How Population III Stars Begin

Cosmological Reionization

John Wise (NASA / GSFC)

w/ Tom Abel (KIPAC / Stanford)
Population III Stars

- Various computational techniques have calculated and verified that the first stars are massive (30 - 300 M☉) and isolated.
  \[ \text{Abel et al. (2002), Bromm et al. (2002), Yoshida et al. (2006)} \]
- \( L \sim 10^6 L_\odot, \sim 10^{50} \) ionizing photons / sec
- Lifetime \( \sim 3 \text{ Myr} \)
  \[ \text{Schaerer (2002)} \]
- \( \text{H}_2 \) is the main coolant, which is easily dissociated by distant sources of radiation.
  \[ \text{Dekel & Rees (1987)} \]
- Provide the first ionizing radiation and metals to the universe.
Motivation

• To calculate key quantities that can be used in semi-analytical or large box calculations.

• Star formation rates, photon escape fractions, clumping factors, photo-evaporation, etc.

• To obtain the characteristics of low mass galaxies: baryon fractions, spin parameters that may affect star formation and photon escape fractions.

• Maybe deconvolve Pop III stellar properties from future observations of low mass z>6 galaxies?
Enzo

Versatile AMR Code

Physics:
Gravity
Hydrodynamics
Non-equilibrium chemistry
Radiation transport
MHD

Refinement:
Baryon overdensity
Dark matter overdensity
Jeans length by 16 cells

Stable to 41 levels
\(10^{14}\) dynamical range

Abel et al. (1997)
Abel & Wandelt (2002)
Truelove et al. (1997)
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Simulation Setup

- Two random phases:
  - Simulation “A” and “B”
- Atomic H, He, and H$_2$ cooling
- Population III stellar formation and feedback
- Radiation transport
- Supernova feedback and metal tracer field
- Max AMR level = 12 (0.1 pc at z=20)

<table>
<thead>
<tr>
<th></th>
<th>Simulation A</th>
<th>Simulation B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Redshift</td>
<td>130</td>
<td>120</td>
</tr>
<tr>
<td>Comoving Box Size</td>
<td>1.0 Mpc</td>
<td>1.5 Mpc</td>
</tr>
<tr>
<td>DM Mass Resolution</td>
<td>30 M$_\odot$</td>
<td>100 M$_\odot$</td>
</tr>
<tr>
<td>Maximum # of Unique Cells</td>
<td>$1.2 \times 10^8$ ($494^3$)</td>
<td>$6.5 \times 10^7$ ($420^3$)</td>
</tr>
</tbody>
</table>
Star Formation and Feedback


Star formation only

- 100 M\odot stars, 1.2 \times 10^{50} ionizing photons / sec, 2.7 Myr lifetime

Plus pair-instability SNe

- 170 M\odot stars, 2.3 \times 10^{50} ionizing photons / sec, 2.3 Myr lifetime

➡ Model radiation with adaptive ray tracing
Adaptive Ray Tracing

- Radiative transfer is computed using an adaptive ray tracing technique.
- We require at least 5 rays per cell. Rays are split when this criterion is not met.
- Direction of the rays and splitting are determined by HEALPix.
- Fully integrated and coupled with the hydrodynamic, chemistry, and energy solvers in Enzo.
- Parallelized with MPI and dynamically load-balanced.

Gorski et al. (2005)
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HII Region of a Primordial Star

- $10^6$ solar mass DM halo; single 100 $M_\odot$ star (no SN)
- Drives a 30 km/s shock wave, expelling most of the gas
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Abel, Wise, & Bryan (2007)
150 comoving kiloparsecs
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No Star Formation, H/He Cooling Only

9 physical kpc; z = 17
Star Formation + SNe

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Star Formation Rates

- Bursting star formation in larger halos
- Higher SFR than analytical estimates because our simulations sample cosmologically overdense regions (3-σ)
Ionized Fractions

- Emissivity in units of ionizing photons per baryon per Hubble time
- Ionizes the nearby IGM to 30% - 75%
- Beware: not representative of global ionization fractions – highly biased (i.e. inside out)
Effective Ionizations

\begin{align*}
\text{Effective Ionizations} &= \frac{n_e}{n_\gamma} \\
&\text{(RT, SN, H+He)} \\
&\text{Photons} \\
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Effective Ionizations

The ratio $n_e / n_{ph} = 3$–$20\%$ takes into account both the UV photon escape fraction and the clumping factor.
Anisotropic H II Regions

