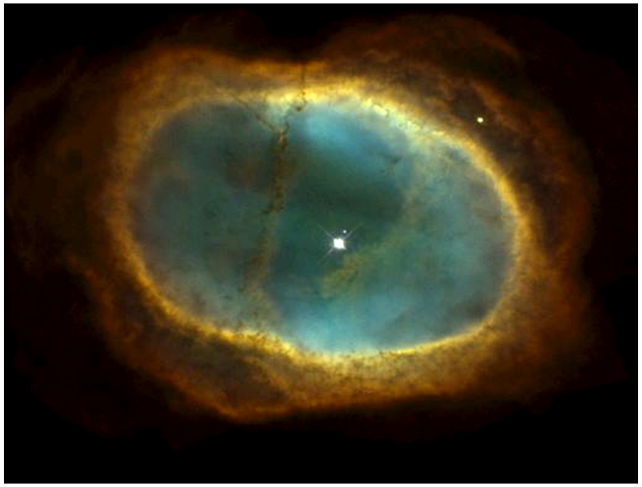
Post Main Sequence Evolution of “Low-Mass” Stars

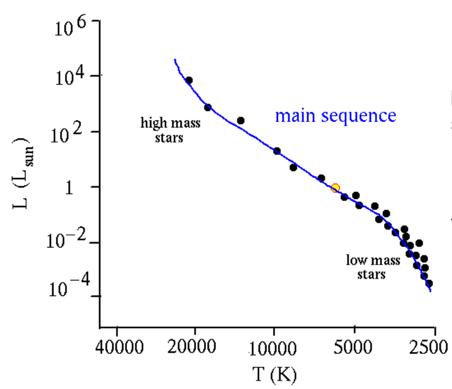
Chapter 19.1-19.3, then 20.1-20.4, then 19.4-19.6



Key points

- Late stages of evolution: Red Giants, Horizontal Branch Stars, Asymptotic Giant Branch Stars, White Dwarfs.
- At each stage, what element is fusing and where?
- How does that change the structure of the star?
- The evolutionary path of the star on the H-R diagram. How do *L, T, R* change at each stage?
- Although evolution is complex, it’s driven by a few basic physical concepts.
- Star clusters and their H-R diagrams
- Variable stars and distance indicators

"Stellar Midlife" - Main Sequence



High-mass stars are hotter and brighter, have larger radius and short lifetime.

Low-mass stars are cooler, fainter, have smaller radius and long lifetime.

MS stars fuse H to He in cores. There is some evolution of *L* and *T* on MS (so may sometimes see ZAMS or Zero-Age Main Sequence referred to – indicates stars’ positions at beginning of MS life).

In stars more massive than about 1M☉ ($T_{core} > 1.6 \times 10^7$ K), H => He fusion more efficient through “CNO cycle”: chain of six reactions where C, N and O are catalysts, but end result same as p-p chain.

$$^{12}C + {}^{1}H \rightarrow {}^{13}N + \text{energy}$$

$$^{13}N \rightarrow {}^{13}C + e^+ + \nu$$

$$^{13}C + {}^{1}H \rightarrow {}^{14}N + \text{energy}$$

$$^{14}N + {}^{1}H \rightarrow {}^{15}O + \text{energy}$$

$$^{15}O \rightarrow {}^{15}N + e^+ + \nu$$

$$^{15}N + {}^{1}H \rightarrow {}^{12}C + {}^{4}He + \text{energy}$$

Nuclear reactions are highly sensitive to core T:

- p-p chain: $\propto T^4$
- CNO cycle: $\propto T^{20}$

Post main sequence evolution: "evolved" stars. Focus on 0.4 $M_\odot$ < M < 7(?) $M_\odot$ case

(This is a condensed version of what's in the textbook, and is what you need to know).

Core hydrogen exhaustion

1. During the MS, H => He in core
   $\Rightarrow$ core runs out of fuel at some point.

   Can it immediately "burn" He?

   No, the Coulomb (electrical charge) barrier is too high.
   => core energy production drops.
   => internal pressure drops.

