Effective timescales of embedded clusters

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Outline

- Embedded clusters
  - Infant mortality & cluster destruction
- Clusters in a molecular cloud
  - Model & simulation
- Cloud dispersion
  - General case
  - Indicator of cluster destruction
- Effective timescales
- Summary
Embedded clusters

Most stars are formed in groups inside molecular clouds.

While with their natal molecular clouds, they are not visible.

The lifetime of molecular clouds is about a few to a few tens of Myr (Blitz & Shu, 1980; Elmegreen, 2000; Hartmann et al., 2001; Bonnell et al., 2006).

The embedded clusters live short, too.

There are many of them, but only 4 to 7% survive (Lada & Lada (2003)).

Infant mortality of stellar clusters in the Milky Way.

Infant mortality found in other galaxies:
Antennae galaxies (Fall et al. (2005)), SMC (Chandar et al. (2006))
Star forming region

30 Doradus
(Spitzer, ESO)

Westerlund 2
(HST, NASA)
~ 70-90% of stars in the Milky Way are formed in stellar clusters and only 4-7% of embedded clusters could survive after natal cloud dissipating (Lada & Lada 2003).

solid line: number of embedded clusters and open clusters from 2 kpc to the Sun
dash line: predicted number for a constant cluster formation rate 2-4 /Myr
Cluster destruction mechanism

Gas removal: $\sim 10^6 - 10^7$ yrs (Adams 2000)

Close encounter with GMCs: $\sim 10^8 - 10^9$ yrs (Gieles et al. 2006)


Evaporation: $\sim 10^{10}$ yrs (Binney & Tremaine 1987)

The lifetime of molecular clouds is between a few to a few tens of Myrs (Blitz & Shu (1980), Elmegreen (2000), Hartmann et al. (2001), Bonnell et al. (2006)). Clusters older than 5 Myr are rare associated with molecular gas (Leisawitz et al. (1989))
Simulation of Clusters

- open clusters in a dispersing molecular cloud (Chen & Ko 2009)

- \( \mathcal{N} \)-body simulation
- clusters with parent molecular clouds
- cloud dispersing
- clusters get loosed, destroyed, or remain intact
Clusters in a Molecular cloud

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Cloud</th>
</tr>
</thead>
<tbody>
<tr>
<td>2500 stars (2500 M☉)</td>
<td>cloud mass: 0.5 - 10 cluster mass</td>
</tr>
<tr>
<td>Plummer distribution</td>
<td>cloud size: 0.125 to 2.5 pc</td>
</tr>
<tr>
<td>initial half-mass radius = 0.8 pc</td>
<td>Plummer distribution</td>
</tr>
<tr>
<td>Salpeter mass function</td>
<td></td>
</tr>
<tr>
<td>no primordial mass segregation</td>
<td></td>
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</tbody>
</table>
Plummer model

\[ \phi_p = \frac{-GM_b}{\sqrt{r^2 + a^2}} \]

Star formation efficiency

\[ \eta = \frac{M_c}{M_c + M_b} \]

Cloud dispersion

\[ a = a_0 e^{t/t_e} \]

*G*: gravitational constant  
*M_c*: cluster mass, 2500 [M_☉]  
*M_c*: cloud mass [M_c]  
*r*: radius [pc]  
*a*: length scale of the cloud [pc]  
*a_0*: initial length scale of the cloud [pc]  
*t_e*: dispersion timescale [Myr]  
*t*: time [Myr]
Parameters

- Particle numbers : 2500
- Cluster mass \((M_c)\) : 2500 \(M_\odot\)
- Cluster size \((a_c)\) : 0.6 pc (length scale)
- Cloud mass \((M_b)\) : 0.5 to 10/19 \(M_c\)
- Cloud size \((a_0)\) : 0.125 to 2.5/10 pc (length scale)
- Dispersion rate \((t_e)\) : 0.33 to 3.3 Myr
- Mass function :
  1. single mass
  2. Salpeter mass function
- Spatial distribution of clusters: Plummer/uniform
General cases

xy-plane projection of stars at 30 Myr after dispersing.

Case B18e destroyed
Case B07h loosed
Case B10g loosed
Case B14s remains intact
Dynamical evolution

- $t_e = 0.625$ Myr.
- with Salpeter mass function
- $M_b = 5 \ M_c$
- $a_0 = 1.125$ pc

- Solid lines: tracks of elliptical orbit which semimajor axes are 10, 15, 20, 25 and 30 pc.

- There are four stages:
  1. initial state,
  2. expansion,
  3. inner part formation,
  4. final structure at 30 Myr.

- Red solid and dash lines in (4) separate inner part, return stars and stars do not reach their aphelion.
Evolution of $r_{hm}$

Same dispersion time (1.1 Myr)

Same SFE (25%)

Expansion ratio: $\epsilon_{r_{hm}} = \frac{r_{hm,f}}{r_{hm,i}}$

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Cluster and cloud have the same initial density profile

- not every cluster survives
- final structures: (i) is destroyed, (ii) has a loose structure, and (iii) has a compact core
- the expansion ratio of half mass radius $\epsilon_{r_{hm}} = \frac{r_{hm,f}}{r_{hm,i}}$ has a relation with $\eta$ (star formation efficiency) in different dispersing timescales
Boundmass fraction

Chen & Ko, 2009

Baumgardt & Kroupa, 2007
Cluster and cloud may have different initial density profiles.

It is difficult to find the relation between $\eta$ and $\epsilon_{r_{hm}}$.

