Endpoints of stellar evolution

The end of stellar evolution is an inert core of spent fuel that cannot maintain gas pressure to balance gravity.

Such a core can be balanced against gravitational collapse by electron degeneracy pressure IF the total mass is less than the Chandrasekhar mass limit:

**Chandrasekhar Mass:**

Only if the mass of a inert core is less than Chandrasekhar Mass $M_{ch}$

$$M_{Ch} \approx 5.85 \, Y_e^2 \, M_\odot$$

Electron degeneracy pressure can prevent gravitational collapse.

In more massive cores electrons become relativistic and gravitational collapse occurs (then $p \sim n^{4/3}$ instead of $p \sim n^{5/3}$).

For $N=Z$  $M_{Ch} = 1.46 \, M_\odot$
Mass and composition of the core depends on the ZAMS mass and the previous burning stages:

<table>
<thead>
<tr>
<th>$M_{ZAMS}$</th>
<th>Last stage</th>
<th>Core</th>
<th>Mass</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.3 $M_0$</td>
<td>H burning</td>
<td>He</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3- 8 $M_0$</td>
<td>He burning</td>
<td>C, O</td>
<td>$M &lt; M_{Ch}$</td>
<td>core survives</td>
</tr>
<tr>
<td>8-12 $M_0$</td>
<td>C burning</td>
<td>O, Ne, Mg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; 8-12 $M_0$</td>
<td>Si burning</td>
<td>Fe</td>
<td>$M &gt; M_{Ch}$</td>
<td>collapse</td>
</tr>
</tbody>
</table>

How can 8-12$M_0$ mass star get below Chandrasekhar limit?
Death of a low mass star: a “Planetary Nebula”

image: HST
Little Ghost Nebula
distance 2-5 kLY
blue: OIII
green: HII
red: NII

Envelope of star blown into space
And here’s the core! a “white dwarf”
Why “white dwarf”?

- core shrinks until degeneracy pressure sets in and halts collapse

  star is HOT (gravitational energy !)

  star is small

\[ R \sim M^{-1/3} \]
Where are the white dwarfs?

there (small but hot white (B~V))
Supernovae

If a stellar core grows beyond its Chandrasekhar mass limit, it will collapse.

Typically this will result in a **Supernova explosion**

→ at least the outer part of a star is blown off into space

But why would a collapsing core explode?

a) CO or ONeMg cores that accrete matter from a companion star can get beyond the Chandrasekhar limit:

Further collapse heats star and CO or ONeMg burning ignites explosively

→ **Whole star explodes – no remnant**

b) collapsing Fe core in massive star (but not too massive) → neutron star

Fe cannot ignite, but collapse halted once densities of ~2x nuclear density are reached (repulsive nuclear force)
Some facts about Supernovae:

1. Luminosity:

Supernovae might be the brightest objects in the universe, and can outshine a whole galaxy (for a few weeks)

   Energy of the visible explosion: $\sim 10^{51}$ ergs (= 1 foe = 1 Bethe)
   Total energy: $\sim 10^{53}$ ergs (most in neutrinos)
   Luminosity: $\sim 10^{9-10} L_0$

2. Frequency:

$\sim 1-10$ per century and galaxy
core collapse supernova mechanism

1. pre SN star
   Fe core
   $v \sim 1/\sqrt{r}$
   Inner core
   $v \sim r$
   ($v = v_{\text{sound}}$ at boundary)

2. proto neutron star
   infalling outer core
   outgoing shock from rebounce

3. proto neutron star
   infalling outer core
   stalled shock (~100-200 km)
   neutrinos
   neutrino heated layer

4. proto neutron star
   matter flow gets reversed - explosion
   revived shock
Neutron star forms
(size ~ 10 km radius)

Matter evaporated off the hot neutron star
r-process site?
Gain layer explained

Neutrino absorption and emission via

\[ \nu_e + n \leftrightarrow p + e^- \]
\[ \bar{\nu}_e + p \leftrightarrow n + e^+ \]

- Cooling rate \( \sim T^6 \)
- Heating \( \sim 1/r^2 \)

As \( T \sim 1/r \) cooling decreases with radius as \( \sim 1/r^6 \)
Requires free protons and neutrons

Diagram showing cooling and heating regions, shock radius, and dissociated p,n.
General Relativistic Collapse of Rotating Stellar Cores in Axisymmetry

Harald Dimmelmeier  
José A. Font  
Ewald Müller

References:

Status of delayed detonation mechanism

- It's considered the most promising avenue by all groups

**1D Models:**
- Reasonable microphysics (neutrino transport) possible
- Most 1D models do not explode (except very low mass end)

