Evolution and Nucleosynthesis of Pop III Stars

Alexander Heger
Stan Woosley
Overview

• Basics of massive star evolution and nucleosynthesis
• Birth, life, and fate of Pop III stars
• Nucleosynthesis in very massive Pop III stars (100–1000 M⊙)
• Nucleosynthesis in massive Pop III stars (10–100 M⊙)
• Ways to blow up very massive stars (25–140 M⊙)
• A brief history of stellar fates
Cosmic Dark Age

(after recombination)

What the Big Bang made…

(The primordial abundance pattern)
Brian Fields (2002, priv. com.)

What We Find Today

(The solar abundance pattern)
Formation and Properties of the First Stars

No metals ➜ no metal cooling ➜ more massive stars

➔ typical mass scale ~100 M☉

First stars are very hot and very bright
➔ ionizing radiation

No metals ➜ no mass loss ➜ end life as massive stars
What is the IMF of the first stars?

Mike Norman’s talk
Once formed, the evolution of a star is governed by gravity: *continuing contraction* to higher central densities and temperatures.
## Nuclear burning stages

<table>
<thead>
<tr>
<th>Burning stages</th>
<th>Fuel</th>
<th>Main Product</th>
<th>20 M(_\odot) Star</th>
<th>200 M(_\odot) Star</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>T (10(^9) K)</td>
<td>Time (yr)</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>He</td>
<td>0.02</td>
<td>10(^7)</td>
</tr>
<tr>
<td></td>
<td>He</td>
<td>O, C</td>
<td>0.2</td>
<td>10(^6)</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>Ne, Mg</td>
<td>0.8</td>
<td>10(^3)</td>
</tr>
<tr>
<td></td>
<td>Ne</td>
<td>O, Mg</td>
<td>1.5</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>O</td>
<td>Si, S</td>
<td>2.0</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Si</td>
<td>Fe</td>
<td>3.5</td>
<td>0.02</td>
</tr>
</tbody>
</table>
net nuclear energy generation (burning + neutrino losses)

net nuclear energy loss (burning + neutrino losses)

total mass of star (reduces by mass loss)

convection

semiconvection

convective envelope (red super giant)

H burning
He burning
C burning (radiative)
C shell burning
Ne O burning
O O O shell burning
Si
# Explosive Nucleosynthesis

in supernovae from massive stars

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Main Product</th>
<th>Secondary Product</th>
<th>T (10⁹ K)</th>
<th>Time (s)</th>
<th>Main Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Innermost ejecta</td>
<td>r-process</td>
<td>-</td>
<td>&gt;10</td>
<td>1</td>
<td>(n,γ), β⁻</td>
</tr>
<tr>
<td>Si, O</td>
<td>⁵⁶Ni</td>
<td>iron group</td>
<td>&gt;4</td>
<td>0.1</td>
<td>(α,γ)</td>
</tr>
<tr>
<td>O</td>
<td>Si, S</td>
<td>Cl, Ar, K, Ca</td>
<td>3 - 4</td>
<td>1</td>
<td>¹⁶O + ¹⁶O</td>
</tr>
<tr>
<td>O, Ne</td>
<td>O, Mg, Ne</td>
<td>Na, Al, P</td>
<td>2 - 3</td>
<td>5</td>
<td>(γ,α), (α,γ)</td>
</tr>
<tr>
<td></td>
<td>p-process</td>
<td>¹¹B, ¹⁹F, ¹³⁸La, ¹⁸⁰Ta</td>
<td>2 - 3</td>
<td>5</td>
<td>(γ, n)</td>
</tr>
<tr>
<td></td>
<td>ν-process</td>
<td></td>
<td></td>
<td>5</td>
<td>(ν, ν'), (ν, e⁻)</td>
</tr>
</tbody>
</table>
Things that blow up

