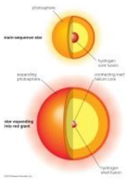
Stellar Evolution 2: The Deaths of Stars

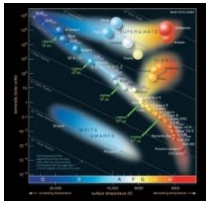
- **A star, regardless of its mass, will stay on the Main Sequence until:**
  It runs out of Hydrogen in the core. Remember the energy provided by H to He fusion provides the pressure to balance gravity.

- **After running out of hydrogen, several different things happen at once:**



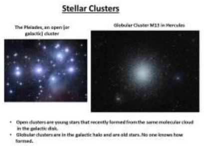
1. The “non-burning” He **core contracts under gravity and heats**.
2. The additional heat from the contracting He core ignites a H → He fusion shell above the core.
3. Due to the higher temperature, the shell fusion produces more energy than main sequence core fusion. This causes the **outer “non-burning” H shell to expand and cool**, and the star becomes a **Giant or Supergiant.**

- **Where are Giants and Supergiants on the HR Diagram? (LC)**
  Since it expands, the <u>surface</u> temperature drops (that’s why some of them are red) and for Giants, the luminosity increases since the surface area increases. So the star “moves” to the upper right.



Stellar Clusters: Evidence for Stellar Evolution

Stellar Clusters are large groups of stars bound by gravity.
To a good approximation:

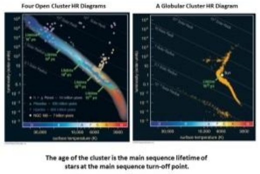


1. All of the stars in the cluster are at about the same distance from the Earth. (So differences in apparent brightness are the same as differences in Luminosity).

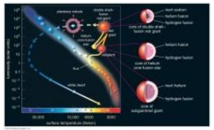
2. All of the stars in the cluster began to form at about the same time from the same material – *like what's going on in the Orion Nebula now – remember the simulations that we saw last class?*

This means that we should be able to predict how a cluster's HR diagram will change over time.
There's a small error in this animation; what is it? (LC)
The high-mass hot stars would evolve off the MS long before the low-mass cool stars even got to the MS – see diagram for the Pleiades.

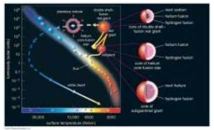
This is what we see as snapshots of HR diagrams for real clusters.



Stellar Deaths of Low Mass Stars ($M < 2M_{sun}$)



- When a lightweight star leaves the main sequence and first expands as a giant, it has a "non-burning" He core that is contracting.
- As the core contracts and heats, it reaches He fusion conditions suddenly in a "Helium Flash".
- With He fusion in the core and H fusion in a shell, the outer layers actually contract and the star moves back toward the main sequence.
- As a "non-burning" Carbon core builds up, contracts, and heats, the He fusion continues in a shell and H fusion in a shell above that. The star begins to expand and moves up the giant branch again.
- **The Carbon core contracts and heats, but never gets sufficiently hot for the Carbon to fuse into anything heavier; so fusion stops in the core.**
- As the star expands, the extreme outer layers are loosely held by gravity, and the strong stellar wind ejects them as a **"Planetary Nebula."**
- The hot Carbon core is left behind and is called a **"White Dwarf".**



Stellar Deaths of Low Mass Stars $(M < 2M_{sun})$

- The gas in the planetary nebula speeds away from the white dwarf, but the dwarf is so hot, it emits UV which ionizes the gas and makes it glow. As the gas disperses and the dwarf cools, planetary nebula fade – they can last for 10s of thousands of years.

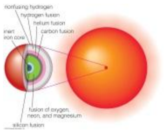
- The White Dwarf that is the core of the star remains. **It is an object with mass about that of the Sun, but the size of the Earth**. Initially, it is very hot, but not very luminous because it is so small. Since no fusion is going on, it just cools and fades. (*We'll talk more about white dwarfs in a the next class.)*

- **This, of course, is the fate of our Sun in about 5 billion years.** **What will happen to the Earth? An important question, since we've grown somewhat attached to it?**
    - As the Sun expands, it's increasing luminosity will blast away the Earth's atmosphere and oceans.
    - The Earth may be consumed by the Sun. If not, it's fate will be to orbit a cooling and fading white dwarf.

