Massive Star and Cluster Formation in Hierarchically Collapsing Molecular Clouds

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Introduction

• High-mass star-forming cores are systematically denser, more massive and have higher velocity dispersions than low-mass star-forming cores (e.g., Garay & Lizano 1999; Kurtz+00; Beuther+07; Tan+14).

• Recent work has proposed that GMCs may be in a generalized process of gravitational contraction (Burkert & Hartmann 2004; VS+07, +11; Heitsch+08; Schneider+10; Ballesteros-Paredes+11a,b).

• This talk:
  – Outline the scenario and discuss massive star and cluster formation in this context.
• Why global collapse?

– Because, if MCs form out of a transition from the *warm/diffuse* to the *cold/dense* atomic phase, they quickly become Jeans-unstable (Gómez & VS 14, ApJ 791, 124):

\[ \rho \rightarrow 10^2 \rho, \quad T \rightarrow 10^{-2} T \]

\[ \Rightarrow \text{Jeans mass, } M_J \sim \rho^{-1/2} T^{3/2}, \]

decreases by \( \sim 10^4 \) upon warm-cold transition.

– Flow collision produces turbulence (Vishniac 94; Walder & Folini 00; Koyama & Inutsuka 02; Heitsch+05; VS+06; Klessen & Hennebelle 10)

• ... but not enough to support a GMC (VS+07, +10).
Collision-driven turbulence is only moderately supersonic w.r.t. cold gas.

• Strongly supersonic velocities typical of GMCs appear later, and are dominated by gravitational contraction.

Accretion-driven turbulence insufficient to support GMC-scale clouds.

(For clump-sized scales, it may be sufficient Klessen & Hennebelle [2010])

Turbulence driven by compression, through NTSI, TI and KHI.

Same in AMR simulations.

• Global collapse implies that *clouds evolve*...
  - ... and SFR *increases in time.*

GMCs in the LMC

Cloud life time $\sim 27$ Myr

Class I
- Only YSOs
- 44 clouds (25.7 %)
- $\sim 7$ Myr

Class II
- Only HII regions
- 88 clouds (51.5 %)
- $\sim 14$ Myr

Class III
- Clusters and HII regions
- 39 clouds (22.8 %) associated with 82 clusters
- $\sim 6$ Myr

Only clusters
- 55 clusters
- $\sim 4$ Myr

Kawamura+2009

Analytical model for SFR (Zamora-Avilés+12)
Time-averaging of individual clouds.


Integration over cloud mass spectrum.

$M_{\text{max}}/M_\odot = 10^3, 10^4, 10^5, 10^6$

  – Turbulence produces small-scale, high-amplitude (nonlinear) density fluctuations.

    ➔ shorter free-fall time than whole cloud.

    ➔ terminate their collapse earlier than whole cloud.
Use simulations of MC formation by colliding flows in diffuse WNM.

SPH simulation includes cooling (leading to TI) and self-gravity (Vázquez-Semadeni+07).

L = 256 pc
Δt = 39 Myr
<n> = 1 cm⁻³
\(v_{\text{inf}}\) = 9.2 km s⁻¹
\(T_{\text{ini}}\) = 5000 K
- **Low-mass cloud**: formed by local collapse of small-scale structure.

16.6 – 19.9 Myr
(\(\Delta t = 2.6\) Myr)

Low SFR
- **High-mass cloud:** formed by focused culmination of collapse of large-scale structure.
22.1 – 24.7 Myr ($\Delta t = 2.6$ Myr)

High SFR
Massive clumps
Central 8 pc resampled @ 0.03 pc resolution.