supernovae

- CO white dwarf $\rightarrow$ Type Ia SN, $E \approx 1 \text{Bethe}$
- MgNeO WD, accretion $\rightarrow$ AIC, faint SN
- “SAGB” star (AGB, then SN) $\rightarrow$ EC SN
- “normal” SN (Fe core collapse) $\rightarrow$ Type II SN
- WR star (Fe CC) $\rightarrow$ Type Ib/c
- “Collapsar”, GRB $\rightarrow$ broad line Ib/a SN, “hypernova”
- Pulsational pair SN $\rightarrow$ multiple, nested Type I/II SN
- Very massive stars $\rightarrow$ pair SN, $\lesssim 100 \text{B}$ ($1 \text{B} = 10^{51} \text{erg}$)
- Very massive collapsar $\rightarrow$ IMBH, SN, hard transient
- Supermassive stars $\rightarrow$ $\gtrsim 100000 \text{ B SN or SMBH}$
Things that blow up

Neutron star-powered supernovae

- CO white dwarf $\Rightarrow$ Type Ia SN, $E \approx 1$ Bethe
- MgNeO WD, accretion $\Rightarrow$ AIC, faint SN
- “SAGB” star (AGB, then SN) $\Rightarrow$ EC SN
- “normal” SN (Fe core collapse) $\Rightarrow$ Type II SN
- WR star (Fe CC) $\Rightarrow$ Type Ib/c
- “Collapsar”, GRB $\Rightarrow$ broad line Ib/a SN, “hypernova”
- Pulsational pair SN $\Rightarrow$ multiple, nested Type I/II SN
- Very massive stars $\Rightarrow$ pair SN, $\approx 100B$ (1B = $10^{51}$ erg)
- Very massive collapsar $\Rightarrow$ IMBH, SN, hard transient
- Supermassive stars $\Rightarrow$ $\gtrsim 100000$ B SN or SMBH
Things that blow up

Thermonuclear supernovae (no $r$-process)

- CO white dwarf $\rightarrow$ Type Ia SN, $E \approx 1$ Bethe
- MgNeO WD, accretion $\rightarrow$ AIC, faint SN
- “SAGB” star (AGB, then SN) $\rightarrow$ EC SN
- “normal” SN (Fe core collapse) $\rightarrow$ Type II SN
- WR star (Fe CC) $\rightarrow$ Type Ib/c
- “Collapsar”, GRB $\rightarrow$ broad line Ib/a SN, “hypernova”
- Pulsational pair SN $\rightarrow$ multiple, nested Type I/II SN
- Very massive stars $\rightarrow$ pair SN, $\lesssim 100B$ ($1B = 10^{51}$ erg)
- Very massive collapsar $\rightarrow$ IMBH, SN, hard transient
- Supermassive stars $\rightarrow$ $\gtrsim 100000$ B SN or SMBH
Things that blow up
Black hole-powered supernovae ("Collapsars")

- CO white dwarf $\rightarrow$ Type Ia SN, $E \approx 1 \text{ Bethe}$
- MgNeO WD, accretion $\rightarrow$ AIC, faint SN
- “SAGB” star (AGB, then SN) $\rightarrow$ EC SN
- “normal” SN (Fe core collapse) $\rightarrow$ Type II SN
- WR star (Fe CC) $\rightarrow$ Type Ib/c
- “Collapsar”, GRB $\rightarrow$ broad line Ib/a SN, “hypernova”
- Pulsational pair SN $\rightarrow$ multiple, nested Type I/II SN
- Very massive stars $\rightarrow$ pair SN, $\lesssim 100 \text{B}$ ($1 \text{B} = 10^{51} \text{ erg}$)
- Very massive collapsar $\rightarrow$ IMBH, SN, hard transient
- Supermassive stars $\rightarrow$ $\gtrsim 100000 \text{ B SN or SMBH}$
Pulsational Pair Instability Supernovae

