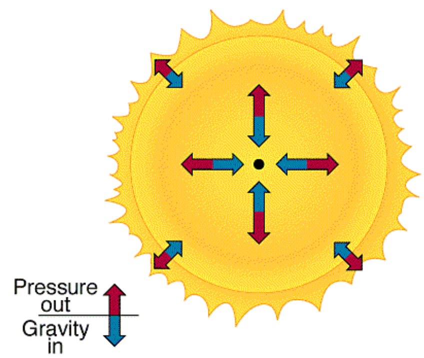
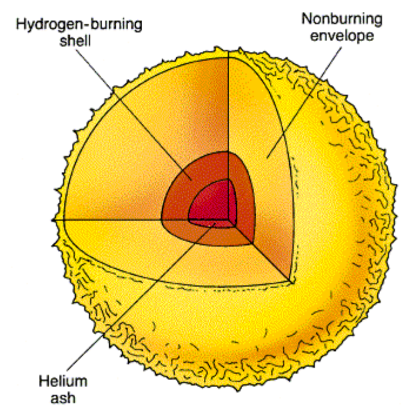
Chapter 12
Stellar Evolution
The Lives and Deaths of Stars

12.1 Leaving the Main Sequence

- Stars and the Scientific Method
  - Nobody has ever witnessed the entire evolution of any star from birth to death.
    - Many of them last for millions, billions, or even trillions of years
  - We can observe billions of different stars in the universe
    - Each of those stars are at different stages of their lives
    - We can use all the different stages to piece together what the normal evolution is
  - The modern theory of the evolution of stars is an example of the scientific method in action
    - As we collect more and more data, the theory is tweaked to account for the data
    - This gives us a very good idea as to the process any particular star will follow
- Structural Change
  - Hydrogen Core Burning is the process of slowly burning hydrogen into helium in its core
    - Remember the "burning" is nuclear fusion, not the chemical reaction of burning
  - The outward pressure of the heat of fusion balances the inward gravitational pressure of the star
    - Small change in one will cause a change in the other
      - If the temperature in the core goes down, the gravity will push inward making the star smaller, causing the temperature in the core to increase until balanced
      - If the temperature in the core goes up, the outward push will expand the star, cooling it until they are balanced again
  - As the H is consumed, the balance of the forces begins to shift
    - The structure and the appearance of the star will change
    - The star leaves the main sequence on H-R Diagram
    - This is the beginning of the death of the star
      - High Mass stars die catastrophically
      - Low Mass stars die gently



