Lecture 8: Stellar evolution II: Massive stars

Senior Astrophysics

2018-03-27

Outline

Mass ranges

Last lecture we identified four regions of the HR diagram:

- **red dwarfs**: $M < 0.7M_\odot$. Main sequence lifetime exceeds age of Universe
- **low-mass**: $0.7M_\odot < M < 2M_\odot$. End lives as WD and possibly PN
- **intermediate-mass**: $2M_\odot < M <$ 8–10$M_\odot$. Similar to low-stars but at higher L; end as higher mass WD and PN
- **massive**: $M >$ 8–10$M_\odot$. Distinctly different evolutionary paths; end as supernovae, leaving neutron stars or black holes
- Boundaries uncertain, mass ranges approximate.

Convection

- Before we talk about evolution, discuss **convection**
- Recall the equation of energy transport,

$$\frac{dT}{dr} = -\frac{3}{4ac}\frac{\kappa\rho}{T^3}\frac{L}{4\pi r^2}$$

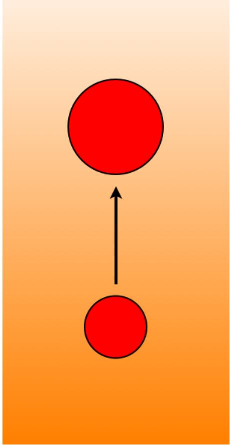
describing the temperature gradient when energy is carried by radiation.

- If luminosity L or opacity κ are large $\Rightarrow$ large (negative) value of dT/dr.

Convection

- For an ideal gas, the energy density (energy per unit volume) is given by $\frac{3}{2}nkT$ where n is the number density of particles.
- Hot gas near the centre of the star has higher energy density than cooler gas above.
- If we could 'swap' the gas over, we could transport energy outward.

Convective instability



- Imagine displacing a small mass element vertically upward by a distance dr
- Assume that **no heat** is exchanged with surrounding gas, i.e. process is **adiabatic**
- Element expands to stay in pressure balance with new environment
- New density will in general *not* equal ambient density at new location

	Initially	After displacement
Surroundings	$\rho(r)$	$\rho(r + dr)$
Element	$\rho(r)$	ρ^*

Convective instability

If

- $\rho^* > \rho(r + dr)$ then the displaced element will be denser than the surroundings and will settle back down $\Rightarrow$ **stable**
- $\rho^* < \rho(r + dr)$ then buoyancy will cause the element to rise even further $\Rightarrow$ **convective instability**

Convective instability

Condition for stability can be shown to depend on the **temperature gradient**. The condition for stability is

$$\left(\frac{dT}{dr}\right)_{star} < \left(\frac{dT}{dr}\right)_{adiabatic}$$

If the temperature gradient in the star is **steeper** than the temperature gradient when an element is moved adiabatically, then this leads to the onset of convection.

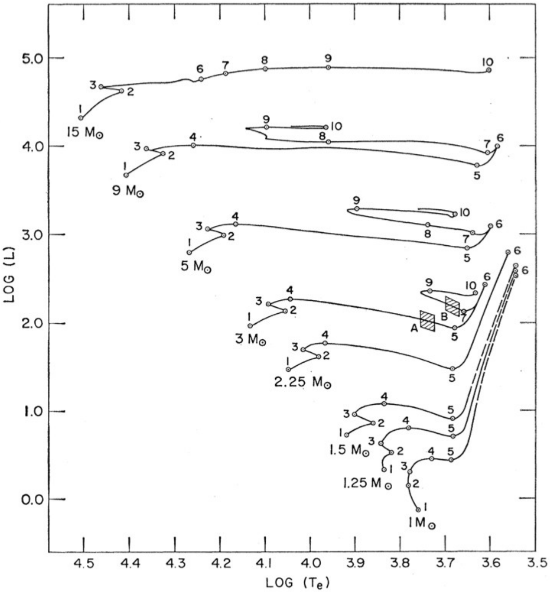
Large luminosities and/or large opacities lead to convection.