- HII regions become more anisotropic in larger halos
- Photon escape fractions decrease with halo mass
Clumpy IGM

\[ \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} \text{ at } t \text{ on} \]

\[ \begin{align*}
\text{Redshift} & \quad \text{SimA} & \quad \text{SimB} \\
30 & \quad & \quad \\
25 & \quad & \\
20 & \quad & \\
15 & \quad & \\
10 & \quad & \\
5 & \quad & \\
0 & \quad & \\
\end{align*} \]
The recombination rate in the IGM on average is increased by the clumping factor.
Minimum Galaxy Mass
(aka Filtering Mass)
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Jean’s Filtering Mass
\[ M_{F}^{2/3} = \frac{3}{a} \int_{0}^{a} da' M_{J}^{2/3}(a') \left[ 1 - \left( \frac{a'}{a} \right) \right] \]
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Jeans Filtering Mass

\[ M_{F}^{2/3} = \frac{3}{a} \int_{0}^{a} d\alpha' M_{J}^{2/3}(\alpha') \left[ 1 - \left( \frac{\alpha'}{a} \right) \right] \]

\begin{align*}
M_{F}, M_{J} [M_{\odot}] & \\
10^{5} & 10^{6} & 10^{7} & 10^{8} & 10^{9} & \\
30 & 25 & 20 & 15 & \\
\langle T \rangle_{V} & \\
10^{3} & 10^{4} & 10^{5} & 10^{6} & 10^{7} & 10^{8} & 10^{9}
\end{align*}

SimA-RT
SimB-RT
SimB-SN
Minimum Galaxy Mass
(aka Filtering Mass)

1st star in halo:
- Minimum mass regulated by an H$_2$ dissociating background
  Machacek et al. (2001)
- Also regulated by photo-evaporation.
  e.g. Haiman et al. (2000), Iliev et al. (2005), Ciardi et al. (2006)

2nd+ star in halo:
- Halo grows by accreting gas heated from previous stars
- Regulated by the Jeans “filtering” mass
  Gnedin & Hui (1998)

Jeans Filtering Mass

\[ M_{\text{F}}^{2/3} = \frac{3}{a} \int_0^a da' \frac{M_{\text{J}}^{2/3}(a')}{1 - \left( \frac{a'}{a} \right)} \]
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Jeans Filtering Mass

$$M_F^{2/3} = \frac{3}{a} \int_0^a da' M_J^{2/3}(a') \left[ 1 - \left( \frac{a'}{a} \right) \right]$$

$$\langle T \rangle_v$$

$$30 \quad 25 \quad 20 \quad 15$$

Redshift

$M_J$, $M_F$, $M_J$, $\langle T \rangle_v$

SimA-RT, SimB-RT, SimB-SN
Shortcomings

- Small box simulation – highly biased region
- Neglecting self-shielding of Lyman-Werner radiation
- Fixed stellar mass – no IMF
- Neglecting \(~30 \,M_\odot\) ("Pop III.2") stars that may form in halos embedded in relic HII regions with HD cooling
- No metal cooling to study the transition to Pop II star formation
Future Directions?

• Similar simulations for less biased regions
• External ionizing source from high sigma peaks. Use “semi-numerical” methods to predict ionization epoch based on a coarse grid?
• Sub-grid models for ~100 Mpc simulations
• Lyman-Werner radiation self-shielding
• Metal line, HD, and dust cooling
• Pop II star formation
• Larger boxes (3–5 Mpc) + Similar mass resolution → Larger halos ($10^9 - 10^{10} \, M_\odot$)

Mesinger & Furlanetto (2007); Zahn et al. (2007)
e.g. Glover & Jappsen (2007); Smith et al. (2007)
Even Low Mass Galaxies are Complex!

- Isolated $M_{\text{vir}} = 10^8 M_\odot$ halo – Radiation Hydro – 100 Myr

Wise & Cen (in prep.)
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830 physical pc

1660 physical pc

Wise & Cen (in prep.)
Conclusions

• Star formation is delayed for \( \sim 50 \, \text{Myr} \) after the first star. Once material is reincorporated into the halo, \( \text{SFR} \sim 10^{-2} \, M_\odot/\text{yr}/\text{Mpc}^{-3} \).

• Clumping factors are highly variable but are, on average, a factor of 2 lower than in the adiabatic case without star formation.

• Roughly 1 in 10 ionizing photons result in a sustained ionization.

• Jeans filtering mass is an excellent measure of the minimum halo mass that undergoes its 2nd instance of star formation.

• Only the beginning toward building galaxies one star at a time!