Today in Astronomy 241: post-main-sequence evolution III (massive stars)

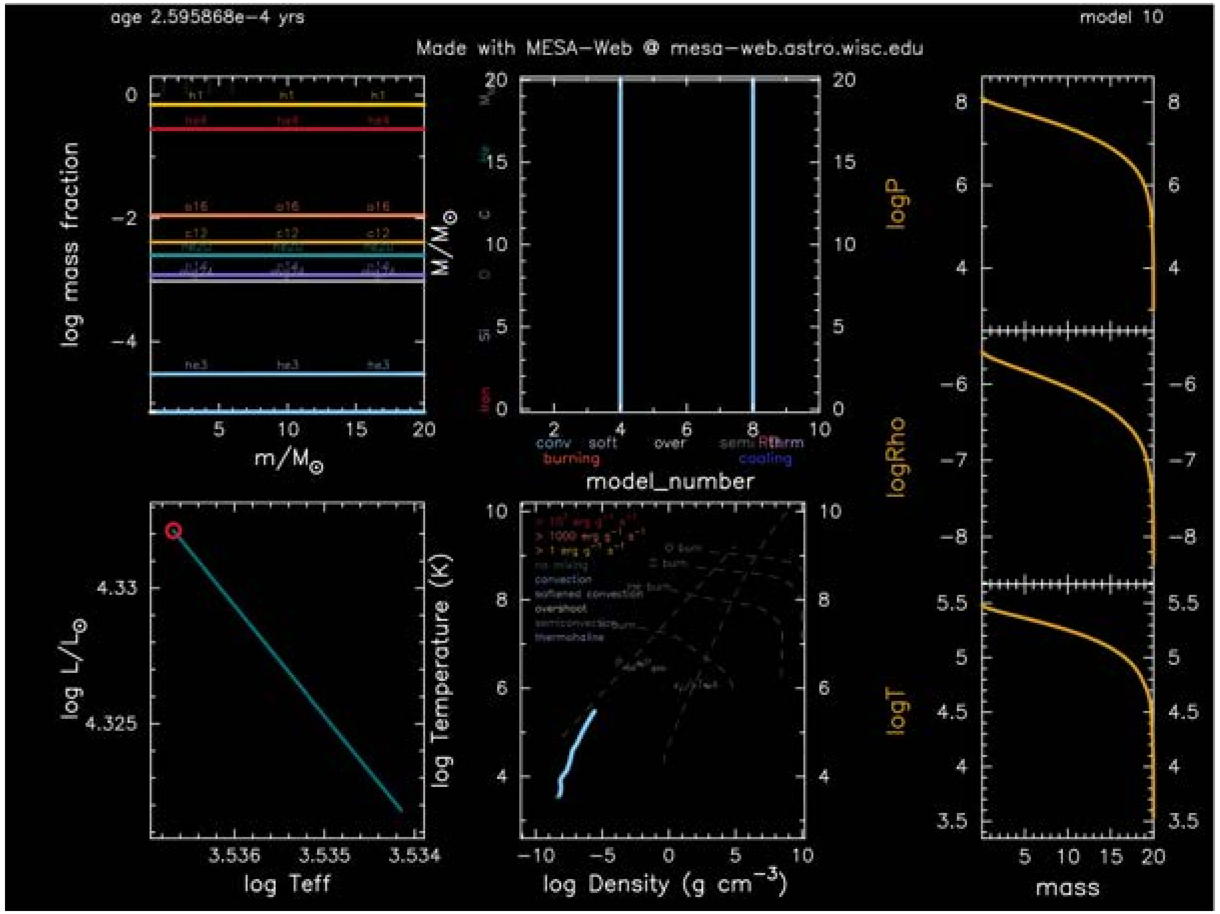
- Neutron star and black hole formation
- Type II supernovae
- Young supernova remnants, their light curves and energetics
- Explosive nucleosynthesis
- **Reading**: C&O chapter 15, pp 518-550

Before and after Supernova 1987A, David Malin, [Anglo-Australian Observatory]

Late stages of evolution of massive stars

For massive stars – those with **core** masses > $2M_{\odot}$, development on the AGB looks like this:

- Repeated core collapse - fusion reignition - nuclear fuel exhaustion occurs, including silicon burning to produce iron-peak elements.
- Each of the successive fuel exhaustions is faster than the last. For a 20 $M_{\odot}$ total-mass star,
  - hydrogen burning (main sequence) lasts 10^7 years
  - helium burning (horizontal branch) lasts 10^6 years
  - carbon burning lasts 300 years
  - oxygen burning lasts 200 days
  - silicon burning lasts 2 days



MESA models of a 20 $M_{\odot}$ star, birth til iron core.

