Overview

- Presupernova Evolution and Nucleosynthesis
- Varieties of Stellar Deaths
- Nucleosynthesis
- Uncertainties
Motivation:
A Brief History of the Universe (Recap)
Cosmic Dark Age
(after recombination)

What the Big Bang made...
(The primordial abundance pattern)
Brian Fields (2002, priv. com.)

What We Find Today
(Pop III star yields)
Heger & Woosley (2008)
Frebel et al. (2005)
(The solar abundance pattern)
Lodders (2003)

time
Abundance by Weight

Universe
- Hydrogen 73%
- Helium 25%
- Other 1%
- Oxygen 1%

Humans
- Oxygen 64%
- Carbon 20%
- Hydrogen 10%
- Calcium 2%
- Nitrogen 5%
Setting the Stage: Pre-Supernova Evolution and Nucleosynthesis (Recap)
Once formed, the evolution of a star is governed by gravity: **continuing contraction** to higher central densities and temperatures.

Evolution of central density and temperature of 15 M☉ and 25 M☉ stars.

Woosley et al. 2002, RvMP, 74, 1015
## Nuclear burning stages

**(20 M. stars)**

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Main Product</th>
<th>Secondary Product</th>
<th>T ((10^9 K))</th>
<th>Time (yr)</th>
<th>Main Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>He</td>
<td>(^{14}\text{N})</td>
<td>0.02</td>
<td>10(^7)</td>
<td>(\text{CNO}) (4 \text{H} \rightarrow \text{^{4}He})</td>
</tr>
<tr>
<td>He</td>
<td>O, C</td>
<td>(^{18}\text{O}, \text{^{22}Ne}) \text{s-process}</td>
<td>0.2</td>
<td>10(^6)</td>
<td>(3 \text{He}^4 \rightarrow \text{^{12}C})</td>
</tr>
<tr>
<td>C</td>
<td>Ne, Mg</td>
<td>\text{Na}</td>
<td>0.8</td>
<td>10(^3)</td>
<td>(\text{^{12}C} + \text{^{12}C})</td>
</tr>
<tr>
<td>Ne</td>
<td>O, Mg</td>
<td>\text{Al, P}</td>
<td>1.5</td>
<td>3</td>
<td>(\text{^{20}Ne(\gamma,\alpha)\text{^{16}O}}) (\text{^{20}Ne(\gamma,\alpha)\text{^{24}Mg}})</td>
</tr>
<tr>
<td>O</td>
<td>Si, S</td>
<td>\text{Cl, Ar, K, Ca}</td>
<td>2.0</td>
<td>0.8</td>
<td>(\text{^{16}O} + \text{^{16}O})</td>
</tr>
<tr>
<td>Si,S</td>
<td>Fe</td>
<td>\text{Ti, V, Cr, Mn, Co, Ni}</td>
<td>3.5</td>
<td>0.02</td>
<td>(\text{^{28}Si(\gamma,\alpha)\ldots})</td>
</tr>
</tbody>
</table>
Hydrogen Burning by CNO Cycle

“normal” CNO cycle

\[
\begin{align*}
\text{14O} & \rightarrow \text{15O} \\
\text{13N} & \rightarrow \text{14N} \\
\text{12C} & \rightarrow \text{13C}
\end{align*}
\]

\[
\begin{align*}
(p,\gamma) \quad & \beta^+ \\
(p,\alpha) \quad & \text{SLOW}
\end{align*}
\]

temperature-sensitive

\[T < 8 \times 10^7 \text{ K}\]

“hot” CNO cycle

\[
\begin{align*}
\text{14O} & \rightarrow \text{15O} \\
\text{13N} & \rightarrow \text{14N} \\
\text{12C} & \rightarrow \text{13C}
\end{align*}
\]

\[
\begin{align*}
(p,\gamma) \quad & \beta^+ \\
(p,\alpha) \quad & \text{SLOW}
\end{align*}
\]

temperature-insensitive

\[T > 8 \times 10^7 \text{ K}\]
Neutrino losses from electron/positron pair annihilation

• Important for carbon burning and beyond

• For $T > 10^9$ K (about 100 keV), occasionally:
  $\gamma \rightarrow e^+ + e^-$
  and usually
  $e^+ + e^- \rightarrow 2 \gamma$
  but sometimes
  $e^+ + e^- \rightarrow \bar{\nu}_e + \nu_e$

• The neutrinos exit the stars at the speed of light while the $e^+$, $e^-$, and the $\gamma$'s all stay trapped.

