Chapter 20:
Stellar Evolution

Prof. Douglas Laurence

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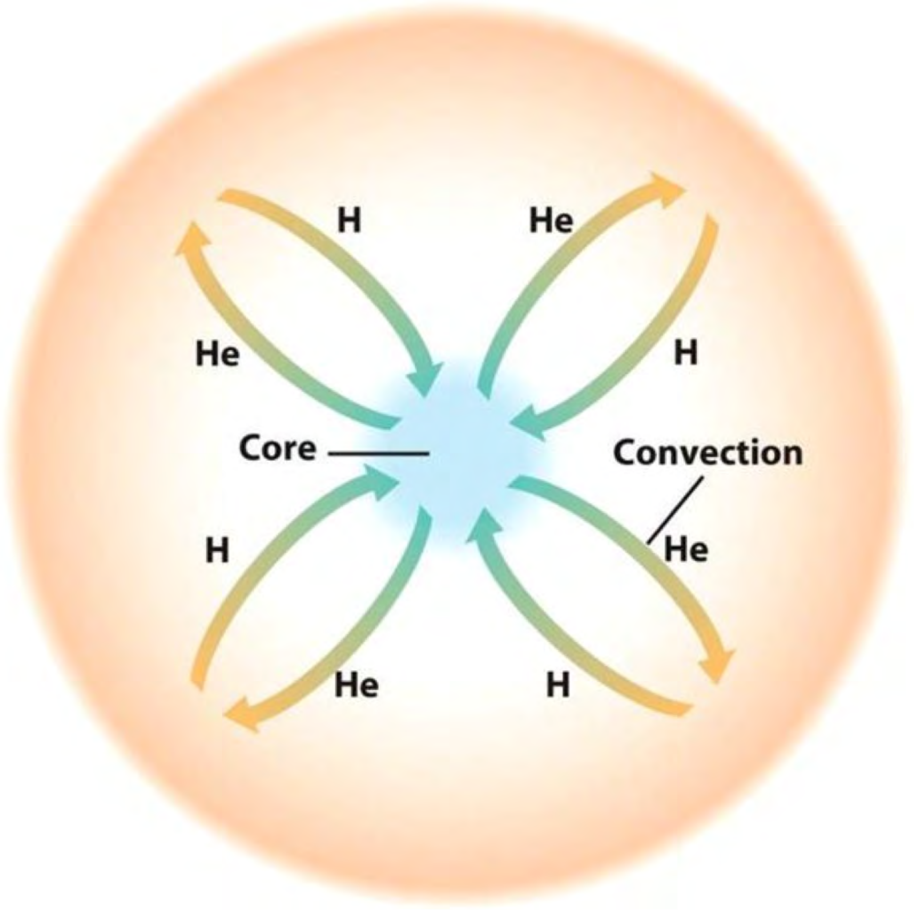
Leaving the Main Sequence

- After a star runs out of hydrogen in its core, it will exit the main sequence.
- What a star does after in its evolution is dramatically different based on its mass.
- We can typically separate stars into two groups: those with a mass less than $0.4M_{\odot}$, and those with a mass greater than $0.4M_{\odot}$.
- Some people say “low mass stars die gently while large mass stars die violently.”

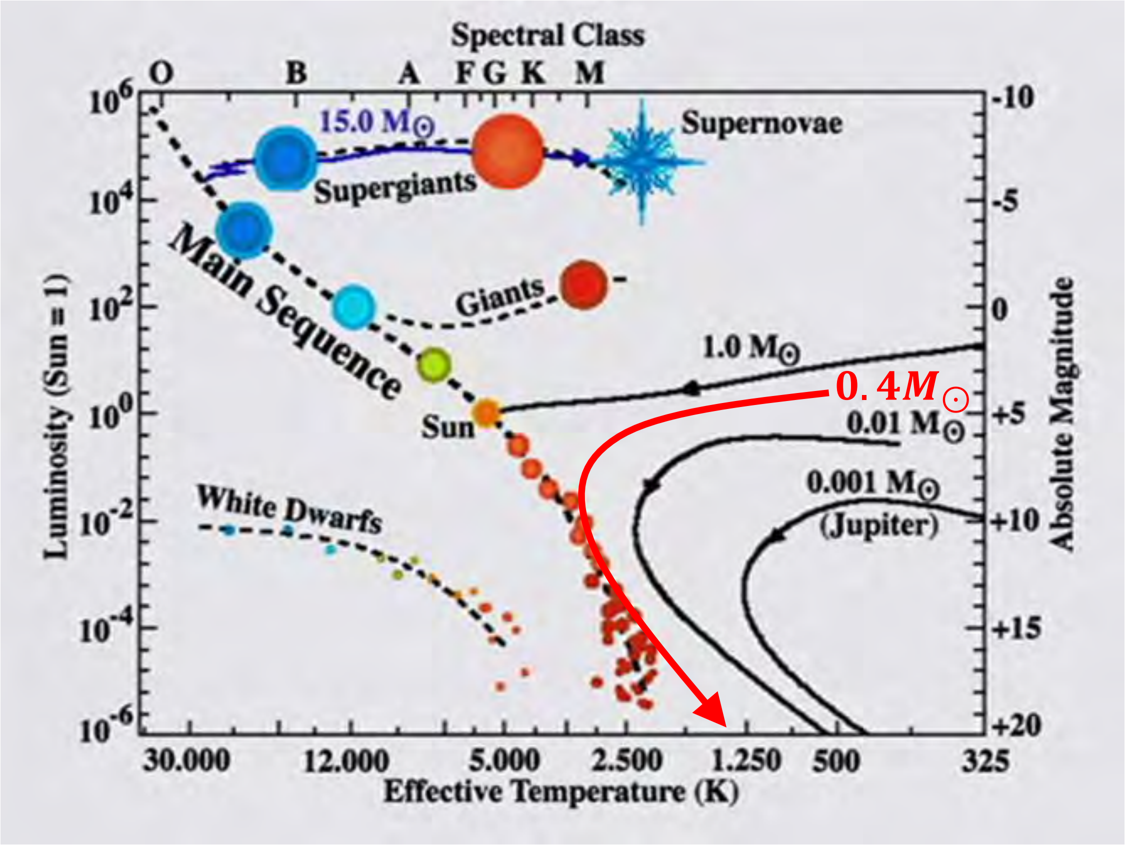
Low Mass Stars (Less Than $0.4M_{\odot}$)

- These stars are all called **red dwarfs**, and behave completely differently than heavier stars like the Sun
- Red dwarfs do not have a radiation zone, they only have a convection zone.
- Convection continuously resupplies hydrogen to the core to burn.



