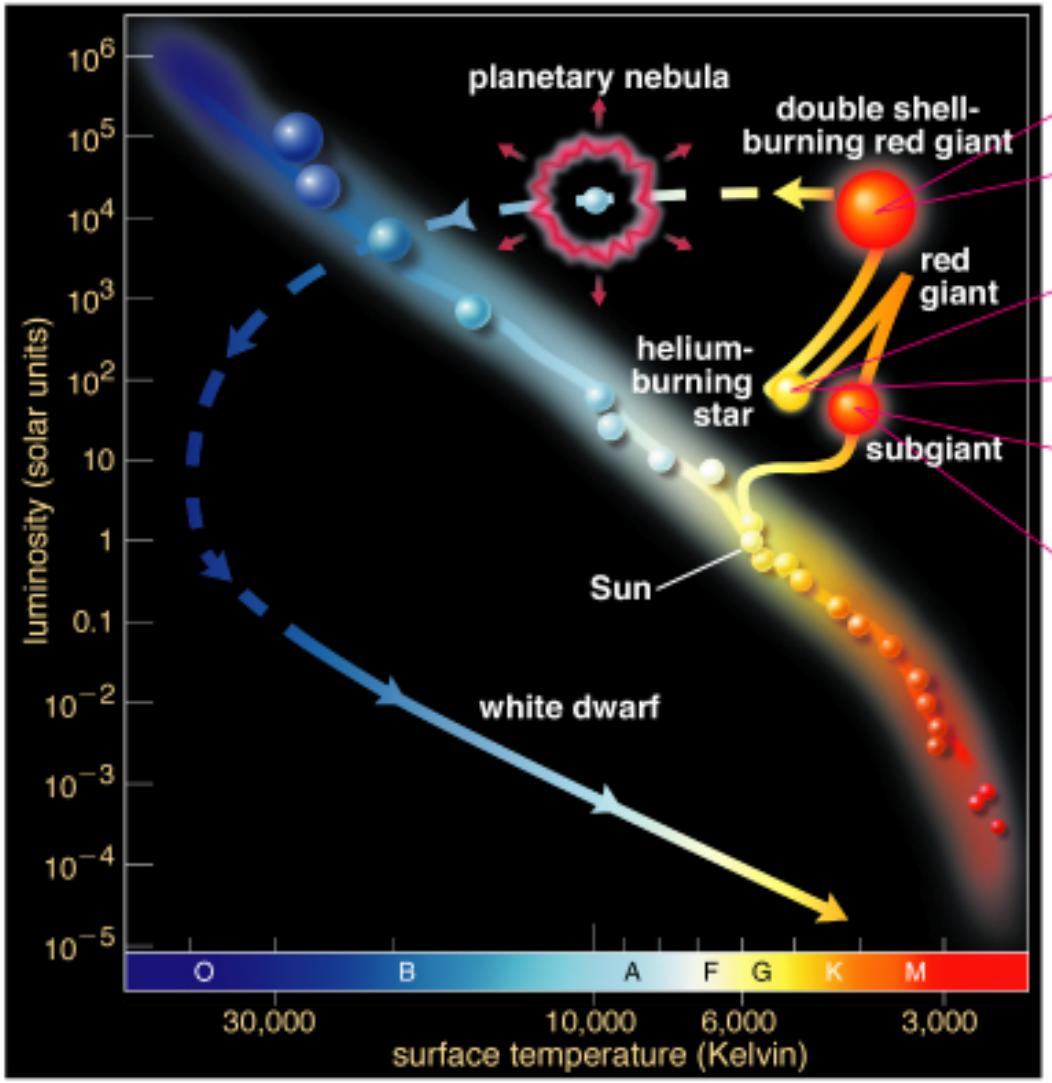
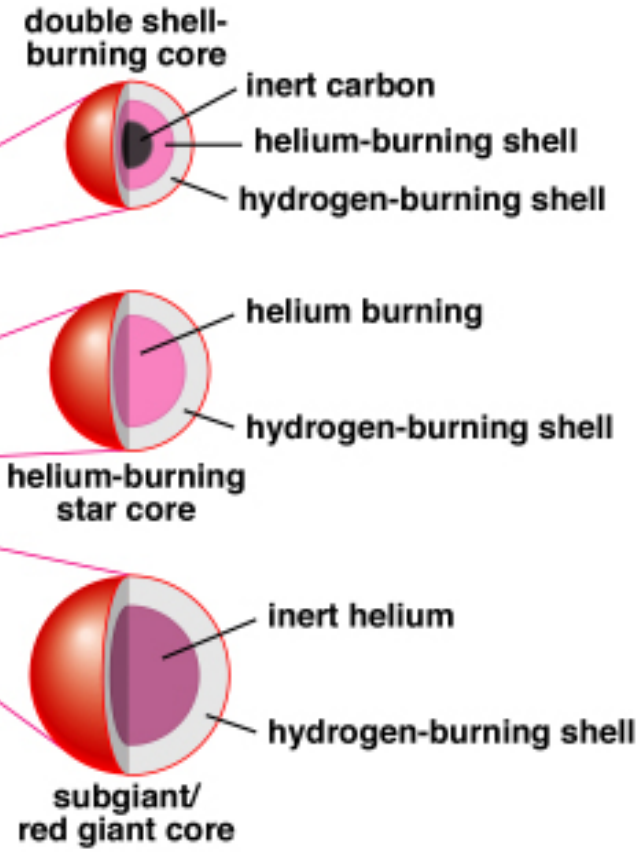
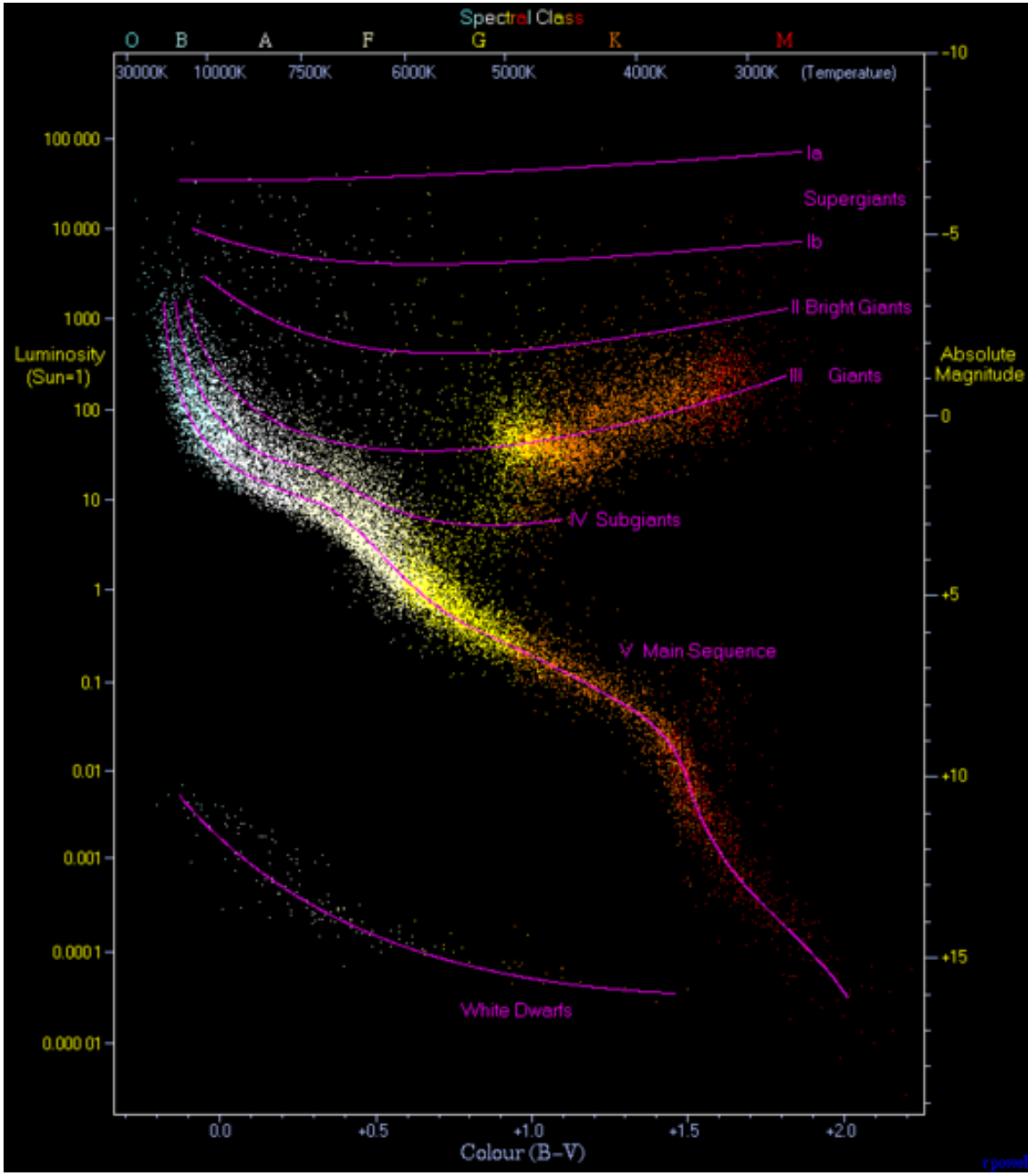
Evolution of the Sun on H-R Diagram





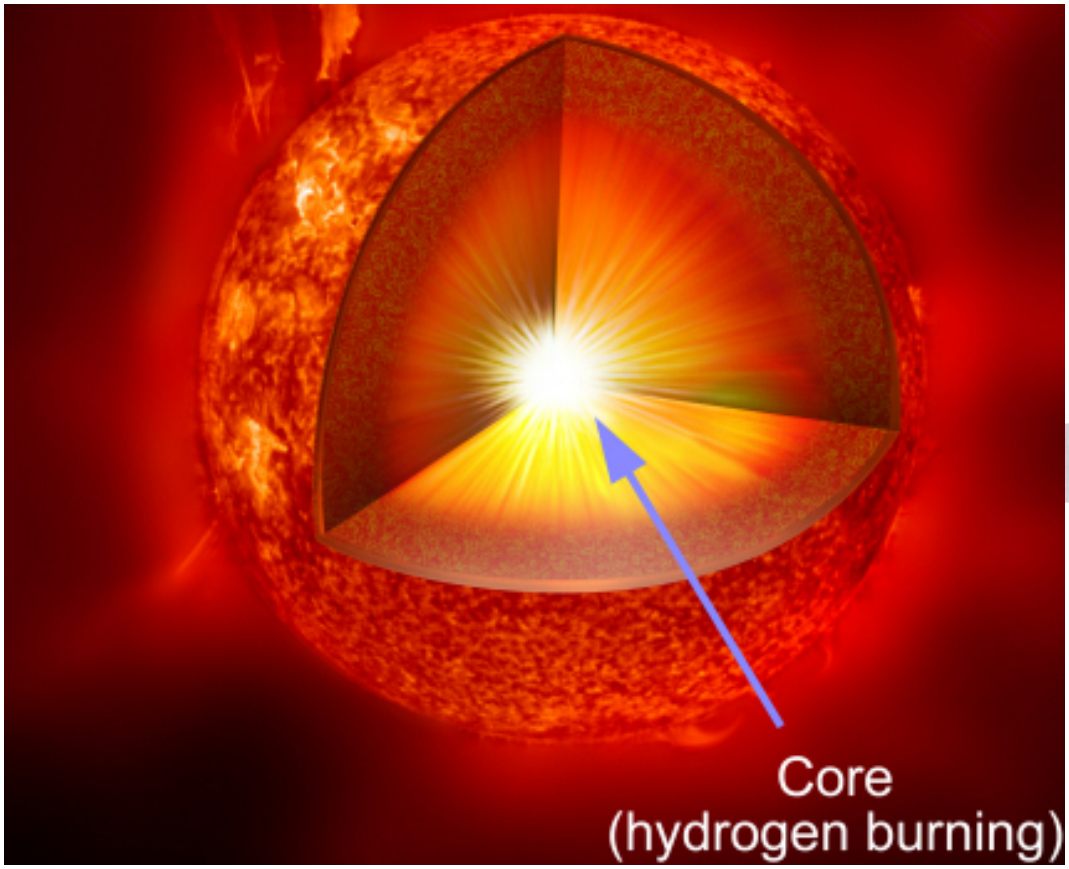
Stellar Evolution

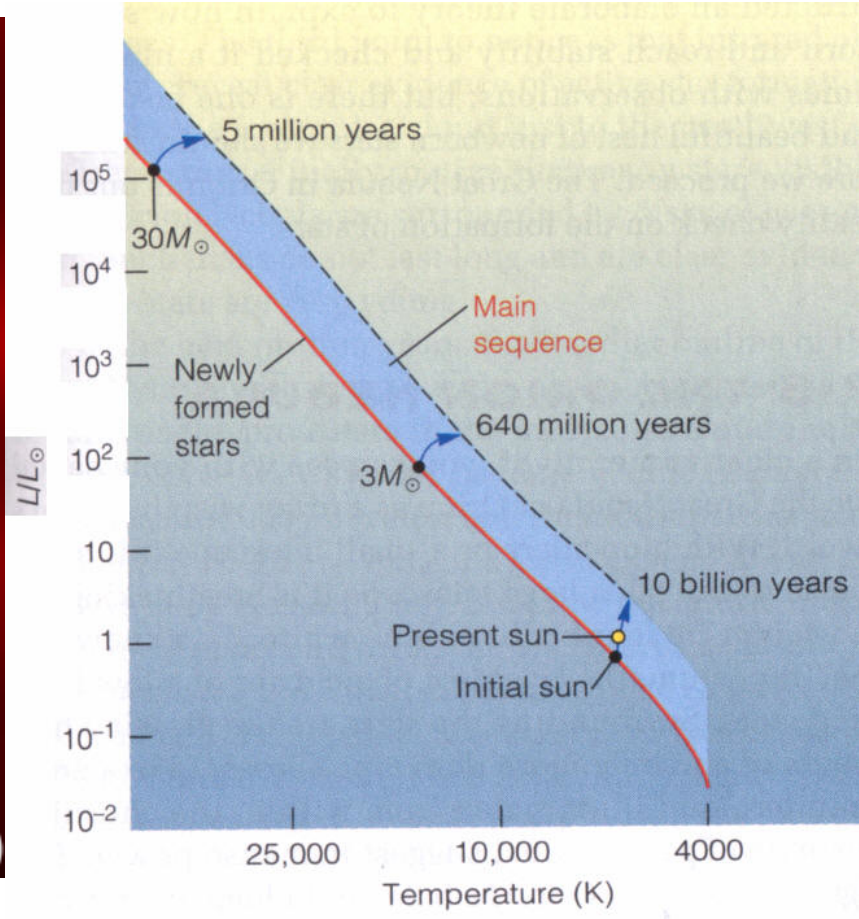
- Stars take billions of years to evolve
- So we can never watch one go thru its life cycle
- But we can observe billions of stars see if they fit the theory



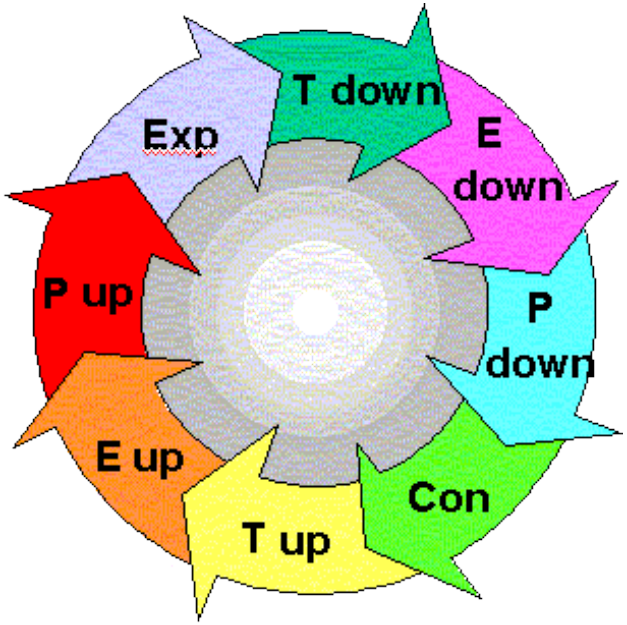
Core Hydrogen Burning

- Hydrogen burns in core & Helium ash builds up during Main-Sequence Lifetime: 10billion years

