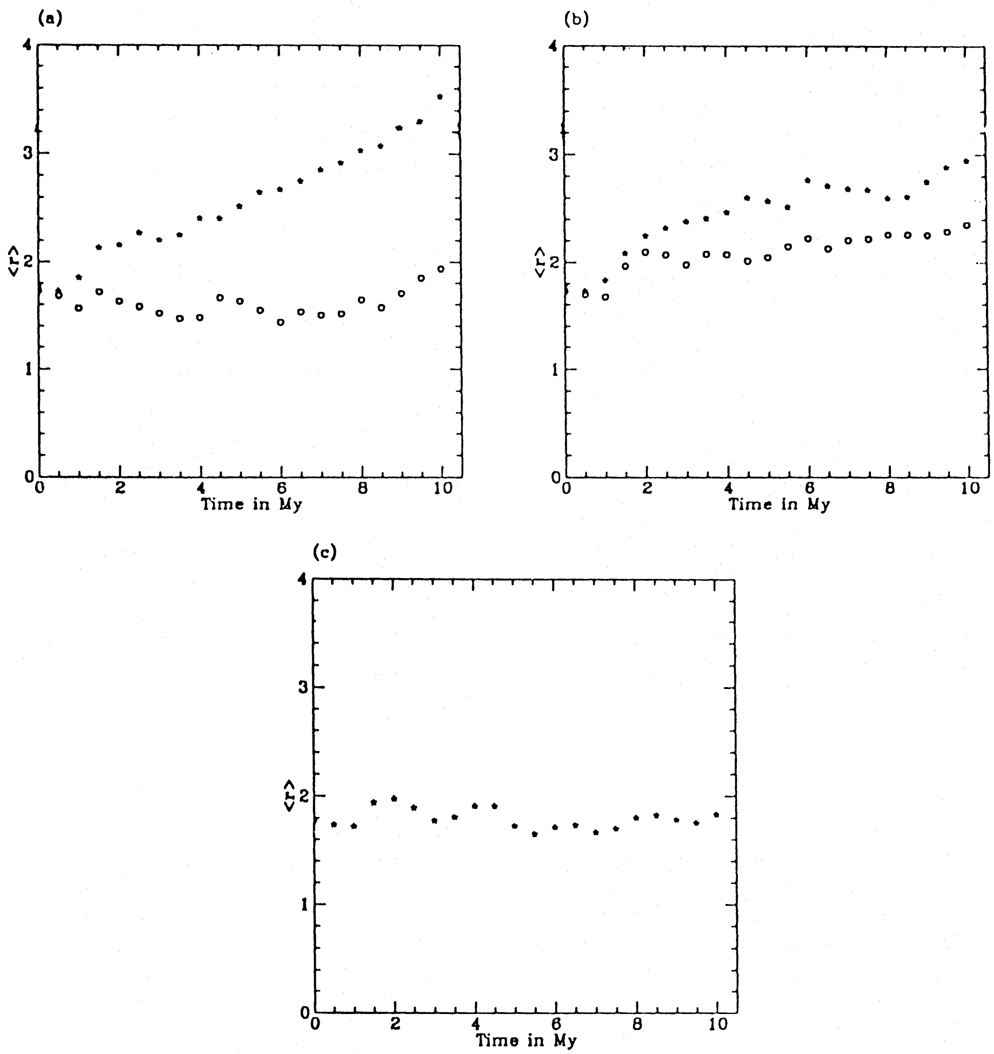

Figure 2. The figure shows the average radial distance for the stars (asterisks) and clumps (open circles) at different times as the system evolves. Panel (a) corresponds to a clumpy gas distribution with drag included, whereas panel (b) corresponds to the case without drag forces. Panel (c) indicates the average position of stars with time for a smoothed-out gas distribution.

additional ejection of cluster members.) As can be seen from Fig. 1, a few objects are ejected in very short time-scales. There is thus a gradual evaporation of stars from the cluster with time, with some of the protostars thrown out to very large distances. Harder encounters than those considered here, such as those involving protostellar binary systems, may lead to further rapid ejection of protostars (Kroupa 1995). The presence of isolated T-Tauri stars far from active star-forming regions and with no associated dense gas can probably be explained by the dynamics of the protostar cluster/cloud from which they formed. It might appear from Fig. 2 that the stars are expanding in an unbound halo. This is not so, however, as the fraction of stars that escape from the system (~ 6 per cent in 10 Myr) is found to be small, even for evolution times longer than 10 Myr. The cloud here is considered to be an isolated system and in more complex environments, external forces could increase the fraction of unbound stars. It should be noted that, in the present calculations, the stars and clumps are initially distributed throughout the cloud and thus star–clump encounters are frequent. For an initial configuration where the stars are in a self-gravitating subsystem, as can result from fragmentation of one of the clumps, close encounters between stars and clumps may be reduced and thus the results obtained might be different.

Another implication of the dynamical evolution of the system is the preferential loss of low-mass objects. If protostar clusters lose their low-mass members in the initial stages of evolution, the real star formation efficiency of the cloud could be very different from that deduced by observations. Observed protostar clusters could very well be systems in an evolved dynamical state that have lost many of their low-mass stars and have formed a dense nuclear region containing the higher mass objects. The apparent SFE of the cloud is then underestimated, as the mass contained in ejected protostars is not accounted for. The increased binding energy of the remaining members of the cluster reduces the size of the sytstem and raises the local SFE of the cloud. It should be noted that, in the present simulation, the stars form a very small fraction of the total cloud mass and hence we do not address the issue of SFE and survival of bound clusters. However, young protostar clusters with high stellar densities, such as the Trapezium, evolve in similar physical conditions and the general results are probably still applicable.

The internal dynamics of a forming star cluster, while it is still embedded in its parent cloud, may thus play a significant role in determining whether the group of protostars emerges as a bound cluster after gas dispersal or whether it is disrupted. In this work, the cloud was treated as an isolated system which contains embedded protostars and clumps with a range of masses. Star-forming molecular clouds are not, however, isolated systems and many of them have multiple star-forming sites. Examples of these are the Orion A cloud with the Trapezium cluster and the BN-KL cluster, the Orion B cloud and the dark cloud complexes such as the Taurus complex which have many groups of stars (e.g. Lada 1991; McCaughrean 1991; Larson 1995). The presence of nearby clusters/clumps can affect the motion of objects which lie on orbits that take them far from the centre of the cloud. These stars may never re-enter the cluster and could be captured by other systems or drift away once they reach the cloud boundaries.

5 CONCLUSIONS

The evolution of an embedded protostar cluster in a molecular cloud has been studied by numerical simulations. Massive clumps in the cloud strongly affect the dynamics of the embedded protostars. Mass segregation of clumps due to dynamical drag by the interclump gas results in the formation of a dense central region, and the lower mass protostars are preferentially ejected from the cloud via gravitational encounters. This explains observations of T-Tauri stars that appear to be isolated from active star-forming sites and are in regions devoid of dense gas. The loss of low-mass protostars in the initial stages of evolution indicates that the real SFE of a cloud is higher than that inferred from observations. Embedded protostar clusters are probably dynamically evolved systems with large haloes of low-mass protostars. Since multiple star formation sites in clouds are common, outer members are subject to velocity perturbations due to massive clumps and other clusters, possibly leading to a faster removal of objects.

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