The First Stars

Volker Bromm

The University of Texas at Austin
From the Dark Ages to the Cosmic Renaissance

(Larson & Bromm, Scientific American, Dec. 2001)

• First Stars → Transition from Simplicity to Complexity
The James Webb Space Telescope:
(Next Generation Space Telescope)

• Launch in ~2013
• Near IR sensitivity of ~1 nJy
• ~4’ x 4’ FOV

→ Direct Imaging of the First Stars
Hierarchical Structure Formation:

- Variant of CDM
- Typical mass scale of collapsed objects increases with time

Region of Primordial Star Formation

- Gravitational Evolution of DM
- Gas Microphysic:
  - Can gas sufficiently cool?
  - $t_{\text{cool}} < t_{\text{ff}}$ (Rees-Ostriker)

- Collapse of First Luminous Objects expected:
  - at: $z_{\text{coll}} = 20 - 30$
  - with total mass: $M \sim 10^6 M_\odot$
What happens inside primordial minihalos?

- Most important question: How massive were the first stars?

Massive Black Hole

Stars (single or multiple)

normal IMF

Top-heavy IMF

\[ M \sim 10^6 \, M_\odot \]
The Physics of Population III

- Simplified physics
  - No magnetic fields yet (?)
  - No metals → no dust
  - Initial conditions given by CDM
    → Well-posed problem

- Problem:
  How to cool primordial gas?
  - No metals → different cooling
  - Below $10^4$ K, main coolant is $H_2$

- $H_2$ chemistry
  - Cooling sensitive to $H_2$ abundance
  - $H_2$ formed in non-equilibrium
    → Have to solve coupled set of rate equations
Simulating the Formation of the First Stars:
(Bromm, Coppi, & Larson and Bromm & Hernquist)

- Use TREESPH / Gadget (both DM and gas)
- Radiative cooling of primordial gas
- Non-equilibrium chemistry
- Initial conditions: \( \Lambda \)CDM
- Modifications to SPH:
  - sink particles
  - particle splitting
Cosmological Initial Conditions

- Consider situation at $z = 20$

Gas density

~ 7 kpc

Primordial Object
The First Star-Forming Region ("minihalos")

projected gas density at $z=20$

$M \sim 10^6 M_\odot$

$\sim 100$ pc

$\sim 7$ kpc (proper)
Formation of a Population III Star
(Bromm, Coppi, & Larson 1999, 2002; Bromm & Loeb 2004)

\[ M_{\text{halo}} \sim 10^6 M_\odot \]
\[ M_{\text{clump}} \sim 10^3 M_\odot \]

~ 25 pc
A Physical Explanation: (Bromm, Coppi, & Larson 1999, 2002)

- Gravitational instability (Jeans 1902)
- Jeans mass: $M_J \sim T^{1.5} n^{-0.5}$

- Thermodynamics of primordial gas

\[ T \text{ vs. } n \]

\[ M_J \text{ vs. } n \]

- Two characteristic numbers in microphysics of H$_2$ cooling:
  - $T_{\text{min}} \sim 200$ K
  - $n_{\text{crit}} \sim 10^3 - 10^4$ cm$^{-3}$ (NLTE → LTE)
- Corresponding Jeans mass: $M_J \sim 10^3 M_\odot$
The Crucial Role of Accretion

- Final mass depends on accretion from dust-free Envelope

Clump: $M \sim M_J$
The Crucial Role of Accretion

• Final mass depends on accretion from dust-free Envelope

• Development of core-envelope structure
  - Omukai & Nishi 1998, Ripamonti et al. 2002

• $M_{\text{core}} \sim 10^{-3} M_\odot \rightarrow$ very similar to Pop. I

• Accretion onto core $\rightarrow$ very different!