However, $\epsilon_{r_{hm}}$ does show a “simple relation” with $\{M_b, a_0\}$.
\{M_b, a_0\}

- $t_e = 3.3$ Myr.
- black solid line: $\epsilon_{r_{hm}}$
- blue dashed line: cluster-cloud mass ratio at certain Lagrangian radius (50% in this case)
- $\epsilon_{r_{hm}}$ is larger/smaller (cluster is destroyed/remains intact) when $a_0$ is smaller/larger and $M_b$ is large/small (or $\eta$ is smaller/larger).
Cluster-cloud Mass Ratio

$$\beta_{r_f} = \frac{M_{c,r_f}}{M_{c,r_f} + M_{b,r_f}}$$

- $r_f$: Lagrangian radius with cluster mass fraction $f$
- $M_{c,r_f}$: $fM_c$, cluster mass within $r_f$ initially
- $M_{b,r_f}$: cloud mass within $r_f$ initially

For each dispersing timescale $t_e$, $f$ can be tuned such that data from the 2-D parameter space $\{M_b, a_0\}$ collapse to a relation in $\beta_{r_f} - \epsilon_{r_f}$ plane.
Cluster-cloud Mass Ratio

\begin{align*}
\text{SFE} & \quad \eta = \frac{M_c}{M_c + M_b} \\
\text{CCMR} & \quad \beta_{rf} = \frac{M_{c,rf}}{M_{c,rf} + M_{b,rf}} \\
\epsilon_{hm} & = \frac{r_{hm,f}}{r_{hm,i}} \\
\epsilon_{r,f} & = \frac{r_{f,f}}{r_{f,i}} \\
\left( \frac{1}{\eta} - 1 \right) & = \frac{f}{F} \left( \frac{1}{\beta_{rf}} - 1 \right) \\
\text{where } f & = \frac{M_{c,f}}{M_c} = \left( \frac{f_f^2}{r_f^2 + a_f^2} \right)^{\frac{3}{2}} \text{ and } F = \frac{M_{b,f}}{M_b} = \left( \frac{f_f^2}{r_f^2 + a_0^2} \right)^{\frac{3}{2}}
\end{align*}
relation between $\eta$ and $\beta_{rf}$:

$$\left( \frac{1}{\eta} - 1 \right) = \frac{f}{F} \left( \frac{1}{\beta_{rf}} - 1 \right)$$

(while using Plummer model for both cluster and cloud)

F = $M_{b,rf} / M_b = r_f^3 / (r_f^2 + a_0^2)^{3/2}$

expansion ratio of radius $r_f$:

$$\epsilon_{rf} = \frac{r_f^{\text{(final)}}}{r_f^{\text{(initial)}}}$$

$\eta = \beta_{rf}$ while $a_0 = a_c$
eSFE (effective SFE)

- mass density profiles with $M_b/M_c = 4$ and $\eta = 0.2$
- $\beta_r \rightarrow \eta$ as $r \rightarrow \infty$
- while $a_0 = a_c$, $\beta_r$ is always 0.2
- while $a_0 < a_c$, $\beta_r$ increases with $r$
  (from $\beta_r < \eta$ towards $\eta$)
- while $a_0 > a_c$, $\beta_r$ decreases with $r$
  (from $\beta_r > \eta$ towards $\eta$)

- similar idea was introduced as eSFE (Goodwin 2008)
- clusters have better/worse opportunities to survive when the eSFE is larger/smaller
Timescales

The evolution of the embedded clusters correlated with the $\beta_{rf}$ tightly, thus we propose the relevant (initial) effective timescales, like the crossing time, should be defined in terms of $\beta_{rf}$ (or roughly of $\beta_{r_{hm}}$).

**General definition**

- Crossing time: $t_{cr} \approx \frac{r_{hm}^3}{M_c}$
- Relaxation time: $t_{rlx} \approx \frac{N}{8 \ln N} t_{cr}$

**Here**

- $\tau_{cr,rf} \approx \sqrt{\frac{\beta_{rf} r_f^3}{fGM_c}}$
- $\tau_{rlx,rf} \approx \frac{fN}{8\beta_{rf}^2} \log(fN/\beta_{rf}) \tau_{cr,rf}$
the $\epsilon_{r_{hm}}$ is also related with $\{\tau_{cr,r_{hm}}, t_e\}$ (figure in the left)

when less/more cloud dominant (larger/smaller $\tau_{cr,r_{hm}}$), $\epsilon_{r_{hm}}$ is less related to the $t_e$ when $t_e$ is larger/smaller

the relation between $\epsilon_{r_{hm}}$ and $\{\tau_{cr,r_{hm}}, t_e\}$ could be separated by $\epsilon_{r_{hm}} = 10$ (boundary of survival and destroyed cases)
\( \epsilon_{rm} \) is related with \( \tau_{cr,rm} * t_e^0 \)

\( \epsilon_{rm} > 10 \)

\( \epsilon_{rm} < 10 \)
we study the survivability of clusters in dispersing clouds by means of N-body simulations

clusters will be **destroyed**, **loosed**, or **remain intact** after cloud dispersing

the expansion and bound mass of clusters are related to the SFE only when clusters and clouds have the same density profile initially

for clusters and clouds with **different initial density profile**, cluster-cloud mass ratio, \( \beta \), (based on \( M_b, a_0 \)) is a better indicator for cluster survivability

we propose the initial \( \tau_{cr} \) and initial \( \tau_{rlx} \) defined in terms of \( \beta \)

\( \beta \) also has a relation with the mass segregation

clusters with different IMF have no significant difference in result