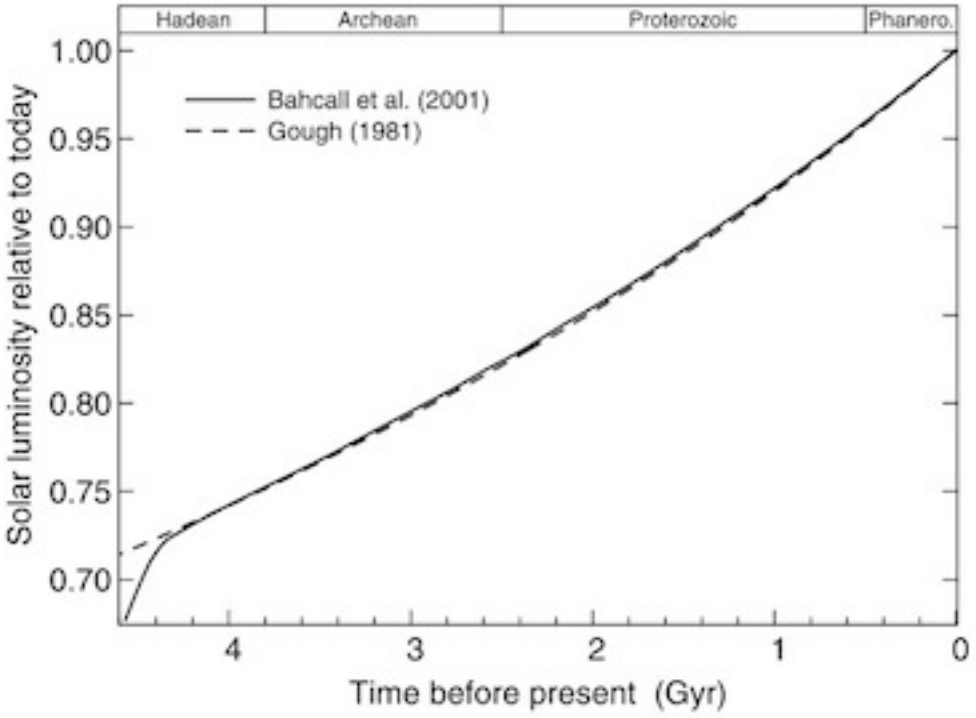




Ideal Gas Law = Pressure-Temperature Thermostat

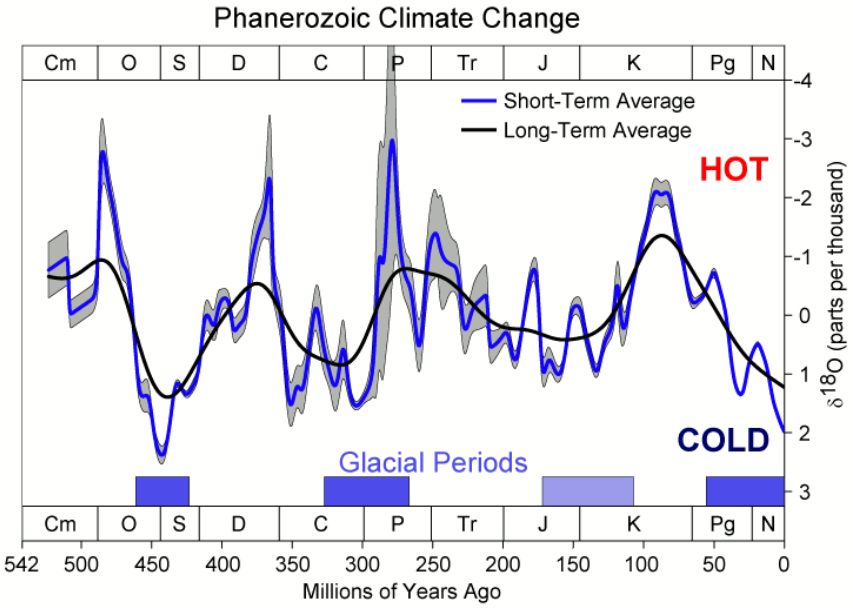


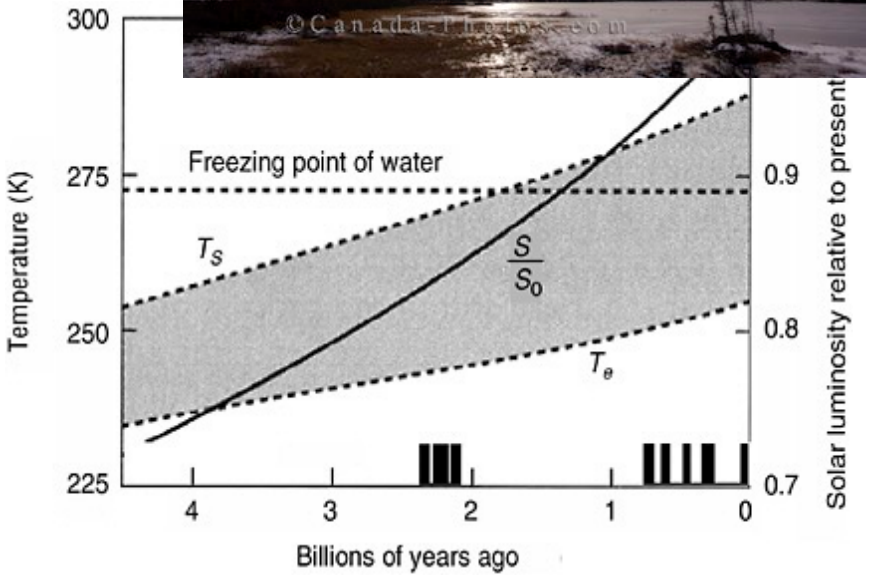
- 4Hydrogens ➔ 1 Helium
- Less pressure
- Core contracts
- Temperature goes up
- Luminosity goes up
- Sun is now 30% brighter than 4 Billion years ago



Faint Young Sun Paradox

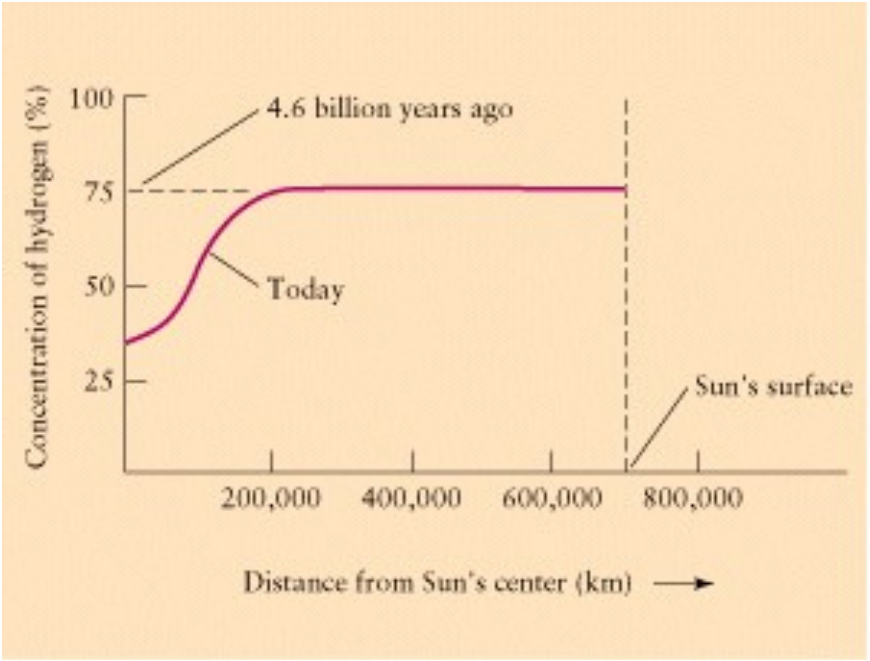
- But there was liquid water on Earth 3Billion yrs ago
- Atmosphere was different – CO_2 CH_4 no O_2 etc.
- Clouds, more Oceans, ???

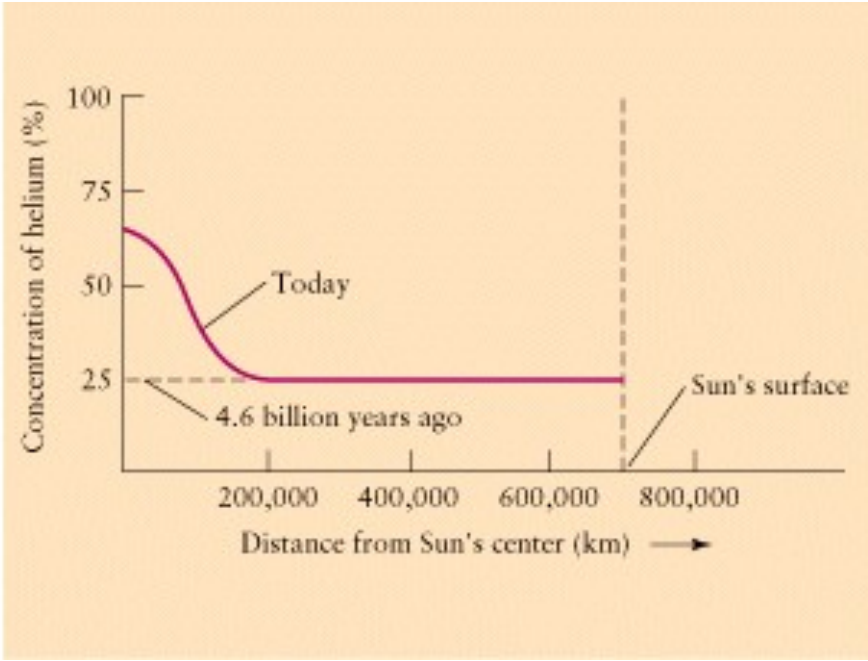




Hydrogen-Shell-Burning

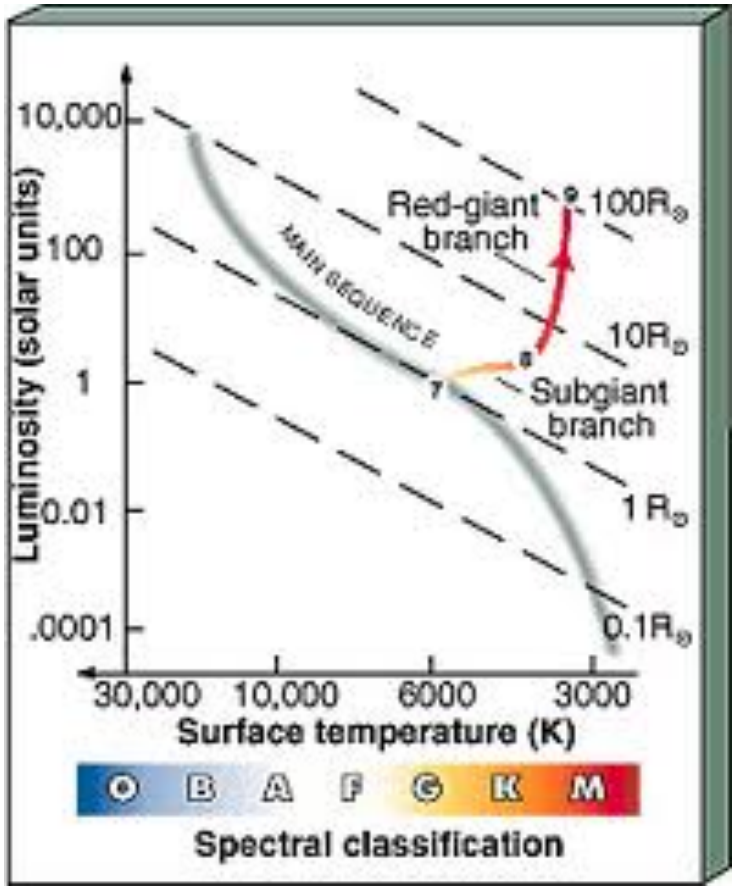
- Eventually core runs out of Hydrogen in core
- Hydrogen burns in shell surrounding core

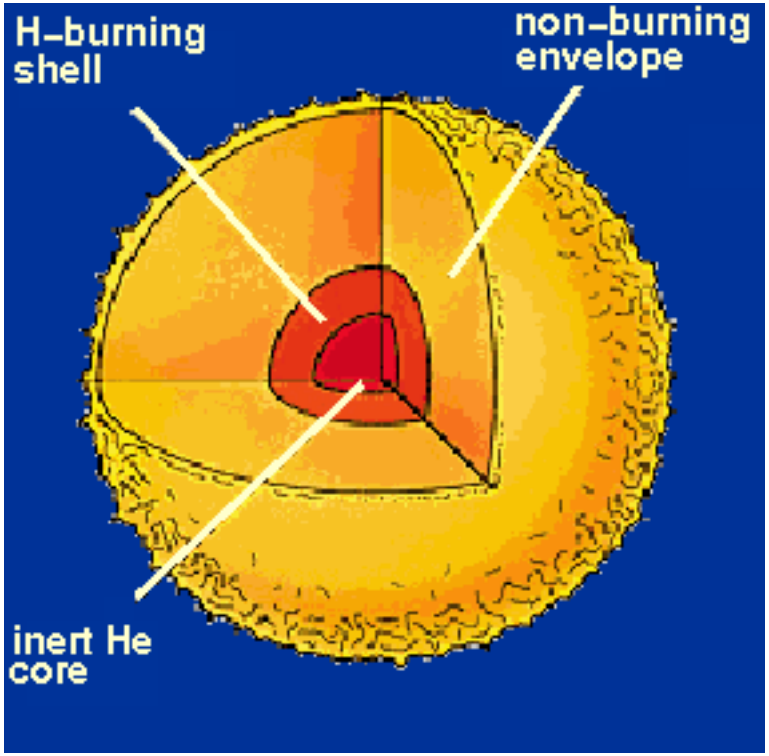




Sun Becomes a **Subgiant**

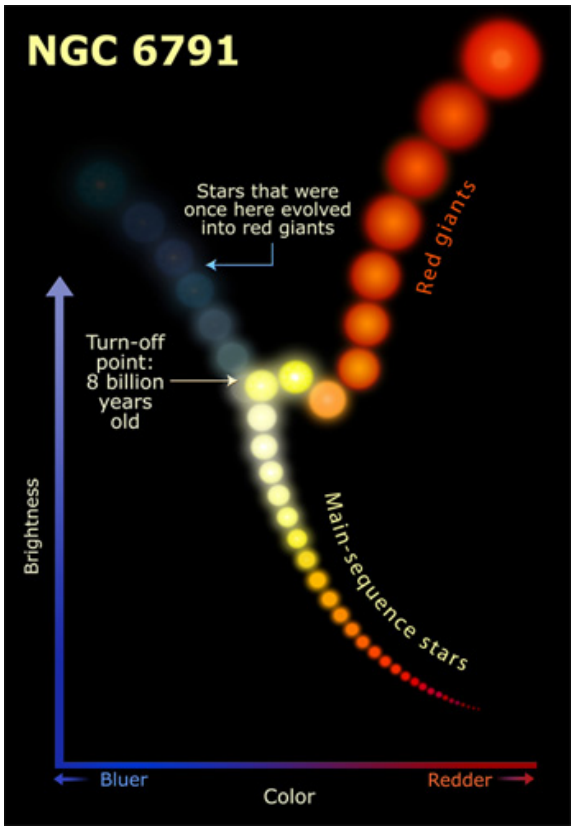
- Sun moves onto **Subgiant Branch**
- Core contracts, core temperature rises, star expands and surface cools

