Supernovae and Nucleosynthesis in Zero and Low Metal Stars

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ITP, July 6, 2006
Why believe anything I say if we don’t know how any star (of any metallicity) blows up?

• The physics of pair instability supernovae is simple and well understood. In the absence of extreme differential rotation, helium cores from 65 to 137 solar masses explode this way. Above 137, they make black holes. From 15 to 65 they probably make black holes.

• The models for solar metallicity supernovae are highly constrained by neutron star masses, nucleosynthesis, and light curves.

• Assume that whatever physics produces SNe at Z-solar works the same in low Z helium cores of the same mass.
The explosion can be characterized by a piston whose location and speed are free parameters.

**The piston location is constrained by:**

- Nucleosynthesis
- Neutron star masses

**The piston energy is constrained by:**

- Light curves
- Fall back
The edge of the iron core sets a lower bound to the mass cut. Otherwise, too many neutron-rich isotopes ...

The location where the entropy \( S/N_A kT = 4 \), typically at the base of the oxygen shell sets an upper limit. Stars that explode in real simulations typically develop their mass cut here. A larger value gives neutron stars that are too massive.

If in the models the mass cut is taken at the edge of the iron core the average gravitational mass for stars in the 10 – 21 solar mass range is (12 models; above this black holes start to form by fall back):

$$1.38 \pm 0.16 \, M_\odot$$

If one instead uses the $S = 4$ criterion, the average from 10 – 21 solar masses is

$$1.45 \pm 0.18 \, M_\odot$$

From 10 to 27 solar masses the average is

$$1.53 \pm 0.22 \, M_\odot$$

1.2 $B$ of kinetic energy at infinity gives good light curves in agreement with observations.

2.4 $B$ gives too bright a supernova making Type II almost as brilliant as Type Ia.

Though not shown here 0.6 $B$ would give quite faint supernovae, usually with very weak “tails”.
Isotopic yields for 31 stars averaged over a Salpeter IMF, $\Gamma = -1.35$

Intermediate mass elements (23 < A < 60) and s-process (A = 60 – 90) well produced.

Carbon and Oxygen over-produced.

p-process deficient by a factor of ~2 for A > 130 and absent for A < 130
But Very Low Metal Stars Are Different (1)

• **They have little or no mass loss**

  Consequently they die with a mass similar to their initial mass. Thus they have higher mass at death even for the same birth function.

• **They are compact stars at death**

  Depending on whether they make primary nitrogen, they will not be red supergiants, but stars even more compact than 87A - very blue giants.
Consequently, they:

- Are harder to explode – more tightly bound

- Experience more fallback (also because they are compact stars, not red giants)

- Make more and bigger black holes

- But still probably produce neutron stars for main sequence masses in the range 10 - 20 solar masses
Solar metallicity – remnant masses

Pop I stars (mass loss)
1.2 B explosions;
mass cut at Fe core

(after fall back)
Above 35 $M_\odot$ black holes form:

$Z = 0$

Remnant masses

Pop III stars (no mass loss)

1.2 B explosions
KE = 0.3 to 10 B

Z = 0

Z = solar
Zero Metal Stars Are Different (2)

• They may have an IMF extending to higher masses

  Above about 100 solar masses, pair instability supernovae are possible with very large kinetic energies and occasionally very bright light curves.

• They are pulsationally stable

  Stars born with 100 – 300 solar masses may die with similarly large masses

• Both of these have changed by the time \([Z] \sim -4\)
Even for “Ordinary” Masses Their Nucleosynthesis is Distinct (3)

• Deficiency of neutrons for $A < 32$ implies an odd-even effect

• No s-process (of the usual sort for $Z = 0$), but

• May make primary nitrogen

• Depending on mixing and fall back may make larger C,O compared with heavier elements
Nucleosynthesis from helium cores
Production factors compared with Mg

\[ p(\bar{\nu}, e^+) n(p, \gamma)^2 H(p, \gamma)^3 He(\alpha, \gamma)^7 Be(e^-, \nu)^7 Li \]

Heger and Woosley(2006)
• Was it as large then as now? Larger?