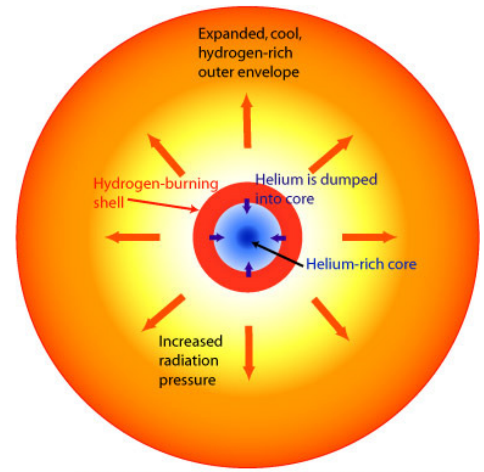
   Hydrostatic equilibrium is being lost.

2. Core contracts (eventually by factor of about 3 in radius)
   => heats up
   => inner part of "envelope" (everything outside core) contracts too, heats up

   => now a zone around He core is hot enough for H burning – "H-burning shell"

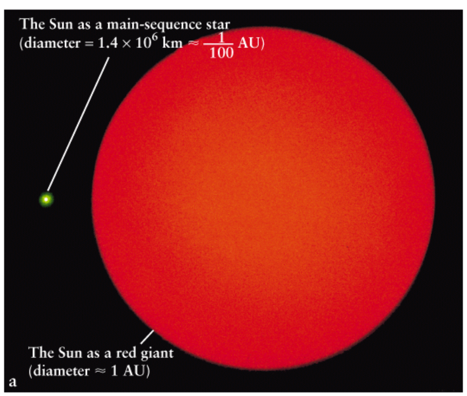
3. T, density higher in shell than in core during MS
   => <u>faster fusion!</u>

4. Faster fusion results in both higher pressure, which pushes out envelope above it, and more radiation



Hydrogen Shell Burning on the Red Giant Branch

(not to scale!)



5. Outer envelope expands and therefore cools => redder. Luminosity rises due to vigorous shell fusion.
6. Result is a <u>Red Giant</u> (ignore subgiant/Red Giant distinction in text for this class)

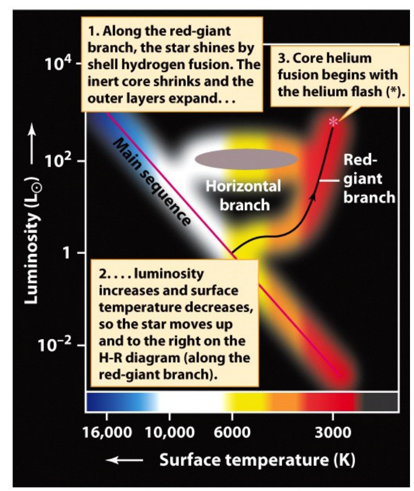
Radius increases roughly 100 times.

Lasts about 1 Gyr for 1 $M_\odot$ stars (c.f. t_{ms}~10 Gyr).

Strong winds

Red giant stars in Auriga

Evolving along the red giant branch (1 $M_\odot$ case)



(a) Before the helium flash: A red-giant star

Figure 20-1
Universe, Ninth Edition

(Aside: evolution of stars < 0.4 $M_{\odot}$, down to brown dwarf limit)

These are fully convective: convection zone extends from center to surface => all gas cycles into core where fusion occurs and out again.

Eventually, all H in star converted to He. This takes 100's of billions of years.

Never hot enough for He fusion.

Result will be dead He star.

Back to Red Giant. Eventually, core hot enough (T almost 10^8 K) to ignite helium:

Helium burning (Sec 19.3, 20.1)

1) He burning starts via:

- The "triple alpha" process:

$$^{4}He + {}^{4}He \Rightarrow {}^{8}Be + \gamma$$
$$^{8}Be + {}^{4}He \Rightarrow {}^{12}C + \gamma$$

Carbon-based life!

- Some C goes on to make O by fusing with another helium nucleus:

$$^{12}C + {}^{4}He \Rightarrow {}^{16}O + \gamma$$

table 21-2 How Helium Core Fusion Begins in Different Red Giants

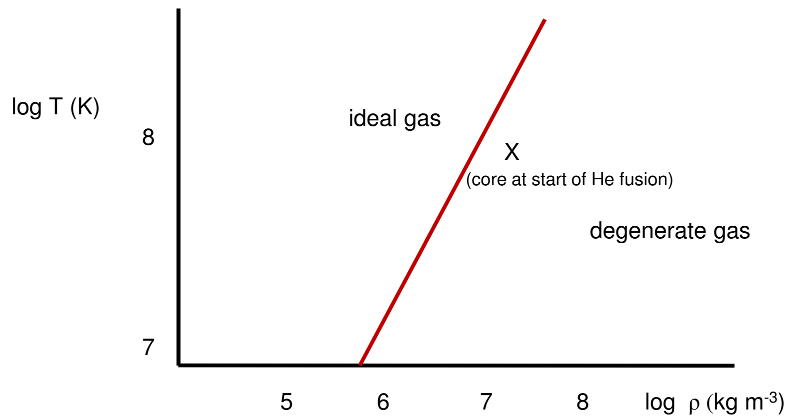
Mass of star	Onset of helium burning in core
Less than 2–3 solar masses	Explosive (helium flash)
More than 2–3 solar masses	Gradual