Hydrostatic Equilibrium

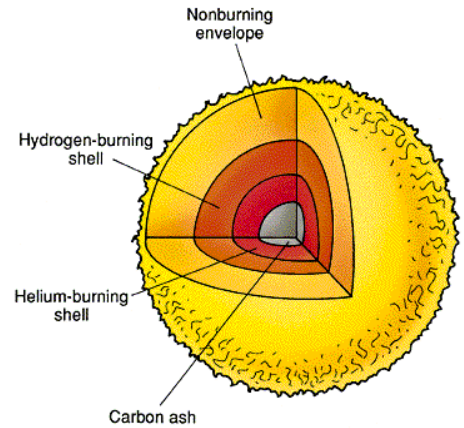


Stage 8-9 Star – Hydrogen Shell Surrounding Helium Ash Core

12.2 Evolution of a Sun-Like Star

- Stages 8 and 9 – Subgiant to Red Giant
  - Hydrogen needs 10^7 K to overcome the electrostatic repulsion of their protons
  - Helium contains more protons, so it requires a much higher temperature to fuse its nuclei together
  - As hydrogen starts to run out, the core builds up with Helium and fusion moves away from the core's center
    - Without as much fusion occurring, the outward pressure starts to weaken and the core will start to shrink due to its steady gravitational pull
  - As the core shrinks, it releases gravitational energy, making the overlying layers of the core hotter, which makes the hydrogen fuse faster than before
    - Hydrogen Shell Burning is the state in which hydrogen is burning at a furious rate in a thin layer surrounding the nonburning inner core of "helium ash"
      - This causes the amount of heat produced to go up, meaning that as the star runs out of hydrogen, it will actually get hotter!
  - The nonburning outer layers of the sun will expand due to the increase in heat making the star swell and leave the main sequence and is about 3 times bigger
    - The Subgiant Branch is the horizontal track off the main sequence to stage 8
  - As the hydrogen fusion moves further out in the core, the nonburning outer layers continue to expand more quickly, taking the star to about 21 times its original size
    - The Red Giant Branch is the vertical track up the H-R Diagram to stage 9
      - It now emits 160 times the energy it did while in the main sequence

- Stage 10 – Helium Fusion
    - The contraction of the inner core and the expansion of the envelope (nonburning layers) cannot continue forever and only goes on for a few hundred million years
        - Once it reaches 10^8 K, fusion of helium can begin
        - When the fusion begins, the core changes drastically
    - A Helium Flash is the violent result of the core's conditions changing within it
        - The Helium ignition expands the core rapidly, making the density go down and the balance of outward pressure comes back to balance with the inward gravitational pressure
        - Temperatures go well above the 10^8 K and helium begins to fuse into carbon
        - The flash stops the climb up the vertical red giant branch and drops the star down and left on the H-R Diagram which results in a drop in luminosity as the star shrinks back down to a smaller size
            - This process takes about 100,000 years (very short time for stars)
    - The Horizontal Branch is the region on the H-R Diagram that stage 10 stars lie on
        - Depending on the mass and size of the red giant, it can lose a lot of its mass before coming down to the horizontal branch
            - Stars with high mass left over will lie on the right side of the branch
            - Stars with low mass left over will lie on the left side of the branch

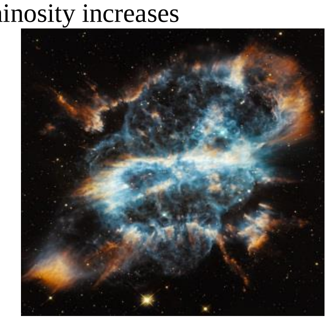


Stage 10 Star – Helium Fusing Into Carbon in the Core

- Stage 11 – A Red Giant Again
    - Just as it did on its way to stage 9, the stars inner carbon core continues to shrink and become more dense, pushing the hydrogen and helium fusion further out in the core making the star expand once again to a red giant
        - The Asymptotic Giant Branch is the the 2nd vertical branch a star takes as it leaves the horizontal branch as the carbon ash core continues to get dense
            - The star is much larger and more luminous than it was in the 1st red giant stage

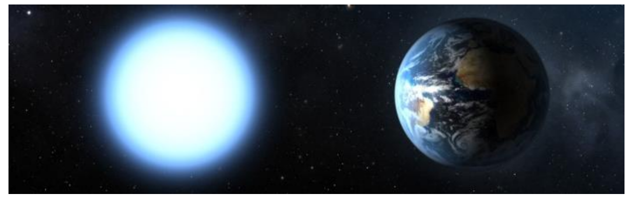
12.3 The Death of a Low-Mass Star

- Stage 12 – A Planetary Nebula
    - Stars the size of our Sun do not have enough mass to fuse elements larger than carbon
    - Stage 12 – A Planetary Nebula
        - The hydrogen and helium burning shells consume fuel at increasing rates as the star ages
        - As it expands, cools, and then reascends the giant branch the star begins to fall apart
        - The radiation from within causes the gas to drift away into interstellar space
            - Starts off slowly at first, but then more rapidly as the core luminosity increases
                - It loses its entire envelope in about a million years
        - It now contains two distinct parts
            - The exposed, very hot, very luminous core
            - A cloud of dust and cool gas that is expanding away
        - As the core exhaust its last remaining fuel, it contracts and heats up moving to the left in the H-R Diagram
            - Eventually it becomes so hot that its UV radiation ionizes the inner parts of the surrounding cloud creating a spectacular display known as a Planetary Nebula
                - Only called this because they looked like the planetary disks in our solar system when observed in the 19th century
                - Nebulae have many different shapes and there is nothing we know of that can predict the shape a nebula will form as it evaporate
            - The temperature will allow the carbon core to fuse in small amounts with the helium to form some heavier elements, but in very low numbers
                - The carbon-rich dust of interstellar medium comes from these nebulae