• How much differential rotation persists at the end?

• Affects:

  How (and if) the star explodes

  The energy of the explosion, fallback, mass limits for pair-instability supernovae

  The possibility of making a gamma-ray burst – as well as its strength, duration, and time variability (the fraction of stars making bright GRBs is small)
millisecond magnetar or accreting black hole (< 1%)

Ordinary SN IIp - SN Ib/c - GRB
never a red giant

Woosley and Heger (2006)
Yoon and Langer (2005)
\[ R = 4.8 \times 10^{10} \text{ cm} \]
\[ L = 1.9 \times 10^{39} \text{ erg s}^{-1} \]
\[ \dot{M} = 2.4 \times 10^{-6} M_\odot \text{ yr}^{-1} \left( \frac{Z}{0.01 Z_\odot} \right)^{0.86} \]
MacFadyen, Zhang, & Woosley (in preparation)
The allowed range for GRB models in this scenario is approximately $10 < \frac{M}{M_\odot} < 60$.

This is the result of evolving a rapidly rotating 35 solar mass star of 1% solar metallicity. The final mass is 31 solar masses. Previous paradigms would have given a maximum He core mass of 15 solar masses.
It may be possible to create pair instability supernovae in regions with metallicity as high as \([Z] = -2\) provided the star has enough rotation. \(M_L \sim 70 - 80\) solar masses.

The rotation rate may be as important as the mass range of Pop III stars.
What About Heavy Element Nucleosynthesis – the $r$, $s$, and $p$-processes?

Only for massive stars that make neutron stars
Anti-neutrinos are "hotter" than the neutrinos, thus weak equilibrium implies an appreciable neutron excess, typically 60% neutrons, 40% protons favored at late times.

\[
\begin{align*}
\bar{\nu}_e + p &\rightarrow n + e^+ \\
\nu_e + n &\rightarrow p + e^- 
\end{align*}
\]

![Diagram of nucleonic wind](image)

Results sensitive to the (radiation) entropy, $T^3/\rho$, and therefore to $aT^4/\rho$, the energy density.


The \( r \)-process is favored by high entropy, i.e., low density at a given temperature, because the reactions that assemble \( \alpha \)-particles to heavy (seed) nuclei between 3 and 5 billion K increase rapidly with density

\[
\alpha(\alpha n, \gamma)^7\text{Be}(\alpha, n)^{12}\text{C} \propto \rho^2
\]

Keeping the density low thus keeps most of the mass in \( \alpha \)-particles and thus increases the ratio of free neutrons to heavy seed.
Integrated abundances in the late time wind resemble the r-process abundance pattern.

But,

The entropy in these calculations by Wilson was not replicated in subsequent analyses which gave $s/k_B$ about 4 times smaller $s/k_B \sim 80$ not 300.
Burrows et al. (2006) find considerable energy input from neutron star vibrations – enough even to explode the star, and surely enough to influence the r-process.
data from Wilson (1994)
15 solar mass star – 20 angle averaged trajectories
The neutrino-assisted rp-process

Pruett et al. (2006)

$T_g = 2.05 \quad \rho_5 = 0.27$
$s / k_b = 77 \quad Y_e = 0.562$

$X_p = 0.124 \quad X_\alpha = 0.844 \quad X_n \approx 10^{-13}$

e.g., $^{92}$Mo
Unmodified trajectory number 6 from Janka et al.
Entropy times two
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Summary – Neutrino Wind

• Very rich site for nucleosynthesis – about half of all the isotopes in nature are made here. Can happen in Z = 0 stars

• Can produce both (part of) the p-process and the r-process nearly simultaneously in one site.

• In both cases, the nucleosynthesis suggests a higher entropy (and outflow with more internal energy per baryon) than traditional models have provided

• Nuclear physics very uncertain

• This has important implications for the explosion model

Energy input from: (Qian & Woosley 1996)
  Alfven waves or reconnection – Suzuki and Nagataki (2005)
Nuclear Astrophysics: The Next 50 Years

Cal Tech
July 23, 2007 (+4 days)