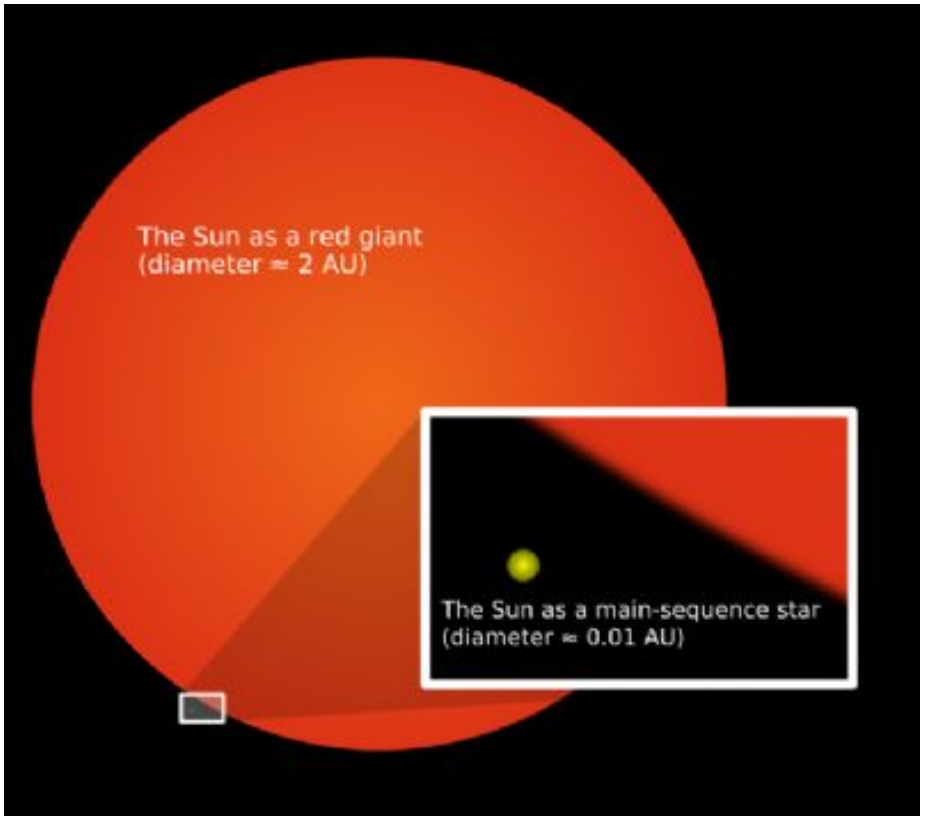




Red-Giant Branch Stage 9

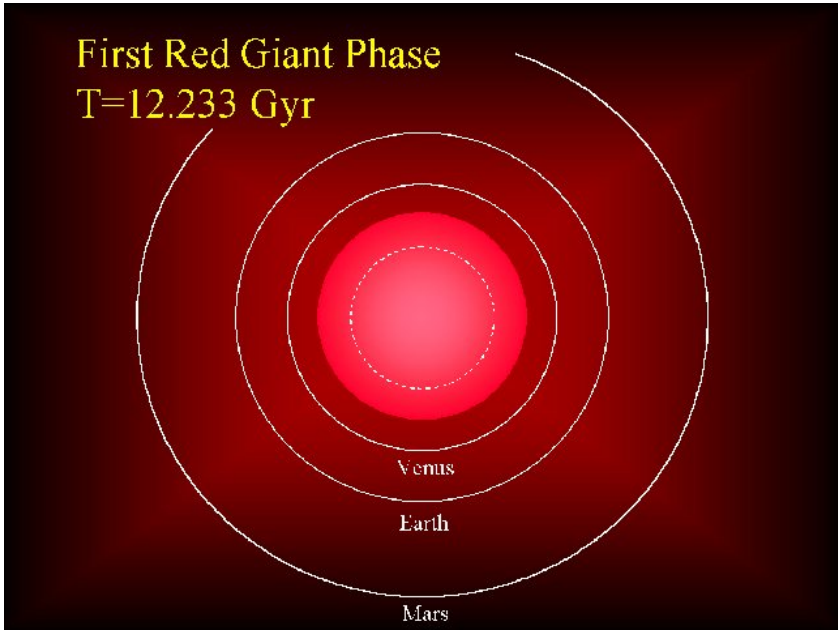
- Helium core (~R_{earth}) contracts & increases temperature
- Hydrogen shell burning increases: Luminosity increases
- Surface temperature constant so Radius increases; more
- 100million years to go up Red Giant Branch

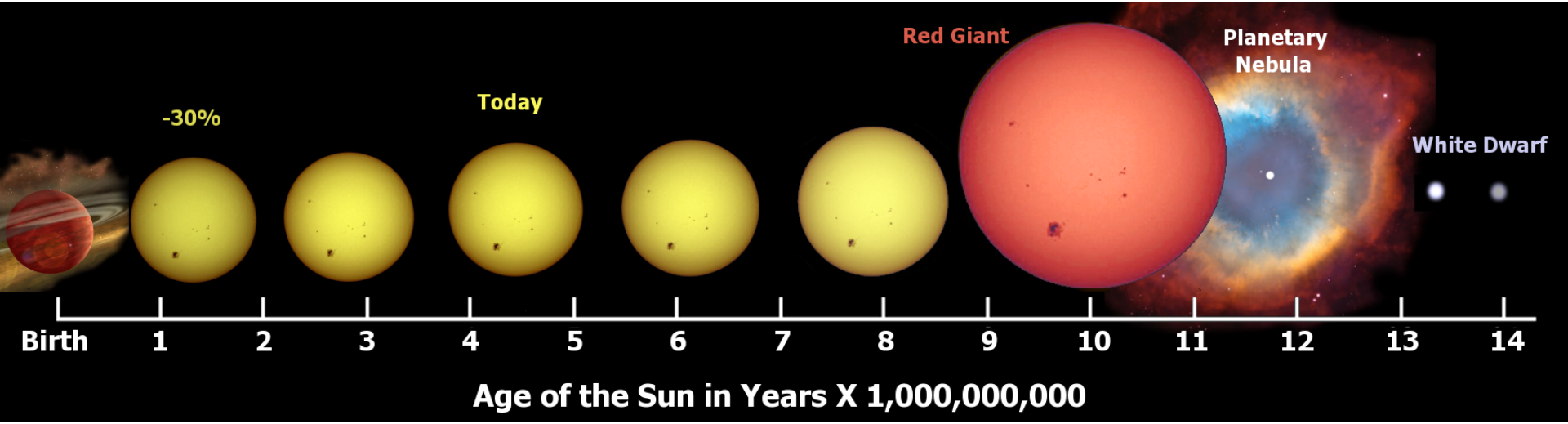




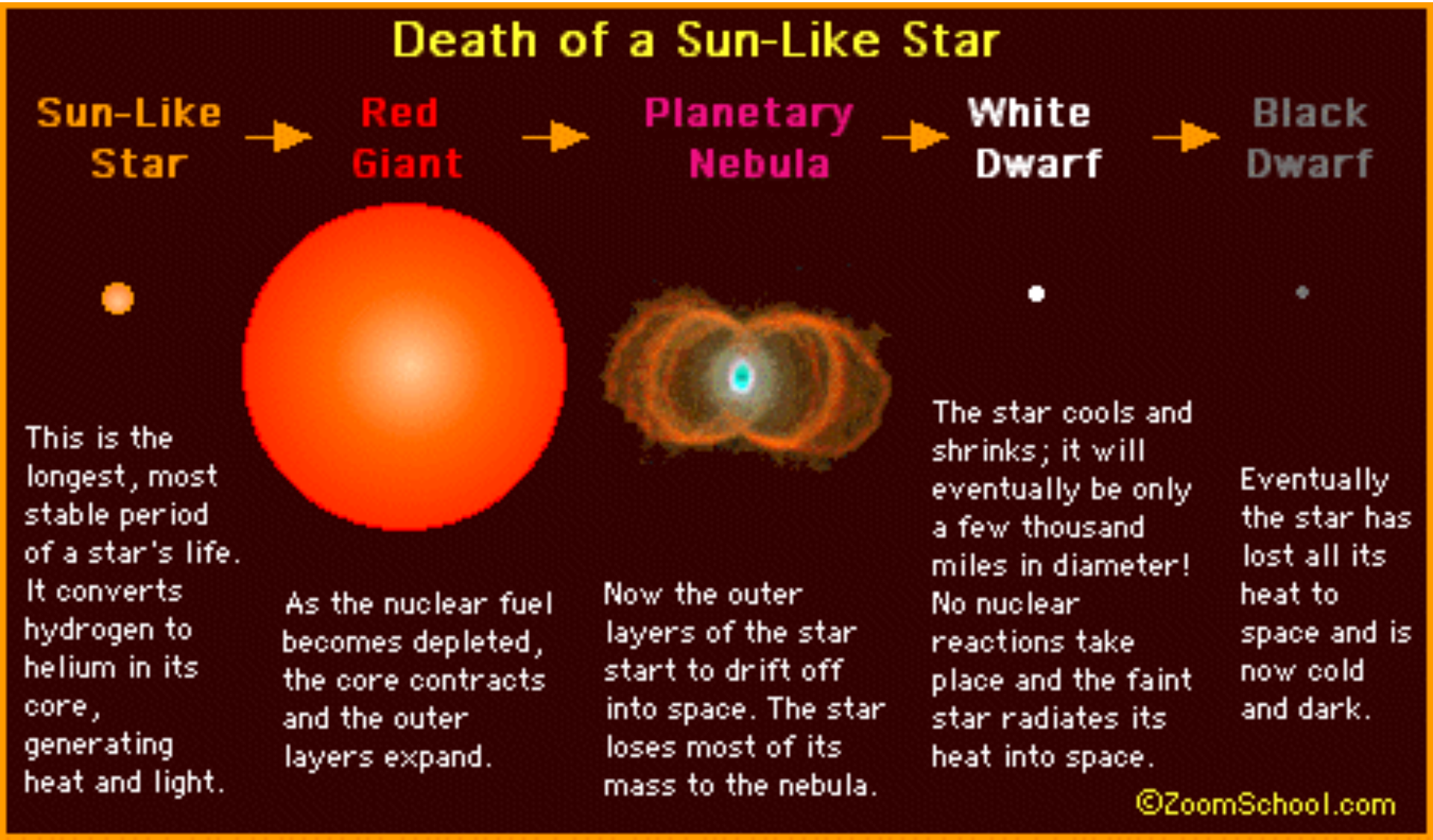
The End of the Earth

- As Sun becomes a Red Giant
- Radius increases 100 times
- Diameter goes from half degree to 50°
- Not 2 minutes to rise – but 3hours
- Oceans will boil & rocks will melt



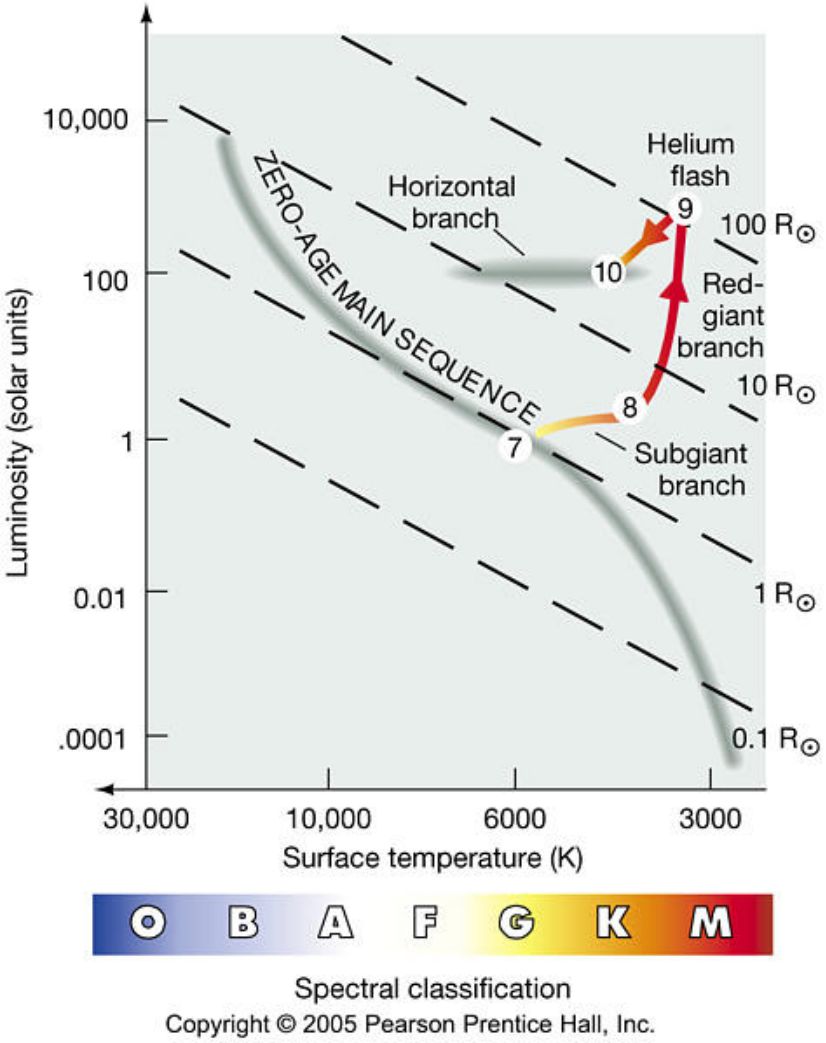


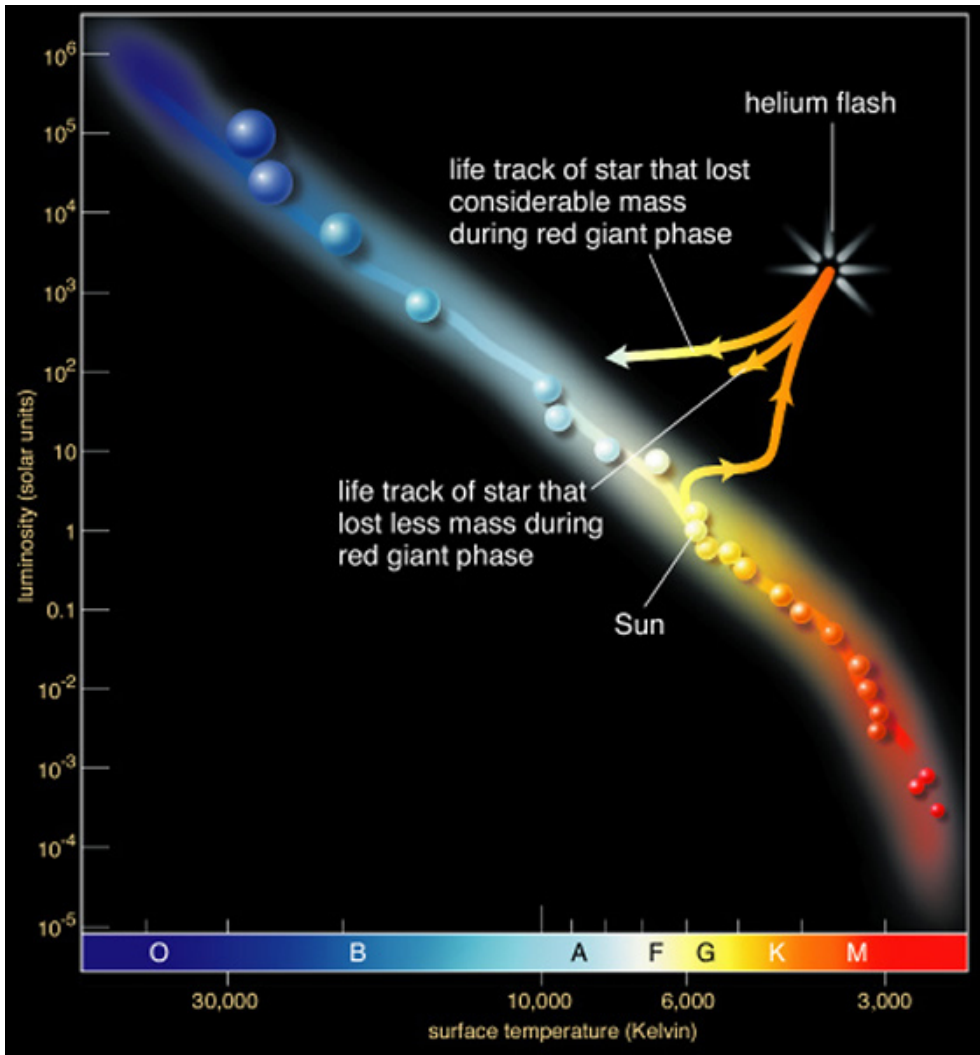
Summary of the Death of a Sun-like Star 0.4-4 M_{sun}



Stage 9: **Helium Flash**

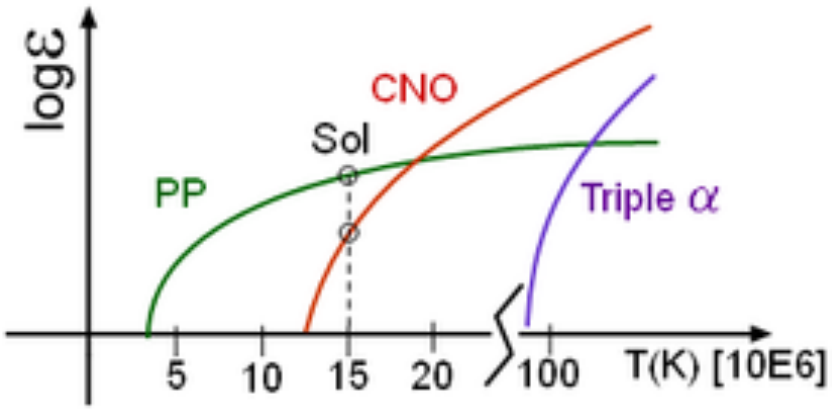
- Helium ignites in core and burns explosively since core is degenerate and pressure does NOT depend on temperature in degenerate matter
- 10billion times suns luminosity is produced in an hour, but not visible

