THE EVOLUTION OF EMBEDDED SMALL CLUSTERS

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A young open cluster is a 2-phase system:
• an ensemble of stars move in a gaseous medium (the mother molecular cloud).

The dynamics and thermodynamics of the system, and so its evolution and final fate (is it stable or unstable?) strongly depends on the mutual feedback between gas and stars.

We present an approach which consists in a (simplified) model where stars (N–bodies) move within a gaseous spherical molecular cloud. The two components influence each other through

– gravity and mass loss.

Among other results (role of IMF, SFE, stellar background, etc., see Conclusions), we find that a significant fraction of small clusters can be destroyed even before SN explosion.

when a significant amount of massive stars are present.

THE MODEL

After the Lada, Margulis and Dearborn (1984, ApJ 285, 141 LMD) work not much has been done to study quantitatively the early evolution and fate of stellar clusters embedded in their mother cloud, following numerically the N–body dynamics of stars moving in a (dispersing) gaseous cloud. The LMD model was not fully self–
consistent, for the gas was assumed to expand with an assumed time law; by the way, this work gave relevant information on the capability of a stellar system to **remain bound after gas removal** in dependence on the star formation efficiency (SFE).

– An answer to the crucial question:

*what conditions on IMF and on SFE allow a small cluster, emerging from a molecular cloud, to remain bound?*

– **necessarily** implies that the mutual feedback between gas and stars is **taken into account**.

To get really **reliable** results one should couple an **N–body code** to a **fully hydro–code** to model the radiative and mechanical interaction between the *stellar* and *gaseous* phases. This has been partially done (see Capuzzo–Dolcetta and Di Lisio, *SPH in Astrophysics*, 1994, Mem.S.A.It., 65, 1107), and is the target of future work (Capuzzo–Dolcetta, Di Lisio, Navarrini, Palla, in preparation).

Results good to order of magnitude, can however be obtained with the present model, which treats the coupled dynamics and thermodynamics of stars and gas in a cluster with the following:

**approximations**

* the gas cloud evolves in time keeping *spherical shape* and a spatially *uniform* density.
* the gravitational force exerted by stars on the cloud is approximated.

**The Equations**

The relevant equations are:

\[
\begin{align*}
\ddot{a}_i &= \frac{\ddot{F}}{m_i} - \frac{dm_i}{dt} \frac{\ddot{v}_i}{m_i} \quad i = 1, \ldots, N \\
\ddot{R} &= \ddot{R}_g + \ddot{R}_p + \ddot{R}_s + \ddot{R}_{ml} + \ddot{R}_{vr} \\
\dot{U} &= \dot{U}_p + \dot{U}_{vr} + \dot{U}_{ml} + \dot{U}_{SN}
\end{align*}
\]

which is a **6N + 3** order system submitted to the appropriate initial conditions.

– \(\ddot{a}_i\) is the *i–th* star’s acceleration,
– \(\ddot{R}\) is the gas–sphere radius,
– \(\dot{U}\) is the gas internal energy.
In the gas motion equation:

\[ \ddot{R}_g = -\frac{GM}{R^2} \text{ (self-gravity)} \]

\[ \ddot{R}_p = \frac{3\gamma(\gamma - 1)U_g}{M_g R_g} \text{ (pressure field)} \]

\[ \ddot{R}_* = \frac{1}{M} \sum_{i=1}^{N} f_i \text{ (stellar-gravity)} \]

\[ \ddot{R}_{ml} = \sum_{i=1}^{N} \left( 1 - 2 \frac{r_i^3}{R^3} \right) \dot{R}_{ml_i} \text{ (stellar mass-loss)} \]

\[ \ddot{R}_{ml_i} = \frac{1}{M} \dot{m}_i v_{ml_i} \]

\[ \ddot{R}_{vr} = -\frac{k_{vr}}{M + M_*} \left( M \dot{R} + \sum_{i=1}^{N} m_i \dot{r}_i \right) \text{ (viol. relax.)} \]

- \( f_i \) is an approximation of the force exerted by the \( i \)-th star on the gas cloud.
- \( v_{ml_i} \) is the \( i \)-th star wind speed (taken from the literature).

In the gas energy equation:

\[ \dot{U}_p = \frac{9}{5} \gamma(\gamma - 1) \frac{\dot{R}U}{R} \text{ (pressure heating)} \]

\[ \dot{U}_{vr} = \frac{3}{5} k_{vr} \frac{M}{M + M_*} \dot{R} \left( M \dot{R} + \sum_{i=1}^{N} m_i \dot{r}_i \right) \text{ (viol. relax.)} \]

\[ \dot{U}_{ml} = \frac{3}{5} M \dot{R}_g \sum_{i=1}^{N} \left( 1 - 2 \frac{r_i^3}{R^3} \right) \dot{R}_{ml_i} \text{ (star mass-loss)} \]

\[ \dot{U}_{SN} = \delta(t - t_{SN}) e_{SN} \text{ (SN contribution)} \]
Parameters of the models

Stars are initially uniformly distributed in space and velocity in a sphere of radius $R_{*0}$ with velocities to satisfy the given virial ratio (here assumed =1).