Convection

- **Low mass stars**: near the surface opacity is large due to atomic processes $\Rightarrow$ **surface** convection zones
- **High mass stars**: very high luminosities, $L \sim M^4$, all generated close to core $\Rightarrow$ **core** convection

Evolution of a massive star

- Massive stars, with $M > 8\text{–}10 M_{\odot}$, have different evolutionary paths to low-mass stars. The main differences are
  - L remains approximately constant in spite of internal changes, so the track in the HR diagram is almost horizontal.
  - Massive stars can undergo the whole sequence of thermonuclear reactions, all the way up to Fe
  - Mass-loss is important at all stages of the star's evolution



Paths in the HR diagram for stars of different mass. (From Iben 1967, Science 155, 785)

Constant luminosity

- Basic physics for how stars evolve is the same, but observational consequences are quite different
- Most notably, massive stars evolve at nearly constant luminosity. This is consequence of radiation pressure being important for massive stars (= photon gas); massive stars are already radiating at $\sim$ their maximum luminosity (Eddington luminosity – will discuss later)
- After they leave the MS and begin burning H in shells, massive stars cannot increase their luminosity, but they can increase their radius and go to lower effective temperature $\Rightarrow$ massive stars never have a red giant phase, since that would require an increase in luminosity.

Internal structure

- Just as for low-mass stars, when the collapsing core reaches high enough temperature the triple-α process can begin. Unlike the low-mass stars, however, helium burning begins when the core is non-degenerate (lower density). There is no helium flash; the onset of He burning is gradual.
- Again, the triple-α process liberates less energy per unit mass than for H-burning, so the lifetime is correspondingly shorter ($\sim 10\%$ of the MS lifetime).
- Once the He core has been converted to ^{12}C and ^{16}O, He burning stops, the core recommences its collapse, and a He burning shell ignites outside the core.
- This time, the temperature rises high enough for C and O to burn to Mg and Si (see lecture 7).

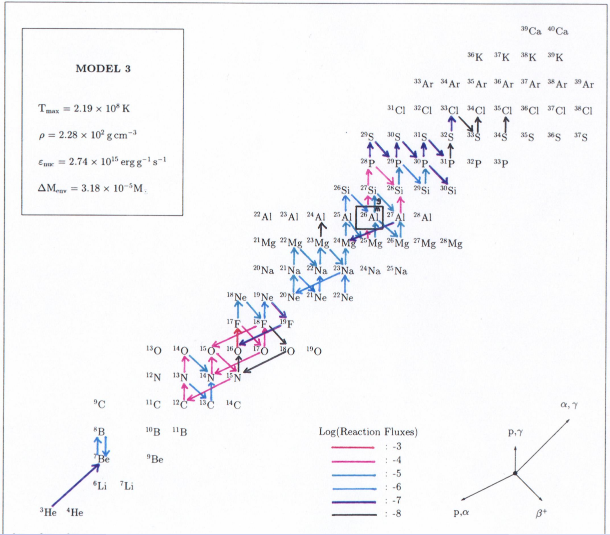
C and O burning

- C burning requires $T \sim 6 \times 10^8$ K
- Several reactions are involved, e.g.

$$
\begin{aligned}
{}^{12}\mathrm{C} + {}^{4}\mathrm{He} &\to {}^{16}\mathrm{O} + \gamma \\
{}^{12}\mathrm{C} + {}^{12}\mathrm{C} &\to {}^{20}\mathrm{Ne} + {}^{4}\mathrm{He} + \gamma \\
&\to {}^{23}\mathrm{Na} + {}^{1}\mathrm{H} + \gamma \\
&\to {}^{23}\mathrm{Mg} + n + \gamma \\
{}^{16}\mathrm{O} + {}^{4}\mathrm{He} &\to {}^{20}\mathrm{Ne} + \gamma \\
{}^{16}\mathrm{O} + {}^{16}\mathrm{O} &\to {}^{28}\mathrm{Si} + {}^{4}\mathrm{He} + \gamma \qquad \text{etc.}
\end{aligned}
$$

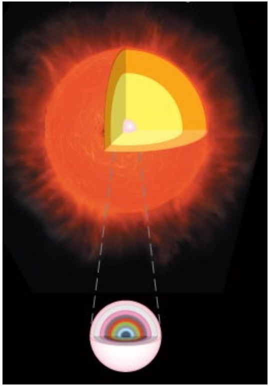
- ^{28}Si burning has hundreds of possible reactions, producing a host of nuclei.