- Starts as vibrational instability during O shell burning at low masses
- Energies: \(~0.0001 \text{ B} \ldots \text{several B}\)
- Recurrence times: days \ldots \text{some } 10^4 \text{ yr}
  (determined by complicated combination of structure/burning phase and explosion energy – cooling by neutrinos or radiation)
- Ringdown after pulse
- Eject outer layers (“Envelope”) including C, O, \ldots -rich layers
- 1\ldots\text{several pulses before collapse}
- Resemble high-M LBVs?
Ejected “metals”
Pair-Instability Supernovae

Many studies in literature since more than 3 decades, e.g.,
Rakavy, Shaviv, & Zinamon (1967)
Glatzel, Fricke, & El Eid (1985)
Woosley (1986)

Some recent calculations:
Umeda & Nomoto 2002
Heger & Woosley 2002
Initial total stellar mass / solar masses

Heger et al. (2000)

yield / solar masses

12C
16O
24Mg
28Si
32S
40Ca
56Ni
E_{expl}

explosion energy / B

helium core mass / solar masses
Problem:

Pair-Instability Supernovae do not reproduce the abundances as observed in very metal poor halo stars!
Hydrogen/carbon mixing on post-MS?
(here for AGB star He shell flash)

nuclear energy generation
\(^{12}\text{C}(\text{p},\gamma)^{13}\text{N}\)

\(^{13}\text{N}\) mass fraction

\(^{13}\text{N}\) mass fraction (later)

\(\rightarrow\) burning – mixing feedback
The “Collapsar Engine”

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

How else can massive stars explode?

$25M_\odot < M < 100M_\odot$, $M > 250M_\odot$
Nucleosynthesis in Collapsars

Components:

1. Wind off accretion disk
2. Magnetic bubble
3. Neutrino irradiation (from disk and pro-NS)
4. Jet-like outflow
5. Shock-heated material (radial and lateral shocks, supernova)
Pop III Nucleosynthesis

Elemental Yields as a function of initial mass
non-rotating stars
120 stellar masses
“complete” reaction network
normalized to Mg

RESULTS:
e.g., Production of $^7\text{Li}$ by neutrino interaction in very compact stellar envelope!

Pop III Nucleosynthesis Grid

Library of yields as a function of explosion energy

10 explosion energies from 0.3 to 10 B

1200 supernova explosions with full stellar/explosive nucleosynthesis

Heger & Woosley (2006)
Massive Stars, normal IMF(s)

1.2 foe and 10 foe explosions

Heger & Woosley 2005

![Graph showing abundance of elements relative to solar values for different elements with charge numbers ranging from 0 to 30. The graph includes elements labeled Li, Be, B, C, N, O, Ne, Mg, Si, S, Ar, Ca, Ti, Cr, Fe, Ni, Zn, H, He, Na, Al, P, Cl, K, Sc, V, Mn, Cu, Ge, and Ga. The vertical axis is labeled as log(production factor relative to solar) and ranges from -2 to 2. The horizontal axis is labeled element charge number and ranges from 0 to 30. The graph includes a legend for IMF: d log \( \xi \) / d log \( M \) = \( \Gamma \) = 1.50 for 10...95 M_\odot stars, 10.0 foe.]
Sc, Zn: neutrino wind (Pruet et al. 2004)
Cr: problem w/ oscillator strength
overall reasonably good fit for 1.2 foe

Summary

Due to their unique composition, the birth, life and death of the first stars is very different from later generations:

- Even stars of several 100 solar masses might survive (if rotating slowly, no winds, no pulsational instability)
- They can encounter the pair-instability, but:
  - strong odd-even effect that has not been observed (without mixing)
  - No heavy elements beyond iron group produced
  - No r-process, no s-process — not directly observed to date

No compelling observational evidence for \( M \gtrsim 140 \, M_\odot \) stars

Need to understand

- IMF and IRF (rotation) of primordial star formation
- Dispersion of metals in the early universe
- Mass loss from critically rotating primordial stars?