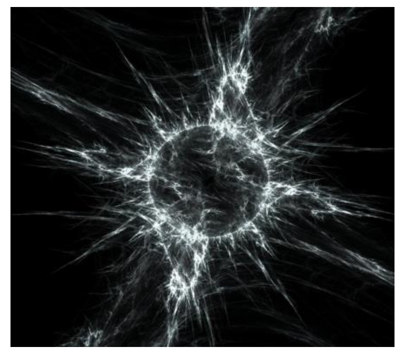
Planetary Nebula

- Dense Matter
  - Before the shrinking core can get hot enough for carbon to fuse the rising pressure stops it and stabilizing the pressure not by the same process as the other stages, but because the core now contains a vast sea of free electrons that have been stripped from all the atoms du e to the heat
  - It's density is about 10^{10} kg/m^3, one cubic centimeter would weigh 100 kg on Earth
    - The Pauli Exclusion Principle does not allow the electrons in the core to be crushed any closer together, which makes it reach equilibrium
      - This temperature is about 300 million K, which is not hot enough to fuse carbon into any of the heavier elements
      - The electron density stops the core from contracting as there is not enough gravitational force to overcome them



White Dwarf

- Stage 13 – A White Dwarf
  - The carbon core is now shining by its stored heat as all nuclear fusion has come to a stop
  - It appears as a bright white-hot surface
  - The path is a large sweeping arc around the main sequence on the H-R Diagram going from red giant around to the white dwarf region of the chart
  - The white dwarf will radiate its heat into space until it runs out
  - Stage 14
    - The white dwarf will travel diagonally down its solar mass line as it cools and will change color from white, to yellow, to orange, to red, then it will not have enough heat to radiate visible light and will become dark
      - A Black Dwarf is a cold, dense, burned-out white dwarf in space



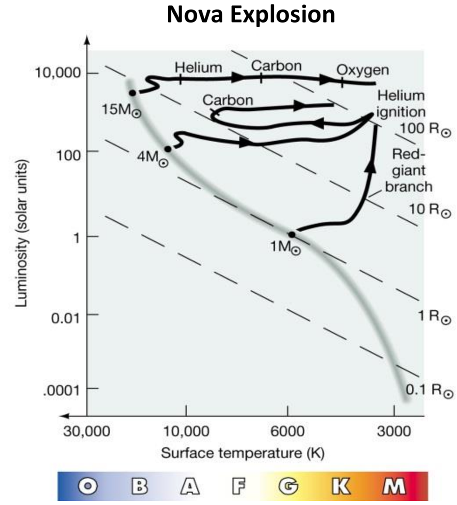
Black Dwarf

- Novae
  - If the white dwarf is part of a binary system and is close enough to the other star in the system, it will gravitationally pull in hydrogen and helium from the companion star
    - The gas swirls around the white dwarf being accelerated by the gravity of the white dwarf as it gets closer and closer, which is known as an Accretion Disk
    - As the gas gets to 10^7 degrees it will ignite and fuse into helium creating a burst of energy released over a short time seen from Earth as a Nova
      - This can happen several times as the process of pulling in gas can start again after a nova explosion

