Environmental Dependence of the First Star Formation

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"Environmental Dependence of the First Star Formation"

1 | Formation of the First Stars
2 | Baryon-DM Relative Motion
3 | Dependence of the First Star Formation
4 | Observational Counterpart
5 | Summary

“Supersonic Gas Streams Enhance the Formation of Massive Black Holes in the Early Universe”

“Formation of the first star cluster and massive star binaries by fragmentation of filamentary primordial gas clouds”
First Stars (1\textsuperscript{st}-generation stars)

formed from the primordial gas (H, He, light atoms).
First Stars (1\textsuperscript{st}-generation stars)

formed from the primordial gas (H, He, light atoms).
Physical properties of the primordial star-forming cloud can be reproduced theoretically & numerically by performing the cosmological simulation.
Formation Path of the First Stars

Cosmological hydro simulation by Gadget-3 (Springel’05)
- N-body (DM) + SPH (Gas)
  + Primordial chemistry
  + Hierarchical zoom-in
  + Particle splitting ($L_{\text{Jeans}}/L_{\text{sph}} > 15$)

Simulation by SH
Visualization by Takaaki Takeda (VASA)

Cosmic web
Dark matter minihalo
Jeans cloud
Molecular core
Protostar core

$10^5$-$10^6[M_\odot]$ at $z \sim 20$
$\sim 1000[M_\odot]$
$\sim 0.01[M_\odot]$

$\sim 20$ [kpc] $300$ [pc] $5$ [pc] $10$ [AU] $25$ [R_\odot]
Star-forming Gas Cloud

First Star Formation Process

Λ-Cold Dark Matter Cosmology

- Primordial density perturbation
- Large-scale structure
- Dark matter minihalo
- Molecular gas cloud
- Tiny protostellar core
- First Star

\[ M_{\text{Jeans}} = 1000 \left( \frac{T_{\text{Jeans}}}{200 \text{ [K]}} \right)^{1.5} \left( \frac{n_{\text{H}}}{10^4 \text{ [cm}^3\text{]}} \right)^{-0.5} \text{ [M}_\odot\text{]} \]

\[ = 0.01 \left( \frac{T_{\text{Jeans}}}{10 \text{ [K]}} \right)^{1.5} \left( \frac{n_{\text{H}}}{10^{10} \text{ [cm}^3\text{]}} \right)^{-0.5} \text{ [M}_\odot\text{]} \]

FS formation is a collaborative work between the cosmology and astrophysics.

Metal-free

Solar-metallicity

Dark Matter dominated

Baryon (gas) dominated
**Star-forming Gas Cloud**

First Star Formation Process

$\Lambda$-Cold Dark Matter Cosmology

→ Primordial density perturbation

→ Large-scale structure

→ Dark matter minihalo

→ Molecular gas cloud

→ Tiny protostellar core

→ First Star

**Dark Matter**

$M_{\text{Jeans}} \propto C_S^3 \rightarrow (C_S^2 + v^2)^{3/2}$

**Metal-free**

$M_{\text{Jeans}} = 1000 \left( \frac{T_{\text{Jeans}}}{200 \text{[K]}} \right)^{1.5} \left( \frac{n_H}{10^4 \text{[cm}^{-3}] \right)^{-0.5} \text{[M}_\odot]$

$= 0.01 \left( \frac{T_{\text{Jeans}}}{10 \text{[K]}} \right)^{1.5} \left( \frac{n_H}{10^{10} \text{[cm}^{-3}] \right)^{-0.5} \text{[M}_\odot]$

**Solar-metallicity**

FS formation is a collaborative work between the cosmology and astrophysics.
1 | Formation of the First Stars

*Ab initio* cosmological simulation ➔ Stellar mass
Star-forming gas cloud = Jeans scale

2 | Baryon-DM Relative Motion
3 | Dependence of the First Star Formation
4 | Observational Counterpart
5 | Summary
Supersonic coherent (~ a few Mpc) flows of the baryons relative to the underlying potential wells created by DM at $z_{\text{rec}}$. 

