Theory of the First Stars: Why are they Massive? What are their Properties?

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● The Formation of the First Star in the Universe
  – Abel, T., Bryan, and Norman, 2002, Science, 295, 93
● Mass of Population III Stars
● The Stellar Initial Mass Function in Primordial Galaxies
● (Formation of the First Stars by Accretion)
Misc. Background

- "Population III"
  - less than 1/1000 solar metallicity
- Why should the first stars be larger?
  - Less efficient cooling => larger Jean's mass => larger stars
- When did they form?
  - z~10-100
The physics should be “simple”:
- Primordial gas simplifies the chemical and radiative processes
- No strong magnetic fields
- No other stars exist to influence the environment

\[ e + H \rightarrow H^- + hv , \]  
\[ H^- + H \rightarrow H_2 + e , \]  
\[ H^+ + H \rightarrow H_2^+ + hv , \]  
\[ H_2^+ + H \rightarrow H_2 + H^+ . \]  
\[ 3H \rightarrow H_2 + H \]
Simulation Setup

- Use an Eulerian structured AMR cosmological hydrodynamical code
- Initial conditions appropriate for a spatially flat CDM cosmology
  - 6% of the matter density contributed by baryons
  - Zero cosmological constant
  - Hubble constant of 50 km/s/Mpc
- 3D volume 128 kpc on a side (co-moving)
- Periodic boundary conditions
Simulation Setup

- Mass resolution of $1.1 \, M_{\text{sun}}$ for the dark matter and $0.07 \, M_{\text{sun}}$ for the gas.
- Follow chemistry of $\text{H}$, $\text{H}^+$, $\text{H}^-$, $\text{e}^-$, $\text{He}$, $\text{He}^+$, $\text{He}^{++}$, $\text{H}_2$, and $\text{H}_2^+$.
- Also track radiative losses from atomic and molecular line cooling, Compton cooling, and heating of free electrons by the cosmic background radiation (in the optically thin limit).
Simulation Setup

- Stop when molecular cooling lines reach an optical depth of 10 at line center
  - Time-dependent radiative line transfer in multiple dimensions is hard
Results: Characteristic Mass Scales

- Four characteristic mass scales:
  - Infall and accretion onto pregalactic halo \((7 \times 10^5 \, M_{\text{sun}})\)
  - Rapid cooling and additional infall \((4000 \, M_{\text{sun}})\)
  - Bonnor and Ebert mass \((100 \, M_{\text{sun}})\)
  - Protostar \((1 \, M_{\text{sun}})\)

 \[ M_{\text{BE}} = 1.18 \, M_\odot \left(\frac{c_s^4}{G^3/2}\right) P_{\text{ext}}^{-1/2} \frac{c_s^2}{\rho} = \frac{\gamma k_B T}{\mu m_H} \]
Results: Angular Momentum

- The collapse is not halted by rotational support for two reasons:
  - The gas starts with little angular momentum
  - Angular momentum is transported
    - Attributed to shock waves during the turbulent collapse
    - Transport is stronger than in present-day star formation due to higher cooling rate
Summary: The Formation of the First Star in the Universe

- Pregalactic object forms a single $100 \ M_{\text{sun}}$ core surrounding a $1 \ M_{\text{sun}}$ protostar
  - No fragmentation observed
- Final mass of star unclear
  - Estimate $70 \ M_{\text{sun}}$ after $10^4 \ yr$
  - $600 \ M_{\text{sun}}$ after 5 Myr
  - BUT a $100 \ M_{\text{sun}}$ star will supernova within 2 Myr
Mass of Population III Stars

- Model filamentary, axisymmetric, ideal gas cloud
- Include H, H\(^+\), H\(^-\), e\(^-\), He, He\(^+\), He\(^{++}\), H\(_2\), and H\(_2\)^{+}
- Assume cooling from H (at T~10\(^4\) K), H\(_2\) (at T<10\(^4\) K), and from chemical reactions
- Follow the 1D hydrodynamics of the system
A Model for a Filamentary Primordial Cloud

- Initially, gravitational instability of cosmological density perturbations forms a “pancake-like” disk
  - $M \sim 10^{5-7} M_{\text{sun}}$
  - $T \sim 200-1000K$
- Fragments into filamentary clouds
  - Assume filaments are infinitely long cylinders
Numerical Results
Spindle Mass
Clouds with Low Initial Temperature ($T_0 \sim 100$ K)

\[ \rho = \rho_0 \left( 1 + \frac{r^2}{fR_{fil}^2} \right)^{-2}, \]  

(15)
Fragmentation of Primordial Gas Clouds

\[ \frac{\delta \rho(t)}{\rho(t)} = A \exp \left[ i k_z z - \int_0^t i \omega(k_z, t') dt' \right], \quad (19) \quad A = A_0 \left( \frac{k_z}{k_{z,0}} \right)^{\rho} \]
Conclusions: Mass of Population III Stars

- Find that the spindles are unstable against fragmentation
- Based on the size of the fragments, the first stars have a minimum mass of $3 \, M_{\text{sun}}$
- Further accretion of the diffuse envelope can increase the mass to a maximum of $16 \, M_{\text{sun}}$
The Stellar Initial Mass Function in Primordial Galaxies

- Include effects of HD cooling
  - Can decrease T<100K*
- Include more species than previous model
  - e, H, H⁺, H⁻, H₂, H, He, He⁺, He++, D, D⁺, D⁻, HD, and HD⁺
- Consider the following thermal processes:
  - H cooling by radiative recombination, collisional ionization, and collisional excitation
  - H₂ line cooling by rotational and vibrational transitions
  - Cooling by H₂ collisional dissociation
  - Heating by H₂ formation
  - HD line cooling by rotational transitions.
Model

- The system is again an infinitely long cylindrical gas cloud that collapses in the radial direction
- 1-D
- Model parameters are $n_{c,0}$, $T_0$, $f$, and $\chi_{H2,0}$
Results: Threshold $H_2$ Abundance
Results:
Low-Density Filaments with High $H_2$ Abundance
Results:
Low-Density Filaments with Low $\text{H}_2$ Abundances
Results: High-Density Filaments
Dependence of the Fragment Mass on the Initial Model Parameters

![Graph showing the dependence of fragment mass on initial model parameters.](image-url)
Summary: The Stellar Initial Mass Function in Primordial Galaxies

- Steep boundary in fragment mass near $n_{c,0} = 10^4 - 10^5 \text{cm}^{-3}$ for $f > 3$, regardless of the initial $\text{H}_2$ abundance
  - Implies IMFs in very metal deficient gas are likely to be bimodal
- Minimum mass is few $M_{\text{sun}}$ (not sensitive to $\text{H}_2$ abundance)
- Maximum mass is $\sim 100 M_{\text{sun}}$ for $\chi_{\text{H}_2,0} < 3 \times 10^{-3}$ and $\sim 10 M_{\text{sun}}$ for $\chi_{\text{H}_2,0} > 3 \times 10^{-3}$
Formation of the First Stars by Accretion
Mass-dependent Accretion Rate

\[ \dot{M}_{\text{acc}} = \dot{M}_{\text{ABN}}(M_*) \]

Protostellar Radius \( R_*(R_\odot) \)

Protostellar Mass \( M_*(M_\odot) \)
Results: Formation of the First Stars by Accretion

- Final mass of star is potentially very large (~600 $M_{\text{sun}}$)
- If you assume star supernovas after 3 Myr, then mass is limited to ~500 $M_{\text{sun}}$
- If you also include the likely formation of an $\text{H}_\text{II}$ region, mass is limited to ~460 $M_{\text{sun}}$