Formation and Evolution of Primordial Protostellar Systems

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Outline:

- Part I: Primordial protostellar systems
- Part II: Streaming motions

Collaborators:

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- Ralf Klessen, Simon Glover, Paul Clark, Rowan Smith (ITA Heidelberg)
- Volker Bromm, Athena Stacy (University of Texas)
- Naoki Yoshida (IPMU Tokio)
Part I: Primordial protostellar systems
Collapse up to formation of protostellar core well understood

(see e.g. Haiman et al. 96, Omukai & Nishi 98, Abel et al. 02, Bromm et al. 02, 04, Yoshida et al. 06, 08)

Subsequent evolution?

➤ Avoid CFL constraint by using sink particles (Bromm et al. 04, Stacy et al. 10, Clark et al. 08, 11, Greif et al. 11)
➤ See Paul Clark’s talk (next)

Alternatively:

➤ Direct simulation without sink particles (this talk)
➤ Very limited timescales: $\sim 10 \text{ yr}$ (however: $\gtrsim 100 \text{ yr}$ soon possible)
Moving-mesh code AREPO (*Springel 10)*:

- Hybrid Lagrangian / Eulerian code
- Voronoi tessellation of space based on a distribution of points
- Hydrodynamic fluxes computed across cell faces
- Mesh-generating points advected with flow
- Galilean-invariant, low diffusivity

Minihalo simulations:

- Cosmological initial conditions
- Four realizations in boxes of size 250 and 500 kpc
- Four-step process to arrive at final simulations on AU scales
Simulations

First step:
- Low-resolution DM-only simulations
- Initialized at $z = 99$ with $\Lambda$CDM (WMAP 7)
- First halo with mass $> 5 \times 10^5 M_\odot$ located

Second step:
- Reinitialization with DM and gas
- Zoom-in on target minihalo ($\times 8^3$) $\rightarrow \sim 1 M_\odot$ gas resolution
- Non-equilibrium primordial chemistry and cooling network
- On-the-fly refinement ensures resolution of Jeans length ($128 \rightarrow 32$)
- Run until $n_H = 10^9 \text{ cm}^{-3}$
Simulations

Third step:
- Central 1 pc cut out (only gas, DM mass fraction $\simeq 10\%$)
- Resimulation with reflective boundary conditions
- Additional equilibrium chemistry solver for $n_H > 10^{14} \text{ cm}^{-3}$
- Run until $n_H = 10^{19} \text{ cm}^{-3}$

Fourth step:
- Central 2000 AU cut out
- Run for $\simeq 10 \text{ yr}$ (3 months on 32 CPU's)
Simulations

Time sequence:
Disk evolution:

- Stability governed by Toomre parameter
  \[ Q = \frac{c_s \Omega}{\pi G \Sigma} \]

Set by:

- \( \Sigma \): surface density
- \( c_s \): sound speed
- \( \Omega \): orbital frequency

For \( Q < 1 \):

- perturbations grow

\[ Q < 1 \text{ at } \lesssim 0.2 \text{ AU and } \simeq 1 \text{ AU} \]
In addition:

- Gammie criterion
- $t_{\text{cool}} \lesssim t_{\text{ff}}$

Fragmentation:

- Occurs at $\sim 1$ AU
- Innermost regions stable
- Below 1 AU: temperature rises rapidly to $\sim 10^4$ K
- $H_2$ fraction drops

→ Relevant cooling mechanisms?

Physics I: Disk Fragmentation
Physics I: Disk Fragmentation

Heating *(red lines)*:

- Compressional heating *(solid line)*
- \( \text{H}_2 \) formation heating *(dotted line)*

Cooling *(blue lines)*:

- Expansion cooling *(solid line)*
- \( \text{H}_2 \) dissociation cooling *(dotted line)*
- Collision-induced emission *(dashed line)*
- \( \text{H}_2 \) line cooling *(dot-dashed line)*

Most important ‘coolant’: \( \text{H}_2 \) dissociation cooling
Subsequent evolution:

- Secondary protostars migrate to center and merge with primary
- Mergers rarely occur between secondary protostars
- Primary protostar dominates mass budget ($\sim$ factor of 5)
Analysis:

- Decomposition into:
  - Gravitational torques
  - $\nabla P$ torques
  - Timescales:
    \[
    t_{grav, pres} = \frac{L}{\tau}
    \]
    \[
    \tau = r \times F_{grav, pres}
    \]

Result:

- Gravitational torques dominate
- Directed inward
- Torquing time agrees with merging time
Merging timescales:

Merging occurs in a free-fall time!
Similar analysis for protostars that survive:

**Slingshot effect:** Migration to higher orbits via N-body interactions
50% of all secondary protostars merge with primary!
Part II: Streaming Motions
Streaming Motions

- Acoustic oscillations source streaming motions between DM and gas
- Become supersonic after recombination
- Typical spatial coherence length of a few Mpc
- In small simulation boxes: additional bulk velocity

\[ k, \text{ Mpc}^{-1} \]

\[ \Delta v_{bc}^2 \]

\[ 0.001, 0.005, 0.010, 0.050, 0.100, 0.500, 1.000 \]

\[ 0, 2 \times 10^{-9}, 4 \times 10^{-9}, 6 \times 10^{-9}, 8 \times 10^{-9} \]

*Tseliakhovich & Hirata 10*
Influence of streaming motions on Population III star formation:

No streaming

With streaming
Same redshift

With streaming
Later redshift
Streaming Motions

- Gas fraction decreases due to higher effective Jeans mass
- Lower central gas density
- Cooling and collapse delayed
- Increased virial mass
Streaming Motions

Consequences:

- Fewer halos massive enough to cool
- Star formation reduced by up to an order of magnitude
- Modulation of Population III star formation on Mpc scales

Further consequences:

- Enhanced 21 cm fluctuations  
  \textit{(Visbal et al. 12)}
- Possibly relevant for ‘missing satellite problem’  
  \textit{(Bovy & Dvorkin 12)}
Main Results:

- Gas in minihalos becomes rotationally supported and fragments
- Very efficient merging (free-fall time)
- Predominant growth of primary protostar
- Slingshot migration of low-mass protostars
- Caveats: magnetic fields / radiative transfer / limited timespan
- Streaming motions delay star formation in low-mass halos