White Dwarf, Accretion Disk, and Nova Explosion

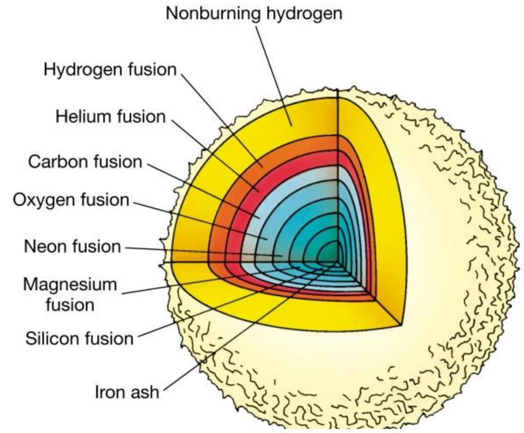
12.4 Evolution of Stars More Massive than the Sun

- Formation of the Heavy Elements
  - Stars of higher mass do not undergo Helium flashes and their luminosities remain fairly constant as they move back and forth across the top of the H-R Diagram
    - The compression of their core reaches the temperature necessary to fuse heavier elements before the star has expanded as much as a solar mass star would
  - Stars bigger than our Sun do not go into the red giant phase as they move more vertically up the H-R Diagram and will become an even bigger star before emitting red color



Stellar Evolution Tracks

- A Red Supergiant is more than $100R_{\odot}$ that has a surface temperature around 4000K
  - Each layer of a red supergiant build just as the layers of the lower mass stars do, with each layer being a heavier element fusing within it and the heaviest ones further in center of the core



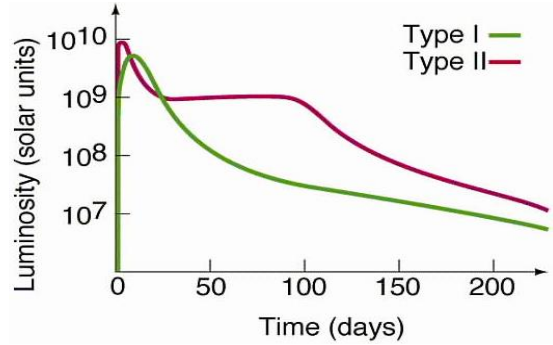
Red Supergiant Internal Structure

- Observations of Supergiants
  - Rigel in the Orion Constellation is an example of a Blue Supergiant star that has left the main sequence
    - It is believed to have begun fusing helium into carbon within its core
  - Betelgeuse in the Orion Constellation is an example of a Red Supergiant star that has left the main sequence
    - It is believed to have fusion up to oxygen within its core
  - It is hard to determine the original mass of the stars when they were on the main sequence because these massive stars are venting clouds of material away from them at their surface
- The End of the Road
  - A star approximately 20 times the mass of our Sun will have the following timeline
    - Burning of Hydrogen for 10 million years
    - Fusion of Helium for 1 million years
    - Fusion of Carbon for 1000 years
    - Fusion of Oxygen for 1 year
    - Fusion of Silicon for 1 week
    - Production of Iron for less than a day
  - Once the star begins to fuse into iron in its core, it is in trouble
    - Iron is the most stable nucleus of all elements and so the fusion of Iron does not release energy, but rather absorbs massive amounts
    - The absorption of energy in the core stops the outward pressure within the star and the inward gravitational force completely takes over
      - The star completely implodes due to gravity reaching almost 10 billion K
      - At this temperature, the light produced has enough energy to “undo” the fusion the star has been working on for millions of years
        - The iron starts to get split into smaller atoms and the smaller atoms get pulled apart into protons, neutrons, and electrons
        - This is called photodisintegration
          - In less than 1 second, the core undoes all the fusion that occurred during the past 10 million years!
      - As the gravity continues to pull in tighter, the protons and electrons are crushed together creating an entirely neutron composed core
      - As the gravity compresses these neutrons together and it happens so fast, it goes beyond the point at which the neutrons should allow it to
        - The neutrons do not want to be squeezed together any closer, so they produce a huge outward pressure to halt the collapse any further
    - A Core-Collapse Supernova is when the core “bounces” back outward and produces an enormous energy shock wave that blasts all the overlying layers out into space
      - Because of the amount of mass most stars emit during their red supergiant phase, only stars >12 times the mass of the Sun will have enough mass to go supernova

