Bimodal regime in young massive clusters leading to formation of subsequent stellar generations

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**Motivation: Cooling winds → multiple populations**

- young massive clusters have winds
  - stellar winds, SNe → collisions → hot shocked wind → outflow
- the wind may become thermally unstable inside the cluster
  - if the cluster is massive and compact enough
- dense warm/cold clumps are formed
  - depends whether they can self-shield against ionising stellar radiation
- new stars form either in-situ or after clumps sink into the centre
  - 2nd generation (2G) stars enriched by products of massive stars chemical evolution
  - similarities with FRMS scenario (desressin+07)
  - even fast winds can be captured
  - predicts formation of 2G stars in the centre (may help with mass budget problem)
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The cluster wind

Star cluster wind: semi-analytical model

- by Chevalier & Clegg (1985, Nat., 317, 44)
- $E_{\text{kin}}$ of stellar winds and SN ejecta thermalized, hot gas fills the cluster
- sources (stars) distributed according to top-hat profile
- solution of 1D spherically sym. HD equations, cooling neglected
- sonic point at the cluster border
- tested by Cantó+00, Raga+01 and others for stellar winds
- interaction of the wind with the parental cloud not covered here
  (harper-clark&murray09, krause+12,14, rogers&pittard13, rosen+14, herrera+, ...)

\[
\frac{1}{r^2} \frac{d}{dr} \left( \rho u r^2 \right) = q
\]

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\rho u \frac{d}{dr} \left( \frac{1}{2} u^2 + \frac{\gamma}{\gamma - 1} \frac{P}{\rho} \right) = Q
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\[
\frac{1}{r^2} \frac{d}{dr} (\rho u r^2) = q
\]

\[
\rho u \frac{du}{dr} = \frac{dP}{dr} - q u
\]

\[
\frac{1}{r^2} \frac{d}{dr} \left[ \rho u r^2 \left( \frac{1}{2} u^2 + \frac{\gamma}{\gamma - 1} \frac{P}{\rho} \right) \right] = Q
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Catastrophic cooling of the wind

- for massive clusters, cooling has to be taken into account
- radiative solution by silich+03 → T drops at a certain radius
- predicts different observed X-ray flux (silich+04) - good agreement with observed X-ray fluxes (NGC4303 nuclear SSC; jiménez-bailón+03)

above certain mass limit, no stationary wind solution exists → catastrophic cooling (silich+03):

\[
\begin{align*}
\text{energy deposition} & \propto M_{\text{SC}} \\
\text{cooling} & \propto \rho_{\text{wind}}^2 \propto M_{\text{SC}}^2 \Rightarrow \text{inevitable}
\end{align*}
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- tenorio-tagle+05 suggests extreme positive feedback (high SFE)
Catastrophic cooling of the wind

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- above certain mass limit, no stationary wind solution exists $\rightarrow$ catastrophic cooling (silich+03):
  - energy deposition $\propto M_{SC}$
  - cooling $\propto \rho_{wind}^2 \propto M_{SC}^2$
  $\Rightarrow$ inevitable

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Three wind regimes

- quasi-adiabatic regime
  - identical with CC85, cooling has no effect
  - mechanical luminosity (cluster mass) substantially below $L_{\text{crit}}$

3 parameters: $L_{\text{SC}}$, $\dot{M}_{\text{SC}}$, $R_{\text{SC}}$
given by $M_{\text{SC}}$

- Quasi-adiabatic

- Thermalization

- Velocity $v_{\infty} = \sqrt{\frac{2L_{\text{SC}}}{M_{\text{SC}}}}$

- Sound speed $v_{s}$

- Density

- Temperature
Three wind regimes

- radiative regime
  - mechanical luminosity (cluster mass) slightly below $L_{\text{crit}}$
  - wind cools down at certain distance out of the cluster
Bimodal regime

Three wind regimes

- **bimodal regime** (tenorio-tagle+07; wünsch+08), cluster split by $R_{st}$
  - outer: wind, stationary solution exists
  - inner: thermal instabilities, mass accumulation - secondary SF