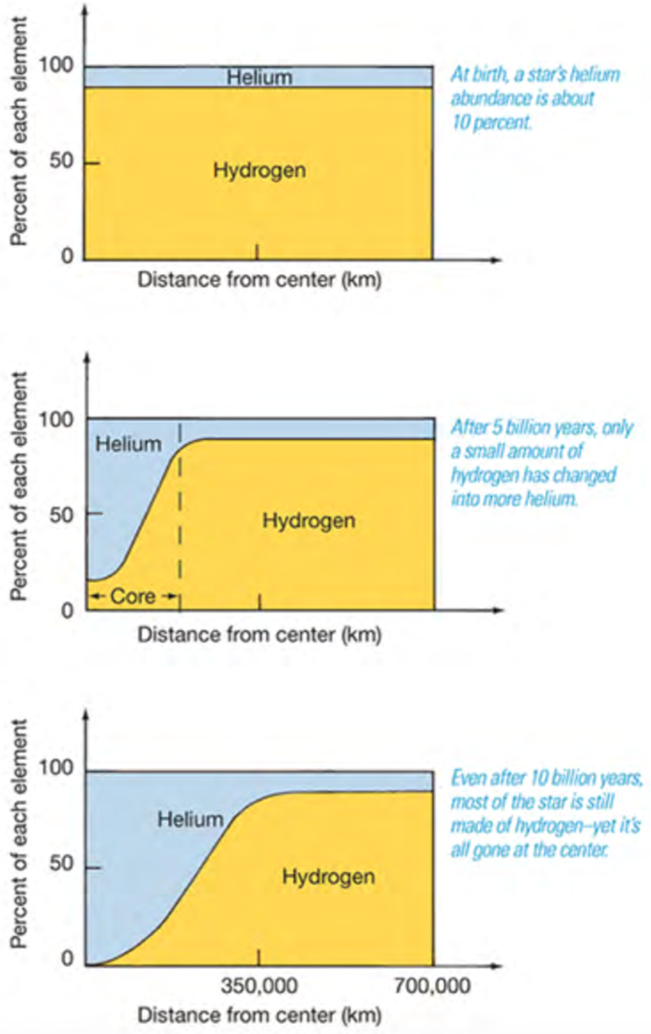
Death of Low Mass Stars

- Eventually, a red dwarf will convert all its mass to helium, and fusion will stop because it can't increase its temperature to burn that helium.
- Slowly, they will radiate their heat, becoming cooler and dimmer.
- Red dwarfs die a "gentle death."