**2D Models:**
- Reasonable microphysics now possible (cutting edge)
- Latest 2D models show some explosions but often too low in energy
  - Garching group gets now explosions for (8.1, 8.8, 9.6, 11.2, 15, and 27 $M_{\odot}$)

**3D Models:**
- Only exploratory studies with simplified microphysics
- Key results:
  - Significant qualitative differences from 2D to 3D – nature of turbulence, SASI very strong in 2D, not at all in 3D
  - 2D might be misleading
  - Tendency of easier explosions from 1D $\rightarrow$ 2D $\rightarrow$ 3D (though debate)
Prospects

- Generally delayed explosion mechanism suspected to solve the problem eventually
- Probably need full 3D to solve the problem

Key effects of multi-D vs 1D:

- Neutrino heating induced convection
  - Pushes shock out and increases gain region
  - Dredges material down into gain region
- SASI (Standing Accretion Shock Instability) would help
  - Possibly not important in 3D?
- Magnetic fields, rotation → might add energy
- Acoustic vibrations?
Tarantula Nebula in LMC (constellation Dorado, southern hemisphere)
size: ~2000ly (1ly ~ 6 trillion miles), distance: ~170000 ly
Tarantula Nebula in LMC (constellation Dorado, southern hemisphere)
size: ~2000ly (1ly ~ 6 trillion miles), distance: ~180000 ly
Supernova 1987A seen by Chandra X-ray observatory, 2000

Shock wave hits inner ring of material and creates intense X-ray radiation
The Crab Nebula in Taurus  (VLT KUEYEN + FORS2)
HST picture

Crab nebula
SN July 1054 AD
Dist: 6500 ly
Diam: 10 ly,
   pic size: 3 ly
Expansion: 3 mill. Mph
   (1700 km/s)
Optical wavelengths
Orange: H
Red   : N
Pink  : S
Green : O

Pulsar: 30 pulses/s
Cas A supernova remnant

… seen over 17 years

youngest supernova in our galaxy – possible explosion 1680
(new star found in Flamsteeds catalogue)
3. Observational classes (types):

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>no hydrogen lines &lt;br&gt; depending on other spectral features there are sub types Ia, Ib, Ic, ...</td>
</tr>
<tr>
<td>Type II</td>
<td>hydrogen lines</td>
</tr>
</tbody>
</table>

Why are there different types?  

Answer: progenitor stars are different

Type II: collapse of Fe core in a normal massive star (H envelope)

Type I: 2 possibilities:

- Ia: white dwarf accreted matter from companion
- Ib,c: collapse of Fe core in star that blew its H (or He) envelope into space prior to the explosion
Origin of plateau:

earlier:

H-envelope
outer part: transparent (H)
inner part: opaque (H⁺)

later:

As star expands, photosphere moves inward along the T=5000K contour (H-recombination)

T,R stay therefore roughly fixed = Luminosity constant
(as long as photosphere wanders through H-envelope)
There is another effect that extends SN light curves: Radioactive decay!

- Radioactive isotopes are produced during the explosion
- There is explosive nucleosynthesis!
$^{44}\text{Ti}$

- $^{44}\text{Ti} \rightarrow ^{44}\text{Sc}$ (EC, 98%)
- $^{44}\text{Sc} \rightarrow ^{44}\text{Ca}$ (EC, 2%)

- $^{44}\text{Ti} \rightarrow ^{44}\text{Sc}$ (EC, 99%)

- $^{44}\text{Sc} \rightarrow ^{44}\text{Ca}$ (EC, 0%)

- $^{44}\text{Ti} \rightarrow 0^+ (0^+)$

- $^{44}\text{Sc} \rightarrow ^{44}\text{Ca} (1^-, 1.46\text{ yr}, 1.46\text{ h})$

- $^{44}\text{Sc} \rightarrow ^{44}\text{Ca} (2^+, 3.93\text{ h})$

- $^{44}\text{Sc} \rightarrow ^{44}\text{Ca} (0^+, 59.2\pm 0.6\text{ yr})$

- $^{44}\text{Sc} \rightarrow ^{44}\text{Ca} (1157\text{ }\gamma\text{-ray}, 99\%)$

- $^{44}\text{Sc} \rightarrow ^{44}\text{Ca} (1157\text{ }\gamma\text{-ray}, 2\%)$
Cas A region, $E_g=1.156\,\text{MeV}, \, \text{PH1+2+3+4+5}$

Distance 10,000 ly
Mass loss and remnants

Different choices of mass loss rates

Nucleosynthesis of Z>2
Hypernovae and faint SN

GRBs?

Kinetic Energy ($10^{51}$ ergs)

Main Sequence Mass ($M_\odot$)

NS
(bounce driven SN)

BH
(L (jet) driven SN)