First Stars: Review of Theory

Volker Bromm

The University of Texas at Austin
FROM THE DARK AGES...

After the emission of the cosmic microwave background radiation (about 400,000 years after the big bang), the universe grew increasingly cold and dark. But cosmic structure gradually evolved from the density fluctuations left over from the big bang.

...TO THE RENAISSANCE

The appearance of the first stars and protogalaxies (perhaps as early as 100 million years after the big bang) set off a chain of events that transformed the universe.

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

- First Stars (Pop III) → Transition from Simplicity to Complexity
Why start with Population III?

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

• Scales for star and galaxy formation overlap at earliest epochs

- 100 pc

\[ \text{length} \]

\[ \text{cosmic time} \]

\[ \text{SF cloud} \]

\[ \text{galaxies} \]
Region of Primordial Star Formation
(e.g., Couchman & Rees 1986; Haiman et al. 1996; Tegmark et al. 1997)

- Gravitational Evolution of CDM
- Gas Microphysic:
  - Can gas sufficiently cool?
  - $t_{\text{cool}} \leq t_{\text{ff}}$ (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?

$M \sim 10^6 \, M_\odot$

Massive Black Hole

Stars (single or multiple)

normal IMF

Top-heavy IMF
The First Stars: The “Standard” Model

• Numerical simulations
  - Yoshida et al. (2006); O’Shea & Norman (2007); Gao et al. (2007)

• Main Result: → Top-heavy IMF

---

\[
\frac{dN}{d\log M} \sim 1 M_\odot \quad \text{Pop I / II}
\]

\[
\sim 10-100 M_\odot \quad \text{Pop III}
\]
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 $\text{H}_2$

• **$\text{H}_2$ chemistry**
  - Cooling sensitive to $\text{H}_2$ abundance
  - $\text{H}_2$ formed in non-equilibrium
    → Have to solve coupled set of rate equations

![Graph showing cooling mechanisms and $T_{\text{vir}}$ for Pop III]
First Stars within WDM

Gao & Theuns 2007, to appear in Science

- Primordial gas first falls into filaments, not minihalos
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)

$M_{\text{halo}} \sim 10^6 M_\odot$

$M_{\text{clump}} \sim 10^3 M_\odot$

1 kpc

$\sim 25$ 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**

**\( T \ vs. \ n \)**

**\( M_J \ vs. \ n \)**

- 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

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

- Accretion onto core → very different!

- $\frac{dM}{dt}_{\text{acc}} \sim M_J / t_{\text{ff}} \sim T^{3/2}$ (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

dM/dt vs. time

- Similar range (~50 - ~ few 100 M⊙) found by:
Several groups found similar accretion rates.

- The rate is very high \( \sim 0.01 \text{M}_\text{sun}/\text{yr} \) because of high prestellar temperature \( \sim 300 \text{K} \) (c.f. \( 10^{-6}-10^{-5} \text{M}_\text{sun}/\text{yr} \) for the present-day case).
- The rate decreases with time.

Glover (2005)
A new born proto-star with $T_\star \sim 20,000$K.

$0.3\text{Mpc}$

$r \sim 10\ R_{\odot}$!

$r \sim 10\ R_{\odot}$!

Protostellar Collapse: Mass accretion

• For continued accretion, need: \( L = L_\star + L_{\text{acc}} < L_{\text{Edd}} \)
  \[ \rightarrow M_{\text{crit}} \sim 5 \times 10^{-3} \, M_\odot \, \text{yr}^{-1} \]

\[ \text{Accretion rate vs. mass} \]

\[ \text{Radius vs. mass} \]

\[ \rightarrow \text{See also: Tan & McKee: } \sim 30 - 100 \, M_\odot \]
Protostellar Collapse: Angular Momentum

- Lowest specific angular momentum gas collapses first!

---

degree of rotational support
Neglected Processes

• Magnetic fields (MHD effects, MRI, dynamos, jets…)
  -- E.g., Tan & Blackman 2004; Machida et al. 2006; Silk & Langer 2006

• Cosmic Rays (ionization, heating, chemistry…)
  ➔ might lead to lower Pop III masses!

