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# Gas dynamical friction on prestellar clumps and open clusters

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**Abstract.** Stars are seen to form in a clustered mode within molecular clouds in galaxies. While most of these clusters emerge as unbound associations, after the system loses gas due to momentum input from the stars that are born, a few percent of them emerge bound as open clusters. Since only less than ten percent of the mass of a cloud gets converted to stars, the formation of open clusters has been a puzzle. Observations have shown that some clusters can show significant mass segregation at a dynamically young age itself. Also, the brown dwarf stars associated with a cluster are seen distributed in a wider region compared to the core. Here, we examine whether gas dynamical friction, operating on prestellar objects in the embedded phase, holds the key to solving some of the puzzles associated with open clusters.

*Keywords* : (Galaxy:) open clusters and associations: general – galaxies: star clusters – stars: pre-main-sequence

## 1. Introduction

Stars are seen to form in a clustered mode within molecular clouds (Lada & Lada 2003). Once stars are born, energy input via stellar outflows, winds and supernova explosions, causes the gas to disperse, putting an end to the star formation process in the cloud. Parent molecular gas is observed to be associated with stellar clusters, only for time scales $\sim 10^7 yrs$ after the formation of massive stars in them (Leisawitz, Bash & Thaddeus 1989). Within star forming molecular clouds, the fraction of the mass that is converted to stars - the Star Formation Efficiency (SFE) - is less than 0.15. Thus in less than ten million years after the formation of massive stars, the gas which

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had been binding the embedded stellar cluster is lost. The fact that a few percent of clusters emerge as bound clusters, thus becomes a puzzle.

Analytical approximations show that the critical SFE above which clusters can emerge bound after gas loss is greater than 0.3, the lower limit being for slow gas loss. Numerical simulations show that, after gas loss, a fraction of the stars can emerge bound, for SFE $\sim$ 0.1 in some scenarios (see Indulekha, Ambili & Jog 2012). However it is difficult to reconcile such a scenario of 'remnant' clusters with the similarity between the mass functions of embedded and open clusters (Lada & Lada 2003).

A number of studies have taken place on mass segregation in stellar clusters (for a review see Hasan and Hasan (2011)). These report segregation of the more massive stars in some young clusters whose ages are shorter than their dynamical relaxation time scales. At the same time, some clusters do not show mass segregation. Observations also indicate that, the very low mass stars associated with a cluster, are distributed in a homogeneous manner, in a volume that is much larger than the core of the cluster (Kumar & Schmeja 2007).

### 1.1 Gas Dynamical Friction

The motion of a massive body, moving in a medium and interacting gravitationally with it, is retarded due to the interaction of the body with its own gravitationally induced over-density wake. The process called dynamical friction (DF) has been considered in both the collisionless limit (Chandrasekhar 1943) as well as in the limit of collisional gaseous backgrounds (Ostriker 1999). Gas dynamical friction (*gdf*) due to an embedding gaseous medium has been invoked in understanding many phenomena, at various scales - from that of planetary systems to that of clusters of galaxies.

Molecular clouds have hierarchical substructure, with dense cores and prestellar clumps embedded in gas that is less dense than them by factors of ten to a hundred (Lada & Lada 2003). By making analytical approximations we explore the physical conditions under which *gdf* on cores and prestellar clumps will be important. We obtain a value for the critical density of the star forming cloud such that the stellar cluster, when it emerges from the parent gas cloud is bound. Segregation of the high mass stars in some clusters and a more diffuse distribution of the sub-stellar objects, as observed, is naturally obtained in our case by the fact that *gdf* is proportional to the square of the mass of the perturber.