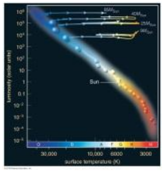
Stellar Deaths of High Mass Stars ($M > 8M_{sun}$)

- We've already seen that the main sequence lifetime of a high mass star is very short compared to low mass stars.
- One reason for this is that the CNO hydrogen fusion cycle dominates in the core of these stars.

- **Unlike low mass stars, the temperature in the cores of high mass star are high enough for Helium fusion to begin immediately, and keep on going to heavier and heavier nuclei.**
- The resulting interior of a fully evolved high mass star is like – *well, let Shrek tell us.*



- Ultimately, at the bottom of these onion layers of fusion, an iron core is formed at the center of the star.
- On an HR diagram, each time a new fusion reaction begins the star moves back and forth horizontally.

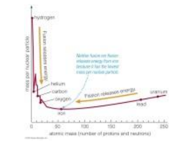


- One important fact left out of these figures is that each fusion sequence proceeds more rapidly than the previous one. **For example, the iron core is formed from silicon fusion in just a few days!**
- **Once the iron core forms, the star has only hours to live.**

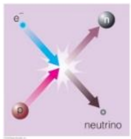
Stellar Deaths of High Mass Stars ($M > 8M_{sun}$)

- **Why does fusion stop at Iron? (LC)**

  Remember the Iron nucleus is the most stable nucleus. Fusion reactions beyond Iron are possible, but they are energy absorbing, not energy releasing.



- As the iron core contracts under gravity, it heats and produces photons energetic enough to tear apart the iron nuclei (photodisintegration). This absorbs energy, and the pressure drops so that nothing is holding the star up. In a few fractions of a second, the core collapses inward.
- As the core collapses, the pressure gets sufficiently high that electrons and protons merge to form neutrons + neutrinos.



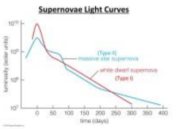
- **Although, it's still a mystery, there are two proposed ways that the material above the neutron core can be blasted away into space in what we call a Massive Star (or Type II) Supernova:**
  1. The neutron core collapses to nuclear densities (~10^{15} g/cm^3) and rebounds. The resulting shock waves from the rebound are energetic enough to blow the rest of the star apart.
  2. There are enough energetic neutrinos to produce shock waves that destroy the outer layers.

SN Demo

It may be that both of these processes are important – or something else that we haven't imagined. ***In any case, you get one hell of an explosion!***

<u>Stellar Deaths of High Mass Stars</u> (M > $8M_{sun}$)

- **How energetic are Massive Star or Type II Supernovae explosions?**



  - For a few weeks, the supernova can have a luminosity of almost 10^{10} L_{sun}. (*i.e. it emits as much energy in these few weeks as the Sun does in its entire 10 billion year life!*)
  - Some say that a supernova can briefly "outshine an entire galaxy."

- **Have we observed supernovae in our galaxy?**

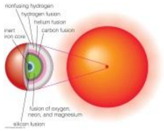
  - In 1054 AD, Chinese astronomers tell of a "guest star" that appeared in Taurus for a few weeks. Today, we see a supernova remnant there, The Crab Nebula.
  - Tycho Brahe saw a supernova in 1572, as did Kepler in 1604.
  - The nearest supernova since then was in the Large Magellanic Cloud (a satellite galaxy of the Milky Way) in 1987 (only visible in the southern hemisphere). But neutrinos were detected!

We do observe scores of supernovae every year in other galaxies.

Stellar Deaths of High Mass Stars ($M > 8M_{sun}$)

What is the human and cosmic significance of Supernovae?

- Remember that high mass stars create elements up to Iron, but nothing heavier. But we have elements beyond Iron on Earth – **where did they come from?**
- Remember the onion layers at the center of the star. When the core collapses and explodes, there's available energy in the explosion to fuse the Carbon, Oxygen, Silicon, etc. into nuclei heavier than Iron and spew the debris into space.



- The nuclei of the atoms that make up you, me, and everything else on Earth literally came out of a Supernova. **As was famously said:**

"We are made of Star Stuff" (LC) **who said this?**

Will there be a naked eye visible supernova in the foreseeable future?

- Maybe, **Betelgeuse** is a red supergiant in the last stages of its evolution and could explode at any time, maybe tomorrow, maybe in a few thousand years.

Some say that the Betelgeuse SN might be about 10X brighter than the full moon!