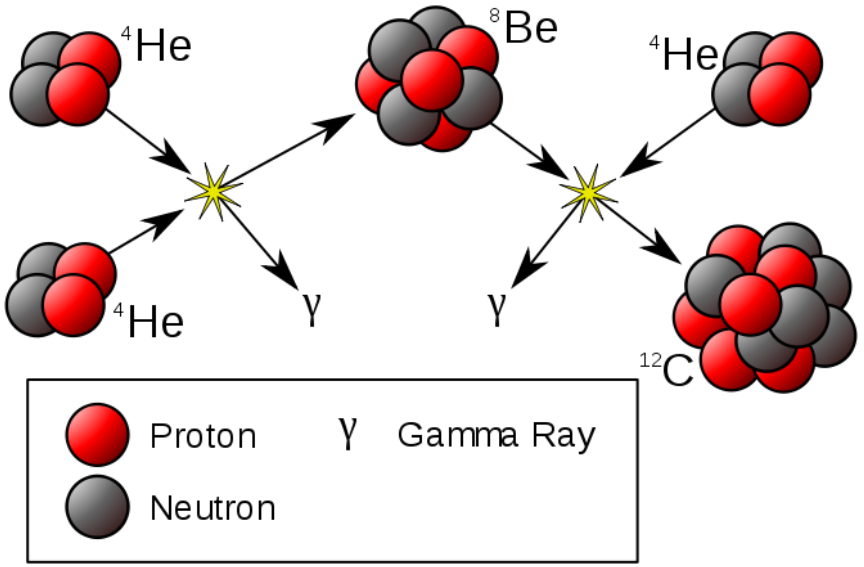




Triple Alpha Process

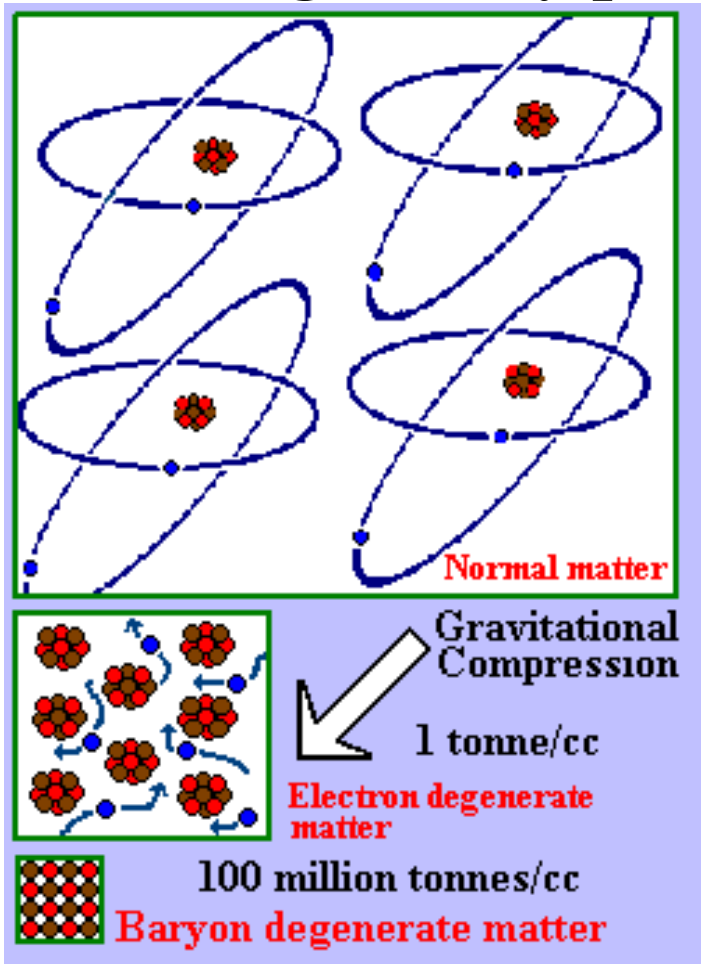
- Helium nuclei = Alpha Particle
- 2 Helium nuclei fuse to make Beryllium, which usually decays before it can get hit again by another Helium
- Helium can not fuse to make Carbon until temperature reaches 100Million Kelvin

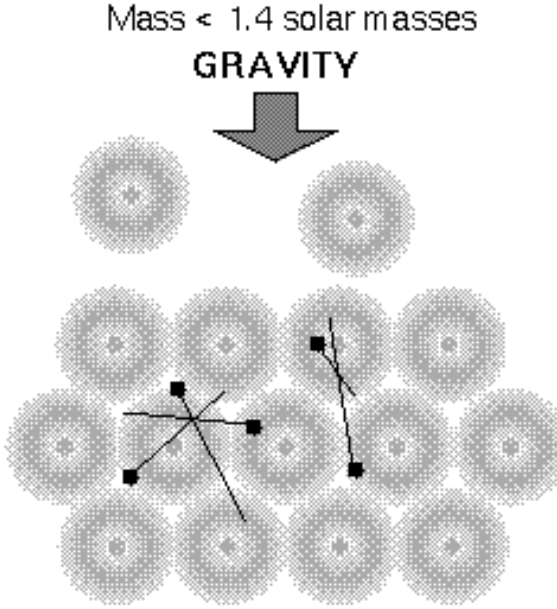




Electron Degeneracy

- Heisenberg Uncertainty principle states that you can not know everything about anything $\Delta x \, \Delta p \geq \frac{\hbar}{2}$
- **Electron Degeneracy pressure**; Independent of temperature





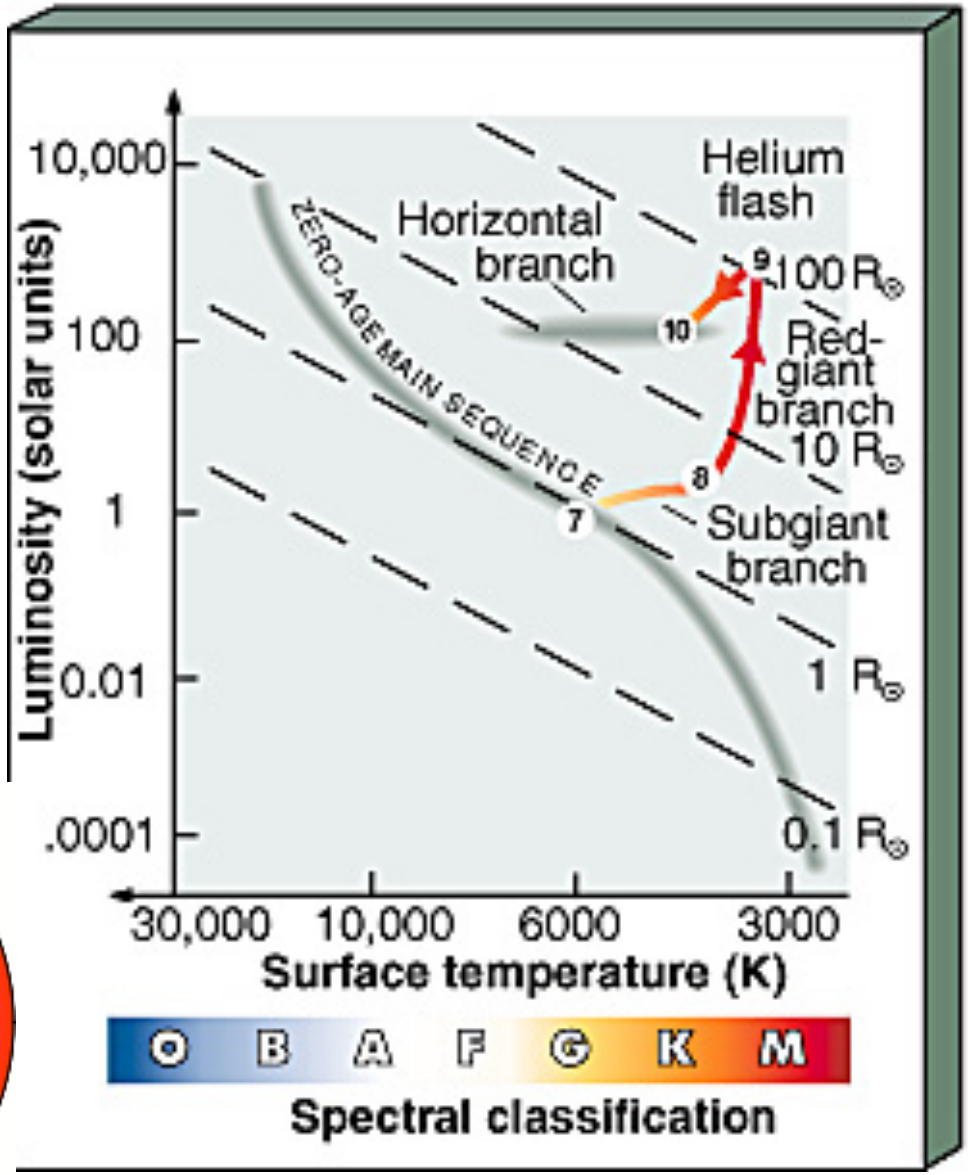
White Dwarf

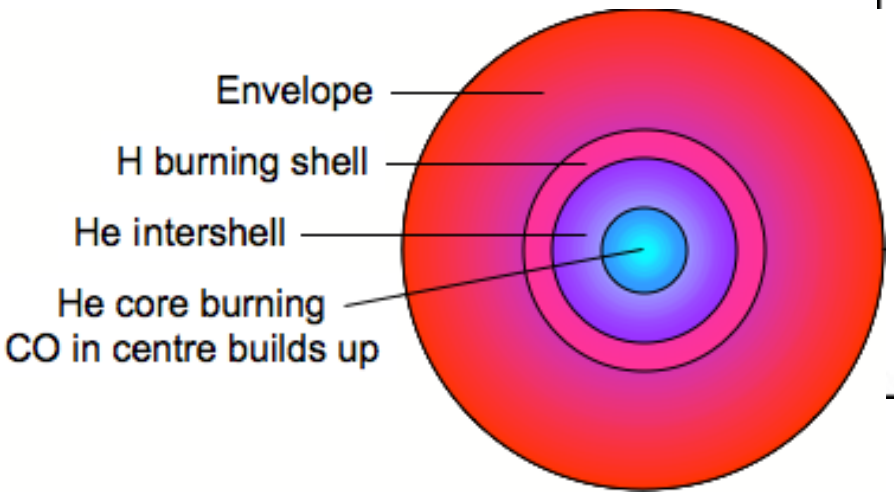
Electrons run out of room to move around. Electrons prevent further collapse. Protons & neutrons still free to move around.

Stronger gravity => more compact.

Horizontal Branch Stage 10

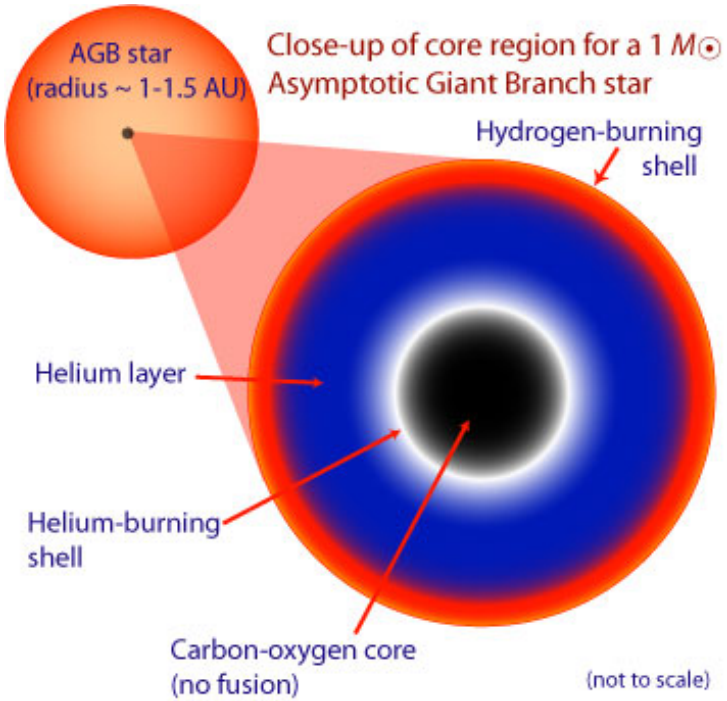
- 9-10 in 100,000 years
- Hydrogen burns in shell
- Helium burns in core
- Carbon & Oxygen ash
- 10 million years on Horizontal branch

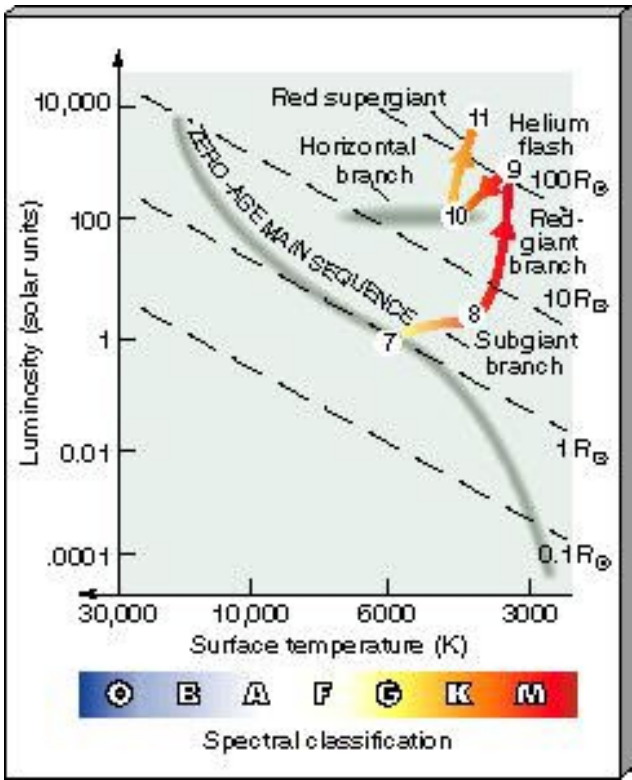


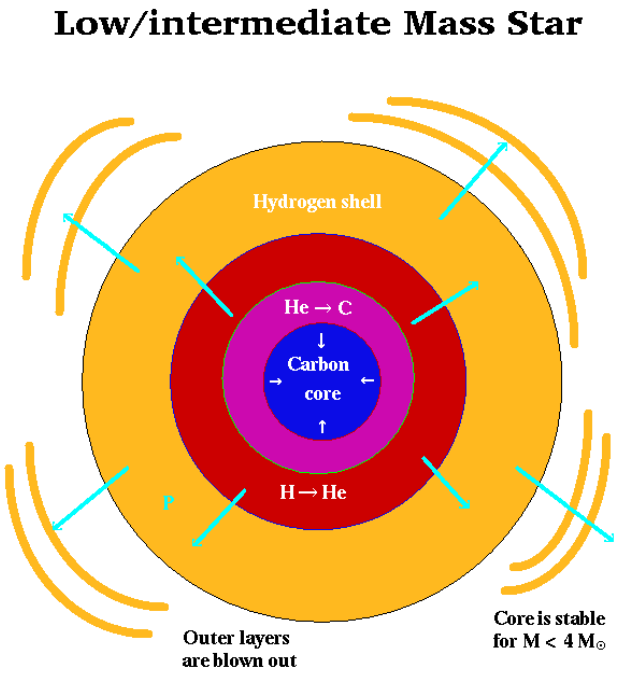


Stage 11: **Asymptotic Giant Branch**

- Horizontal Branch (10) to end of AGB (11) ~50 million yrs
- Core contracts, core temperature increases, star expands becomes Red Giant again
- Helium burns in shell - Carbon ash builds up in core

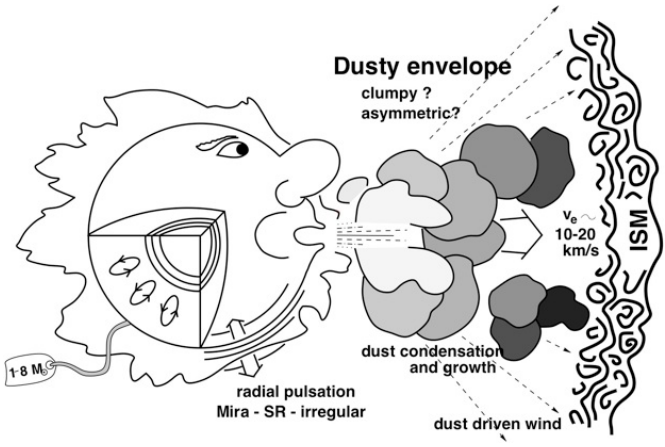




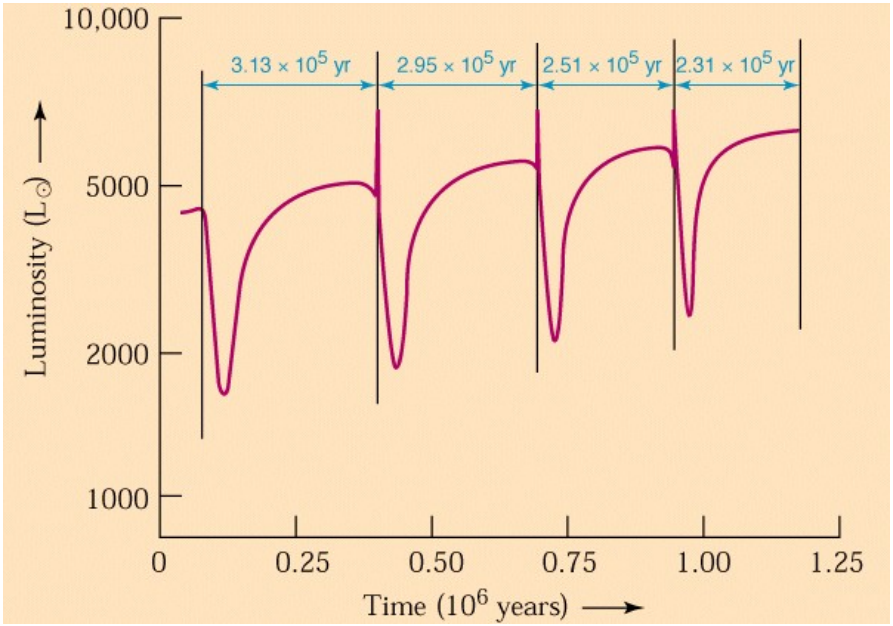


Helium Shell Flashes:

- Ejecting the envelope
- Star can lose half its mass

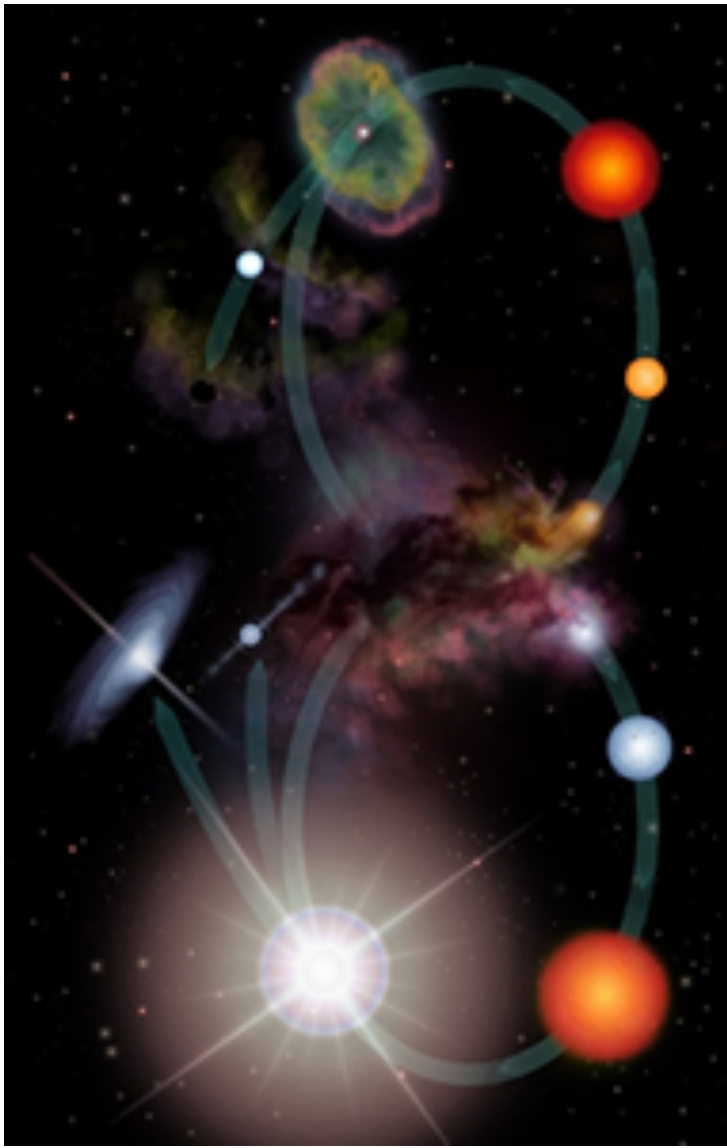


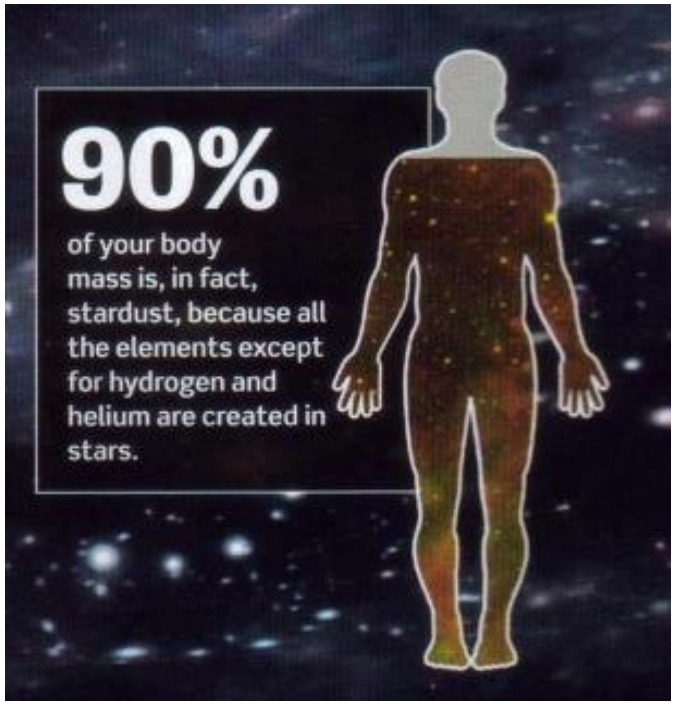
M. Marengo



Dust from AGB Stars Enriches Interstellar Medium

- New stars made from old stars
- New stars have more carbon, nitrogen, oxygen
- <u>You</u> are made of star dust



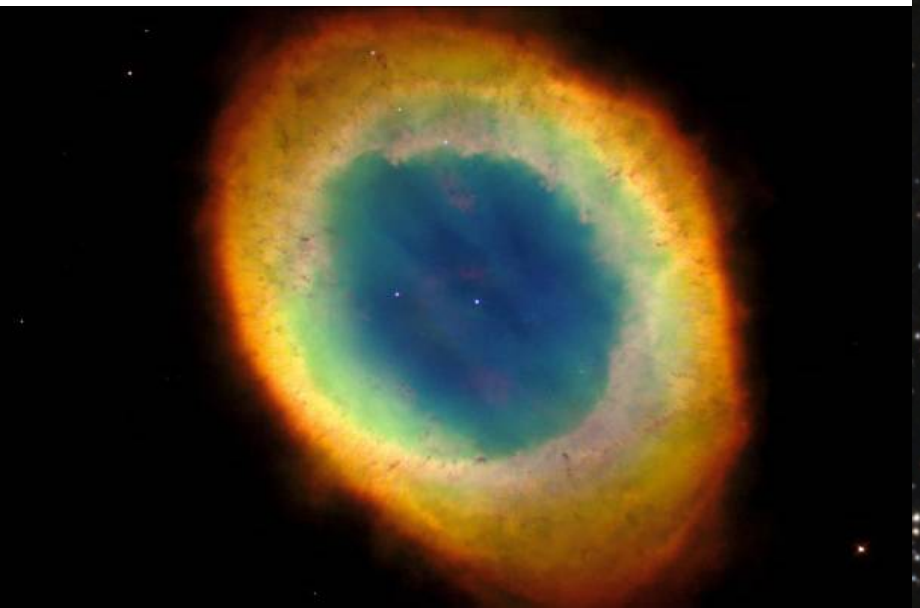


Planetary Nebula
Stage 12

- Gas ejected by “Thermal Pulses” during Helium-shell flashes
- Ionized by hot core (white dwarf)

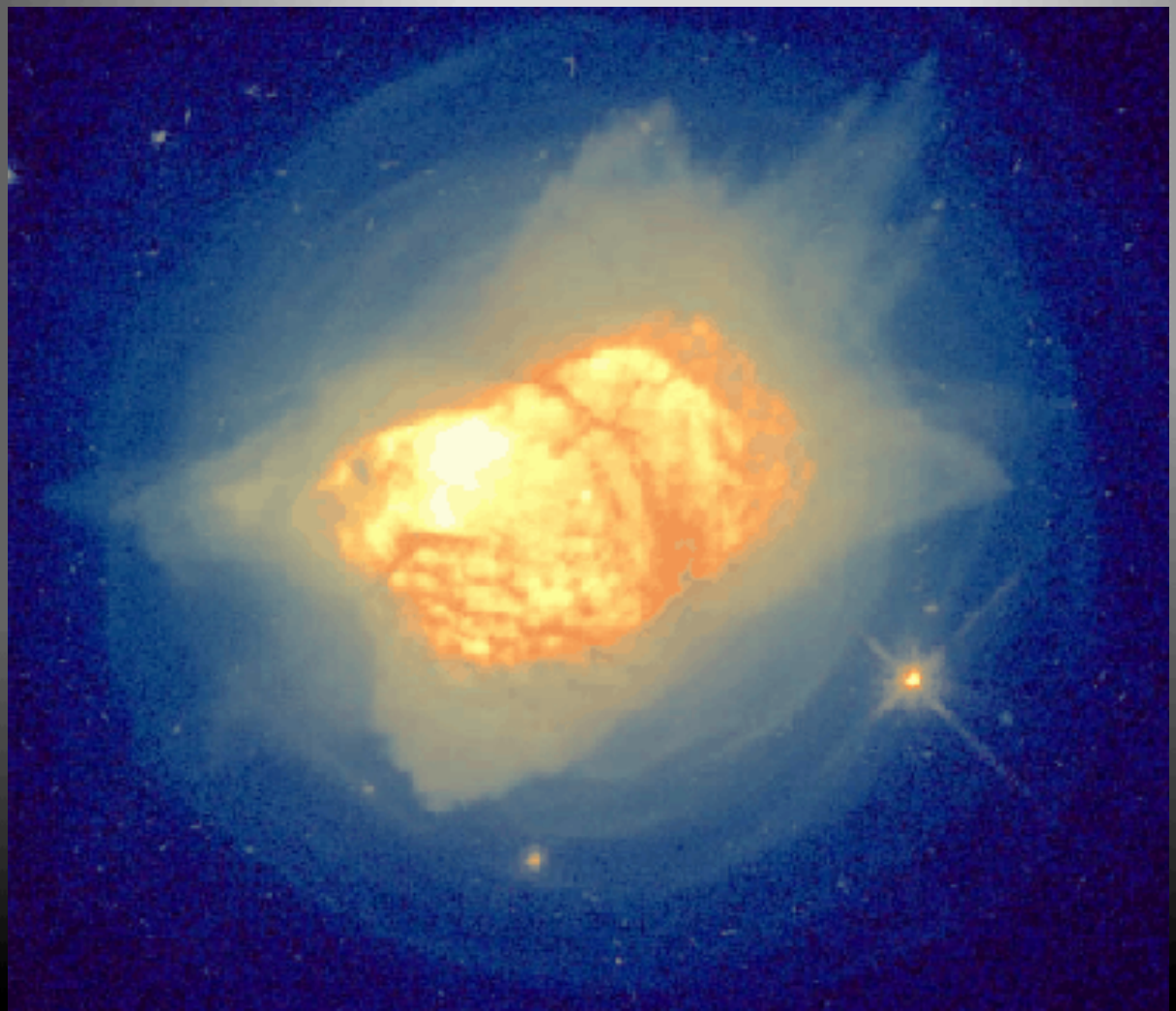
Planetary Nebulae

- M57 the "Ring Nebula" is the most famous of ~1500
- Originally named Planetary by W. Herschel in 1790 because they resembled Uranus, which he discovered



Planetary Nebula - NGC 7027

- Slow wind initially and fast wind later catches it and compresses
- Shape distorted by binary companion or asymmetrical ejections