C and O burning



Stars have layers

- This pattern of core ignition and shell ignition continues, until the star develops a layered structure.
- Heavier and heavier elements are built up, until the iron group elements of Ne, Fe and Co are formed. The core is surrounded by a series of shells at lower T and lower ρ.



- Typical timescales ($15M_{\odot}$ star)

Phase	$\boldsymbol{\tau}$ **(yrs)**
Hydrogen (MS)	10×10^6
Helium	1×10^6
Carbon	400
Oxygen	1
Silicon	10^{-2}

Website of the Week:

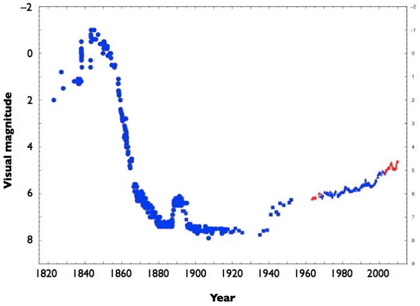
SIMBAD
http://simbad.u-strasbg.fr/simbad/
Astronomical database for basic data, cross-identifications, bibliography and measurements for astronomical objects outside the solar system.

Mass loss

- Even on the main sequence, massive stars can lose significant amounts of mass. The winds are driven by **radiation pressure**: UV photons from a hot, very luminous star are absorbed by the optically thick outer atmosphere layers.
- An extreme example of this is the massive star η Car ($\sim 100 M_{\odot}$).

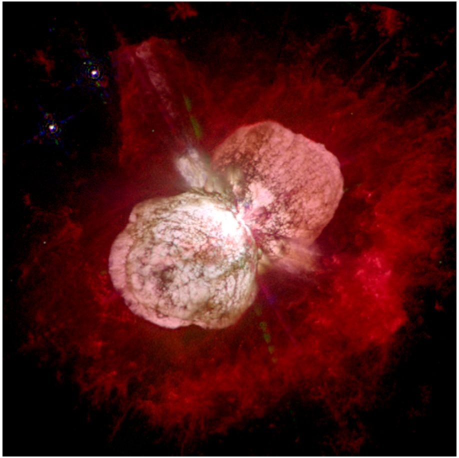
- Brightness has changed by nearly 10 mags over the last 200 yr; for a while it was one of the brightest stars in the sky.

from http://etacar.fcaglp.unlp.edu.ar/



η Carinae

- Hubble images show the star is surrounded by two enormous bubbles of gas

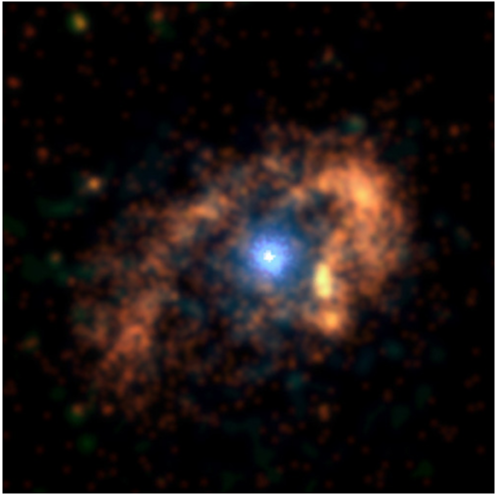


- 150 years ago the star erupted in a huge wind, during which it lost a solar mass of material
- Cooling cloud of gas now hides the star, dimming its light

η Car from the Hubble Space Telescope

η Carinae

- X-ray images show a hot central source (star), a hot inner core about 3 light months in diameter, and an outer ring about two light years in diameter.
- Must be the remnant of another large explosion > 1000 yr ago



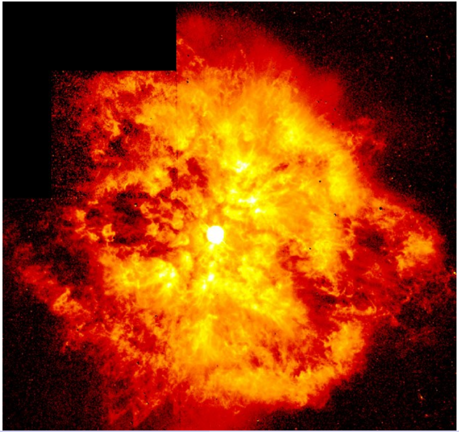
η Carinae

- η Car is an example of a **luminous blue variable** — stars with $M > 85 M_\odot$ which lose mass in a rapid and unstable manner.