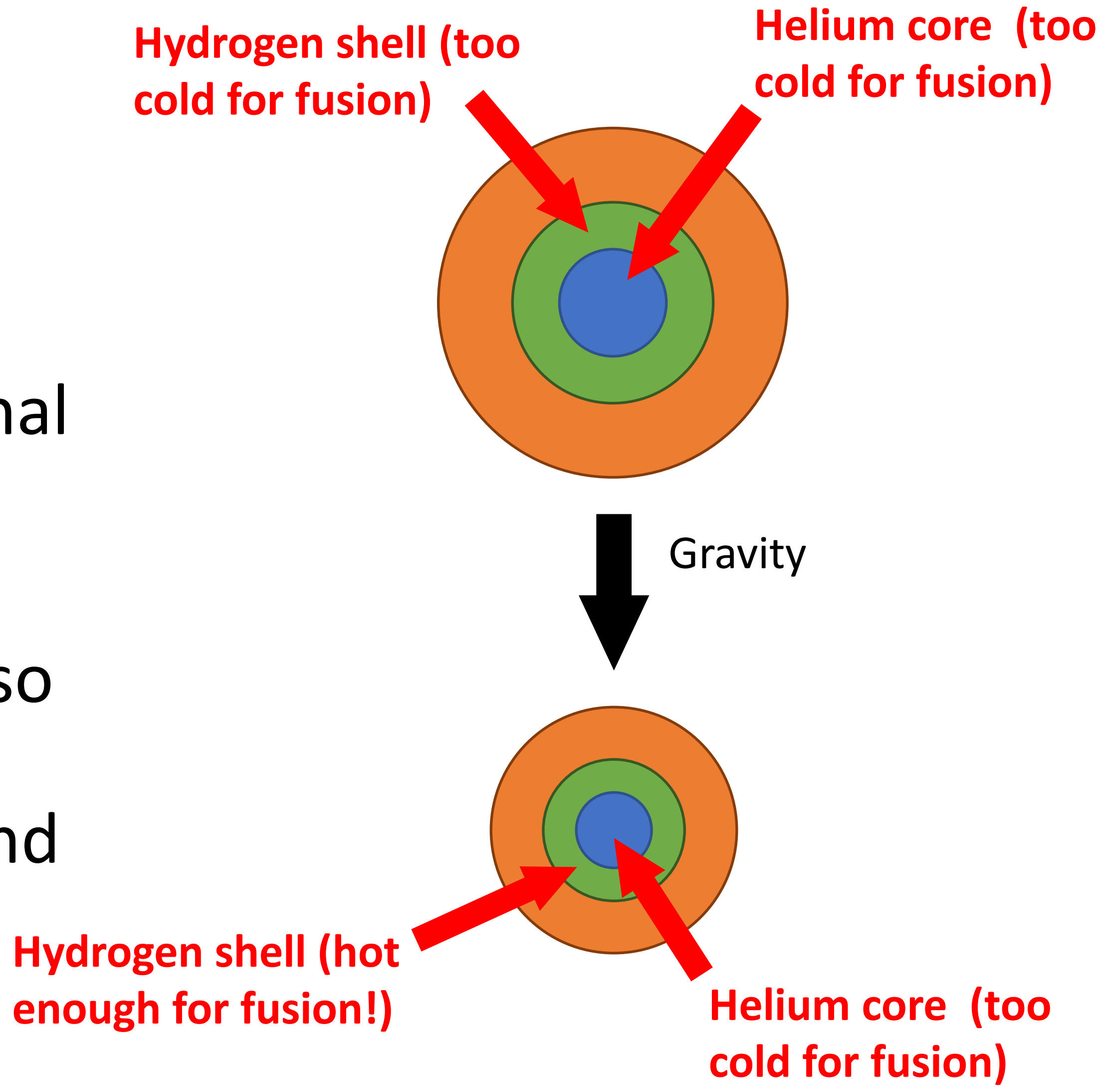
Hydrogen Distribution within a Star

- As hydrogen near the core is converted into helium, the star begins to lose its fuel.
- Because the helium in the core can't move through the radiation zone (there are no currents like in the convection zone), whatever helium is produced is stuck in the core. This is called **helium ash**.
    - This is different for red dwarfs; they have no radiation zone, so the helium from within the core does touch the convection zone, and can be swapped for hydrogen, fueling the core.
- When all hydrogen from near the center is gone, the star must evolve.
    - The goal is to allow the core temperature to rise enough to burn that helium ash that's hanging around.



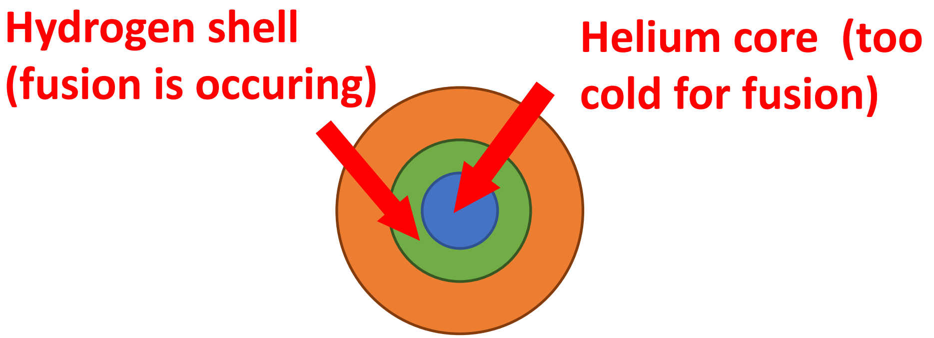
Initial Stage of Red Giant Formation

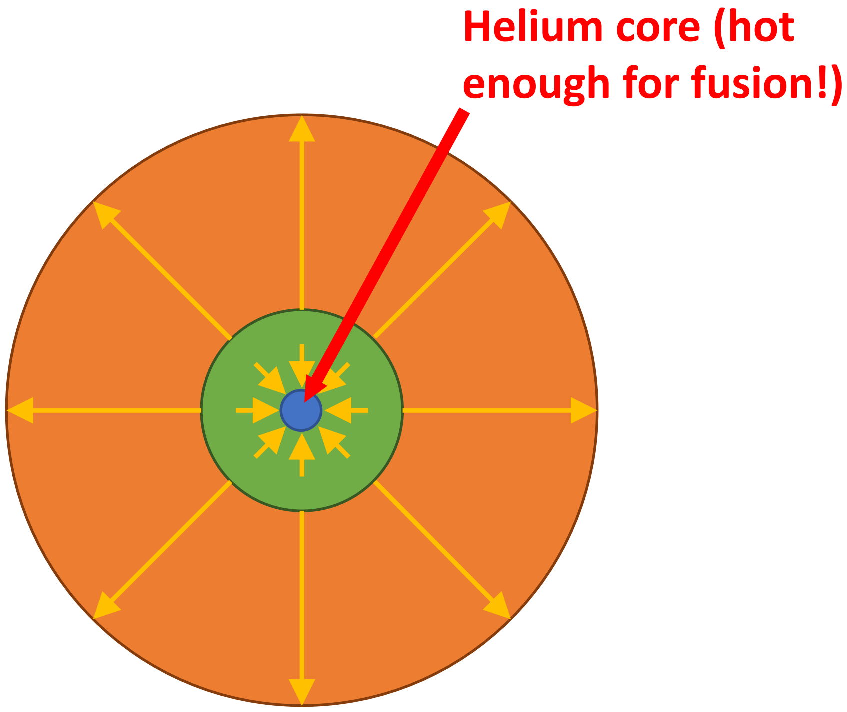
- Large mass stars form **red giants** when they run out of hydrogen.
- When the core is out of hydrogen, thermal pressure drops and gravitational pressure crushes the helium core. No fusion occurs here yet.
- A **hydrogen shell** around the core is also compressed by the gravitational pressure, increasing its temperature and starting fusion in the shell.



Intermediate Stage of Red Giant Formation

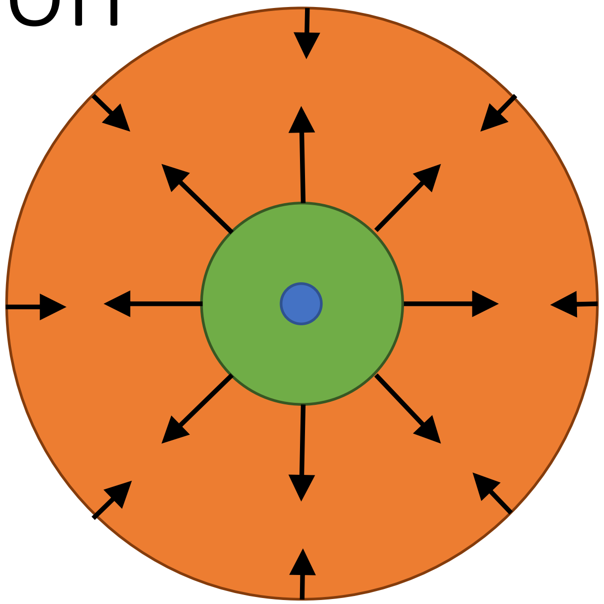
- Outward photons produced by the hydrogen shell have more energy when they reach the outer layers of the star because they travel shorter distances. This expands the star (hence the term “giant”).
- The outward photons from the hydrogen shell also “crush” the helium core, raising the core temperature high enough for helium fusion (T > 100 MK).
  - Further, some helium produced by hydrogen fusion in the shell falls into the core, adding extra helium fuel.