“The relative motion suppresses the abundance of the first objects”  
(Tseliakhovich & Hirata 2010)
Suppression of the Early Structure Formation

**Small-Scale**

Gas density distributions of width 50 kpc/h at z=20 (O’Leary & McQuinn 2012)

\[ v_{rel} = |v_{\text{Baryon}} - v_{\text{DM}}| = 0 \]
\[ v_{rel} = 1\sigma_{rel} \]
\[ v_{rel} = 2\sigma_{rel} \]

**Large-Scale**

Gas fraction in star-forming halos at z=40 (Visbal et al. 2012)

\[ v_{rel} = |v_{\text{Baryon}} - v_{\text{DM}}| = 0 \]
\[ v_{rel} = |v_{\text{Baryon}} - v_{\text{DM}}| > 0 \]

**Suppression of gas condensation:**
- Abundance of DM halo
- Baryon fraction
- Subsequent star formation
- Stellar/galactic feedbacks
- ...

**Inhomogeneous influence on large-scale structure:**
- Cosmic reionization
- 21-cm intensity distribution
- B-mode polarization of CMB
- Missing satellite problem
- ...

\[ v_{\text{rel}} = v_{\text{Baryon}} - v_{\text{DM}} \]
Influence on the FS Formation

$L_{\text{coherent}} \sim \text{a few cMpc} >> L_{\text{1st-object}} (~10 \text{ kpc})$

$v_{bc}(z) = |v_{\text{baryon}} - v_{\text{CDM}}| = v_{bc,\text{rec}} (1+z)/(1+z_{\text{rec}})$

$M_{\text{Jeans}} \propto (c_s^2 + v_{bc}(z)^2)^{3/2}$

- $c_s \sim 1 \text{ [km/s]}$ for the FS formation
- $\sigma_{bc} = 30 \text{ [km/s]}$ … RMS value of $v_{bc}$ at $z = z_{\text{rec}}$

$c_s \sim v_{bc}(z=30) \text{ for } v_{bc,\text{rec}} = 1.17\sigma_{bc}$
$c_s \sim v_{bc}(z=20) \text{ for } v_{bc,\text{rec}} = 1.73\sigma_{bc}$
$c_s \sim v_{bc}(z=10) \text{ for } v_{bc,\text{rec}} = 3.30\sigma_{bc}$
1 | Formation of the First Stars

2 | Baryon-DM Relative Motion
   Supersonic coherent flows of the baryon relative to DM
   Suppression and delay of the early structure formation

3 | Dependence of the First Star Formation

4 | Observational Counterpart

5 | Summary
[0] **Initial Condition** (with the \( \Lambda \)-CDM cosmology)
by “MUSIC” (hierarchical zoom-in technique; Hahn & Abel 2011)

+ Coherent, relative motion between baryon and DM

**MODEL PARAMETERS**

\[
v_{bc} = |v_{\text{baryon}} - v_{\text{CDM}}| = X \sigma_{bc} \quad (X = 0, 1, 2, 3)
\]
\[
\sigma_{bc} = 30 \text{ [km/s]} \quad \text{... root-mean-square value of } v_{bc} \text{ at } z = z_{\text{rec}}
\]

[1] **Collapse Phase** (until \( n_{H,\text{cen}} = 10^{13} \text{ [cm}^{-3}\text{]} \))
by parallel N-body + SPH code “Gadget-3” (Springel 2005)
+ Primordial chemistry (Yoshida et al. 2006; 2007; SH et al. 2015)
+ Particle splitting \( (L_{\text{HSML}} / L_{\text{Jeans}} > 10; \text{Kitsionas}&\text{Whitworth 2002}) \)

[2] **Accretion Phase** (after the protostar formation)
by 3D-RHD code “PLUTO”
+ stellar evolution code “STELLAR”
Simulation of FS Formation

Initial Condition
(with the Λ-CDM cosmology)
by "MUSIC" (hierarchical zoom-in technique; Hahn & Abel 2011) + Coherent, relative motion between baryon and DM

\[ v_{bc} = |v_{\text{baryon}} - v_{\text{CDM}}| = \sigma_{bc} (X = 0, 1, 2, 3) \]

