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 $M_{\text{ch}}$

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

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 $N=Z$ $M_{\text{Ch}} = 1.46 M_\odot$
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>$M &lt; M_{Ch}$</td>
<td>core survives</td>
</tr>
<tr>
<td>0.3- 8 $M_0$</td>
<td>He burning</td>
<td>C,O</td>
<td></td>
<td></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”

Ensemble of star blown into space

And here’s the core! a “white dwarf”

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

Fe cannot ignite, but collapse halted by degenerate NUCLEON gas at a radius of ~10 km
core collapse supernova mechanism

1. pre SN star
   - Fe core
   - inner core

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

3. proto neutron star
   - infalling outer core
   - stalled shock
   - neutrinos
   - neutrino heated layer

4. proto neutron star
   - matter flow gets reversed - explosion
   - revived shock
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
   Luminosity: $\sim 10^{9-10} L_0$

2. Frequency:

   $\sim 1-10$ per century and galaxy
Tarantula Nebula in LMC (constellation Dorado, southern hemisphere)
size: ~2000ly (1ly ~ 6 trillion miles), disctance: ~180000 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)

© European Southern Observatory
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</td>
</tr>
<tr>
<td></td>
<td>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*)

photosphere

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!
44Ti

59.2\pm0.6 \text{ yr}

3.93 \text{ h}

1157 \gamma\text{-ray}
Distance 10,000 ly
Measure the half-life of $^{44}$Ti

It’s not so easy: Status as of 1997:
Method 1:

Prepare sample of $^{44}$Ti and measure activity as a function of time

number of sample nuclei $N$:

$$N(t) = N_0 e^{-\lambda t}$$

activity = decays per second:

$$A(t) = \lambda N(t) = \lambda N_0 e^{-\lambda t}$$

Measure $A$ with $\gamma$-ray detector as a function of time $A(t)$ to determine $N_0$ and $\lambda$

$$\lambda = \frac{\ln 2}{T_{1/2}}$$
ANL:

Ahmad et al. PRL 80 (1998) 2550
Berkeley:

$T_{1/2} = 59.2 \text{ yr}$

Norman et al. PRC57 (1998) 2010
National Superconducting Cyclotron Facility at Michigan State University

Cyclotron 2
K1200
Ion Source

Cyclotron 1
K500

Fragment Separator
A1900

Make $^{44}$Ti by fragmentation of $^{46}$Ti beam

$10^{10}$ $^{46}$Ti/s

$10^6$/s $^{44}$Ti
Fast beam feature 1: production of broad range of beams

Example: Fragmentation Technique
(for different beam)

Color: 1e-4 to >1000/s
Might sound low, but ....
Method 2:

Measure $A$ AND $N_0$ at a one time

$$A(t) = \lambda N(t) = \lambda N_0 e^{-\lambda t}$$

Standard Setup:

Use this setup from time to time:
Fast beam feature 2: high selectivity – step 1: Separator

Recall in B-field: \( r = \frac{mv}{qB} \)

Recall: \( \frac{dE}{dx} \sim Z^2 \)
Fast beam feature 2: high selectivity – step2: Particle ID

measure m/q:

\[ B\rho = \frac{mv}{q} \text{ (relativistic } B\rho = \gamma \frac{mv}{q} !) \]

\[ m/q = \frac{B\rho}{v} \]

\[ v = \frac{d}{\text{TOF}} \]

Measure Z:

\[ dE \sim Z^2 \]
determine number of implanted $^{44}\text{Ti}$

$60.3 \pm 1.3$ years  

Explosive Nucleosynthesis

Shock wave rips through star and compresses and heats all mass regions

Explosive C-Si burning

- similar final products
- BUT weak interactions unimportant for >= Si burning (but key in core !!!)
- BUT somewhat higher temperatures
- BUT Ne, C incomplete (lots of unburned material)

Explosive Si burning:

Deepest layer: full NSE $^{28}\text{Si} \rightarrow ^{56}\text{Ni}$

Further out: $\alpha$-rich freezeout

- density low, time short $\rightarrow 3\alpha$ cannot keep up and $\alpha$ drop out of NSE (but a lot are made from $2p+2n$ !)
- result: after freezeout lots of $\alpha$
- fuse slower – once one $^{12}\text{C}$ is made quickly captures more

$\rightarrow$ result: lots of $\alpha$-nuclei ($^{44}\text{Ti}$ !!!)
The “mass zones” in “reality”:

Contribution of Massive Stars to Galactic Nucleosynthesis

Displayed is the overproduction factor $X/X_{\text{solar}}$
This is the fraction of matter in the Galaxy that had to be processed through the scenario (massive stars here) to account for today's observed solar abundances.

To explain the origin of the elements one needs to have
- constant overproduction (then the pattern is solar)
- sufficiently high overproduction to explain total amount of elements observed today

"Problem" zone these nuclei are not produced in sufficient quantities

Type Ia supernovae
Novae

Calculation with grid of massive stars 11-40$M_\odot$ (from Woosley et al. Rev. Mod. Phys. 74 (2002)1015)
Type Ia supernovae

white dwarf accreted matter and grows beyond the Chandrasekhar limit

→ star explodes – no remnant
Nucleosynthesis contribution from type Ia supernovae

CO or ONeMg core ignites and burns to a large extent into NSE
Mass loss and remnants
Supernova remnants – neutron stars

SN remnant Puppis A (Rosat)

Neutron star kicked out with ~600 mi/s
An isolated neutron star seen with HST:
Neutron star properties

Mass:

- PSR B1518+49
- PSR B1518+49 companion
- PSR B1534+12
- PSR B1534+12 companion
- PSR B1913+16
- PSR B1913+16 companion
- PSR B2127+11C
- PSR B2127+11C companion
- PSR B2303+46
- PSR B2303+46 companion

Radius:

~10 km!
A NEUTRON STAR: SURFACE and INTERIOR

- **CORE:** Homogeneous Matter
- **CRUST:**
  - Nuclei
  - Neutron Superfluid

- **ATMOSPHERE**
- **ENVELOPE**
- **CRUST**
- **OUTER CORE**
- **INNER CORE**

- **Magnetic field**
- **Polar cap**
- **Cone of open magnetic field lines**

- **Neutron Superfluid**
- **Neutron Vortex**
- **Nuclei in a lattice**
- **Neutron Superfluid + Proton Superconductor**
  - Neutron Vortex
  - Magnetic Flux Tube