Overview

• Evolution of massive stars
• Remnants of the First Stars
• Remnants of Modern Stars
• Stellar Remnants as a Function of Mass and Metallicity
• Explosions and Nucleosynthesis Signature
• Open Questions
Once formed, the evolution of a star is governed by gravity: *continuing contraction* to higher central densities and temperatures.
net nuclear energy generation (burning + neutrino losses)

net nuclear energy loss (burning + neutrino losses)

total mass of star (reduces by mass loss)

convection

semiconvection

H burning

He burning

C burning (radiative)

C shell burning

O shell burning

Si
IMF of the First Stars

Predicted to be heavy to very heavy
by theory – insufficient cooling due to lack of metal
(e.g., Larson 1999)
and by numerical simulations
(Bromm, Coppi, & Larson 1999, 2002;
Abel, Bryan, & Norman 2000, 2002;
Nakamura & Umemura 2001)
with a typical mass scale of ~100 M☉

→ The first stars may have had a
significant very massive population
The Mass of the First Stars

Nakamura & Umemura (2001)

Peak of initial mass function at \( \sim 100 \, M_\odot \) stars?

Similar results by Abel, Bryan, Norman; Bromm et al.; Larsen et al.

Maybe second peak at \( \sim 2-3 \, M_\odot \) ?

Not confirmed by other authors.
Additional Ingredient

Essentially negligible mass loss in Pop III stars

in contrast:

The Pistol Star

- Galactic star / solar+ metallicity
- Extremely high mass loss rate
- Initial mass: 150-200 $M_\odot$ (?)
- Will die as much less massive object
• Very massive metal-free stars spend most of life as blue giants / supergiants

• Typical surface temperatures \( \sim 100,000 \text{ K} \ldots 50,000 \text{ K} \)

• Only stars above \( \sim 500 \, M_\odot \) become red supergiants
Mass Loss in Very Massive Primordial Stars

- Negligible line-driven winds (mass loss $\sim$ metallicity\(^{1/2}\))
- No opacity-driven pulsations (no metals)
- Continuum-driven winds not yet well understood likely very small contribution
- Epsilon mechanism
The Epsilon Mechanism

Classical:
- affects stars above $60M_\odot$

Reason:
- high T-dependence of CNO cycle hydrogen burning ($\sim T^{18}$) at $T_{CNO}=3\times10^7$ K

Primordial Stars:
- no initial CNO
- contract till $T=10^8$ K
- produce CNO seeds ($10^{-9}$)
- CNO-H burning at $T=10^8$ K
- lower T-sensitivity ($\sim T^{14}$)
- pulsational instability weaker
Mass Loss in Very Massive Primordial Stars

- Negligible line-driven winds (mass loss $\sim$ metallicity$^{1/2}$)
- No opacity-driven pulsations (no metals)
- Continuum-driven winds not yet well understood likely very small contribution
- Epsilon mechanism inefficient in metal-free stars below $\sim 1000$ M$_{\odot}$

From pulsational analysis we estimate:
- 120 solar masses: $< 0.2 \%$
- 300 solar masses: $< 3.0 \%$
- 500 solar masses: $< 5.0 \%$
- 1000 solar masses: $< 12. \%$

during central hydrogen burning

- Red Super Giant pulsations could lead to significant mass loss during helium burning for stars above $\sim 500$ M$_{\odot}$
Instability Regimes

adiabatic index $< 4/3$

Compression does not result in sufficient increase in pressure (gradient) to balance higher gravity at lower radius

$\text{e}^+/\text{e}^-$-Pair Instability

Internal gas energy is converted into $\text{e}^+/\text{e}^-$ rest mass (hard photons from tail of Planck spectrum)

Photo disintegration

Internal gas energy is used to unbind heavy nuclei into alpha particles and at higher temperature those into free nucleons

Kippenhahn & Weigert (1990)
Pair BH

$X_a = 0.1$
$X_a = 0.5$
$X_a = 0.9$

PHASE TRANSITION

Fe core collapse
(S = 0.7)

Si (S = 1.1)

C (S = 2.5)

$\Omega$ WZW 25$M_\odot$ star

ignition points

$\gamma$ = 4/3

$\tau_0 = 1$ S

$M_a = 32$

O (S = 1.6)

$M_a = 8$

$M_a = 16$

$M_a = 4$

Bond, Arnett, Carr (1984)
Super-massive stars

• $M \gtrsim 50,000 \, M_\odot$

• adiabatic index $\gamma \rightarrow 4/3$

• GR: $\gamma$ for stability $> 4/3$

• $\rightarrow$ dynamic collapse on "ZAMS"

• burning cannot halt collapse at $Z=0$ (metal-free stars)
The Remnants of Modern Massive Single Stars

Evolution at high masses, $M > 35M_\odot$ is dominated by mass loss due to stellar winds
Massive Star Fates as Function of Mass and Metallicity (single stars)
Alternative Ways to Blow Up Stars: Collapsars & Jet-Driven SNe ("Hypernove, JetSNe")
Hypernova Branch
jet-driven SNe?
(JetSN)

Faint SN Branch

jet-driven SNe?
(JetSN)

(Nomoto 2002)
How to blow up those massive stars?

1. black hole forms inside the collapsing star
2. The infalling matter forms and accretion disk
3. The accretion disk releases gravitational energy (up to 42.3% of rest mass for Kerr BH)
4. Part of the released energy or winds off the hot disk explode the star
The Collapsar Engine

Accretion disk around black hole may power jet by neutrino annihilation or by MHD process. Jet or winds off disk will explode star ("hypernova") and may power high-E transient if it can escape from the stellar interior; requires relativistic jet with high $\Gamma > 100$ and low baryon loading.

$R = 10^{15}\text{cm}$
300 $M_\odot$ star at onset of collapse

Composition

Structure

Rotation

(Fryer, Woosley, & Heger 2000)
Collapse of a 300 $M_\odot$ star

Formation of a $\sim 20 M_\odot$ “proto-black hole”

(Fryer, Woosley, & Heger 2000)
“Proto-BH” before Collapse

Possibility of Triaxial Instability

(Fryer, Woosley, & Heger 2000)
Accretion of $100 \ M_\odot$ at up to $\sim100 \ M_\odot \ s^{-1}$

→ long duration X-ray transient may result if
  • jet is made
  • jet escapes the star

(long duration due to high redshift and big mass & radius scale)

(Fryer, Woosley, & Heger 2000)
Forensics of the First Stars

- Ultra-metal poor old stars we find in our galaxy today show unique fingerprint of element production in the early universe
- high resolution spectra allow identification of a host of light to heaviest elements!
- nucleosynthesis constraints on the IMF through detailed modeling of the element production in early stars

(Westin et al. 2000)
Production Factor of Pop III Pair Creation Supernovae

IMF: d log ζ / d log M = Γ = -0.5, -1.5, -3.5
65 - 130 M_☉ He helium cores

Heger & Woosley (2001)

log(production factor relative to solar) vs Z

He, C, O, Ne, Mg, Si, S, Ar, Ca, Cr, Fe, Ni, Co, Zn, Ge
Production Factor of Primordial Massive Stars

IMF: $d \log \xi / d \log M = \Gamma = 1.50$

12...40 $M_\odot$ stars and 12...40 + 140...260 $M_\odot$ stars (1.2 foe)
Questions:

- Mass loss for $M > 1000 \, M_\odot$?
- Rotation:
  - Mass limits (2SNe)
  - Explosion
  - Remnant Masses
- Nucleosynthesis Signatures as Probe of IMF?