**PARAMETERS**

\[ \sigma_{bc} = 30 \text{ [km/s]} \] root-mean-square value of \( v_{bc} \) at \( z = z_{\text{rec}} \)

Collapse Phase (until \( n_{H,\text{cen}} = 10^{13} \text{[cm}^{-3}] \)) by parallel N-body + SPH code "Gadget-3" (Springel 2005) + Primordial chemistry (Yoshida et al. 2006; 2007; SH et al. 2015) + Particle splitting (LHSML/LJeans > 10; Kitsionas & Whitworth 2002)

Accretion Phase (after the protostar formation)
by 3D-RHD code "PLUTO" + stellar evolution code "STELLAR"

Simulation of FS Formation

- **DM density at \( z = 30.5 \)**
- **Gas density**
- **Streaming Velocity**
  \[ v_{SV} = 3\sigma_{SV} \]

- **DM density at \( z = 7 \)**
  \[ R_{\text{Virial}} \]
  \[ M_{\text{Virial}} \approx 2 \times 10^7 \text{ M}_\odot \]

- **Gas**
  \[ R_{\text{Jeans}} \]
  \[ M_{\text{Jeans}} \approx 3 \times 10^4 \text{ M}_\odot \]

- **Z_{ini} = 499**
- **L_{box} = 10 h^{-1} \text{ Mpc} \text{ (comov.)}**
- **l_{soft} = 12.2 h^{-1} \text{ pc} \text{ (comov.)}**
- **m_{DM,\text{zoom}} = 16.4 \text{ M}_\odot**
- **m_{\text{Gas,\text{zoom}} = 3.0 \text{ M}_\odot}**
- **|v_{DM} - v_{\text{Gas}}| = 0, 1, 2, 3\sigma_{SV} \text{ (along x-axis)}**
Baryon-DM relative velocity decreases with time as $v_{bc}(z) = v_{bc,\text{rec}}(1+z)/(1+z_{\text{rec}})$.
Density map $| \frac{v_{bc}}{\sigma_{bc}} = 0, 1, 2, 3 |

$\frac{v_{bc}}{\sigma_{bc}} = 0, 1, 2, 3$

for high-$\sigma_8$ seed

<table>
<thead>
<tr>
<th>$\frac{v_{bc}}{\sigma_{bc}}$</th>
<th>Streaming Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$= 0$</td>
<td></td>
</tr>
<tr>
<td>$= 1$</td>
<td></td>
</tr>
<tr>
<td>$= 2$</td>
<td></td>
</tr>
<tr>
<td>$= 3$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$M_{\text{halo}} \left[ M_\odot \right]$</th>
<th>$1.6 \times 10^5$</th>
<th>$2.2 \times 10^6$</th>
<th>$3.4 \times 10^7$</th>
<th>$2.2 \times 10^7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\text{Jeans}} \left[ M_\odot \right]$</td>
<td>$360$</td>
<td>$1,000$ (twin)</td>
<td>$200-400$ (multiple)</td>
<td>$26,000$</td>
</tr>
</tbody>
</table>
Large filamentary structure (with \(\sim 10^4 \, [M_\odot]\)) fragments to 8 clouds with \(\sim 200 - 400 \, [M_\odot]\) (filamentary instability)

\(\Rightarrow\) First stars with 50 – 120 \([M_\odot]\)

\(v_{bc} / \sigma_{bc} = 2\) | Cluster of the First Stars
\[ \frac{v_{bc}}{\sigma_{bc}} = 3 \] Supermassive first star

3D RHD Simulation of the mass growth of the protostar via mass accretion

<table>
<thead>
<tr>
<th>( v_{bc} )</th>
<th>( \sigma_{bc} )</th>
<th>( z )</th>
<th>( R_{\text{virial}} ) (pc)</th>
<th>( M_{\text{virial}} ) (( M_\odot ))</th>
<th>( V_{\text{virial}} ) (( \text{km s}^{-1} ))</th>
<th>( M_{\text{jeans}} ) (( M_\odot ))</th>
<th>( t_{\text{acc}} ) (10^6 yr)</th>
<th>( M_{\text{star}} ) (( M_\odot ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1.2</td>
<td>30.5</td>
<td>171</td>
<td>2.2 \times 10^7</td>
<td>13.3</td>
<td>26,000</td>
<td>0.60</td>
<td>34,000</td>
</tr>
</tbody>
</table>
Dependence of the First Star Formation