• Possible modifications to CDM (WDM, annihilation heating…)
  -- E.g. Yoshida et al. 2003; Gao & Theuns 2007; Spolyar et al. 2007
Impact of Cosmic Rays on Pop III Star Formation


$\Psi_* = 2 \times 10^{-3}$ M$_\odot$ yr$^{-1}$ Mpc$^{-3}$

$\Psi_* = 2 \times 10^{-2}$ M$_\odot$ yr$^{-1}$ Mpc$^{-3}$

$\epsilon_{\text{min}} = 10^6$ eV

$\epsilon_{\text{min}} = 10^7$ eV

$\epsilon_{\text{min}} = 10^8$ eV

→ Lowering Pop III mass scale?

(see also: Jasche, Ciardi & Ensslin 2007)
The Death of the First Stars:
(Heger et al. 2003)
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
The First Supernova Explosions

The First Supernova-Explosion
(Greif et al. 2007; arXiv:0705.3048)

Temperature

- $E_{SN} \sim 10^{52}$ ergs
- Complete Disruption (PISN)
The First Supernova-Explosion
(Greif et al. 2007; arXiv:0705.3048)

\[ <Z> \sim 10^{-4} - 10^{-3} Z_\odot \]

215 kpc
Paradise Lost: The Transition to Population II  

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

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

$Z = 10^{-4} Z_o$

- Insufficient cooling
  → Critical metallicity: $Z_{\text{crit}} \sim 5 \times 10^{-4} Z_o$

$Z = 10^{-3} Z_o$

- Vigorous fragmentation

Recently confirmed by Smith & Sigurdsson (2007)
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!
Physics of the Critical Metallicity:

→ Highly complex!

• What is primary coolant?
  - Dust (e.g., Schneider et al. 2006) vs. fine-structure cooling?
  - Molecules (CO…)?
  - Fine-structure cooling: Which elements? (C, O, Si, Fe,…)
    → Bromm & Loeb (2003); Santoro & Shull (2006)
  - Equation of state arguments:
    → e.g., Omukai (2000); Omukai et al. (2005); Spaans & Silk (2005)

• $Z_{\text{crit}} = f (\text{environment, formation history,} \ldots)$
  → Realistic Initial Conditions are crucial!
Relics from the Dawn of Time:

- **HE0107-5240**: $[\text{Fe/H}] = -5.2$ (Christlieb et al. 2002)
- **HE1327-2326**: $[\text{Fe/H}] = -5.4$ (Frebel et al. 2005)

$M \sim 0.8M_\odot$

• How could such a low-mass star have formed?
Forming the First Low-mass Stars:

`Transition discriminant’ ($D_{\text{trans}}$): C + O abundance
The First Dwarf Galaxies

- What is character of star formation?

- 2 sigma peak
- $M \sim 10^8 \, M_\odot$, $z \sim 10$
- $T_{\text{vir}} > 10^4 \, \text{K}$
- Cooling possible
  Due to atomic H

1 co-moving Mpc
Setting the Stage for Pop II Star Formation:
- Influence of previous episodes of star formation

Z~15
no feedback

minihalos

Z~10
with radiative feedback

atomic halos ($T_{\text{vir}}>10^4\text{K}$)

`Pop III.2'?
Fate of shock-heated primordial gas

1) Minihalo-case ($T_{\text{vir}} \sim$ few 1,000 K): Pop III

$\bullet$ HD makes no difference! ($M_{\text{char}} \sim$ few 100 $M_\odot$)
Fate of shock-heated primordial gas
(Johnson & Bromm 2006, 366, 247)

2) Shocked-case \((T_{\text{vir}} > 10,000 \text{ K})\): Pop III.2

- HD may make difference! \((M_{\text{char}} \sim \text{few } 10 \ M_{\odot})\)
Fate of shock-heated primordial gas

• Star formation in high-z universe:
  • Pop III:
    - $M_{\text{char}} \sim \text{few } 100$ $M_\odot$
  • Pop III.2:
    - $M_{\text{char}} \sim \text{few } 10$ $M_\odot$
  • Pop II:
    - $M_{\text{char}} \sim \text{few } 1$ $M_\odot$

• How abrupt is Pop III $\rightarrow$ Pop II transition?
Towards the First Dwarf Galaxies
Towards the First Dwarf Galaxies


$H_2$ abundance (green color)

- HII regions: white-gray overlay
  - Movie credit: Paul Navratil (Texas Advanced Computing Center)

Photon Interaction with Hydrogen Density during Star Formation and Decay

~ 660 kpc (comoving)
Summary

• Primordial gas typically attains:
  - $T \sim 200 - 300$ K
  - $n \sim 10^3 - 10^4$ 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

• 2nd generation of intermediate-mass stars (“Pop III.2”)
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?