Stellar core collapse

- The latter stages happen so fast that there isn't time for the star to eject much more of its envelope.
- The mass of the iron core is greater than the maximum mass for white dwarf stars: electron degeneracy pressure cannot support the weight of the core.
- Iron lies at the peak of binding energy per nucleon. No further heat can be generated from fusion reactions.
- Thus the star collapses under its weight. The core collapses fastest, as it's densest: recall the free-fall collapse time,

$$t_{ff} = \sqrt{\frac{3\pi}{32G\rho_0}} = 1.5 \text{ sec for } \rho_0 = 2\times10^6 \text{ gm cm}^{-3}.$$

- As it goes from a diameter of about r_0 = 5000 km to r = 25 km, it reaches a radial speed of about

$$\frac{dr}{dt} = -r_0\sqrt{\frac{8\pi G\rho_0}{3}\left(\frac{r_0}{r}-1\right)} = -7\times10^9 \text{ cm sec}^{-1} = 0.23c \quad .$$

Stellar core collapse (continued)

- As collapse proceeds, the medium gets hot enough for highly endothermic reactions to take place - nuclear disintegration and reverse β-decay - and it turns into a neutron gas. It is very luminous in neutrinos at this stage. For a 20 $M_\odot$ star, and from $e^- + p \rightarrow n + \nu_e$: 3.1×10^{45} erg sec^{-1}, ten million times more than the light output.

- When the core reaches dimensions of tens of kilometers, neutron degeneracy pressure suddenly sets in.

- The degenerate-neutron EOS is very stiff, so

- This imploding material **bounces**, and rebounds into the collapsing envelope, carrying a kinetic energy larger than the envelope's gravitational binding energy.

- This results in the explosion of the star, giving it an enormous luminosity for a while (10^9 $L_\odot$ or so, for a few weeks) - a **Type II supernova**.

- If the core is less massive than 2.2-2.4 $M_\odot$, the collapse of the core will stop - a **neutron star** is formed.

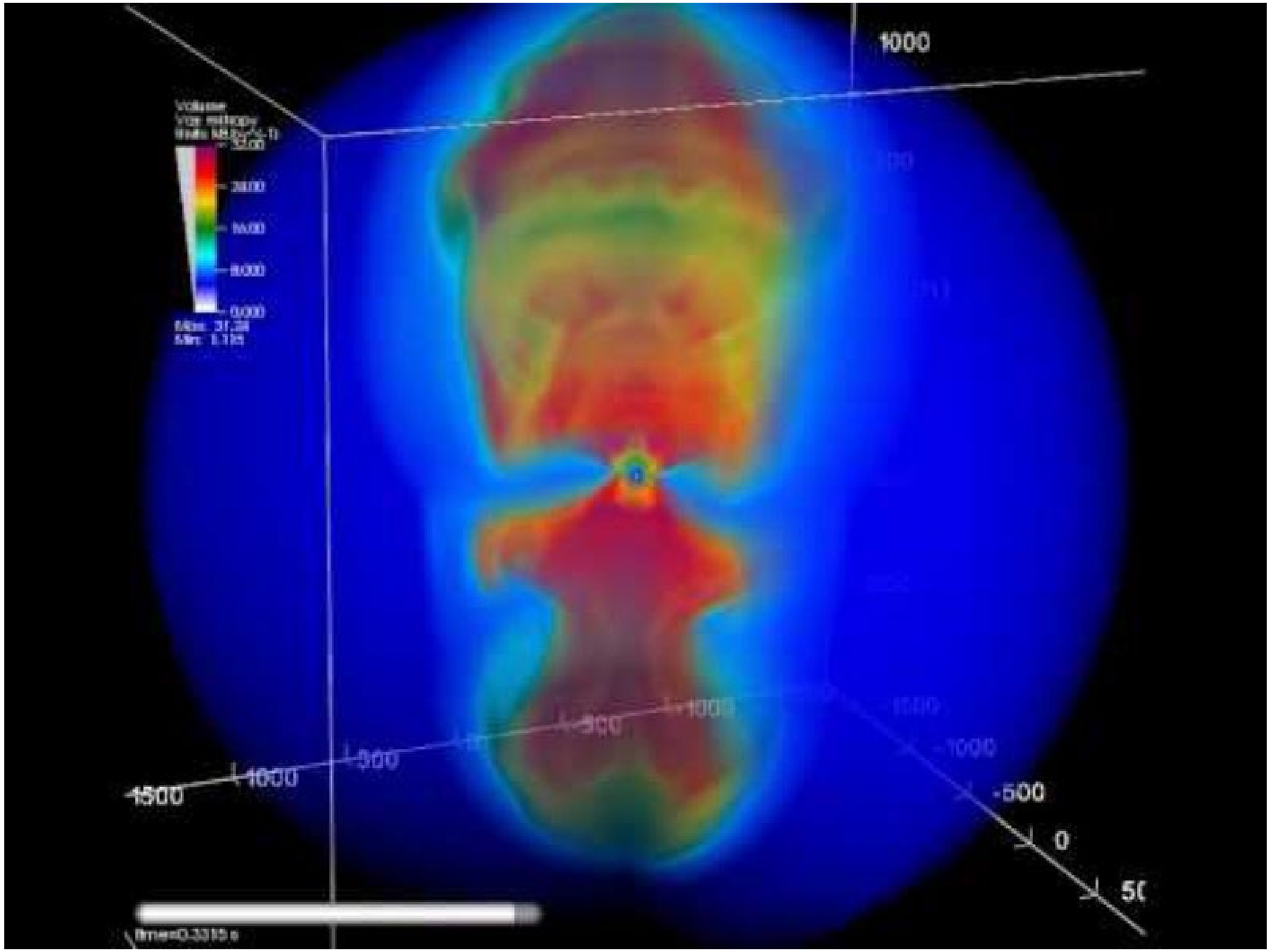
- If the core is more massive than that, it will collapse to form a **black hole**.