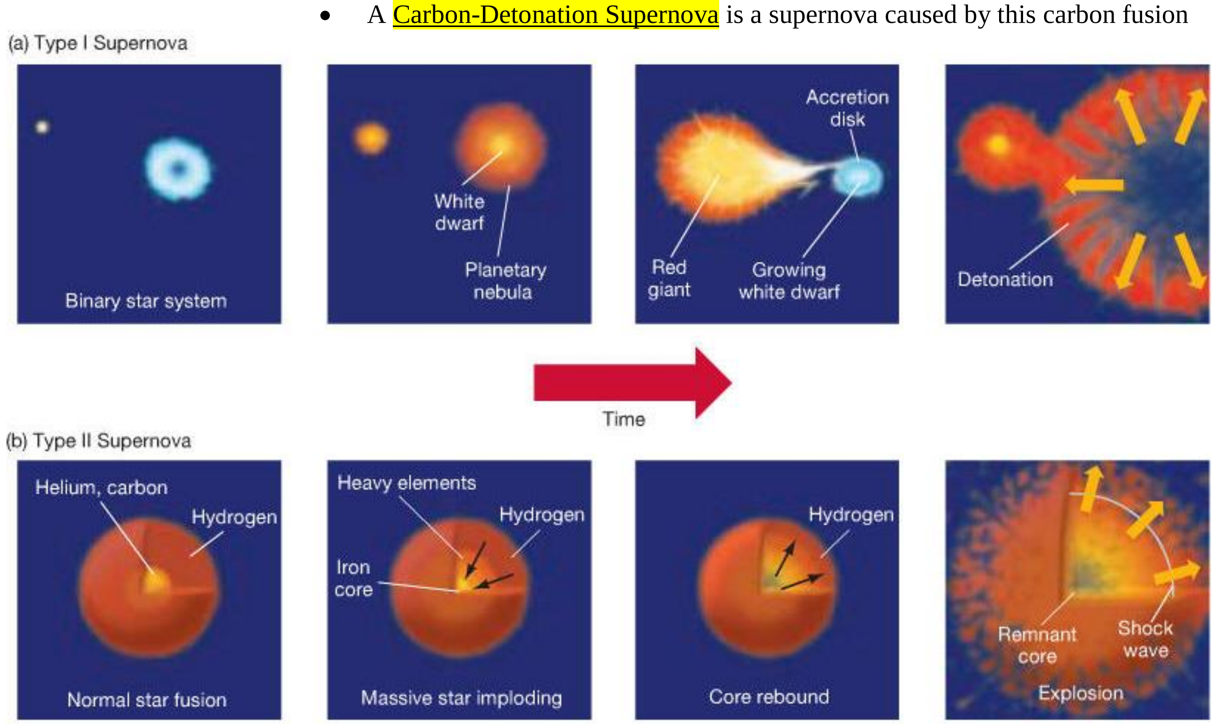
End Points of Evolution for Stars of Different Masses	
Initial Mass (solar masses)	Final State
Less than 0.08	Hydrogen Brown Dwarf
0.08 – 0.25	Helium White Dwarf
0.25 – 8	Carbon-Oxygen White Dwarf
8 – 12	Neon-Oxygen White Dwarf
More than 12	Supernova

12.5 Supernova Explosions

- Novae and Supernovae
  - Supernovae are similar to Novae, except they produce a burst of light billions of times brighter than the Sun and will emit more energy in a couple of months than the Sun does in its lifetime
    - A Type I Supernova contains very little hydrogen and have light curves similar to a typical Nova explosion
      - They have a sharp rise and a slow, steady decrease over time
    - A Type II Supernova contains lots of hydrogen and have a slightly different light curve than a typical Nova explosion
      - They have a plateau in the light curve a few months after the maximum