3 parameters: $L_{SC}$, $\dot{M}_{SC}$, $R_{SC}$ given by $M_{SC}$

![Diagram showing bimodal regime with parameters and variables](image)
Heating efficiency and mass loading

- hot gas inside cluster seems to be colder than energy / mass deposited by stars → two new parameters:
  - $\eta_{\text{ML}}$: mass loading - additional (pristine) gas added to the hot phase
  - $\eta_{\text{HE}}$: heating efficiency - some thermal energy is lost from the hot phase (on the top of standard cooling)
- mass loading - evidence for mixing with pristine gas $\sim 1 : 1$
  (e.g. prantzos+07)
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- obs. evidence for low heating efficiency
  - missing energy from X-ray luminosities (rosen+14)
  - recombination line profiles of SSCs in Antennae have moderately supersonic widths (gilbert&graham07)
HII region coinciding with SSCs in M82 are very compact (silich+09)

evidence for high heating efficiency in M82 defined globally: $\eta_{\text{HE}} = 30 - 100\%$, strickland&heckman09)
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Evolution of Massive Compact Clusters (wünsch+11)

- evolution of the critical luminosity ($L_{\text{crit}}$) for $10^7 M_\odot$ cluster with $R_{\text{SC}} = 3$ pc
- Starburst99 with Geneva evolutionary tracks (HighMass winds)
### Influence of ionising radiation

**Analytical estimate (palouš+14)**

- **dense warm gas sinks into centre: stream + central clump**
- **self-shielding mass of the central clump**
  \[
  m_{\text{self}} = \dot{N}_{UV,SC} \frac{\mu m_H}{\alpha^*} \frac{kT_{\text{ion}}}{P_{\text{hot}}}
  \]
- **can streams of falling mass cool before they fall into centre?**
  \[
  t_{SS} = \frac{1}{4} \pi q_{UV}^2 R_{SC}^5 R_{st}^{-2} (1 + \eta_{ml})^{-1} \dot{M}_{SC}^{-1} \mu m_H \alpha^*^{-2} \left( \frac{kT}{P_{\text{hot}}} \right)^3.
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RHD simulations:

- radiation treated by TreeRay: tree + reverse ray-tracing; wünsch+(in prep.)
RHD simulation

- AMR code Flash
- $128^3$ grid
- M&E src: Schuster distribution
- optically thin cooling: raymond+76
- fixed stellar gravity
- self-gravity: tree code (wünsch+15)
- heating by ionising radiation: TreeRay
Evolution of accumulated mass

\( M_{sc} = 10^7 \, M_{\text{Sun}} \), \( \beta = 1.5 \), \( R_h = 2.38 \, \text{pc} \), \( \eta_{HE} = 0.05 \), \( \eta_{ML} = 1.0 \)

First supernova
total mass inserted
sinks+gas
sinks
gas
windcal
Evolution of accumulated mass

Mass budget at 3.5 Myr:
- 1G stellar mass: $10^7 \, M_\odot$
- inserted by winds: $4 \times 10^5 \, M_\odot$
- mass loaded: $4 \times 10^5 \, M_\odot$
- 2G stellar mass: $7 \times 10^5 \, M_\odot$
  \(\rightarrow\) very compact, in the centre
  \(\rightarrow\) should stay in the cluster during 1G tidal removal (khalaj&baumgardt15)
- remains in dense phase: 14000 $M_\odot$
  \(\rightarrow\) rapidly removed by SNe
Parameter space study

- Bimodal regime
- Simulations

- Log accumulated mass [M$_{\text{Sun}}$]
- η$_{ml}$
- η$_{he}$

- bimodal but no self-shielding
- extended 2G
- compact 2G
- not bimodal
Summary

- Wind cooling leading to bimodal regime is inevitable for high and compact enough cluster.
- Dense gas formed by thermal instability stays in the cluster and self-shields against ionising radiation → secondary SF.
- Heating efficiency ⇒ compact/extended 2G:
  - Low heating efficiency → SF in the central clump: 2G concentrated in the cluster centre;
  - High heating efficiency → SF in streams: 2G dispersed throughout the cluster.
- Much more difficult to capture SN ejecta; rapidly remove remaining accumulated gas.
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Thank you!