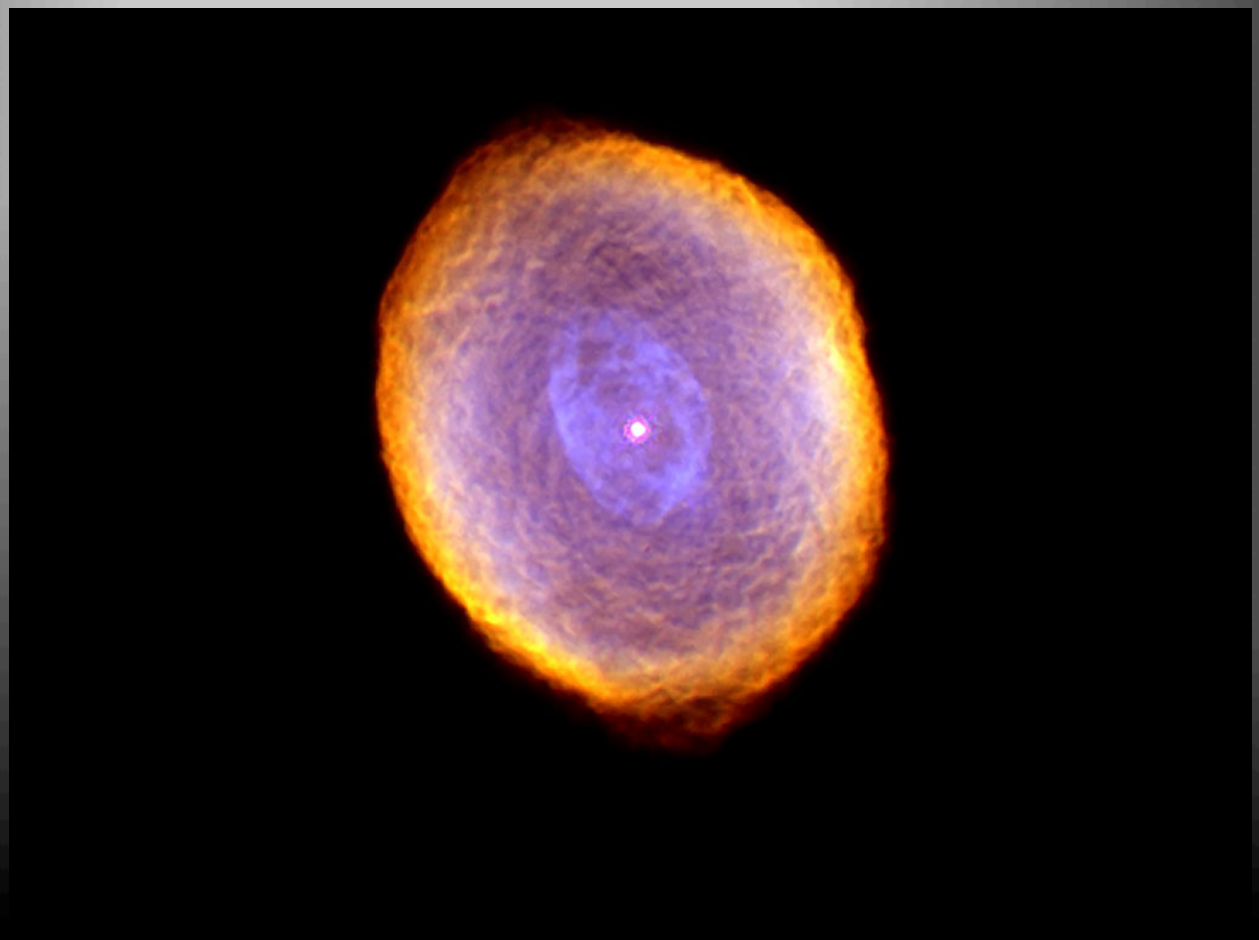


Planetary Nebula-NGC 6751

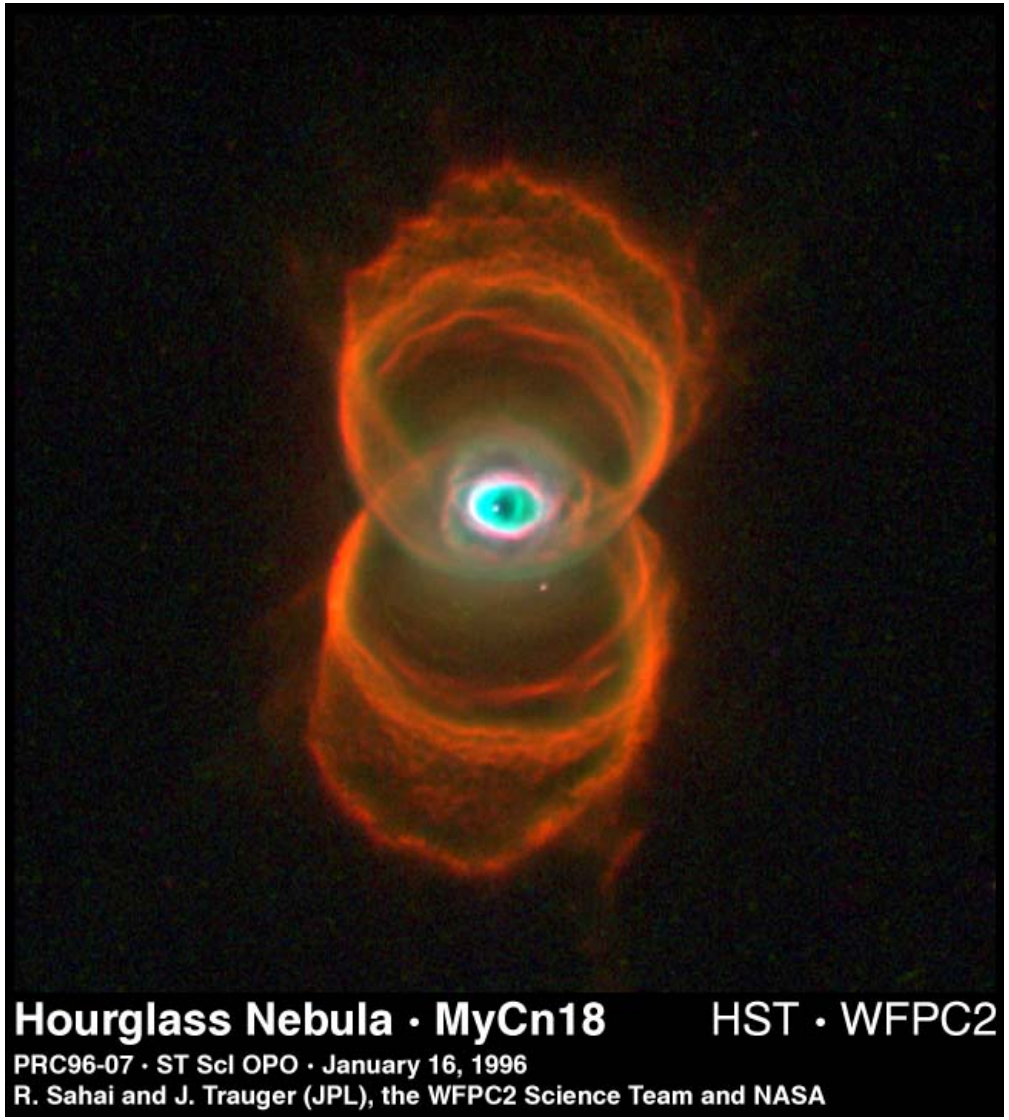
- From apparent size and proper motion the age is 1000's years
- From expansion velocity of ~10 km/sec the distance is 1000 lightyears
- From distance and apparent size the linear size is ~a light year

Planetary Nebula

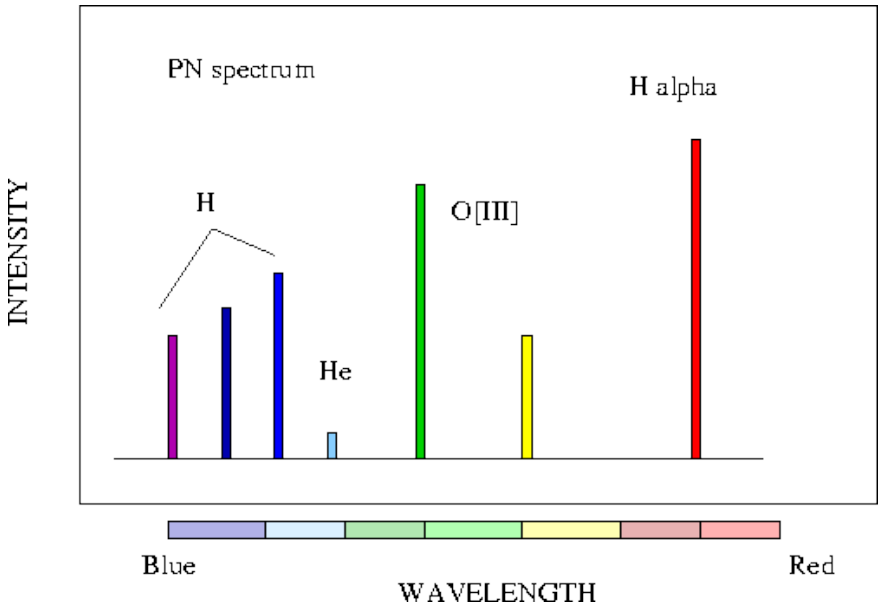
- Short lived phase of star's life (tens of thousands of years)
- Yet we see thousands so most stars must produce planetary nebulae
- Most white dwarfs do not have a planetary nebula



Hourglass Nebula

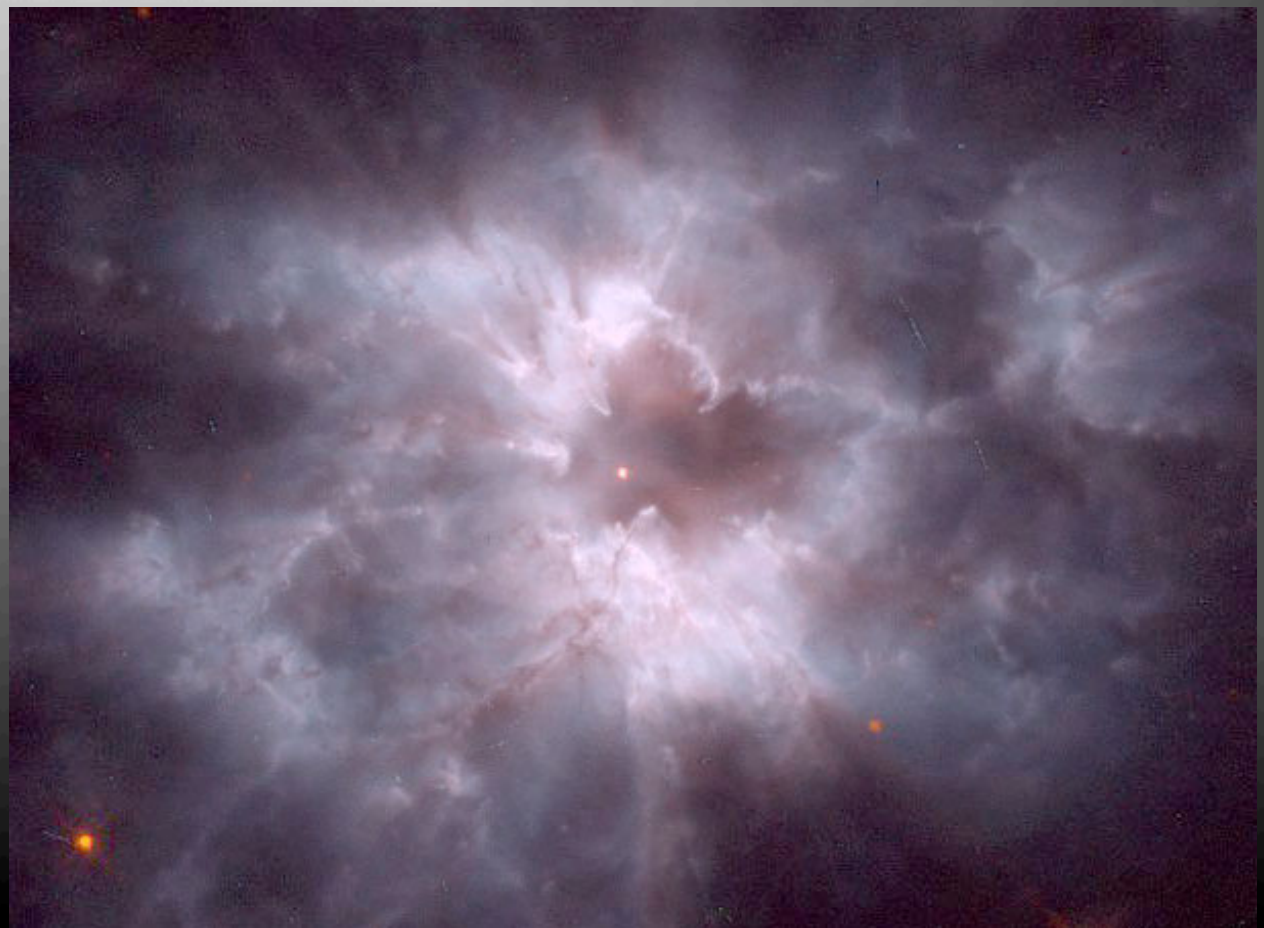


- Emission lines indicate a low density gas
- And a hot (>25,000K) central star
- Nitrogen red & Hydrogen green & Oxygen blue

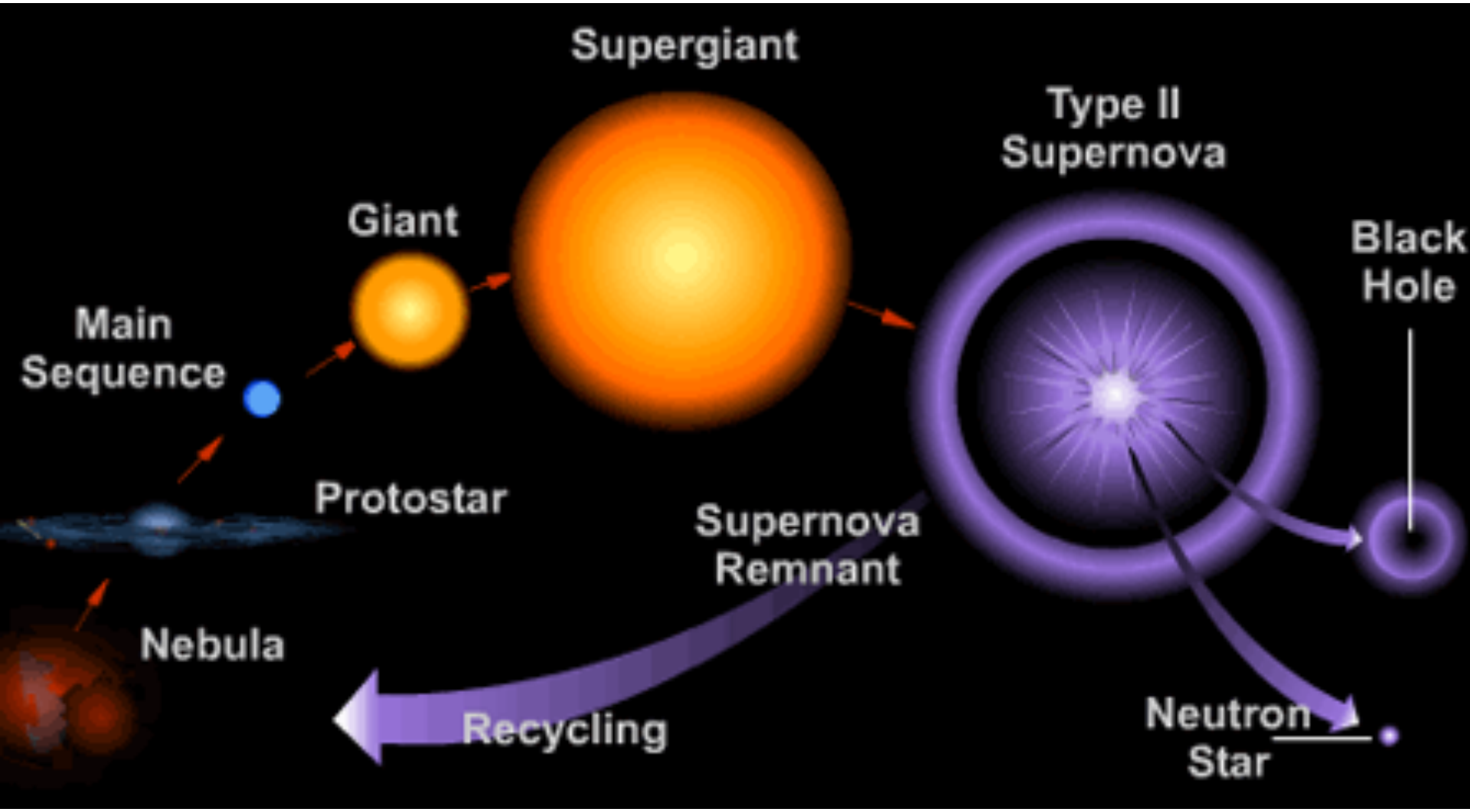


Stage 13: A New White Dwarf

- In center of NGC 2440 is 200,000K temp white dwarf
- Mass loss from solar wind & esp. dust in atmosphere
- 8 Solar masses can become $5M_{\odot}$ in 500,000 years