## 2. The gas dynamical friction time scale

For a mass $m$ moving with speed $v$ in a medium with density $\rho_{gas}$ and sound speed $c_s$, Ostriker (1999) obtained an expression for the *gdf* force, in the linear regime as, $F_{Lin} = -\frac{4\pi\rho_{gas}(Gm)^2}{v^3} f(M)\mathbf{v}$. Here $M = \frac{v}{c_s}$ is the Mach number, $t$ is the time for which the perturber has been moving in the medium, and $r_{min}$ is a minimum radius introduced to avoid singularity in the force evaluation. From $\sim M^3/3$ for $M << 1$, $f(M)$ rises sharply to $\sim ln\frac{vt}{r_{min}} - 2$ at $M = 1$ and tends to $ln\frac{vt}{r_{min}}$ for $M >> 1$. With the rate of energy dissipation $dE/dt = \mathbf{F}_{gdf}.\mathbf{v}$, and introducing $\epsilon_{gas} = \frac{M_{gas}}{M_c}$ the fraction of the total mass $M_c$ of the cloud that constitutes the embedding medium, and normalizing mass, length and time with the mass, the size and the crossing time $t_{cross}$ of the embedding cloud, we write $t_{gdf} \sim \frac{E}{dE/dt} = \frac{\beta^3}{10k\epsilon_{gas}f(M)}\frac{M_c}{m}t_{cross}$ for a mass $m$ moving at $\beta$ times the virial speed in a spherical embedding cloud of mass $M_c$; k is a numerical factor that accounts for departures from linear theory (Indulekha et al. 2012). This may be compared with the expressions for $t_{gdf}$ obtained by Ostriker (1999) and Sanchez-Salcedo and Brandenburg (2001) for masses orbiting in a gaseous sphere. Here $\beta^2 M_c$ comes from the expression for the kinetic energy of the mass and one more $\beta$ comes from the fact that the rate of energy dissipation due to *gdf* is inversely proportional to the speed of the mass, since this decides the distance from the mass to its over-density wake. $f(M)$ is related to the speed with which pressure forces can redistribute the density enhancement in the wake. Relaxing sphericity and homogeneity, introduces only changes by factors of order unity in virial analysis (Chandrasekhar & Elbert 1972; Som Sunder & Kochhar 1985; Verschueren 1990).

In turbulent molecular clouds the pressure perturbations induced in the medium may be taken as propagating at the turbulent speed of the gas rather than at the sound speed (Saiyadpour, Deiss & Kegel 1997). Also turbulence will prevent the formation of long wakes. We take $ln\frac{vt}{r_{min}} = 4$, which implies a length of wake $\sim 50$ times the size of the perturber. Masses that are initially supervirial are likely to escape from the system and hence we take $\beta \sim 1$. With $k \sim 0.8$ (Indulekha et al. 2012) and $\epsilon_{gas}$ close to unity, $t_{gdf}$ will depend chiefly on the mass ratio $\mu = M_c/m$ and whether the motion is supersonic.

For *gdf* to operate, the mass should be embedded in gas. We take the length of time before gas expulsion takes place as 5 Myr (Gieles 2010). We notice that this is only a fraction of the pre -main -sequence time scale for one solar mass stars. Molecular outflows which can push away the ambient gas, thus reducing *gdf*, have dynamical time scales of the order of 0.1 Myr only (Frank 1999). Since condensed masses, which do not enjoy the support of the gas, will attain virial speeds, we expect dynamical friction to be significant in clouds with subvirial turbulence. Supersonic turbulence is expected to dissipate in an eddy turnover time, which, for small length scales is expected to be less than the dynamical time in the system and observations show that clouds which harbor stellar clusters are subvirial while those with no evidence of clusters as yet, have supervirial turbulence (Hirota et al. 2011). Thus we expect *gdf* to be operative in clouds and cores for which $t_{gdf} < 5$ Myr. With $t_{\rm cross} = 1/\sqrt{G\rho}$, we get the condition $\frac{3\beta^3}{10k\epsilon_{\rm gas}f(M)}\mu(\rho_{M_\odot pc^{-3}})^{-\frac{1}{2}} < 1$. Given a mass ratio $\mu$, this translates to a critical density for the cloud, above which objects of mass $m$ are strongly affected by *gdf* and can congregate, or given $M_c$ and $\rho$, to a critical mass, such that, objects with masses greater than this are influenced by *gdf* and would undergo mass segregation. We see that typical stars of one solar mass would be retarded and can congregate within clumps of mass 500 $M_\odot$ and densities > $1.25 \times 10^5$ cm$^{-3}$. The higher apparent SFE can then lead to bound cluster formation. In clumps with comparatively lower densities, higher mass stars can show segregation. The brown dwarfs however will not be significantly affected by *gdf*.

## 3. Results and discussion

Thus we see that in our scenario those clusters which form in gas clouds with very high densities will emerge bound – which is consistent with observations (Lada & Lada 2003) – while those which form in clumps with slightly lower densities can show segregation of objects of correspondingly higher masses - and brown dwarfs will be distributed in a wider region than the core, in all clusters. We also notice that the critical densities for which we expect formation of bound clusters / mass segregation are consistent with the density values for which Saiyadpour et al. (1997) obtain bound clusters in their analysis and Gorti and Bhatt (1995) notice mass segregation in their numerical simulations involving *gdf*. Our results are consistent with the observations of Goddard, Bastian & Kennicutt (2010) that suggest that, in galaxies, the fraction of clusters that survive bound, is strongly dependent on the surface gas density. Clusters with large masses can form by clumps losing energy and congregating. Clusters which form thus will show substructure and also retain the signature of mass segregation that was present in the clumps, as is observed (Allison et al. 2009).

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