Vázquez-Semadeni+09
Physical properties:

- Whole 8-pc region:
  - $<n> = 450 \text{ cm}^{-3}$
  - $\sigma_{3D} = 5.0 \text{ km s}^{-1}$
  - $M \approx 7000 \, M_{\odot}$

- Clump A ($L = 1.5 \text{ pc}$):
  - $<n> = 1.27 \times 10^4 \text{ cm}^{-3}$
  - $\sigma_{3D} = 3.6 \text{ km s}^{-1}$
  - $M \approx 1400 \, M_{\odot}$

- Clump B ($L = 0.8 \text{ pc}$):
  - $<n> = 1.72 \times 10^4 \text{ cm}^{-3}$
  - $\sigma_{3D} = 2.8 \text{ km s}^{-1}$
  - $M = 300 \, M_{\odot}$

- High-density cores: (simple density threshold criterion, $n > 5 \times 10^4 \text{ cm}^{-3}$, $M > 4 \, M_{\odot}$).
  - Found 15 cores with
    - $n_{\text{max}} \approx 10^{5-6} \text{ cm}^{-3}$.
    - \textit{Lifetimes} \(\ll 1.3 \times 10^5 \text{ yr}\) (appear and disappear in \(\ll \text{dt between frames}\)). Compare to Motte’s estimate: $\approx 10^3 \text{ yr.}$

- Mass accretion rate $\approx 3 \times 10^{-3} \, M_{\odot} \, \text{yr}^{-1}$
  - $\sigma_x = 2.3 \text{ km s}^{-1}$
  - $\sigma_y, \sigma_z \approx 3.1 \text{ km s}^{-1}$

\textit{“Typical”} massive clump (Motte+07/Schneider+07):
- $M \approx 1000 \, M_{\odot}$
- $L \approx 0.7 \text{ pc}$
- $\sigma \approx 2 \text{ km s}^{-1}$
- $n \approx 1.4 \times 10^4 \text{ cm}^{-3}$
Core statistics:

- (Zeroth order confrontation with observations.)
  
  Vázquez-Semadeni+09

Conclude:
The central region of collapse exhibits similar statistical properties to regions of massive SF.

Note: Velocity field in simulation has a large infall component, not just random turbulence. 
Implications for cluster formation

- Stellar population of an evolved star-forming region consists of:
  - Slightly older, scarce component formed by early, low-mass, low-SFR, and
  - Younger, more abundant component formed at later, massive, high-SFR collapse.

2000-M$_{\odot}$ model:


• **Age gradients** (Vázquez-Semadeni et al, in prep.)

  - Small-scale SF sites are infalling onto large-scale potential well.

    • Have $\sigma_v$ of large-scale collapse.
    • Stars formed there do not dissipate their $E_k$.
      ➔ “Puffed-up” component.

  - Large-scale SF sites shock at the potential trough and dissipate their $E_k$, so stars formed there have lower $\sigma_v$.

• **Clusters have a fractal structure** (Vázquez-Semadeni et al, in prep.)

– Large-scale structures consist of substructures (Larson 1995).

• Due to *hierarchical collapse* of parent MC.
Applying a friends-of-friends algorithm:

- Linking parameter = 2
  - 4 groups

- Linking parameter = 1
  - 9 groups

- Linking parameter = 0.5
  - 13 groups
• **Conclusions:**

  – MCs probably in *global, hierarchical* gravitational collapse.

  • SFR increases over time, until cloud disrupted/evaporated.

  • Hierarchical: collapses within collapses.
    – Local, small scale, early collapses $\Rightarrow$ low-mass, low-SFR regions
    – Global, later collapse $\Rightarrow$ high-mass, high-SFR regions.

  • Implications for clusters:
    – Age segregation.
    – Fractal structure.
Diffuse ISM

SF-ing GMCs and their HI envelopes

Stars
The End
• Global collapse implies that *clouds evolve*...
  – ... and SFR *increases in time* (before cloud is destroyed).

Colín+10, MNRAS 435, 1701 (simulation)

Comparison between low- and high-mass clouds

Both defined as the material above $n = 500 \text{ cm}^{-3}$ in the corresponding regions.

$$t_0 = \begin{cases} 
17.3 \text{ Myr for low-mass region,} \\
22.6 \text{ Myr for high-mass region.}
\end{cases}$$

22.1 – 24.7 Myr (Δt = 2.6 Myr)
Krumholz & Tan 2007