Wolf-Rayet stars

- Less massive stars also lose large amounts of mass, though in a less violent manner. The Wolf-Rayet stars have atmospheres containing very little hydrogen: they are essentially the bare cores of massive stars.

- WR stars lose mass at rates $\sim 10^{-5} M_{\odot}$/year, producing spectacular nebulae which can look like planetary nebulae.



HST image of the Wolf-Rayet star WR124, showing the star surrounded by hot clumps of gas being ejected at high speed.

“Thor’s Helmet” (NGC 2359), a bubble-like nebula blown from the hot Wolf-Rayet star in its centre.
http://antwrp.gsfc.nasa.gov/apod/ap021205.html

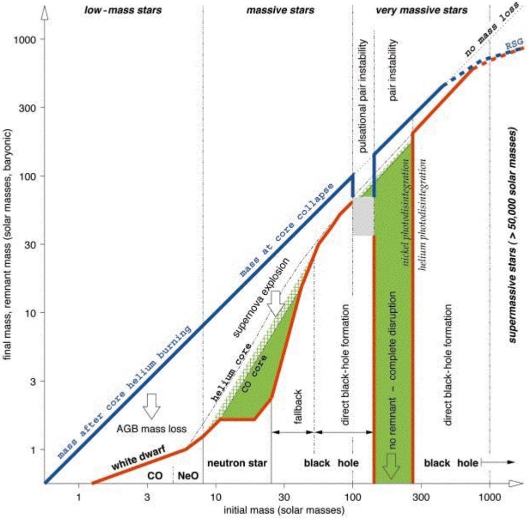
Mass loss and the fate of stars

- The amount of mass lost can have a dramatic effect on the fate of the star. Our own Sun has a solar wind which reaches speeds of 400–700 $\mathrm{km\,s^{-1}}$ with a mass loss rate of about $10^{-14}\ M_\odot/\mathrm{yr}$. Over a ten billion year lifespan, at this rate the Sun will lose about 0.01% of its mass to the solar wind.
- By contrast, the winds from hot stars can be a billion times stronger, losing up to $10^{-5}\ M_\odot/\mathrm{yr}$ at speeds of up to 3000 km/s. This means that even during the much shorter lives of the stars (a few million years), they can lose on the order of half or more of their mass: a $100 M_\odot$ star may have a mass of only $30 M_\odot$ by the time it leaves the main sequence.

Mass loss and the fate of stars

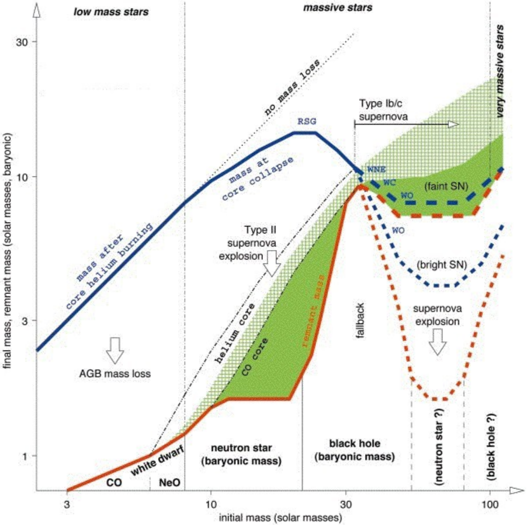
- This has substantial implications for the evolution of the star. Reducing the mass of the star reduces the pressure and temperature in the interior, which can reduce the mass of the core.
- And it is the mass of the core when fusion stops which governs whether the star explodes as a supernova, and what kind of remnant it leaves behind.

Without mass loss



Woosley, Heger and Weaver 2002, Rev Mod. Phys. 74, 1015; http://adsabs.harvard.edu/abs/2002RvMP...74.1015W

With mass loss



Woosley, Heger and Weaver 2002, Rev Mod. Phys. 74, 1015; http://adsabs.harvard.edu/abs/2002RvMP...74.1015W

Next lecture

Supernovae

- Core collapse
- Supernovae
- Type Ia supernovae
- SN 1987A