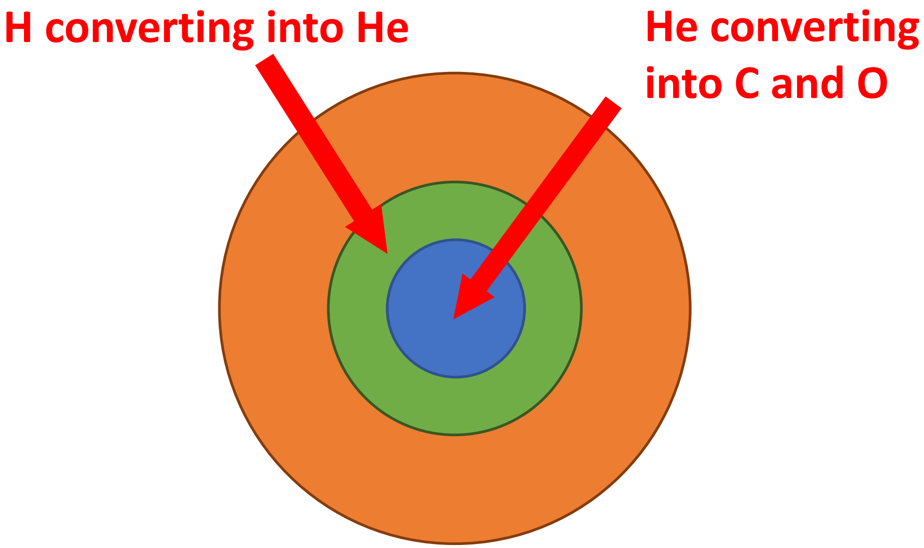




Final Stage of Red Giant Formation

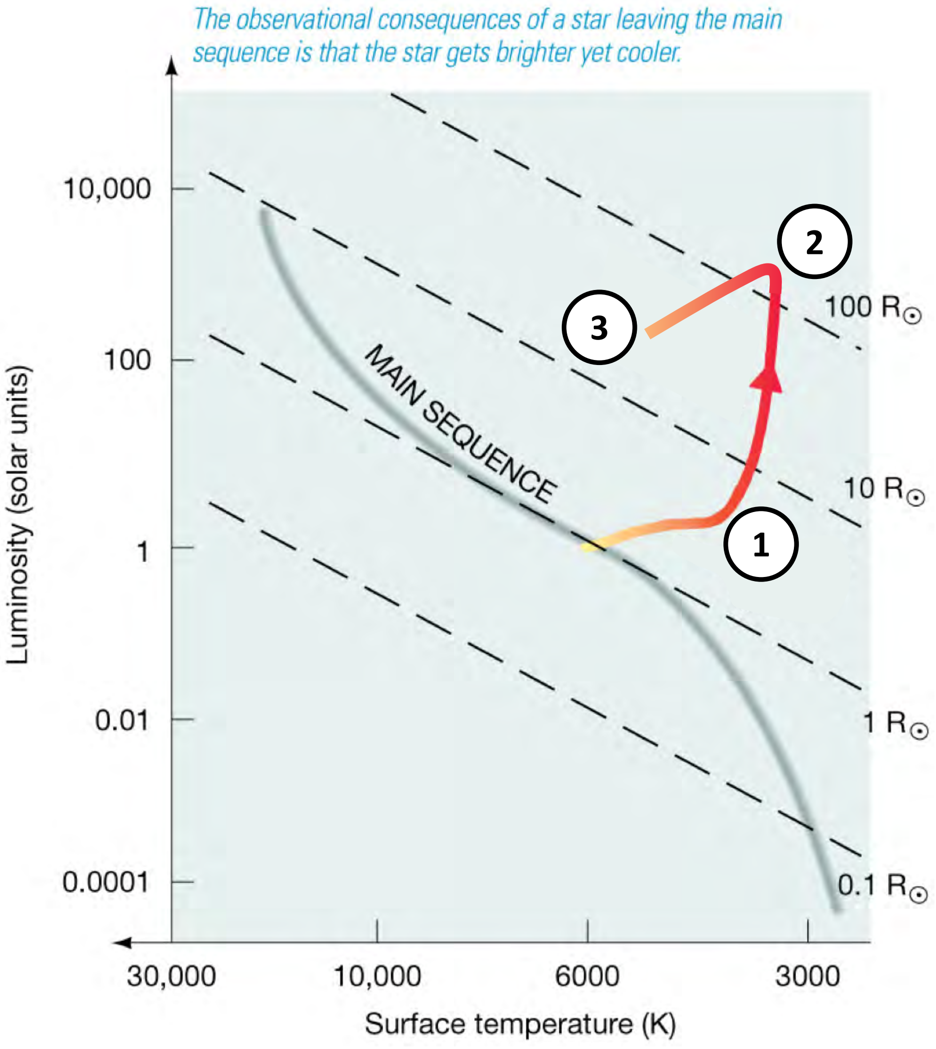
- As helium is burned at the core, the thermal pressure of the core causes it to expand and cool. It also causes the hydrogen shell to expand and cool, as well.
- Since the hydrogen shell is now much cooler than it was in the intermediate stage, it’s outputting a lot less energy, which causes the outer layers of gas to pull back in, reducing the radius. The result is a mature **red giant**, burning helium.





Red Giant Evolution on the HR Diagram

1. **Initial stage**: Fusion in hydrogen shell, no fusion in core. Rapid expansion of star. Increase in luminosity because the larger hydrogen shell can produce more photons.
2. **Intermediate stage**: Start of core helium burning, and decrease in radius.
3. **Final stage**: Final equilibrium state of mature red giant.