• This is an important energy loss with

  $\varepsilon_{\nu} \approx -10^{15} \left( T / 10^9 K \right)^9$ erg g$^{-1}$ s$^{-1}$

• For carbon burning and beyond, each burning stage gives about the same energy per nucleon, thus the lifetime goes down as $T^{-9}$
Nitrogen Burning

\[ ^{14}N(\alpha, \gamma)^{18}F(\beta + \nu_e)^{18}O(\alpha, \gamma)^{22} \]

**Ne**

- \(^{14}N\) is made as slowest reactant in CNO cycle
- It is made from initial metals, not as a primary product
- Depending on metallicity, the abundance can become significant; it will be more important for more metal-rich stars.
- \(^{14}N\) burning occurs at the onset – before – central helium burning and can have its own convective burning phase, taking a few percent of helium burning time.
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 burning
Ne burning
Si burning
O shell burning

Heger et al. 2003, From Twilight to Highlight: The Physics of Supernovae, Springer-Verlag, 3
Multi-Dimensional Convection

(Meaken & Arnett 2007)
Multi-Dimensional Convection

(Meaken & Arnett 2007)
Change of the stellar structure as a function of initial mass

- Mass loss becomes more important
- The “cores” becomes bigger, the density gradients more shallow
- The evolution time-scale of all burning phases accelerates
- Central carbon burning becomes radiative, central entropy and $Y_e$ increase
A First Look
Core Collapse
Supernovae
(Massive Stars, Pop I)
Core Collapse Supernovae

Entropy and electron per baryon ($Y_e$) at different time snapshots in a core collapse supernova (simulation: equatorial band)

(Janka 2001)

(Woosley & Janka 2006)

(Buras et al. 2006)
Core Collapse Supernovae – 3D

Cold inflow and hot outflow in 3D simulations \(\Rightarrow\) similar to dipolar flow pattern observed in 2D rotationally symmetric simulations

Singing Supernovae?

Can sound waves from convection heat bubble and power a supernova explosion?

(Burrows et al. 2005)
Neutron Star Kicks

Dipolar oscillation may explain observed neutron star kicks of several 100 km/s.
A First Look
Supernovae & Nucleosynthesis
(Massive Stars, Pop I)
Presupernova production factors relative to solar composition

"band of acceptable co-production" defined by $^{16}\text{O}$ production $(\pm$ a factor 2)$

## Explosive Nucleosynthesis in supernovae from massive stars

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Main Product</th>
<th>Secondary Product</th>
<th>$T$ ($10^9$ 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>$(n,\gamma), \beta^-$</td>
</tr>
<tr>
<td>Si, O</td>
<td>$\nu p$-process $^{56}\text{Ni}$</td>
<td>iron group</td>
<td>&gt;4</td>
<td>0.1</td>
<td>$(\alpha,\gamma)$</td>
</tr>
<tr>
<td>Si, S</td>
<td>$p$-process</td>
<td>Cl, Ar, K, Ca</td>
<td>3 - 4</td>
<td>1</td>
<td>$^{16}\text{O} + ^{16}\text{O}$ $(\gamma,\alpha)$</td>
</tr>
<tr>
<td>O, Mg, Ne</td>
<td>$p$-process</td>
<td>Na, Al, P</td>
<td>2 - 3</td>
<td>5</td>
<td>$(\gamma,\nu)$</td>
</tr>
<tr>
<td></td>
<td>$\nu$-process $^{11}\text{B}, ^{19}\text{F}$, $^{138}\text{La}, ^{180}\text{Ta}$</td>
<td>-</td>
<td>2 - 3</td>
<td>5</td>
<td>$(\nu, \nu'), (\nu, \text{e}^-)$</td>
</tr>
</tbody>
</table>
Explosive Nucleosynthesis contribution

→ production of p-process and iron group

25 $M_\odot$ star

some destruction

Heger et al. 2003, NuPhA, 718, 159
25 $M_\odot$ star

Production factors relative to solar composition

“band of acceptable co-production” defined by

$^{16}$O production

($\pm$ a factor 2)

15 M\(_{\odot}\) star

Production factors relative to solar composition

“band of acceptable co-production” defined by \(^{16}\text{O}\) production (± a factor 2)

25 solar mass star s-process yields for different evolution stages

“Relocation” of the $\gamma$-process

$\gamma$-process can be made in implosive O shell burning, but peak abundance is destroyed by SN and recreated further out.

Heger et al. 2003, NuPhA, 718, 159
The Production of $^{138}{\text{La}}$

by $\gamma$-process and $\nu$-process

$^{138}{\text{Ba}}$ enhanced by s-process

Heger et al. 2005, PhLB, 606, 258
Presolar grains
Direct access to pristine SN nucleosynthesis?

However:
need to understand
• chemistry
• condensation
• SN mixing
• implantation

see Denault, Clayton & Heger (2003)
Overview:

Varieties of Cosmic Explosions
(of most kind)
jet-driven SNe?