• $\frac{dM}{dt_{\text{acc}}} \sim \frac{M_J}{t_{\text{ff}}} \sim T^{3/2}$ (Pop I: $T \sim 10$ K, Pop III: $T \sim 300$ K)

• Can the accretion be shut off in the absence of dust?
Protostellar Collapse
Bromm & Loeb 2004, New Astronomy, 9, 353

- Simulate further fate of the clump
Accretion onto a Primordial Protostar

\[ \frac{dM}{dt} \text{ vs. time} \quad M \text{ vs. time} \]

Upper limit: \[ M_* \ (t = 3 \times 10^6 \text{ yr}) \approx 500M_\odot \]
Accretion onto a Primordial Protostar

Kelvin-Helmholtz time: \( t_{KH} \sim \frac{GM^2}{LR} \sim 10^5 \) yr

- Onset of nuclear fusion
- Violent radiative feedback
  \[ \rightarrow \text{accretion stops} \]

More realistic mass estimate: \( M(t=t_{KH}) \sim 120 \, M_{\odot} \)
The First Stars: The “Standard” Model

• Numerical simulations

• Main Result: $\rightarrow$ Top-heavy IMF
Implications of a Heavy IMF For the First Stars

• Consider: $100 \, M_\odot < M < 1000 \, M_\odot$ (VMO)
• Structure determined by:
  - Radiation pressure, Luminosity close to EDDINGTON limit

$log L$ vs. $log T_{\text{eff}}$

• For Pop III:
  $T_{\text{eff}} \sim 110,000$ K
  $\lambda$ peak $\sim 250$ Å
(close to He II ionization edge)
Wilkinson Microwave Anisotropy Probe:

Polarization → optical depth to Thomson scattering:

$(\tau = 0.09 \pm 0.04)$ → Signature of the First Stars
CMB photon-scattering from free electrons

Z = 0

Z ~ 7

e^{-}

Z ~ 1,100

$\sim 0.06$

$\sim 0.09$

LSS
Ionization History of the Universe

(Greif & Bromm 2006; astro-ph/0604367)

SFR vs z

Ionized fraction vs z

Pop III star formation must have been terminated $z \gtrsim 10$
Primordial HII Regions
(Alvarez, Bromm, & Shapiro 2006; astro-ph/0507684)

$z = 20$

$M_{\text{vir}} = 10^6 M_\odot$

I-front (D-type)

13.6 kpc (proper)

300 pc
Primordial HII Regions
(Alvarez, Bromm, & Shapiro 2006; astro-ph/0507684)

- density suppression (photo-heating)

\[ n \text{ vs } r \]

- self-similar “champagne flow” (Shu et al. 2002)

\[ M_{\text{vir}} = 10^6 M_\odot \]

\[ 300 \text{ pc} \]
Primordial HII Regions
(Alvarez, Bromm, & Shapiro 2006; astro-ph/0507684)

$z = 20$

$13.6 \text{ kpc}$

$M_* = 80 M_\odot$

$M_* = 200 M_\odot$
The Death of the First Stars:
(Heger et al. 2003)
The First Supernova Explosions


\[ M \sim 10^6 M_\odot \]

\[ \sim 7 \text{kpc} \]

\[ 1 \text{kpc} \]
Physics of Pair-instability Supernovae

$M \sim 140 - 260 \, M_\odot$

- $T > 10^9 K$
- $ph + ph \rightarrow e^- e^+$
- grav. runaway collapse
- large jump in core $T$
- explosive nuclear burning
- implosion $\rightarrow$ explosion
- no compact remnant
- all heavy elements dispersed
- distinct nucleosynthetic pattern
HII Regions around the First Stars

1 kpc
The First Supernova-Explosion

Gas density

- $E_{SN} \sim 10^{53}$ ergs
- Complete Disruption (PISN)

$\sim 1$ kpc
The First Supernova-Explosion

Metal Distribution

~ 1 kpc

- Add trace amount of metals
- Limiting case of no H$_2$
- Heating by photoelectric effect on dust grains

Consider two identical (other than Z) simulations!
Effect of Metallicity:

\[ Z = 10^{-4} Z_o \quad \text{and} \quad Z = 10^{-3} Z_o \]

- Insufficient cooling
- Vigorous fragmentation

\[ Z_{\text{crit}} \sim 5 \times 10^{-4} Z_o \]
The Pop III \rightarrow Pop II Transition