Why is the onset of helium burning explosive in lower mass stars?
To understand that, we need the concept of degeneracy, and degenerate matter.

Low-mass (<2-3 $M_{\odot}$) stars: Electron degeneracy and the Helium Flash (not required to learn)

- In cores of low-mass red giants conditions are extreme: very high temperature and density, gas is completely ionized.
- With core contracting, density rises to about 10^7 kg m^{-3}.
- Electrons and nuclei of the ionized gas are tightly squeezed.
- Electrons reach a limit set by quantum mechanics where they greatly resist further compression. This is a "<u>degenerate</u>" gas, different from an ideal gas. Its <u>pressure</u> depends on density only, not on temperature, and it dominates the normal, ideal gas pressure.

- Whether you have an ideal gas or a degenerate gas depends on both density and temperature.



- So when fusion starts it adds thermal energy and raises temperature, making fusion go even faster. But pressure is hardly changing, so core is not re-expanding and cooling, so fusion accelerates. Runaway fusion. This all takes a few seconds!

- Eventually, temperature so high that ideal gas pressure becomes dominant again, and gas acts like a normal, ideal gas.

- Now the rapidly rising temperature causes pressure to rapidly rise, and core to violently re-expand. Re-expansion of core takes a few hours.

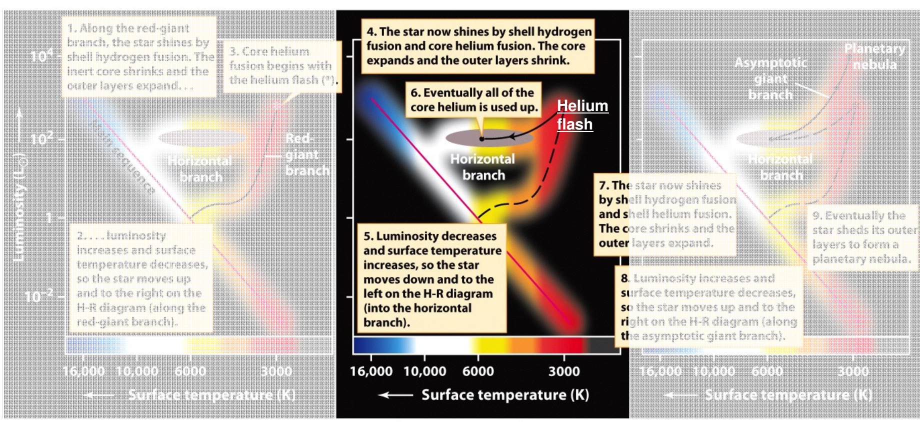
- Note: no flash at surface of star!

2. Expansion of core causes it to cool, and pushes out H-burning shell, which also cools

3. Fusion rate drops. Envelope contracts and luminosity drops

4. Moves onto Horizontal Branch of H-R diagram. Stable core He burning (and shell H burning)

HB lasts about 10^8 years for 1 M☉ star. All HB stars < 3 M☉ have luminosity of almost 100 L☉.

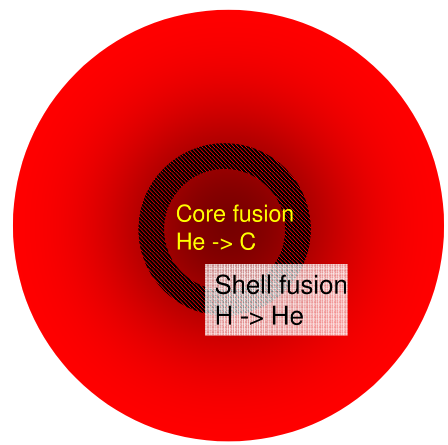


(a) Before the helium flash: A red-giant star

(b) After the helium flash: A horizontal- branch star

(c) After core helium fusion ends: An AGB star

Horizontal-branch star structure (not to scale)