① Supersonic gas streams in the early Universe left over the Big Bang

② Gas cloud formation is prevented until rapid gas condensation is triggered in a protogalactic halo

③ Dense, turbulent gas cloud forms (a) cluster of massive stars or (b) single supermassive star
Dependence of the First Star Formation

Supersonic gas streams in the early Universe left over the Big Bang

- Dense, turbulent gas cloud forms (a) cluster of massive stars or (b) single supermassive star

Gas cloud formation is prevented until rapid gas condensation is triggered in a protogalactic halo.

- Rapid Relative Vel.
  - Single supermassive first star
  - $10^4-10^5 [M_{\odot}]$ Pop III star at $z \approx 30$
  - Seed of high-$z$ quasars with $10^9 [M_{\odot}]$ at $z > 7$

- Slow Relative Vel.
  - Binary/Cluster of first stars
  - ~10 Pop III stars with $100 [M_{\odot}]$ at $z \approx 15$
  - Massive BH binary (GW progenitor)

Negligible Relative Vel.

- Pop III stars with ~100 [$M_{\odot}$] around $z \approx 15-25$
  - Parent stars of observed EMPs

Relative Velocity between baryon and DM fluids

- 100 pc
- 10 pc
3 | Dependence of the First Star Formation

Coherent flows increase the Jeans scale and stellar mass
SINGLE / MULTIPLE / SUPERMASSIVE first star(s)
Source of the Gravitational Wave Signal

LIGO-Virgo Black Holes

X-ray Binary Black Holes
Source of the Gravitational Wave Signal

- ~10 Pop III stars with $100[M_\odot]$ at $z \sim 15$
- 10 pc
- Binary/Cluster of first stars
- Massive BH binary (GW progenitor)

$$t_{\text{coal}} \sim 10 \text{ Gyr} \left( \frac{a_0}{0.2 \text{ au}} \right)^4 (1 - e_0)^{7/2} \left( \frac{M_1}{30 M_\odot} \frac{M_2}{30 M_\odot} \frac{M_1 + M_2}{60 M_\odot} \right)^{-1}$$

Massive BH close binary (possible GW source)
Seed of the SuperMassive Black Holes
Seed of the SuperMassive Black Holes

- **Interpretation:**
  - **First Star (Pop III):** ~$10^4 - 10^5 [M_\odot]$ at $z \approx 30$
  - **Intermediate Mass BH (IMBH):** ~$100 [M_\odot]$ at $z \approx 7$
  - **Eddington limit:** $t_{\text{grow}} \geq 0.05 \ln(M_{\text{BH}}/M_{\text{BH,0}})$ Gyr
  - **SMBH:** $\sim 10^9 [M_\odot]$ at $z > 6$ (N ~ a few [Gpc$^{-3}$])

- **Rapid Relative Vel.**
  - Single supermassive first star
  - Seed of high-$z$ quasars with $10^9 [M_\odot]$ at $z \approx 7$
  - First star with $10^4 - 10^5 [M_\odot]$ at $z \approx 30$
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<td>Source of the gravitational wave signal</td>
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<td>Seed of the high-z quasars</td>
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<td>5</td>
<td>Summary</td>
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Supersonic gas motions left over from the Big Bang are intrinsically generated in the early universe according to the standard model of structure formation.

The baryonic streaming motions prevent early gas cloud formation until rapid gas condensation is triggered in a protogalactic halo.

“Environmental Dependence of the First Star Formation”

➤ SINGLE, MULTIPLE, and SUPERMASSIVE first star(s) form depending on the degree of the streaming velocity.
Acceptable FS formation have to be realized.

- WIMPs DM self-annihilation
- Not yet observationally constrained primordial power-spectrum
- Warm, Fuzzy, … DM(s)
- Baryon-DM cross-section (EDGES 21cm signal)
- …