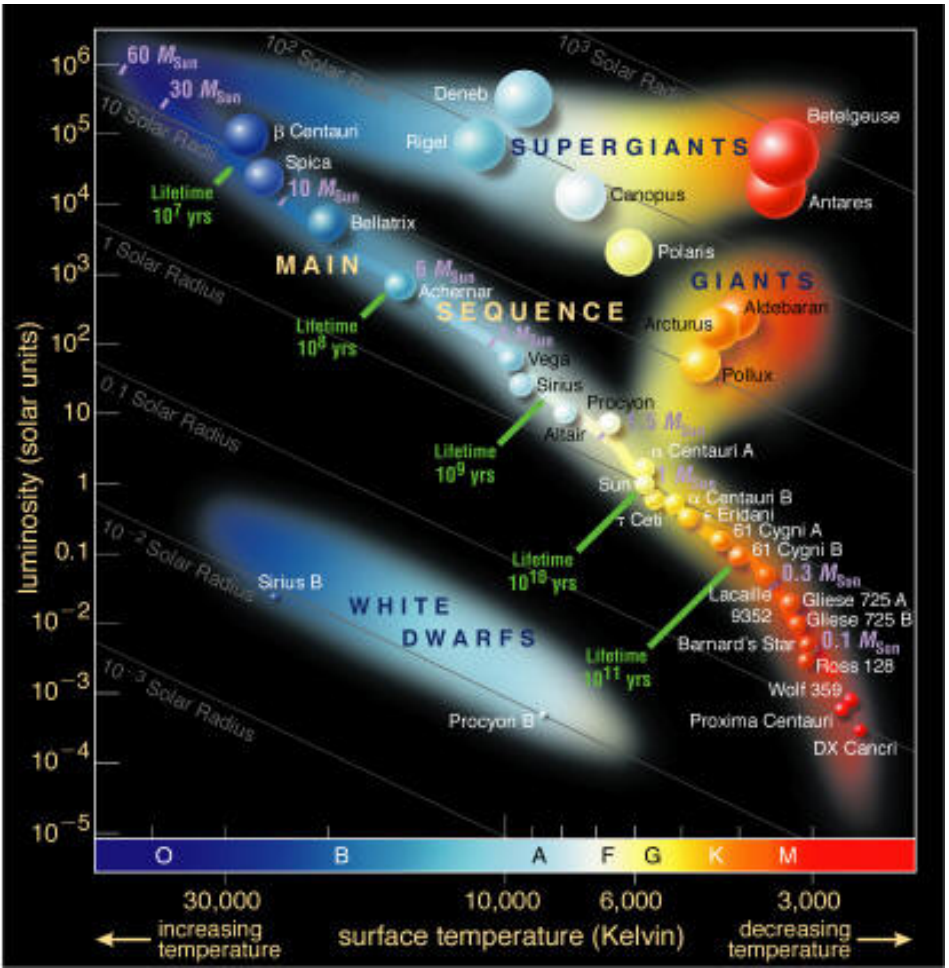


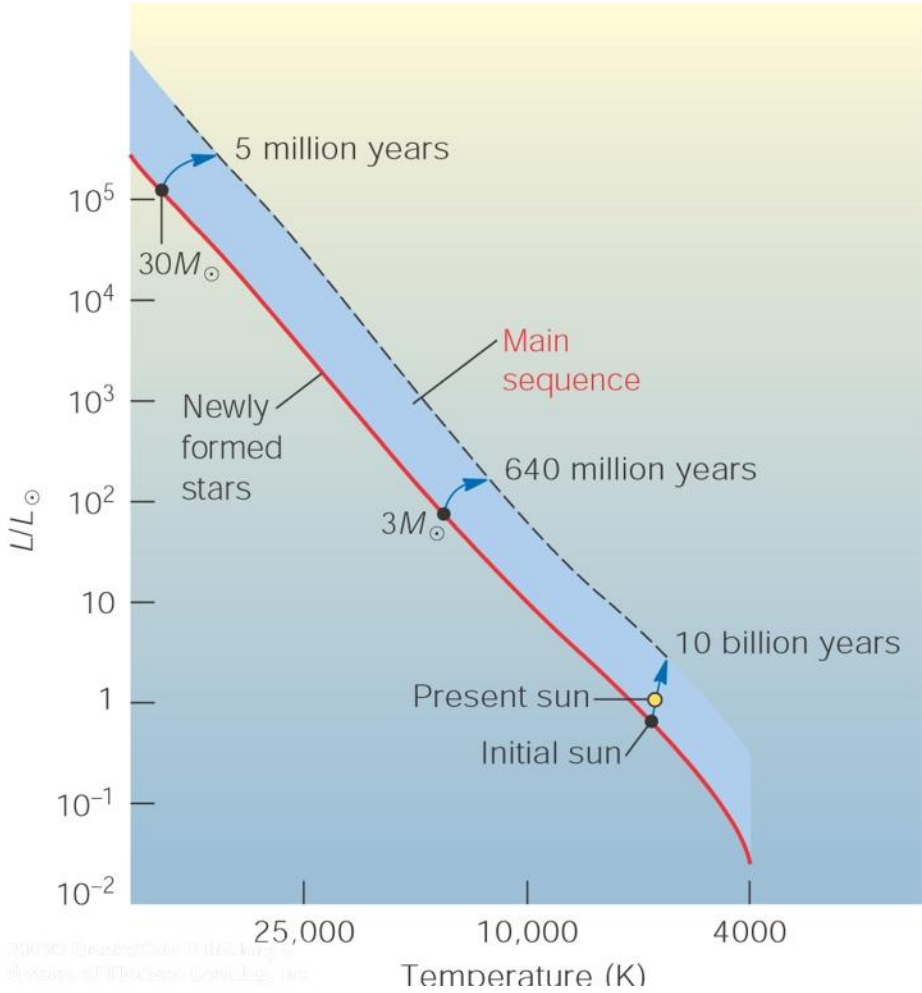
Death of a Massive Star



CMD with Main-Sequence Lifetimes

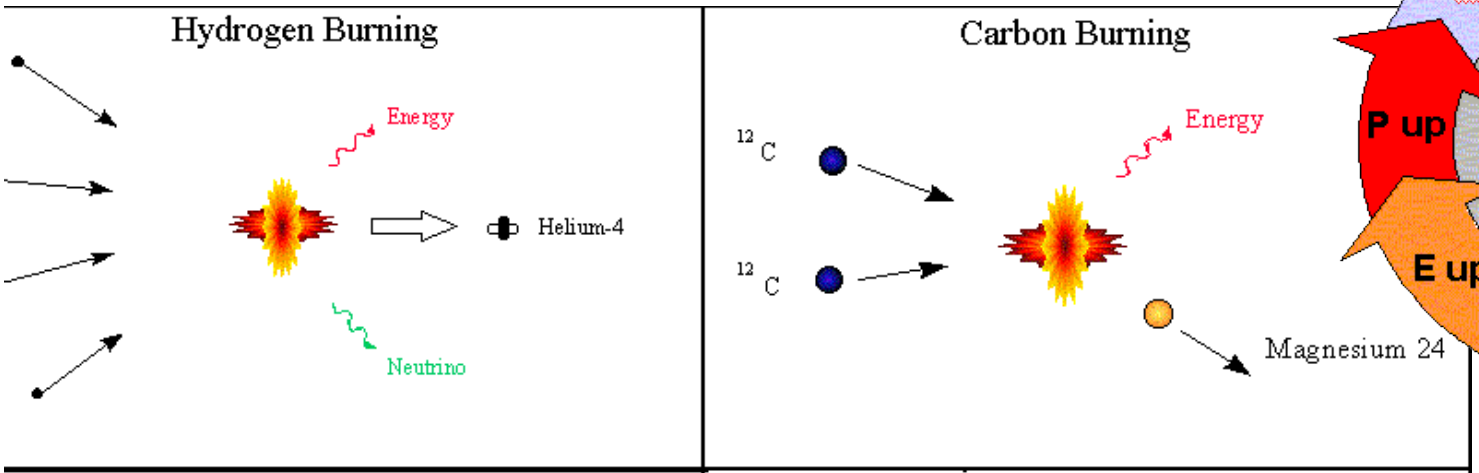
- Massive stars join ZAMS more quickly than Sun
- Massive stars also leave main sequence more quickly

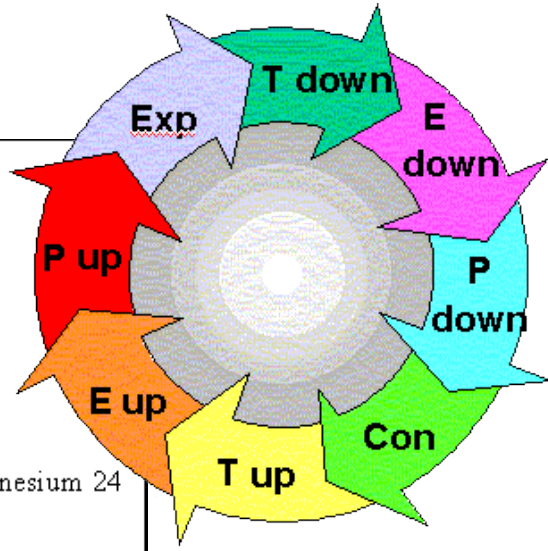




Fusion of Heavier Elements

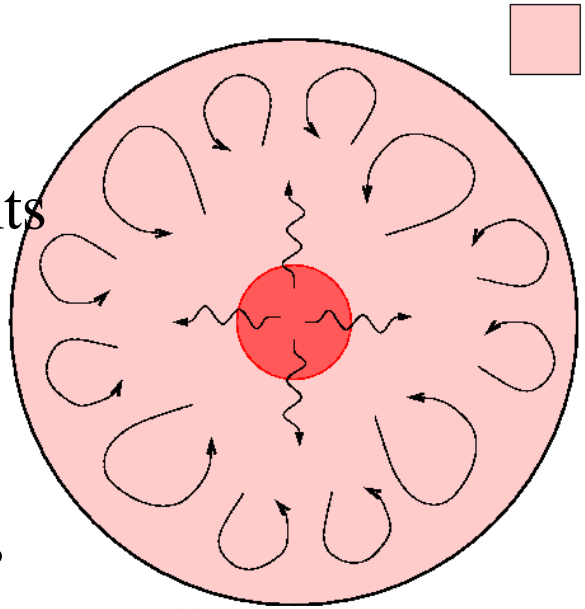
- Electrostatic repulsion (Coulomb barrier) larger for heavy elements
- Higher temperature & pressure is needed to fuse heavy elements
- Helium fuses into Carbon non-explosively

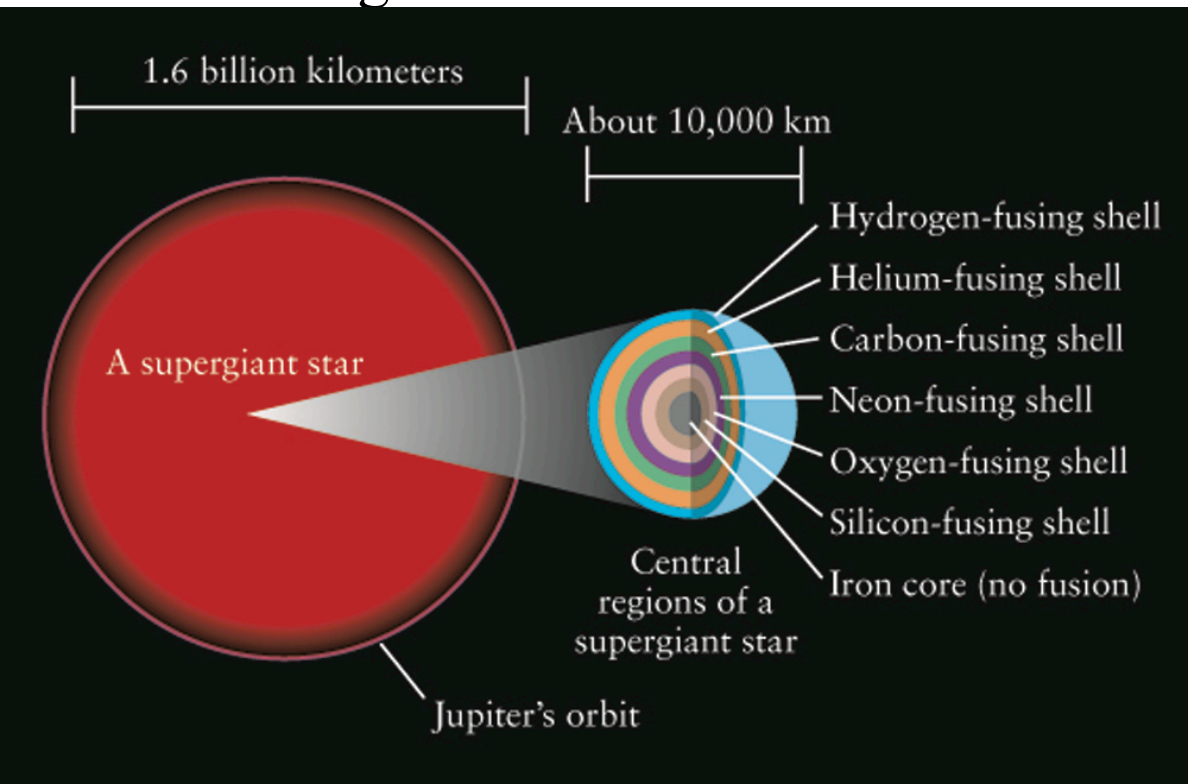


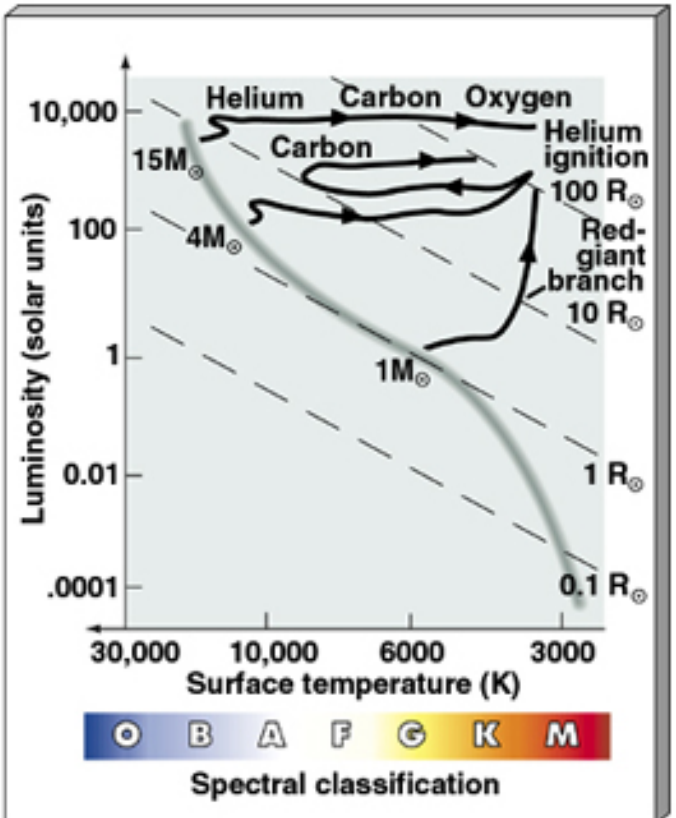


Supergiants

- Higher core temperatures fuse elements into heavier elements until iron
- Each element burns more quickly, giving less energy than the last
- Supergiants can make many crossings of HR Diagram

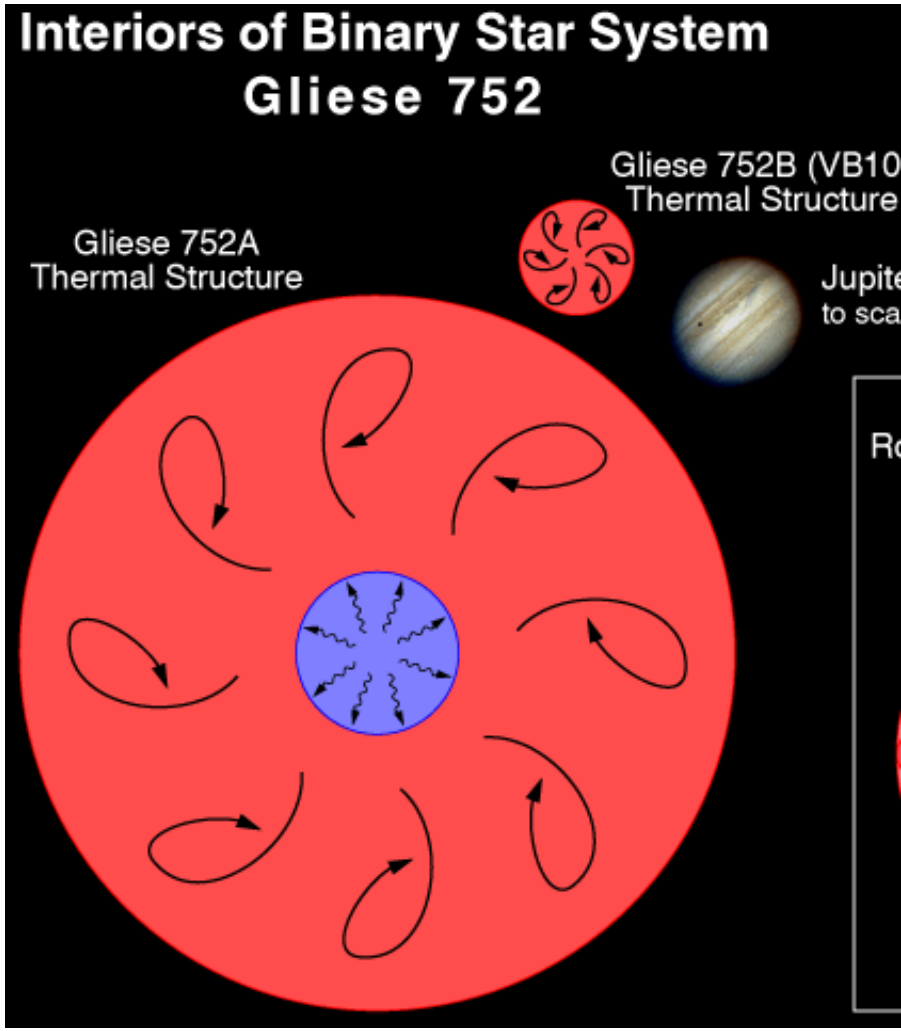






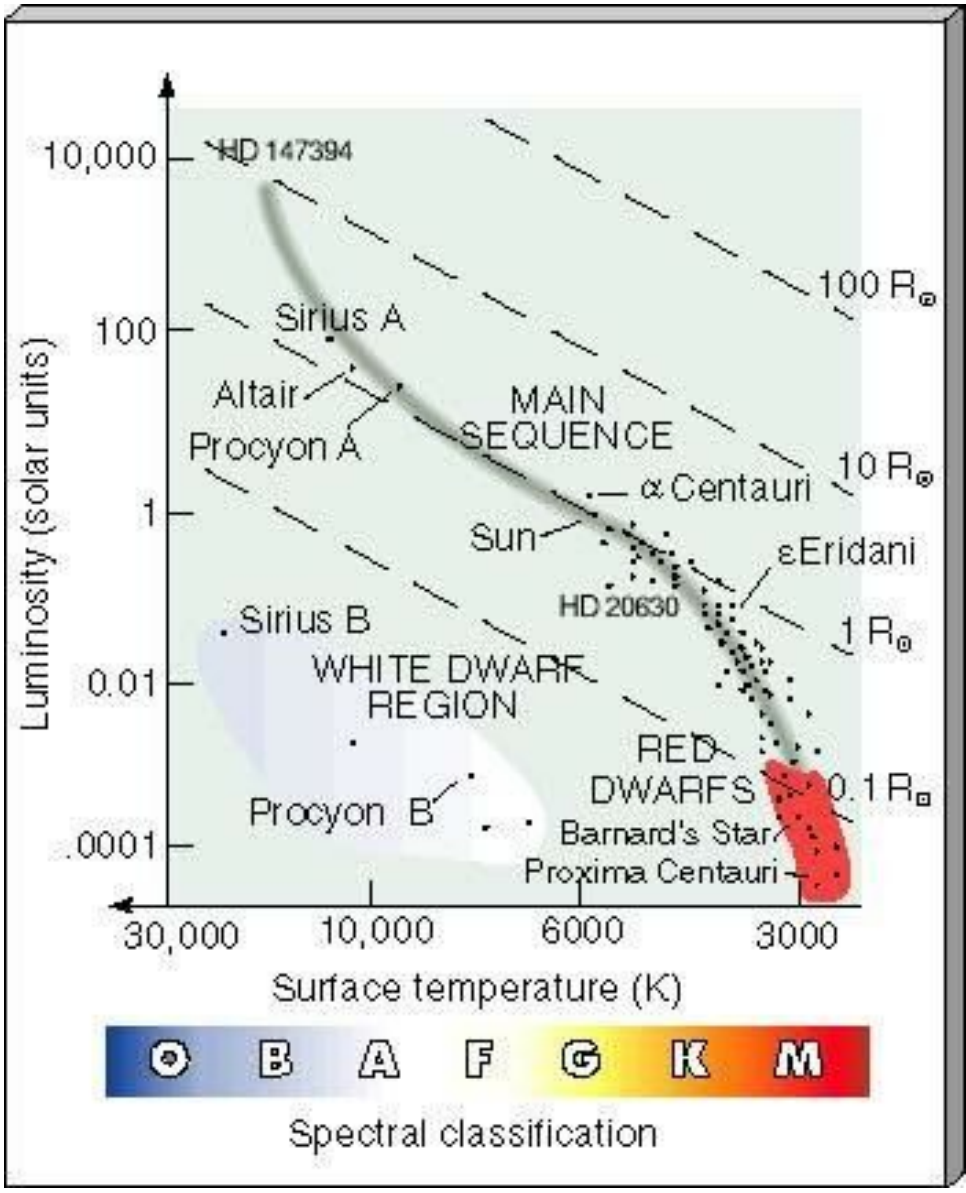
Low Mass Stars

- Gliese 752A is 0.3 M_{sun}
- B is ~0.09 M_{sun}
- B's temperature is so low; it's fully convective/mixed
- All its hydrogen becomes helium
- Proxima Centauri



