From the Dark Ages to the Cosmic Renaissance

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.

First Stars (Pop III)

...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 $\rightarrow$ Transition from Simplicity to Complexity
Initial Simplicity: Chemical Elements

Chemical Abundances (in Solar System)
Synthesis of Chemical Elements

**Big Bang:**

- H, He (D, Li, Be)

**Massive Stars:**

- C, N, O, ..., U

- Before First Stars: primordial gas was pure H/He!
Initial Simplicity: The Primordial Fireball

Cosmic Microwave Background (CMB): Temperature map

Remove “dipole”
(due to Solar System’s Motion w.r.t. CMB):
Initial Simplicity: Tiny Irregularities

Cosmic Microwave Background (CMB): Temperature map

\(~10^{-3}\) 

\(~10^{-5}\)  

\(~10^{-5}\) 

Disk of Milky Way

Seeds for galaxy formation
Initial Fluctuations: Quantum noise + Inflation

(Quantum gravity???)

“Planck time”

Photons of CMB emitted
Dark Matter Models

**Two basic models:**

**Hot Dark Matter (HDM)**
- Top-down scenarios require that dark matter be composed of a weakly interacting, high velocity particle
  - A massive neutrino is a good candidate for an HDM particle

**Cold Dark Matter (CDM)**
- Bottom-up scenarios require that dark matter be composed of a highly massive, slow moving particle
  - Note that neither of these particles are baryons, the ordinary matter makes up stars or planets

**Fluctuation Spectrum:**

![Graph showing fluctuation spectrum with labels for HDM and CDM](image)
The Neutrino Universe

- Q: How much mass is needed to confine (coral in) neutrinos?
- Early on (first 10,000 years), neutrinos move (almost) with speed of light (thus: `Hot Dark Matter')

- Small mass
  Small structures are `erased’ by neutrino free-streaming!

- Large mass
  ~ $10^{15}$ solar masses
  mass of a cluster of galaxies (e.g., Coma)
Dark Matter Models

Hot Dark Matter:

- **Top-Down Structure Formation**: in a top-down scenario, large pancakes of matter form first, then fragment into galaxy-sized lumps.

Cold Dark Matter:

- **Bottom-Up Structure Formation**: in a bottom-up scenario, small, dwarf galaxy-sized lumps form first, then merge to make galaxies and clusters of galaxies.

now known to be correct!
The Cold Dark Matter Model:

Hierarchical Merger Tree:
Cold Dark Matter Model: The Cosmic Web

• Big Q: What happens to cosmic gas?
Cosmic gas (baryons): Dissipative Collapse

- Dissipation = energy loss by emitting radiation
Cooling of Primordial Gas

- **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
Cooling via Molecular Hydrogen ($\text{H}_2$)
Q: Where do First Stars Form?
A: In "minihalos"!

- 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)

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

normal IMF

Top-heavy IMF
Simulating the Formation of the First Stars:

- use state-of-the-art supercomputers
- multi-processor (parallel) "Beowulf" machines

- "Lonestar" at Texas Advanced Computing Center
- UT Austin, J.J. Pickle Research Campus
The Universe at the End of the Dark Ages

200 million years after Big Bang

~ 300 light-years

~ 20,000 light-years
Formation of the First Star: Zooming-in
(Bromm, Coppi, & Larson 1999, 2002; Bromm & Loeb 2004)
Zooming in Further
Bromm & Loeb 2004, New Astronomy, 9, 353

- Computer simulation with very high resolution

75 Light-years

1 Light-years

- Result: The First Stars were very massive!
  (100 times the solar mass)
The Crucial Role of Accretion

- Final mass depends on accretion from dust-free Envelope

Clump: $M \sim M_J$
Accretion onto a Primordial Protostar

dM/dt vs. time

M vs. time

Upper limit: \[ M_\ast \ (t = 3 \times 10^6 \text{ yr}) \approx 500M_\odot \]
First Stars were Massive

<table>
<thead>
<tr>
<th>STAR STATS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>COMPARING CHARACTERISTICS</strong></td>
</tr>
<tr>
<td>Computer simulations have given scientists some indication of the possible masses, sizes and other characteristics of the earliest stars. The lists below compare the best estimates for the first stars with those for the sun.</td>
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<table>
<thead>
<tr>
<th><strong>SUN</strong></th>
<th><strong>FIRST STARS</strong></th>
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<tbody>
<tr>
<td>MASS: $1.989 \times 10^{30}$ kilograms</td>
<td>MASS: 100 to 1,000 solar masses</td>
</tr>
<tr>
<td>RADIUS: 696,000 kilometers</td>
<td>RADIUS: 4 to 14 solar radii</td>
</tr>
<tr>
<td>LUMINOSITY: $3.85 \times 10^{23}$ kilowatts</td>
<td>LUMINOSITY: 1 million to 30 million solar units</td>
</tr>
<tr>
<td>SURFACE TEMPERATURE: 5,780 kelvins</td>
<td>SURFACE TEMPERATURE: 100,000 to 110,000 kelvins</td>
</tr>
<tr>
<td>LIFETIME: 10 billion years</td>
<td>LIFETIME: 3 million years</td>
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First Stars: High-energy Radiation


200 million years after Big Bang

40,000 Light-years

A bubble of ionized gas!
Reionizing the Universe

(IIiev et al. 2006)
The Death of the First Stars:
(Heger et al. 2003)
Physics of Pair-instability Supernovae

M ~ 140 - 260 M₀

- $T > 10^9$K
- $\text{ph} + \text{ph} \rightarrow e^- e^+$
- grav. runaway collapse

- large jump in core $T$
- explosive nuclear burning
- implosion $\rightarrow$ explosion

- no compact remnant
- all heavy elements dispersed
- distinct nucleosynthetic pattern
First Stars: Supernova-Explosion

- 100 times the explosion energy of normal supernova!
- Complete disruption (no remnant left behind)!

~ 3,000 Light-years
The James Webb Space Telescope:
(NASA’s successor to the *Hubble*)

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

→ Direct Imaging of the First Stars
Gamma-Ray Bursts as Probes of the First Stars:

- GRB progenitors → massive stars
- GRBs expected to trace star formation
- Swift mission:
  - Launched in 2004
  - Sensitivity → GRBs from $z > 15$
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?
Probing the First Stars: Hobby-Eberly Telescope

Extending famous Sloan Sky Survey!

- High-resolution Spectra of oldest stars in our Milky Way
- pattern of chemical elements tells us about first stars and supernovae
Perspectives:

• Very dynamic, rapidly developing field

• Closing the final gap in our worldview

• driven by supercomputers and our best telescopes

• Texas will play an important role (HET, theory,...)