- Type I and Type II Supernovae Explained
  - A Type II Supernova is consistent with the Core-Collapse Supernova
  - A Type I Supernova has a different mechanism, which gives it the different light curve
    - The maximum mass of a white dwarf is about 1.4 solar masses
      - The Chandrasekhar Mass is the 1.4 solar mass minimum required for a star to have enough mass to go supernova
    - If an accreting white dwarf brings in enough mass to get over the Chandrasekhar Mass, carbon fusion will begin everywhere throughout the white dwarf almost simultaneously, which produces enough energy to overcome its gravity and it will go supernova
      - A Carbon-Detonation Supernova is a supernova caused by this carbon fusion

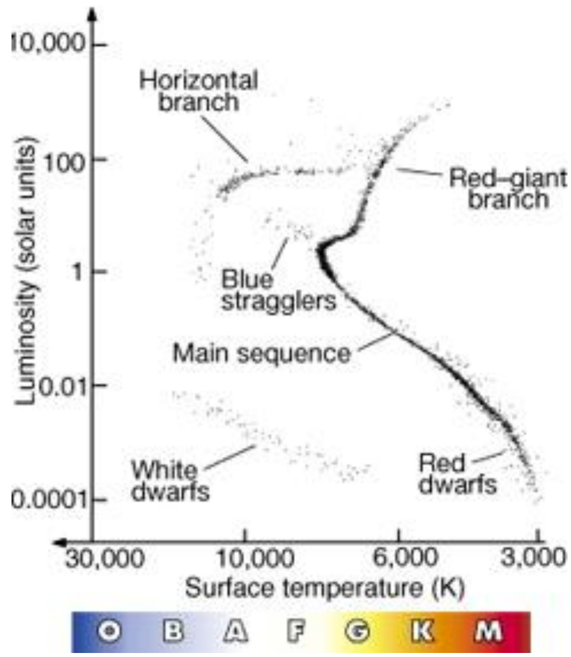


- Supernova Remnants
  - Some supernovae can be seen but many can only be detected by the expanding clouds of gas expanding from the supernova explosion
    - Crab Nebula is what is left over from a star that went supernova in 1054 AD and is still expanding at several thousand kilometers per second
      - Type II Supernova that was documented by Chinese and Middle Eastern astronomers as it was visible even during the day for almost a month
    - Vela exploded about 9000 BC and is 500 pc from Earth.
      - Type II Supernova that could have been as bright as the moon for months

- Formation of Heavy Elements
  - All elements bigger than Helium are fused together in stars
    - Fusion can only create up to Iron
  - During Supernova explosions, the heat and energy is so great that protons and electrons that are free-moving combine to create elements larger than Iron

12.6 Observing Stellar Evolution in Star Clusters

- Clusters of stars are formed from the same interstellar clouds and have very similar compositions, so only their mass is what separates stars within a cluster
  - These clusters are used to test our models of stellar evolution as the stars will show movement on the H-R Diagram at different times based on their masses
- As a cluster of stars forms, they all arrive on the main sequence with more low mass than high mass stars
  - As time goes on, the larger massed stars will evolve faster
- The cluster will appear to "peel away" from the main sequence beginning at the top left
  - The Main-Sequence Turnoff is the area where the stars are leaving the main sequence
- Over time the various branches become evident as the main sequence peels away and the formation of the other types of stars begins
  - The Horizontal Branch
  - The Asymptotic Giant Branch
  - The Red Giant Branch
  - The Subgiant Branch
  - White Dwarfs
  - Blue Stragglers



12.7 The Cycle of Stellar Evolution

- The universe continually recycles materials through a 4 stage process
  - Interstellar Medium
    - Clouds of gas and dust dispersed throughout regions of space
  - Star Formation
    - Gas and dust form stars condense under gravity and create stars
  - Stellar Evolution
    - Stars fuse lighter elements into heavier ones and release energy
  - Supernova & Heavy Elements
    - Supernovas and other explosions seed space with more gas and dust to start the cycle over again