The Formation of the First Stars

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Outline:

- (Never)mind the gap!
- Tour over 25 orders of magnitude in density
- Low densities ($n_H \sim 1 \text{ cm}^{-3}$): Runaway cooling and Jeans instability
- Intermediate densities ($n_H \sim 10^8 \text{ cm}^{-3}$): Chemo-thermal instability
- High densities ($n_H \sim 10^{19} \text{ cm}^{-3}$): Evolution of protostellar systems
Population III Star Formation

To zeroth order:

- Virialization of $\gtrsim 10^5 \, \text{M}_\odot$ DM minihalos at $z \gtrsim 20$
- Adiabatic and dissipative heating of gas to $T_{\text{vir}} \approx 1000 \, \text{K}$
- H$_2$ formation $\rightarrow$ cooling $\rightarrow$ further collapse $\rightarrow$ star formation

*Abel et al. 02*
Runaway cooling and Jeans instability:

- $H_2$ formation: $H + e^- \rightarrow H^-; \ H^- + H \rightarrow H_2 + e^-$
- $T_{\text{vir}} \approx 1000$ K: hot enough for significant $H_2$ formation
- Collisional excitation of $H_2$ ro-vibrational states
- Radiative de-excitation cooling to $\approx 200$ K
- $n_H \approx 10^4$ cm$^{-3}$: Jeans instability
- Jeans mass: $100 - 1000 \, M_\odot$

Galli & Palla 98, Omukai & Nishi 98, Abel et al. 97, 98, 00, 02, Bromm et al. 99, 02
Nearly isothermal collapse:

- $n_H \gtrsim 10^4$: $t_{\text{cool}} \simeq t_{\text{ff}} \rightarrow n_H^{-1/2} \propto T^{1-\alpha}$ since $\Lambda \propto T^\alpha$
- $T \propto n_H^{\gamma_{\text{eff}}-1}$ with $\gamma_{\text{eff}} = 1 + 1/(2\alpha - 2) \simeq 1.1$
- Reduced contraction rate, mild increase in temperature

*Yoshida et al. 06*
Chemo-thermal instability:

- $n_H \gtrsim 10^8 \text{ cm}^{-3}$: 3-body $\text{H}_2$ formation
- Rapidly increasing $\text{H}_2$ fraction $\rightarrow$ potential runaway cooling
- Counteracted by:
  - Decreasing $\text{H}_2$ fraction
  - Three-body formation heating
  - Increasing opacity to $\text{H}_2$ line emission

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*Omukai & Yoshii 03, Ripamonti & Abel 04, Yoshida et al. 06, Turk et al. 09*
Chemo-thermal instability

One-zone model:

- **Governing equations:**
  - $\dot{\rho} = \rho / t_{\text{ff}} \propto \rho^{3/2}$
  - $\dot{u} = \gamma u / t_{\text{ff}} - c y_{\text{H}_2} \rho T^4$

- **Blue curve:** $y_{\text{H}_2} = \text{const}$

- **Green curve:** $\dot{y}_{\text{H}_2} \propto \rho^2 / T$
  - Asymptotic $\gamma_{\text{eff}} \to 0.5$

- **Red curve:**
  Decreasing $H_2$ fraction

- **Cyan curve:**
  3-body formation heating

- **Magenta curve:**
  $H_2$ line $f_{\text{esc}} \propto \rho^{-0.5}$
Methodology:

- 3D hydro + DM simulations
- Moving-mesh approach (AREPO; *Springel 10*)
- Cosmological initial conditions ($z_{\text{init}} = 100$)
- Nine realizations in boxes of size 1 Mpc
- Non-equilibrium primordial chemistry and cooling network
- On-the-fly refinement, up to 256 cells per Jeans length ($3 \times 10^9$ cells)
- Four-step process to arrive at final simulations

Central 200 au
Chemo-thermal Instability

Result:

- Thermal instability: $t_{\text{cool}} \lesssim t_{\text{ff}}$ on 100 au scales
- Gravitational instability: $t_{\text{ff}} \lesssim t_{c_s}$ on a few 10 au scales
- Potential fragmentation
Chemo-thermal Instability

All halos:

MH1  MH2  MH3
MH4  MH5  MH6

MH7  MH8  MH9

log(t_{ff}/t_{cs})

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Chemo-thermal Instability

Density:

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**Chemo-thermal Instability**

\( \frac{M_{\text{enc}}}{M_{\text{BE}}} \) (top panel):
- In MH1, MH5 and MH7:
  - \( M_{\text{enc}} \) exceeds \( M_{\text{BE}} \) well away from central clump
- Other halos:
  - Indistinguishable from central clump

\( \frac{t_{\text{ff}}}{t_{\text{acc}}} \) (bottom panel):
- Clumps in MH1, MH5 and MH7 likely to collapse before they are accreted

→ Fragmentation in 3 out of 9 halos
Protostar Formation

- \( n_H \gtrsim 10^{12} \): gas fully molecular, H\(_2\) line cooling ceases
- \( n_H \gtrsim 10^{14} \): radiative cooling via collision-induced emission
- \( n_H \gtrsim 10^{16} \): chemical cooling via collisional dissociation
- \( n_H \gtrsim 10^{19} \): adiabatic contraction
- Protostar with \( \sim 10^{-2} M_\odot \) forms

\[ \text{molecular fraction} \]

\[ \begin{array}{cccc}
10^{-5} & 10^{-4} & 10^{-3} & 10^{-2} \\
10^0 & 10^1 & 10^2 & 10^3
\end{array} \]

\[ \begin{array}{cccc}
300 \text{ parsec} & 5 \text{ parsec} & 25 \text{ solar−radii} & 10 \text{ astronomical unit}
\end{array} \]

(A) cosmological halo  (B) star−forming cloud

(C) fully molecular part  (D) new−born protostar

\( \text{Yoshida et al. 06, 08} \)
Reaching protostellar scales:

- Four realizations in boxes of size 250 and 500 kpc
- \( \approx 1 \, M_\odot \) gas resolution
- 32 cells per Jeans length
- Equilibrium chemistry solver above \( n_H = 10^{14} \, \text{cm}^{-3} \)
- Final resimulations: central 2000 AU
- Run for \( \approx 10 \, \text{yr} \) (1-2 months on 32 CPU’s)
Simulation Setup

Time sequence:

MH1
0.02 yr  1.96 yr  3.91 yr  5.87 yr  7.82 yr  8.31 yr
MH2
0.02 yr  1.96 yr  3.91 yr  5.87 yr  7.82 yr  11.38 yr
MH3
0.02 yr  1.96 yr  3.91 yr  5.87 yr  7.82 yr  9.60 yr
MH4
0.02 yr  1.96 yr  3.91 yr  5.87 yr  7.82 yr  8.94 yr

Side Length: 10 AU

$\log n_{H} \text{ [cm}^{-3}\text{]}$

12  14  16  18  20

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Disk stability:

- Toomre criterion:
  
  \[ Q = \frac{c_s \Omega}{\pi G \Sigma} \lesssim 1 \]

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

- Collisional 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
  - Time scales:
    \[ \frac{t_{\text{grav, pres}}}{\tau} = \frac{L}{\tau} \]
    \[ \tau = r \times F_{\text{grav, pres}} \]

Overall:
- Gravitational torques dominate
- Directed inward
- Torquing time agrees with merging time
Merging occurs in a free-fall time!
Migration

Evolution of multiplicity:

50% of all secondary protostars merge with primary!
Summary

- Chemo-thermal instability operates in primordial gas clouds
- Origin: three-body H$_2$ formation
- Triggers gravitational instability
- Potential fragmentation (here: 3 out of 9 halos)
- After initial collapse: disk formation and fragmentation
- Migration and merging in a free-fall time
- Predominant growth of primary protostar