6.3 EVOLUTION OF MASSIVE STARS \((M \gtrsim 13 M_\odot)\)

- massive stars continue to burn nuclear fuel beyond hydrogen and helium burning and ultimately form an iron core

- alternation of nuclear burning and contraction phases
  - carbon burning \((T \sim 6 \times 10^8 K)\)
    \[
    ^{12}\text{C} + ^{12}\text{C} \rightarrow ^{20}\text{Ne} + ^4\text{He}
    \]
    \[
    \rightarrow ^{22}\text{Na} + ^1\text{H}
    \]
    \[
    \rightarrow ^{23}\text{Mg} + n
    \]

- oxygen burning \((T \sim 10^9 K)\)
  \[
  ^{16}\text{O} + ^{16}\text{O} \rightarrow ^{28}\text{Si} + ^4\text{He}
  \]
  \[
  \rightarrow ^{30}\text{P} + ^1\text{H}
  \]
  \[
  \rightarrow ^{31}\text{S} + n
  \]
  \[
  \rightarrow ^{30}\text{S} + 2^1\text{H}
  \]
  \[
  \rightarrow ^{24}\text{Mg} + ^4\text{He} + ^4\text{He}
  \]

- silicon burning: photodisintegration of complex nuclei, hundreds of reactions \(\rightarrow\) iron

- form iron core

- iron is the most tightly bound nucleus \(\rightarrow\) no further energy from nuclear fusion

- iron core surrounded by onion-like shell structure
6.4.1 EXPLOSION MECHANISMS (ZG: 18-5B/C/D)

- two main, completely different mechanisms

Core-Collapse Supernovae

- triggered after the exhaustion of nuclear fuel in the core of a massive star, if the iron core mass > Chandrasekhar mass
- energy source is gravitational energy from the collapsing core (~ 10% of neutron star rest mass ~ $3 \times 10^{46}$ J)
- most of the energy comes out in neutrinos (SN 1987A!)
  - unsolved problem: how is some of the neutrino energy deposited (~ 1%, $10^{44}$ J) in the envelope to eject the envelope and produce the supernova?
- leaves compact remnant (neutron star/black hole)

Thermonuclear Explosions

- occurs in accreting carbon/oxygen white dwarf when it reaches the Chandrasekhar mass
  - carbon ignited under degenerate conditions; nuclear burning raises $T$, but not $P$
  - thermonuclear runaway
  - incineration and complete destruction of the star
- energy source is nuclear energy ($10^{44}$ J)
- no compact remnant expected
- main producer of iron
- standard candle (Hubble constant, acceleration of Universe?)

but: progenitor evolution not understood
  - single-degenerate channel: accretion from non-degenerate companion
  - double-degenerate channel: merger of two CO white dwarfs
6.4.2 SUPERNova CLASSIFICATION

observational:
- Type I: no hydrogen lines in spectrum
- Type II: hydrogen lines in spectrum

theoretical:
- thermonuclear explosion of degenerate core
- core collapse $\rightarrow$ neutron star/black hole

relation no longer 1 to 1 $\rightarrow$ confusion
- Type Ia (Si lines): thermonuclear explosion of white dwarf
- Type Ib/Ic (no Si; He or no He): core collapse of He star
- Type II-P: “classical” core collapse of a massive star with hydrogen envelope
- Type II-L: supernova with linear lightcurve (thermonuclear explosion of intermediate-mass star? probably not!)

complications
- special supernovae like SN 1987A
- Type IIb: supernovae that change type, SN 1993J (Type II $\rightarrow$ Type Ib)
- some supernova “types” (e.g., IIn) occur for both explosion types (“phenomenon”, not type; also see SNe Ic)
- new types: thermonuclear explosion of He star (Type Iab?)
6.4.3 SN 1987A (ZG: 18-5)

- SN 1987A in the Large Magellanic Cloud (satellite galaxy of the Milky Way) was the first naked-eye supernova since Kepler’s supernova in 1604
- long-awaited, but highly unusual, anomalous supernova
  - progenitor blue supergiant instead of red supergiant
  - complex presupernova nebula
  - chemical anomalies: envelope mixed with part of the helium core

Confirmation of core collapse

- neutrinos ($\nu_e + p \rightarrow n + e^+$), detected with Kamiokande and IMB detectors
  - confirmation: supernova triggered by core collapse
  - formation of compact object (neutron star)
  - energy in neutrinos ($\sim 3 \times 10^{46} \text{J}$) consistent with the binding energy of a neutron star
SUMMARY III(B): IMPORTANT STELLAR TIMESCALES

- Dynamical timescale: \( t_{\text{dyn}} \approx \frac{1}{\sqrt{4G\rho}} \)
  \( \sim 30 \text{ min } (\rho/1000 \text{ kg m}^{-3})^{-1/2} \)

- Thermal timescale (Kelvin-Helmholtz): \( t_{\text{KH}} \approx \frac{GM^2}{2RL} \)
  \( \sim 1.5 \times 10^7 \text{ yr } (M/M_\odot)^2 (R/R_\odot)^{-1} (L/L_\odot)^{-1} \)