Stellar core collapse (continued)

The explosion of an 11.2 $M_\odot$ star upon its core turning to iron. Note the explosion is not spherical, as the star was initially rotating (slowly).

From Markus Rampp, Max Planck Computing and Data Facility, Garching.

[View on YouTube]



Type II supernovae

Enough free energy is present in the blast to enable explosive nucleosynthesis:

- rapid formation of lots of carbon and oxygen, among others, from helium and hydrogen.
- endothermic nuclear reactions (r-process, s-process) that form elements heavier than iron.
- The exploding shell is kept hot for a while, due to radioactive decay of heavy elements (see problems 15.11 – today – and 15.12).
- It’s very bright for a month or so, after which the luminosity declines at the rate of a magnitude every couple of months.
- Expanding shell encounters interstellar gas, eventually forming a nebula of the type we call supernova remnants. This is discussed at length and in detail, in ASTR 232.

Today’s in-class problems

Just C&O 15.11.

With remaining time, we will increase everyone’s traction on Homework #9.

Answers and/or secrets to in-class problems

15.11 (a) With $\varepsilon = 3.72\text{ MeV} = 5.96\times10^{-6}$ erg as the energy released per Co decay, and $\lambda = \ln 2/\tau_{1/2} = 1.03\times10^{-7}\text{ sec}^{-1}$ as the decay constant,

$$L = -\varepsilon\frac{dN}{dt} = \varepsilon\lambda N_0 e^{-\lambda t} = \varepsilon\lambda N$$

$$L_0 = 9.8\times10^{41}\text{ erg sec}^{-1} = 2.6\times10^{8} L_\odot$$

This is often reported in magnitudes (problem 15.9): the absolute bolometric magnitude and rate of change are

$$M_{bol} = M_{\text{Sun}} - 2.5\log\left(L/L_\odot\right) = 4.83 - 2.5\log\left(2.6\times10^{8}\right) = -16.2 \quad ,$$

$$\frac{dL}{dt} = \varepsilon\lambda^2 N$$

$$\frac{dM_{bol}}{dt} = 2.5\frac{d}{dt}\left(\log L/L_\odot\right) = 2.5\frac{d}{dt}\left(\log e \log L/L_\odot\right) = \frac{2.5\log e}{L}\frac{dL}{dt} = \frac{2.5\log e}{\varepsilon\lambda N}\varepsilon\lambda^2 N$$

$$= 2.5\lambda\log e = 1.1\times10^{-7}\text{ sec}^{-1} = 0.3\text{ mag per month} = 3.5\text{ mag per year.}$$

Answers and/or secrets to in-class problems (continued)

15.11 (b) Plug into the expressions above to get $L = 9.9 \times 10^6 L_\odot$.

15.11 (c) And of course this is consistent with figure 15.12, or they wouldn't have asked.