IGM Metallicity vs. redshift

\[ Z_{\text{crit}} \]

\[ Z_{\text{tran}} \sim 15 \pm 5 \]
Chemical Feedback: Pop III \quad Pop II transition
(Bromm & Loeb 2006; astro-ph/0509303)

SF History

strength of chemical feedback
weak \quad strong

(cf. Scannapieco, Schneider, & Ferrara 2003)
Forming the First Low-mass Stars:
(Bromm & Loeb 2003, Nature 425, 812)

- Abundance pattern:
  - HE0107-5240, 1327-2326
  - very Fe-poor
  - very C/O-rich

- Pop III → Pop II:
  - driven by: CII,OI
    (fine-structure transitions)

- Minimum abundances:
  - [C/H] ~ -3.5
  - [O/H] ~ -3.1
  - Identify truly 2nd gen. stars!
Relic from the Dawn of Time:

- HE0107-5240: \([\text{Fe/H}] = -5.3\) (Christlieb et al. 2002)

\[ M \sim 0.8M_\odot \]

- How could such a low-mass star have formed?
Formation of the First Quasars

• Seed BH by direct collapse of primordial gas cloud

  • Problem:
    - Gas cooling
    - Fragmentation
    - Star Formation
    - Negative Feedback (SNe)

  → No compact central object!

Mass $\sim 10^9 M_\odot$, $R \sim 1$ kpc
$z_{vir} = 5$, no DM
First Dwarf Galaxies as Sites of BH Formation

- 2 sigma peak
- \( M \sim 10^8 M_\odot \), \( z_{\text{vir}} \sim 10 \)
- \( T_{\text{vir}} \sim 10^4 \text{ K} \)

\[ \text{-> Cooling possible due to atomic H} \]

- Suppress star formation:
  - Photo-dissociation of \( \text{H}_2 \):
    \[ \text{H}_2 + h \nu \rightarrow 2 \text{ H} \]
  - Lyman – Werner photons:
    \[ h \nu = 11.2 - 13.6 \text{ eV} \]
Cosmological Context

$Z = 10$

$Z < Z_{\text{crit}}$

1 co-moving Mpc
En Route to a Supermassive Black Hole?

- Consider gas distribution in central 100 pc

**Low-spin**

**High-spin**

Single object: $M \sim 10^6 \, M_\odot$

Binary: $M_{1,2} \sim 10^6 \, M_\odot$
What is further fate of gas cloud?

Supermassive Star

- Radiation-pressure supported: \( t_{\text{cool}} >> t_{\text{ff}} \)
- Supermassive star or disk: \( t_{\text{vis}} < t_{\text{cool}} \) → SMS?
Gamma-Ray Bursts as Probes of the First Stars:

- GRB progenitors → massive stars
- GRBs expected to trace cosmic SFH
- *Swift* mission:
  - Launched in 2004
  - Sensitivity → GRBs from $z > 15$
High-z GRBs from Population III Progenitors:  
( Bromm & Loeb 2006; astro-ph/0509303 )

**SF History**

- Expect only small number of Pop III bursts over ~5 yr *Swift* mission
- Fraction of GRBs detected by *Swift* from $z > 5$: ~10%

**GRB Redshift Distribution**
Summary

• Primordial gas typically attains:
  - T ~ 200 – 300 K
  - n ~ \(10^3 – 10^4\) cm\(^{-3}\)

• Corresponding Jeans mass: \(M_J \sim 10^3\) M\(_\odot\)

• Pop III SF might have favored *very massive stars*

• Transition to Pop II driven by presence of metals
  \((Z_{\text{trans}} \sim 15 \pm 5)\)

• PISNe completely disrupt mini-halos and enriches surroundings

• 2\(^{nd}\) generation of intermediate-mass stars (“Pop II.5”)
Perspectives:

• Further fate of clumps
  - Feedback of protostar on its envelope
  - Inclusion of opacity effects (radiative transfer)

• The "Second Generation of Stars" (high-z dwarf galaxies)

• SN feedback and metal enrichment from the first stars

• What were the seeds for the first quasars?

• When did QSO activity first begin?