Carbon Cores and “Dead” Stars

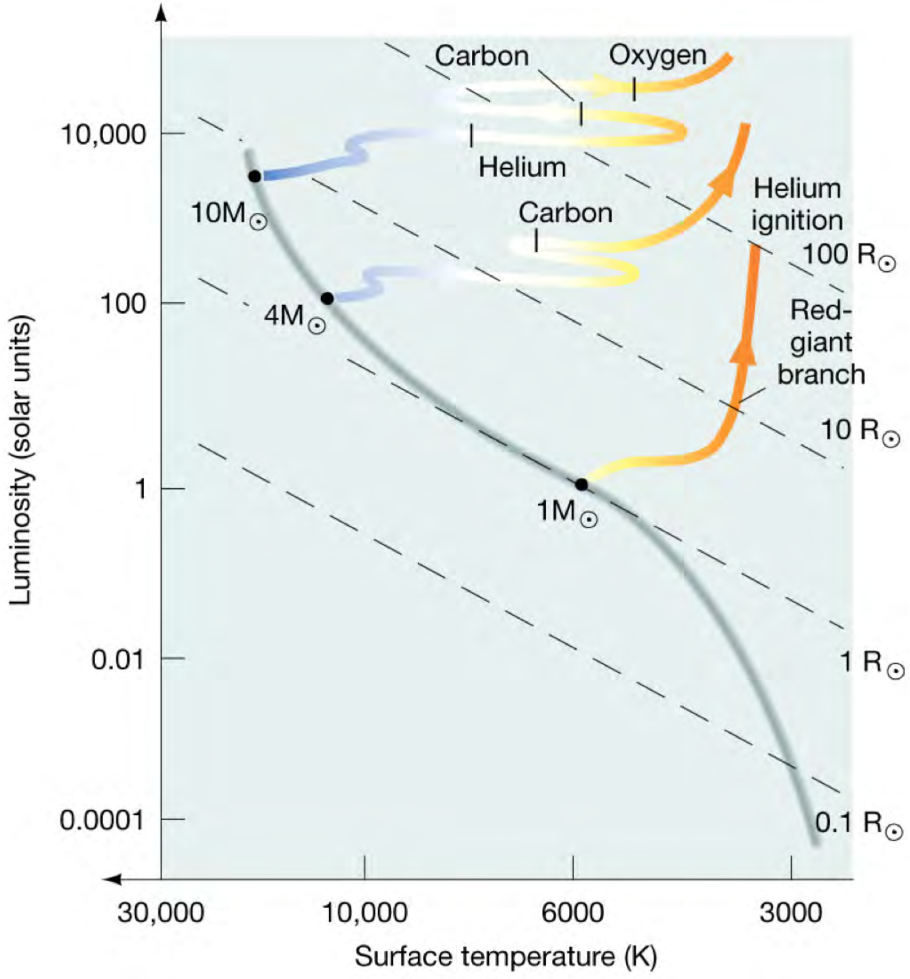
- Helium fusion occurs like (triple-α process):

$$^{4}\mathrm{He} + \ ^{4}\mathrm{He} + \ ^{4}\mathrm{He} \rightarrow \ ^{12}\mathrm{C}$$

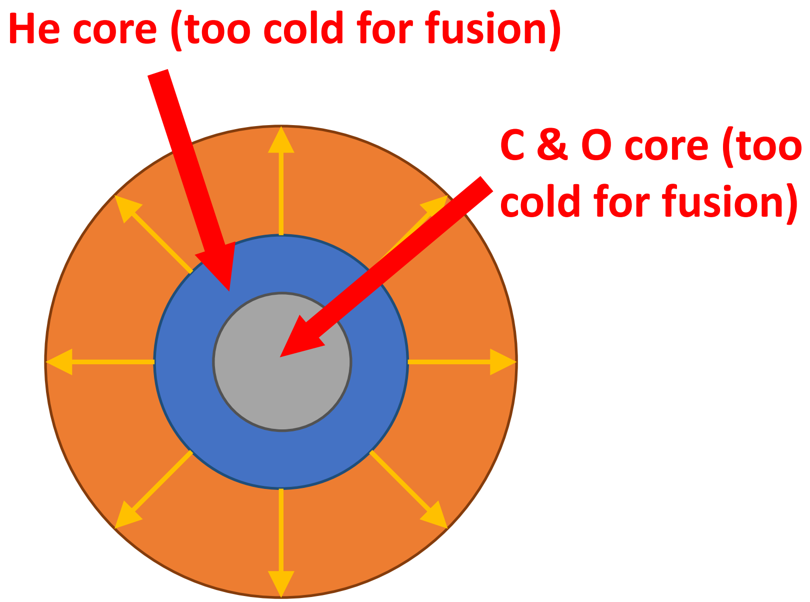
- Some hydrogen can fuse with carbon, to produce oxygen

$$^{12}\mathrm{C} + \ ^{4}\mathrm{He} \rightarrow \ ^{16}\mathrm{O}$$

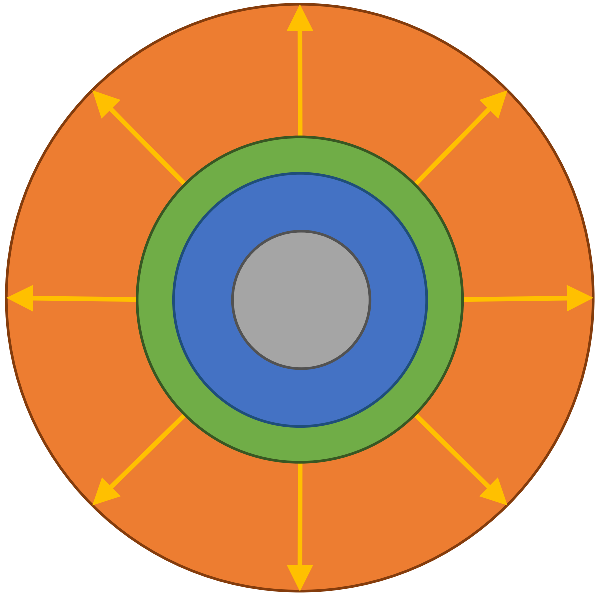
- When some giants reach the “carbon core” or “carbon-oxygen core” stage, they are effectively “dead”. Stars with larger mass can burn C into Si and Si into Fe.