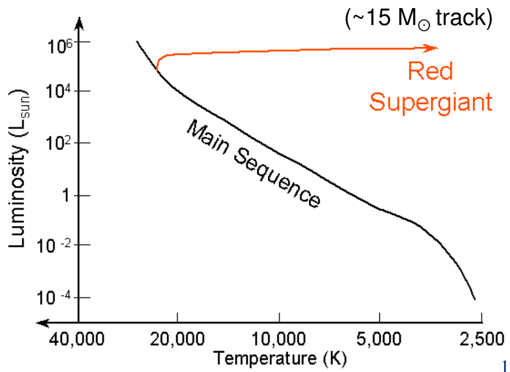
Higher-mass stars: helium burning onset

- In higher mass stars, cores hotter and less dense. He fusion can start before core contracts to such a high density, so never gets degenerate.

=> H burning shell, then steady onset of He burning

- Moves more horizontally across the H-R diagram, especially for stars > 5 $M_\odot$ or so.

- But structure is same, with He -> C,O fusion in core, and H-> He in shell.

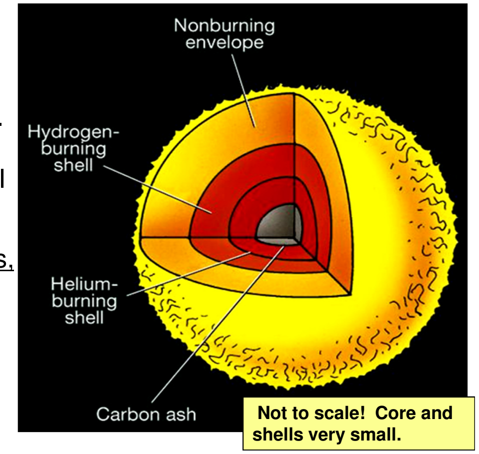


Helium Runs out in Core (Sec 20.1)

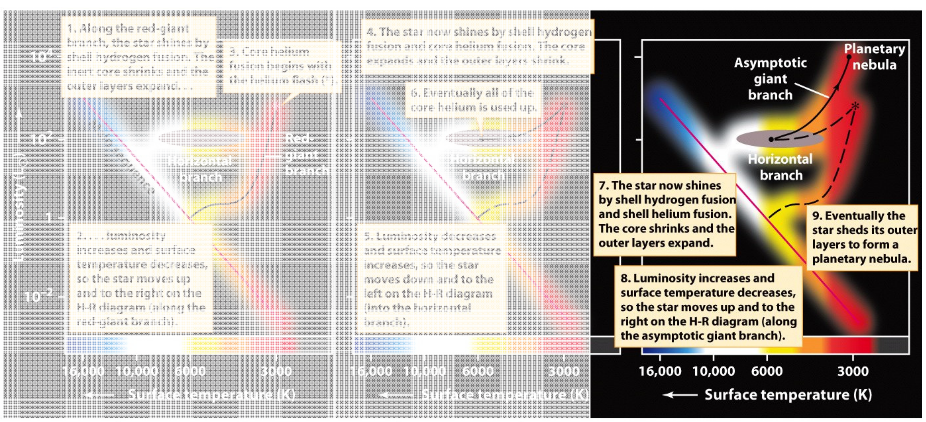
1. All He -> C, O in core. Not hot enough for C, O fusion.
2. Core shrinks (to ~1R_{Earth}), heats up, becomes degenerate again. Shell also contracts and heats up.
3. Get new, intense He-burning shell (inside H-burning shell).
4. <u>High rate of burning, star expands, luminosity way up!</u>
5. H shell also pushed out by He shell fusion, eventually turns off

- Called <u>Asymptotic Giant Branch</u> (AGB) phase.

- Only ~10^6 years for 1 $M_\odot$ star.



AGB star



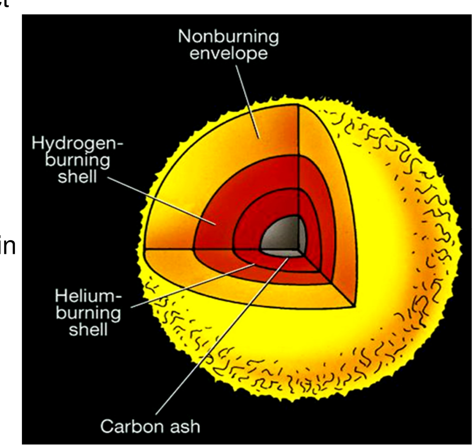
(a) Before the helium flash: A red-giant star

(b) After the helium flash: A horizontal- branch star

(c) After core helium fusion ends: An AGB star

Helium Shell Flashes

1. As He in shell used up, shell contracts, so H shell must contract too and heat up
2. H shell reignites, creating new supply of He. He shell gains mass, shrinks, heats up, becomes “degenerate”.
4. Eventually He shell reignites, but in a flash
5. H shell re-expands, fusion stops
6. Cycle repeats



L and *R* vary on ~10^3 - 10^5 year timescales, depending on mass.