Hypernova Branch

jet-driven SNe?
(JetSN)

Main Sequence Mass, (M_☉)

Kinetic Energy (10^{51} ergs)
# Energy Scales

<table>
<thead>
<tr>
<th>Log E</th>
<th>Explosion</th>
<th>Thermonuclear</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>X-ray Bursts</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>Long-Duration He Bursts</td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>X-ray Superbursts</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>Classical Novae</td>
<td></td>
</tr>
<tr>
<td>48</td>
<td>Faint SN (visible LC?)</td>
<td></td>
</tr>
<tr>
<td>49</td>
<td>SN (visible LC)</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>Bright SN (LC?)</td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>SN (kinetic)</td>
<td>SN Type Ia total</td>
</tr>
<tr>
<td>52</td>
<td>Hypernova? GRB?</td>
<td>Pair-SN total (low-mass end)</td>
</tr>
<tr>
<td>53</td>
<td>SN (neutrinos – several $10^{53}$erg)</td>
<td>Pair-SN total (upper limit)</td>
</tr>
<tr>
<td>54</td>
<td><em>(a lot of energy - 0.5 M. c²)</em></td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>GR He SN</td>
<td>GR He SN (upper limit)</td>
</tr>
<tr>
<td>56</td>
<td>GR H SN, Z &gt; 0 (Fuller <em>et al.</em> 1986)</td>
<td></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
• GR He instability $\rightarrow$ $>100 \text{B} \ SN+\text{SMBH}$, or $10,000 \text{B}$
• Supermassive stars $\rightarrow$ $\gtrsim 100000 \text{B} \ SN$ or SMBH

$1 \text{B}=10^{51} \text{erg}$
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, $\leq 100B$ ($1B = 10^{51}$ erg)
- Very massive collapsar $\rightarrow$ IMBH, SN, hard transient
- GR He instability $\rightarrow$ $> 100$ B SN+SMBH, or 10,000 B
- Supermassive stars $\rightarrow$ $\geq 100000$ 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, $\leq 100B$ ($1B = 10^{51}$ erg)
- Very massive collapsar $\rightarrow$ IMBH, SN, hard transient
- GR He instability $\rightarrow$ $> 100$ B SN+SMBH, or 10,000 B
- Supermassive stars $\rightarrow$ $\geq 100000$ 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
- GR He instability $\rightarrow$ $> 100\text{ B}$ SN+SMBH, or 10,000 B
- Supermassive stars $\rightarrow$ $\geq 100000\text{ B}$ SN or SMBH
Massive Star Fates as Function of Initial Mass (solar metallicity)
Ejected "metals"

Heger et al. 2003, From Twilight to Highlight: The Physics of Supernovae, Springer-Verlag, 3
How do the most massive stars evolve?

- Reduced mass loss on the main sequence followed by LBV & giant eruptions?
- What are these eruptions? (physics, number, recurrence)
- When do they occur? (internal evolution stage?)
- How do we model these eruptions?
- Pulsational Pair-Instability Supernovae (PPSN)?
The Most Massive Stars Today

R136

- young massive star cluster
- Age around 1.5 Myr
- Star “a1”: maybe 200 Mₜ, initial mass

(Crother et al. 2010)
Advanced Topics
Rotation and Gamma-Ray Bursts
2704 BATSE Gamma-Ray Bursts

Fluence, 50-300 keV (ergs cm\(^{-2}\))

Source: http://www.batse.msfc.nasa.gov/batse/grb/skymap/
How else can massive stars explode?

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”

25\(M_\odot\) < \(M\) < 100\(M_\odot\), \(M > 250M_\odot\)
GRB Mechanisms
Mass Loss due to Critical Rotation

- How important is mass loss due to critical (or fast) rotation?
- How do we quantify mass loss and angular momentum loss?
- How does it effect our stellar models?

(Langer, Meynet, Maeder, Hirschi,...)
Black Holes and GRBs from Rotating Stars

A small fraction of single stars is born rotating rapidly.

The fastest rotators evolve chemically homogeneously, become WR stars on the MS, and may lose less angular momentum.

(Yoon & Langer 2006; data from Mokeim et al. 2006)
Advanced Topics
Remnant Masses
Of Supernovae
Pop III stars show much more fallback than modern Pop I stars due to their compact hydrogen envelope.
Fallback and Remnants

2.3 M. baryonic mass $\Rightarrow$ 2.0 M. gravitational mass

(Zhang, Woosley, Heger 2007)
Pop III Stars

Much fallback for compact stars (“+”)

Less fallback for RSG (“Δ”)

(Zhang, Woosley, Heger 2007)
Pop III Star Remnant Masses
(from Zhang, Woosley, Heger 2007)
[Z] = -4 Star Remnant Masses
(from Heger, Woosley, Zhang, in prep. 2011)
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)

Heger et al. 2003, From Twilight to Highlight: The Physics of Supernovae, Springer-Verlag, 3
Advanced Topics

The First Stars in the Universe
Formation and Mass of the First Stars

No metals $\Rightarrow$ no metal cooling $\Rightarrow$ more massive stars
$\Rightarrow$ typical mass scale $\sim 10...300 \text{ M}_\odot$?

Heating by WIMP annihilation $\Rightarrow$ longer accretion $\Rightarrow$ even bigger stars...

- **Now** simulations indicate binaries may exist
- We still don't have a really strong constrain on Pop III star masses in general
- But what happens in regions of large DM halos collapsing? (these are not the first to collapse)
- Can this make dense star clusters?
- Or really big stars? (supermassive stars)
Ejected “metals”

References 1

- Woosley, S. et al. 2002, The evolution and explosion of massive stars, RvMP, 74, 1015
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