The relevant initial parameters are:

**Stars:**

\[ N = \text{number of stars} \]
\[ R_{*0} = \text{initial cluster radius} = 1 \text{ pc} \]
\[ IMF \propto m^{-\alpha}, \ 0.2 \leq m/M_\odot \leq 20 \]
\[ \text{local SFE} \equiv \varepsilon \]
\[ \text{chemical composition} = (X, Y, Z) = (0.7, 0.27, 0.025) \]
\[ \text{virial ratio} \equiv \nu_0 = \frac{2 \times \text{kinetic energies}}{\text{potential energy}} = 1 \]

**Gas Clump:**

\[ R_0 = \text{initial radius} = R_{*0} \]
\[ \rho_0 = \text{initial gas density} = 500 M_\odot/\text{pc}^3 \]
\[ \dot{R}_0 = \text{initial collapse velocity} = 0 \]
\[ U_0 = \text{initial internal energy} \]
CONCLUSIONS

• A small cluster ($N \lesssim 100$, $0.2 \leq m/M_\odot \leq 20$) embedded in a gas clump of typical density $\rho \simeq 500M_\odot/pc^3$

  is lost to the background

at the time $t \simeq 10\text{Myr}$ when first SN explode (see Fig. 1), if $\text{SFE} \lesssim 0.4$.

• When $\text{SFE} > 0.4$, the cluster resists to the explosion whenever the IMF is not biased towards large masses.

• When the exponent of the IMF $\propto m^{-\alpha}$ is sufficiently negative ($\alpha \lesssim -2$) and $\text{SFE} \gtrsim 0.35$, the gas cloud and its embedded cluster are disrupted by powerful stellar winds in a shorter time (few $\text{Myrs}$). In this case,

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just very high SFE allow the cluster to survive (Fig. 2, Fig. 3 and Fig. 4).

• The capability to distinguish a small cluster over a background strongly depends on the cut-off magnitude (the density contrast falls of a factor 50 when $V_{\text{cut}}$ is changed from 14 to 18!). This means that intrinsically bound cluster can be misconsidered as unbound just because they are observed over a too crowdy background:

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so any practical definition of cluster lifetime must take into account the backround over which the cluster is projected (Fig. 5 and Fig. 6).
Figure Captions

**Fig. 1**: Super–Nova explosion time vs star mass (chemical composition $X = 0.7$, $Y = 0.27$, $Z = 0.025$).

**Fig. 2**: Gas cloud dissolution time vs SFE for the IMF exponent $\alpha = -2$.

**Fig. 3**: Rough delimitation of regions of bound and unbound clusters in the $(\alpha, \varepsilon)$ plane, where $\alpha =$ IMF exponent, $\varepsilon =$SFE. Values of $\varepsilon$ above the upper horizontal line have not yet been investigated.

**Fig. 4**: For the models whose $\alpha$, $\varepsilon$, $N$ are labelled on the top:

- **solid** lines — cluster Lagrangian radii of 25%, 50%, 75% and 100% of the mass
- **dashed** lines - - gas cloud radii.

Bottom panels are the enlargements of the upper ones.

**Fig. 5 a,b**: Time evolution of the cluster density contrast $\Delta \rho/\rho_{bg} = (\rho - \rho_{bg})/\rho_{bg}$. $V_{cut}$ is the lower luminosity cut–off of the background, which is taken at latitudes $b = 0^\circ$ and $b = 45^\circ$ (upper and lower curves, respectively, in each panel). Horizontal lines correspond to $\Delta \rho/\rho_{bg} = 1$, below which the cluster is undistinguishable over the estimated background. The various cases studied label the panels.

**Fig. 6**: Enlarged view of part of Fig. 5b, to show clearly the transition from ”visible” to ”unvisible” cluster.
Fig. 1

Fig. 2

$\alpha = -2$
$V_{\text{cut}} = 18$

$\frac{\Delta \rho}{\rho_{bg}}$

$t \, (\text{Myr})$

$\alpha = -1$
$\varepsilon = 0.15$
$N = 20$

$\alpha = -3$
$\varepsilon = 0.15$
$N = 16$

$V_{\text{cut}} = 14$

$\frac{\Delta \rho}{\rho_{bg}}$

$t \, (\text{Myr})$

$\alpha = -1$
$\varepsilon = 0.15$
$N = 20$

$\alpha = -3$
$\varepsilon = 0.15$
$N = 16$
$V_{\text{cut}} = 18$

![Graph showing density variations with time for $V_{\text{cut}} = 18$.](image)

$V_{\text{cut}} = 14$

![Graph showing density variations with time for $V_{\text{cut}} = 14$.](image)
$V_{\text{cut}} = 18$

$\Delta \rho \over \rho_{bg}$

$\alpha = -1$
$\varepsilon = 0.35$
$N = 61$

$\alpha = -3$
$\varepsilon = 0.35$
$N = 51$

$V_{\text{cut}} = 14$

$\Delta \rho \over \rho_{bg}$

$\alpha = -1$
$\varepsilon = 0.35$
$N = 61$

$\alpha = -3$
$\varepsilon = 0.35$
$N = 51$