36 — The End of High-Mass Stars [$Revision$: 1.1]

- Burning through to iron
  - Stars with masses $M \gtrsim 9\,M_\odot$ burn all the way through to iron:
$$^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{16}_{8}\mathrm{O} + \gamma$$
$$^{16}_{8}\mathrm{O} + {}^{16}_{8}\mathrm{O} \rightarrow {}^{28}_{14}\mathrm{Si} + {}^{4}_{2}\mathrm{He}$$
    Si burns via whole series of reactions built on alpha-particle capture, e.g.
$$^{28}_{14}\mathrm{Si} + {}^{4}_{2}\mathrm{He} \leftrightarrow {}^{32}_{16}\mathrm{S} + \gamma$$
    Eventually produces nucleii centered around $^{56}_{26}\mathrm{Fe}$ (most stable)
  - Star has onion-line structure, with sequence of burning shells surrounding inert iron core supported by electron degeneracy pressure
  - Time to burn each stage becomes shorter and shorter; silicon burning is a few days long
  - Eventually, temperature in iron core large enough for photodisintegration:
$$^{56}_{26} + \gamma \rightarrow 13{}^{4}_{2}\mathrm{He} + 4n$$
$$^{4}_{2}\mathrm{He} + \gamma \rightarrow 2p^{+} + 2n$$
  - Also, electrons captured by free protons:
$$p^{+} + e^{-} \rightarrow n + \nu_{\mathrm{e}}$$
    (removes degeneracy pressure)
  - Net result: dramatic drop in central pressure; **core collapse**

- Core collapse
  - Occurs due to loss of pressure in core
  - Core collapses on dynamical timescale of few seconds
  - Collapse only halted by neutron degeneracy pressure, when $\rho \sim 10^{15}\,\mathrm{g\,cm^{-3}}$
  - Estimate energy released:
    * Threshold density for electron capture that triggered collapse $\sim 10^{10}\,\mathrm{g\,cm^{-3}}$
    * Assume collapsing core contains $1\,M_\odot$ of iron
    * Initial radius calculated from mass and initial density as $R_{\mathrm{in}} \sim 3 \times 10^{7}\,\mathrm{cm}$
    * Final radius calculated from mass and final density as $R_{\mathrm{fin}} \sim 8 \times 10^{5}\,\mathrm{cm}$
    * Grvitational energy change:
$$\Delta U \sim GM^2 \left(\frac{1}{R_{\mathrm{fin}}} - \frac{1}{R_{rmin}}\right) \sim 3 \times 10^{53}\,\mathrm{erg}$$
  - This is equivalent to entire luminous output of galaxy for 10^9 seconds (31 years!)
  - However, only a tiny fraction is eventually released as light
  - Initially, energy released goes into kinetic energy of shock wave, which propagates out through (still uncollapsed) outer core
  - Shock loses energy by photodisintegration and electron capture; 99% of energy converted into neutrinos

- Shock also creates heavy nucleii via neutron capture process:

$$^{A}_{Z}\mathrm{X} + n \rightarrow {}^{A+1}_{Z}\mathrm{X} + \gamma$$

$$^{A+1}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z+1}\mathrm{X} + e^{-} + \bar{\nu}_{\mathrm{e}}$$

  If second reaction (β decay) is short compared to neutron capture timescale, this is known as *s*-process nucleosynthesis ('slow'); occurs throughout star's life. If long, known as *r*-process ('rapid'); occurs in shock, leads to unstable, neutron-rich nucleii
- Shock eventually stalls due to energy losses
- However, shock is optically thick to neutrinos trapped beneath it; reabsorbs enough energy to resume outward progress
- Shock eventually blows off outer core layers and envelope; **supernova**!
- 1% of initial energy release goes into kinetic energy of ejecta
- Ejecta itself releases about 1% of its energy as photons ($\sim 10^{49}$ erg); radiated away over a few months

• Supernova Types

- Core-collapse supernovae classified on the basis of spectra and light curves:
  * Hydrogen lines present $\rightarrow$ collapse occured in star that still has hydrogen-rich envelope
    · Classified as type II
    · Type II-L shows linear decline in brightness over time, after initial peak
    · Type II-P shows plateau superimposed on linear decline; plateau comes from gradual release of energy from optically thick envelope
    · Long-time parts of light curve powered by radioactive decay
  * Hydrogen lines absence $\rightarrow$ collapse occured in star that has lost its envelope
    · Classified as type I
    · Type Ia shows Silicon lines — **not actually core collapse**, occurs in low-mass binary stars
    · Type Ib shows no Silicon, but does show Helium; collapse occured in star with helium envelope
    · Type Ic shows no Silicon or Helium; collapse occured in star with C/O envelope
- But how does a massive star lose its envelope?

• Radiation driven winds

- All massive stars have radiation driven winds
- Eddington Γ is less than unity, so not electron scattering opacity — instead, **line** (bound-bound) opacity
- Doppler shifts due to the wind are responsible for moving lines out of their own shadow
- Mass-loss rates range up to $10^{-5}\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$; over a $\sim$ 3 million year lifetime, much mass can be lost
- In fact, mass loss *must* be accounted for during massive-star evolution
- Extreme mass loss leads to optically thick winds showing emission lines — Of stars (on main sequence) and **Wolf-Rayet** stars (after main sequence)
- Wolf-Rayet stars show evidence of having lost their envelopes