- Nuclear timescale: \( t_{\text{nuc}} \approx \frac{M_\odot}{M_{\text{core}}} \frac{\eta}{\text{mass efficiency}} \frac{(M c^2)/L}{10^{10} \text{ yr } (M/M_\odot)^{-3}} \)

### Example

<table>
<thead>
<tr>
<th>Main-sequence stars</th>
<th>( t_{\text{dyn}} )</th>
<th>( t_{\text{KH}} )</th>
<th>( t_{\text{nuc}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) M = 0.1 M_\odot, L = 10^{-3} L_\odot, R = 0.15 R_\odot</td>
<td>4 min</td>
<td>10^9 yr</td>
<td>10^{12} yr</td>
</tr>
<tr>
<td>b) M = 1 M_\odot, L = 1 L_\odot, R = 1 R_\odot</td>
<td>30 min</td>
<td>15 \times 10^6 yr</td>
<td>10^{10} yr</td>
</tr>
<tr>
<td>c) M = 30 M_\odot, L = 2 \times 10^5 L_\odot, R = 20 R_\odot</td>
<td>400 min</td>
<td>3 \times 10^3 yr</td>
<td>2 \times 10^6 yr</td>
</tr>
</tbody>
</table>

| Red giant (M = 1 M_\odot, L = 10^3 L_\odot, R = 200 R_\odot) | 50 d | 75 yr |
| White dwarf (M = 1 M_\odot, L = 5 \times 10^{-3} L_\odot, R = 2.6 \times 10^{-3} R_\odot) | 7 s | 10^{11} yr |
| Neutron star (M = 1.4 M_\odot, L = 0.2 L_\odot, R = 10 \text{ km}, T_{\text{eff}} = 10^6 K) | 0.1 ms | 10^{13} yr |

### SUMMARY V: THE END STATES OF STARS

**Three (main) possibilities**

- The star develops a degenerate core and nuclear burning stops (+ envelope loss) \( \rightarrow \) degenerate dwarf (white dwarf).
- The star develops a degenerate core and ignites nuclear fuel explosively (e.g. carbon) \( \rightarrow \) complete disruption in a supernova.
- The star exhausts all of its nuclear fuel and the core exceeds the Chandrasekhar mass \( \rightarrow \) core collapse, compact remnant (neutron star, black hole).

#### Final fate as a function of initial mass \( (M_0) \) for \( Z = 0.02 \)

| \( M_0 \approx 0.08 \) M_\odot | no hydrogen burning (degeneracy pressure + Coulomb forces) | planets, brown dwarfs |
| [0.08, 0.48] M_\odot | hydrogen burning, no helium burning | degenerate He dwarf |
| [0.48, 8] M_\odot | hydrogen, helium burning | degenerate CO dwarf |
| [8, 13] M_\odot | complicated burning sequences, no iron core | neutron star |
| [13, 80] M_\odot | formation of iron core, core collapse | neutron star, black hole |
| \( M_0 \gtrsim 80 \) M_\odot | pair instability? complete disruption? | no remnant |
| also (?) [6, 8] M_\odot | degenerate carbon ignition possible (but unlikely), complete disruption | no remnant |
6.4.4 NEUTRON STARS (ZG: 17-2; CO: 15.6)

- are the end products of the collapse of the cores (mainly Fe) of massive stars (between 8 and ~ 20 M⊙)
- in the collapse, all nuclei are dissociated to produce a very compact remnant mainly composed of neutrons and some protons/electrons

Note: this dissociation is endothermic, using some of the gravitational energy released in the collapse.

▷ these reactions undo all the previous nuclear fusion reactions

- since neutrons are fermions, there is a maximum mass for a neutron star (similar to the Chandrasekhar mass for white dwarfs), estimated to be between 1.5 – 3 M⊙
- typical radii: 10 km (i.e. density ~ 10^{18} kg m^{-3}!)

6.4.5 SCHWARZSCHILD BLACK HOLES (ZG: 17-3; CO: 16)

- event horizon: (after Michell 1784)
  - the escape velocity for a particle of mass m from an object of mass M and radius R is \( v_{\text{esc}} = \sqrt{\frac{2GM}{R}} \)
  - (11 km s\(^{-1}\) for Earth, 600 km s\(^{-1}\) for Sun)
  - assume photons have mass: \( m \propto E \) (Newton’s corpuscular theory of light)
  - photons travel with the speed of light c
  - photons cannot escape, if \( v_{\text{esc}} > c \)

  \[ R < R_s \equiv \frac{2GM}{c^2} \] (Schwarzschild radius)

  \[ R_s = 3 \text{ km} \left( \frac{M}{M_\odot} \right) \]

Note: for neutron stars \( R_s \approx 5 \text{ km} \); only a factor of 2 smaller than \( R_{\text{NS}} \rightarrow \) GR important

Orbits near Schwarzschild Black Holes