Evolution of Carbon Core Giants



- When the core converts entirely to carbon/oxygen, and becomes inert, fusion moves out to the shell, which is now mainly helium.
- A new hydrogen shell forms around the helium shell, repeating the giant-formation process from before.
  - Since helium burns at a higher temperature than hydrogen, the star once again expands.
  - As the star expands, its surface cools.
- This star is known as a **double-shell giant**.



Stellar Death Begins

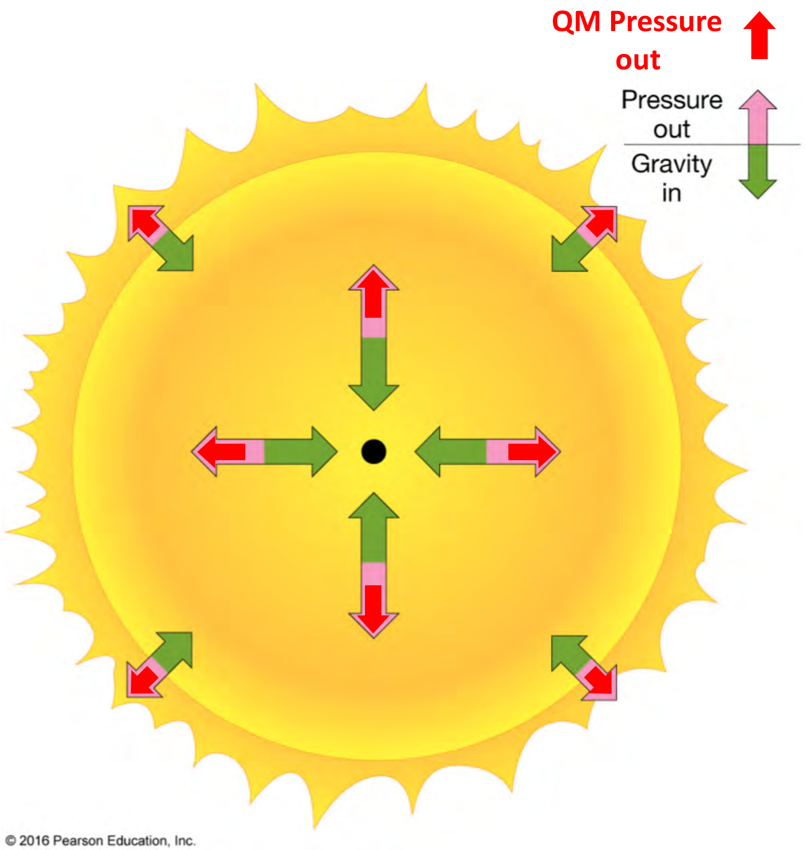
- For each star, since it only has so much mass, it can only compress the core so much. This means that, for a given mass, there is a **maximum temperature** the core can reach.
  - If this maximum temperature is above the silicon burning temperature (> 3 billion K), then the star will keep evolving until it has an inert Fe core.
  - However, if the temperature is less than this, stellar evolution will stop at whatever process the star can produce at its maximum core temperature.
- Once a star's core is full of ash (helium ash, carbon/oxygen ash, nickel ash, whatever element it can't burn), stellar death begins.

Different Routes of Stellar Death

- The resulting object at the end of stellar death is known as the **stellar remnant**. There are three kinds:
  - White dwarves
  - Neutron stars
  - Black holes
- As we discussed earlier, white dwarves come from moderate-mass stars ($< 8M_{\odot}$), neutron stars from large-mass stars ($< 25M_{\odot}$), and black holes from very large-mass stars ($> 25M_{\odot}$).
  - Note that all of these masses are main-sequence masses, not remnant masses!

Quantum Mechanical Pressure

- So far, the two pressures we've discussed for stars include the inward gravitational pressure and the outward thermal pressure.
- There is a third pressure, and outward **quantum mechanical pressure** (QM pressure), which only matters when the core becomes very small.
  - Remember! Quantum effects only rear their heads when things are small.
- There are two quantum mechanical pressures:
  - Electron degeneracy pressure, which occurs in white dwarves.
  - Neutron degeneracy pressure, which occurs in neutron stars.