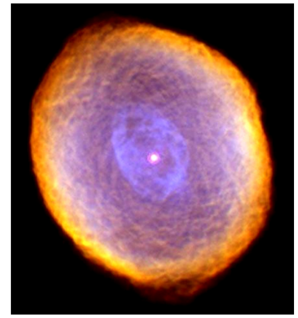
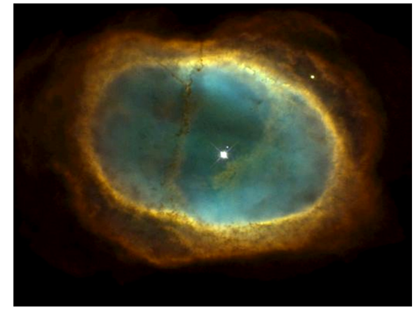
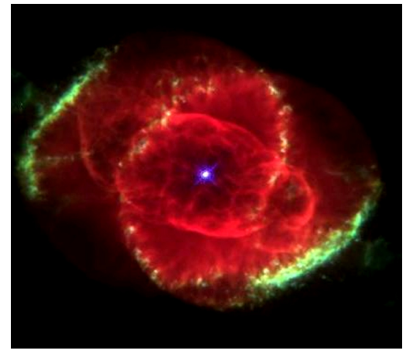
Strong winds

Planetary Nebulae

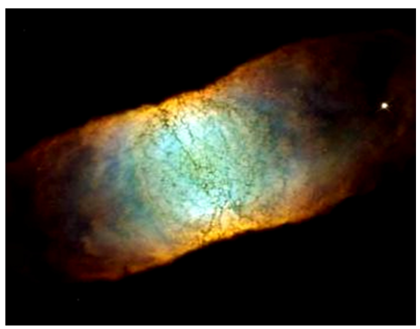
• Pulsations become more violent. Eventually envelope ejected, at speeds of a few 100 km s^{-1}, taking up to 40% of mass

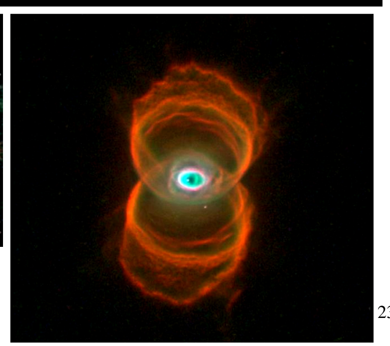
• Envelope eventually visible as a nebula with emission lines

• Remaining C-O core is a White Dwarf

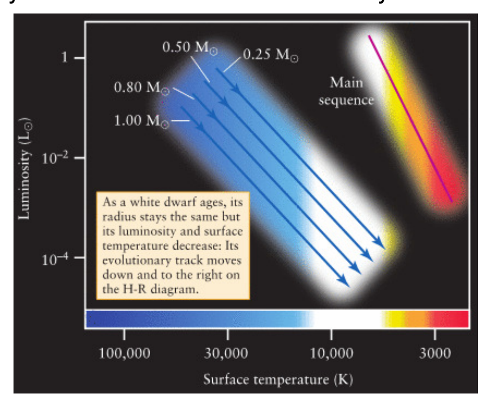






Remnant Core – a White Dwarf

- Mass 0.25 $M_\odot$ – 1.4 $M_\odot$, depending on mass of progenitor star
- Supported by electron degeneracy pressure
- With no further fusion, they cool to oblivion over billions of years
- Radius about 1 $R_\oplus$
- Hence enormous densities, ~ 10^9 kg m^{-3}
- Composition C, O.
- Residual H, He atmosphere seen in spectra of most WDs



How did this understanding come about? Had to connect expectations from physics of stellar interiors with observations, refine thinking, etc.

Powerful test of theory: compare theoretical “evolutionary tracks” on the H-R diagram with real stars – specifically star clusters.