Simulating the Formation of the First Stars

Thomas Greif

Harvard-Smithsonian CfA
Outline:

- (i) Previous work
- (ii) Recent simulations
- (iii) Disk fragmentation
- (iv) Protostellar migration and merging

Collaborators:

- Volker Springel, Simon White (HITS, MPA)
- Ralf Klessen, Simon Glover, Paul Clark, Rowan Smith (ITA Heidelberg)
- Volker Bromm (University of Texas)
- Jarrett Johnson, Athena Stacy (Goddard, LANL)
- Naoki Yoshida (IPMU)
Stage for Pop III SF: \( \gtrsim 10^5 \, M_\odot \) DM ’minihalos’ at \( z > 20 \)

Gas collapses and heats to \( T_{\text{vir}} \sim 1000 \, \text{K} \)

_Abel et al. 02_
- Gas becomes dense enough for H$_2$ formation (Bromm et al. 02)
- Cooling by ro-vibrational transitions of H$_2$ to $\sim$ 200 K
From Cosmological to Protostellar Scales

- Central gas cloud becomes gravitationally unstable
- Nearly isothermal contraction to very high densities
- Protostar with \( \approx 5 \times 10^{-3} \, \text{M}_\odot \) forms

Yoshida et al. 06, 08

Thomas Greif
Simulating the Formation of the First Stars
Subsequent evolution?

- Avoid CFL constraint by using sink particles
  \[(Bromm et al. 04, Stacy et al. 10, Clark et al. 08, 11, Greif et al. 11)\]

Recently:

- Direct simulation without sink particles
- Very limited timescales: \(\sim 10\,\text{yr}\) (however: \(\gtrsim 100\,\text{yr}\) now 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

Simulation Setup:

- 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 ($\times 8^3$) $\rightarrow \approx 1 \, M_\odot$ gas resolution
- Non-equilibrium primordial chemistry and cooling network
- On-the-fly refinement ensures resolution of Jeans length ($128 \rightarrow 32$)
- Run until $n_H = 10^9 \, cm^{-3}$

Density

Temperature

Width: 5 kpc (comoving)
Simulations

Third step:
- Central 1 pc cut out (only gas, DM mass fraction \( \approx 10\% \))
- 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 \( \approx 10 \text{ yr} \) (1 month on 32 cores)
Simulations

Time sequence:

MH1  MH1  MH1  MH1  MH1  MH1
0.02 yr 1.96 yr 3.91 yr 5.87 yr 7.82 yr 8.31 yr

MH2  MH2  MH2  MH2  MH2  MH2
0.02 yr 1.96 yr 3.91 yr 5.87 yr 7.82 yr 11.38 yr

MH3  MH3  MH3  MH3  MH3  MH3
0.02 yr 1.96 yr 3.91 yr 5.87 yr 7.82 yr 9.60 yr

MH4  MH4  MH4  MH4  MH4  MH4
0.02 yr 1.96 yr 3.91 yr 5.87 yr 7.82 yr 8.94 yr

Side Length: 10 AU

$\log n_H \, [\text{cm}^{-3}]$

12 14 16 18 20
Disk Fragmentation

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

\[
Q < 1 \text{ at } \lesssim 0.2 \text{ AU and } \simeq 1 \text{ AU}
\]
Disk Fragmentation

In addition:

- Gammie criterion:
  \[ t_{\text{cool}} \lesssim t_{\text{ff}} \]

Fragmentation:

- Occurs at \( \simeq 1 \text{ AU} \)
- Innermost regions stable
- Below 1 AU: temperature rises rapidly to \( \simeq 10^4 \text{ K} \)
- \( \text{H}_2 \) fraction drops

→ Relevant cooling mechanisms?

Thomas Greif
Simulating the Formation of the First Stars
Disk Fragmentation

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

Cooling:
- 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
Migration

Torques:

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

Overall:

- 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
Migration

Evolution of multiplicity:

50% of all secondary protostars merge with primary!
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

Final mass function unclear, but most likely top-heavy ($\lesssim 50 \, M_\odot$)

Caveats: magnetic fields / radiative transfer / limited timespan