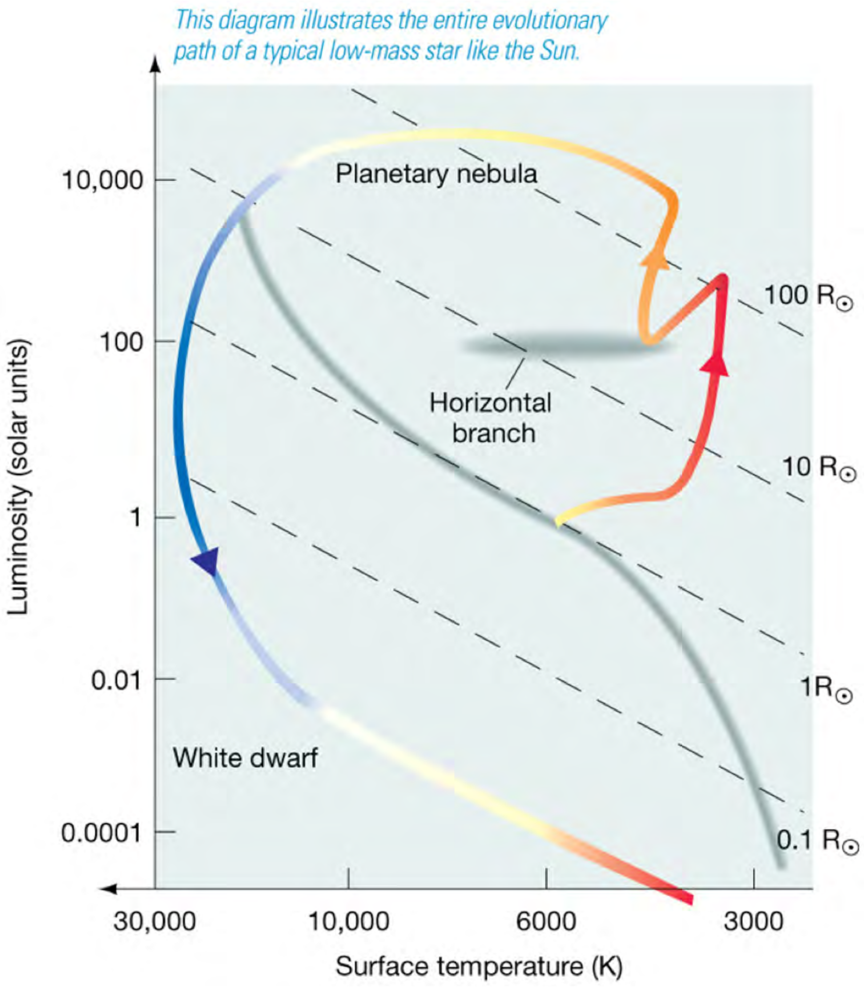


Electron Degeneracy Pressure

- In a white dwarf, the carbon/oxygen core becomes so compact that the electrons in each atom get *very* close to one another.
- Electrons are **fermions**, which resist getting close to one another.
- This resistance produces the electron degeneracy pressure.
- As long as the mass is small enough, the gravitational pressure won't be able to overcome the thermal + electron degeneracy pressure, and the star will reach equilibrium.
  - If the star were more massive, enough to overcome electron degeneracy pressure, it would be able to burn O in its core into Si and continue along the giant phase.

White Dwarfs

- If a star has a moderate mass, less than $8M_\odot$, its outer layers will continue burning hydrogen and helium and just float away. The high temperature of the outer gas, which is still fusing, provides the energy for this process.
- This forms what is known as a **planetary nebula**. The carbon/oxygen core that's left is known as a **white dwarf**.



Ten percent or more of a complete stellar inventory consists of white dwarfs, just sitting there, radiating away the thermal (kinetic) energy of their carbon and oxygen nuclei from underneath very thin skins of hydrogen and helium. They will continue this uneventful course until the universe recontracts, their baryons decay, or they collapse to black holes by barrier penetration. (Likely time scales for these three outcomes are 10^{14}, 10^{33}, and $10^{10^{76}}$—years for the first two and for the third one it doesn't matter.)

—Virginia Trimble, *SLAC Beam Line* **21**, 3 (fall, 1991).

Neutron Degeneracy Pressure

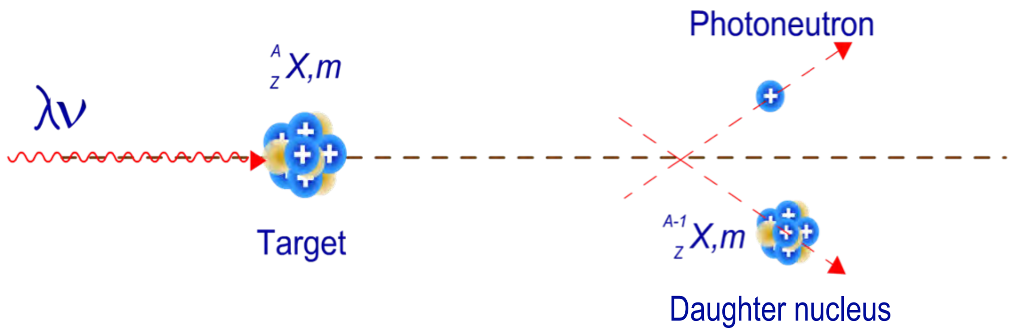
- For a star whose mass is greater than $8M_{\odot}$, core burning of O and Si will occur, and the core will burn until it's composed of Fe ash. These stars will become neutron stars.
  - Except if their mass is greater than $25M_{\odot}$; then they become black holes.
- There is so much gravitational pressure, the usual electron degeneracy pressure is overcome. This starts smashing electrons into protons, which undergo* "inverse" beta decay to produce neutrons.
- Neutrons, like electrons, are fermions, and so exert a force on one another. This produces the neutron degeneracy pressure.

*This is a very simplified view. See next slide for more technical details.

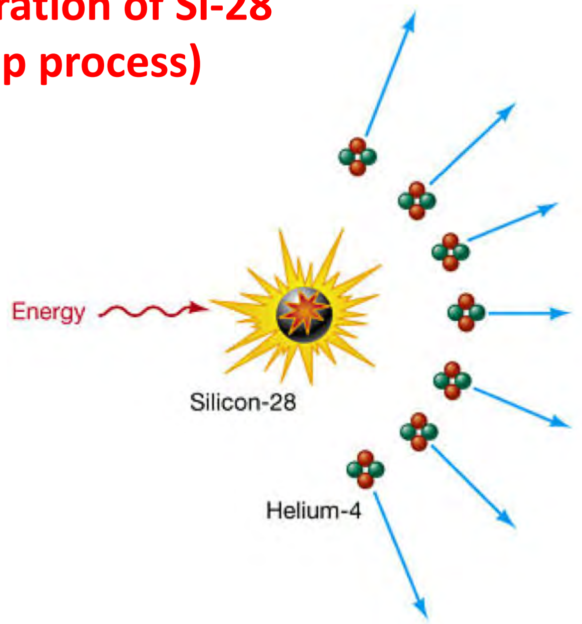
Photodisintegration

- The massive gravitational pressure, due to the large mass of the star, causes temperatures to skyrocket, leading to photodisintegration.
- **Photodisintegration** occurs when a nucleus absorbs a very high energy photon and kicks out a proton, neutron, or α particle.
  - Starting with a heavy nucleus, photodisintegration will eventually lead to the disintegration of *all* nuclei into basic components such as protons, neutrons, electrons, and α particles.

General photodisintegration process

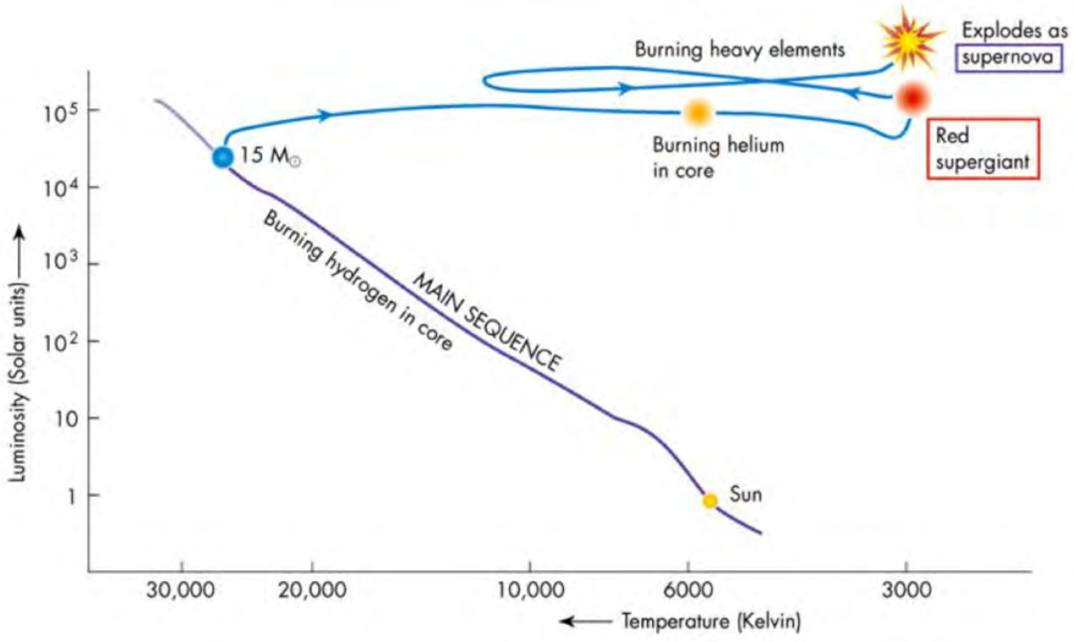


Photodisintegration of Si-28
(a multistep process)



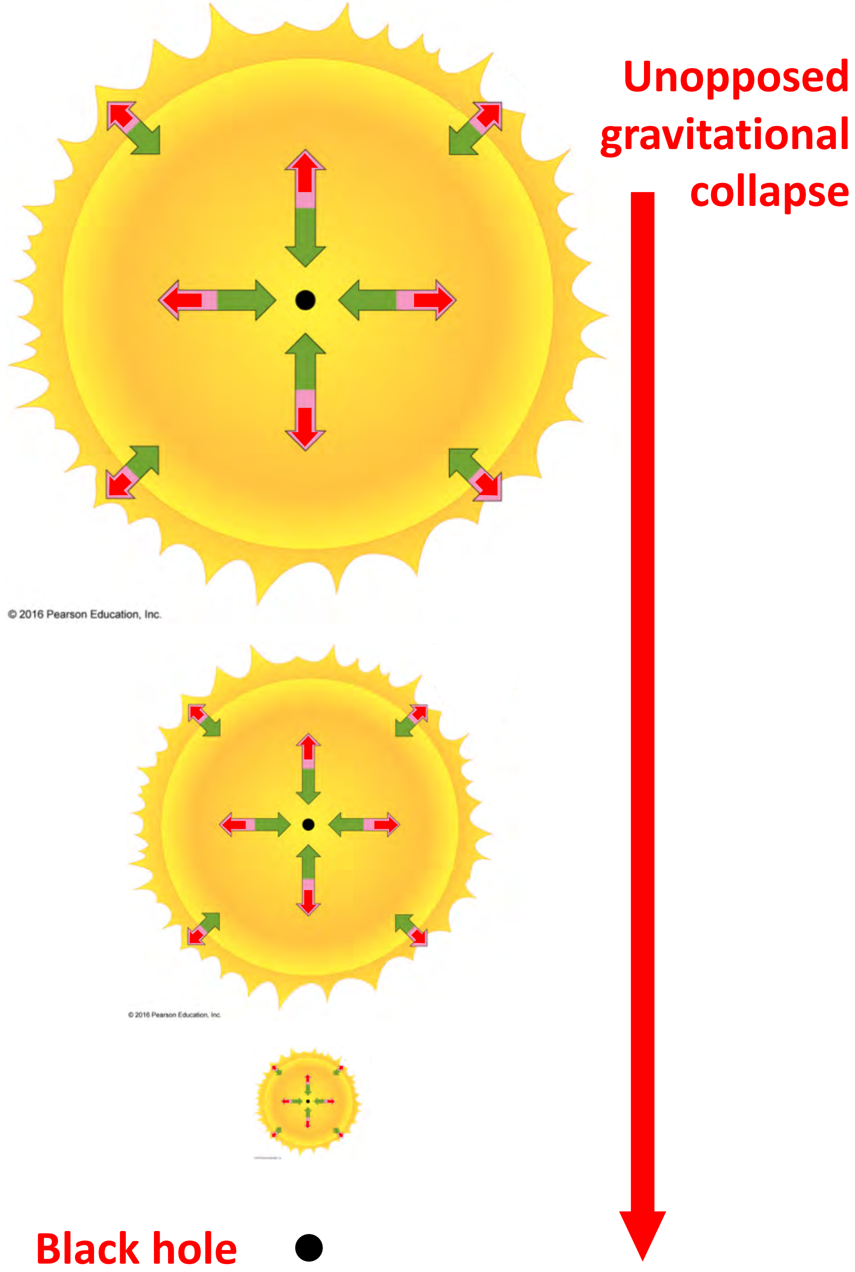
Neutron Stars

- If a star has a large mass, greater than $8M_{\odot}$ but less than $25M_{\odot}$, it will collapse into a spherical mass of densely packed neutrons.
  - All heavy nuclei in the core photodisintegrate into neutrons.
  - What remains, if the mass isn't too large, balances the gravitational pressure with neutron degeneracy pressure, and is known as a **neutron star.**



(A First Look at) Black Holes

- Like electron degeneracy pressure, neutron degeneracy pressure can only get so large. What if a star is so massive that its inward gravitational pressure is more than the neutron degeneracy pressure?
  - In quantum mechanics, the **only** QM pressures are electron degeneracy and neutron degeneracy; there are no more after that.
  - This means that gravitational collapse is "unopposed" – no outward pressure can overcome the inward gravitational pressure, and the core collapses forever. What's left is a **black hole**.



Alternatives to White Dwarfs