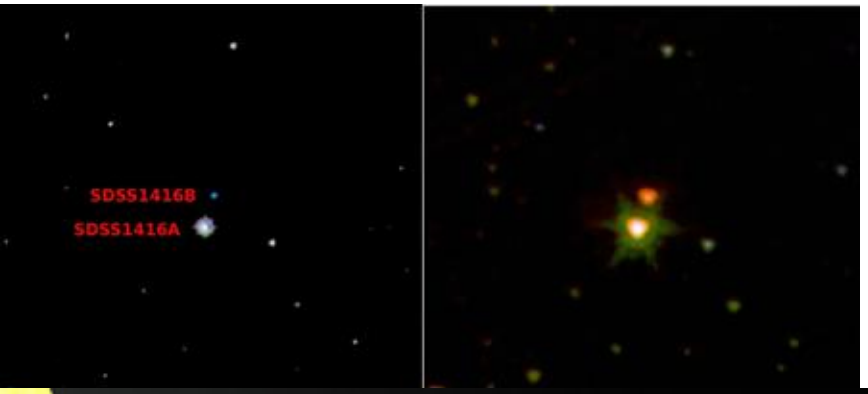
Red Dwarfs Become White Dwarfs

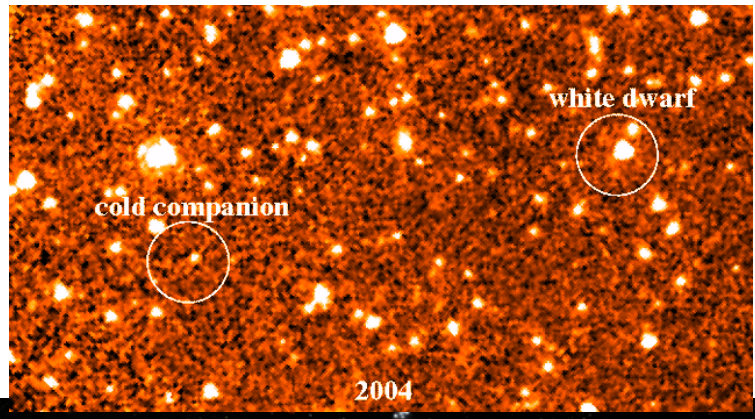
- 2 Billion years to contract
- 6 Trillion years on Main Sequence burning hydrogen (longer than lifetime of the universe)
- No Hydrogen shell burning phase so no red giant phase
- Eventually will contract to white dwarf

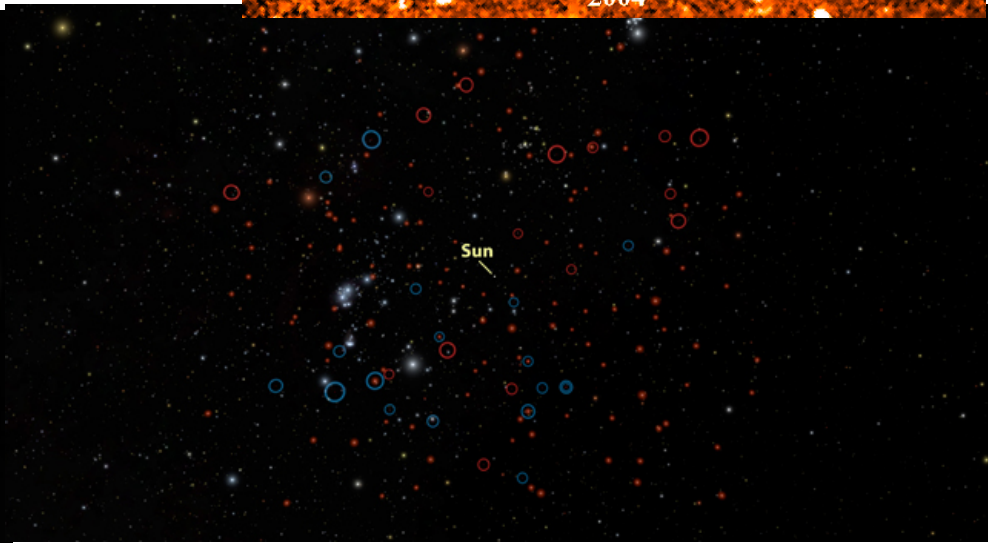


Red, White & Brown Dwarfs

- Red dwarfs: the small, faint, end of the main sequence stars
- White dwarfs: remnants of star with less than 8 solar masses
- Brown dwarfs: less than $0.08M_{sun}$=80 Jupiters; never burn Hydrogen
- Planets are less massive than 13 Jupiters & cannot burn deuterium

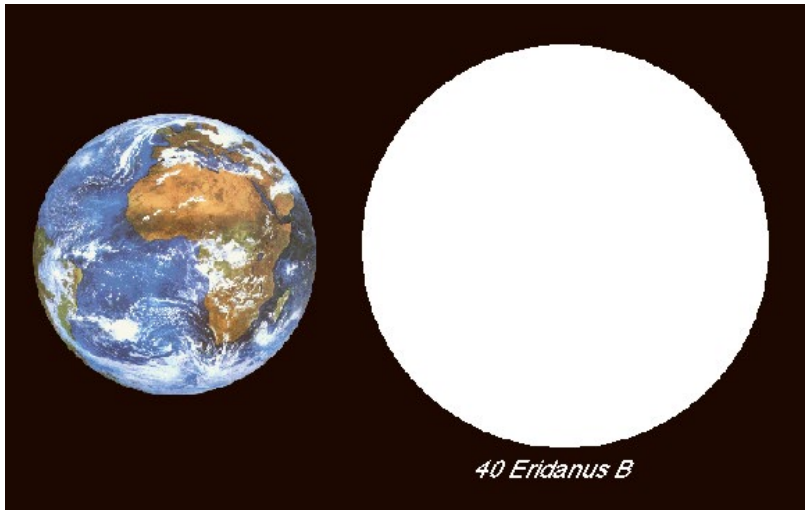


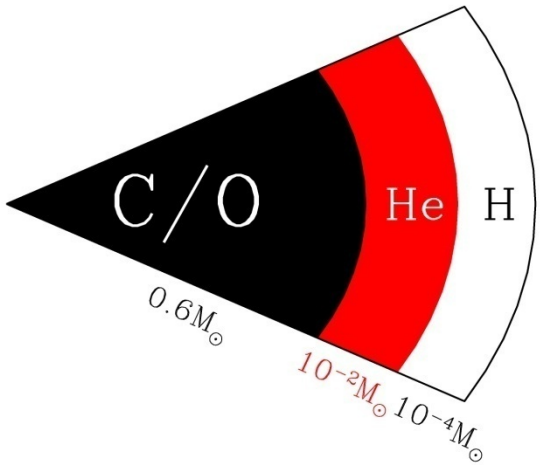


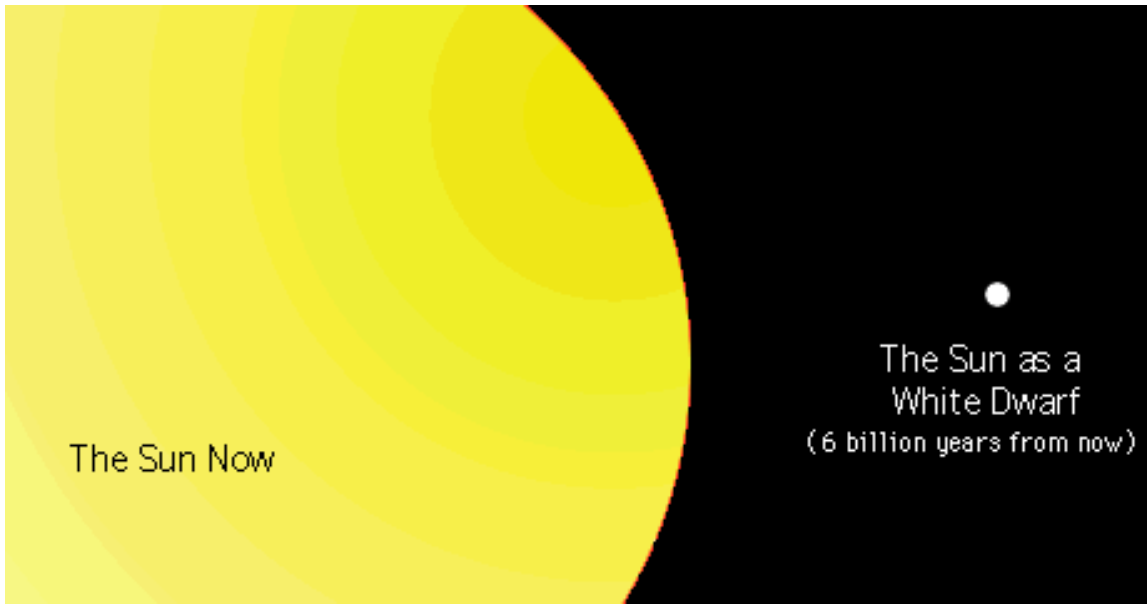


Star's Core Becomes **White Dwarf**

- One Example is Sirius B
- Radius about the Earth's
- Surface temperature is 25000K
- Mass is ~1 solar mass
- Gravity = 100,000 Earth's
- No nuclear fusion

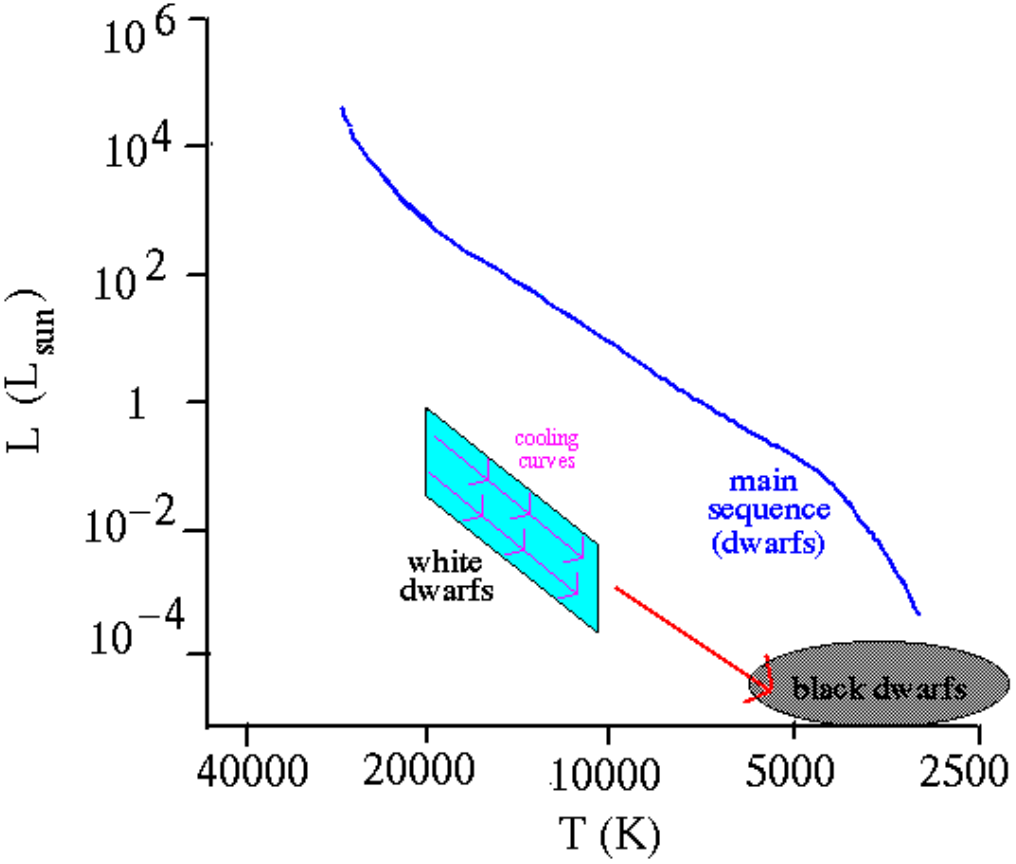


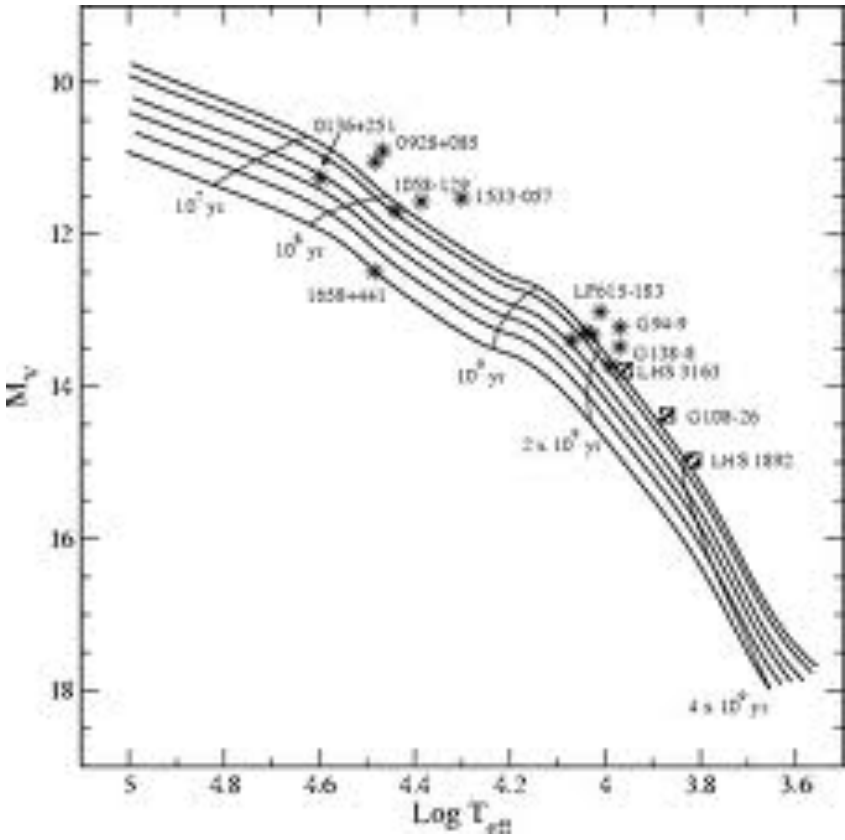




Black Dwarfs

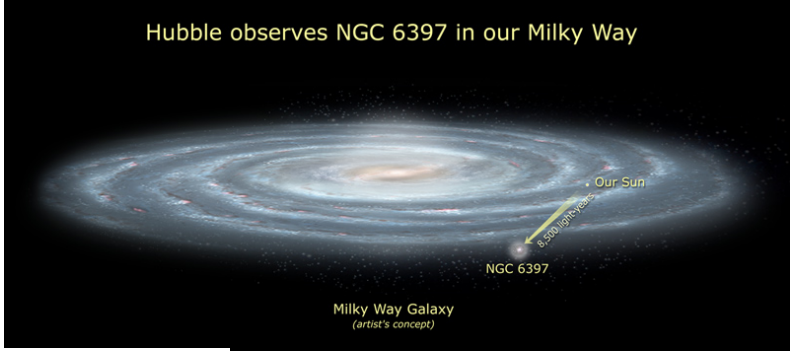
- After formation a white dwarf continues to cool – no energy sources
- Supported by Electron Degeneracy so it does not contract

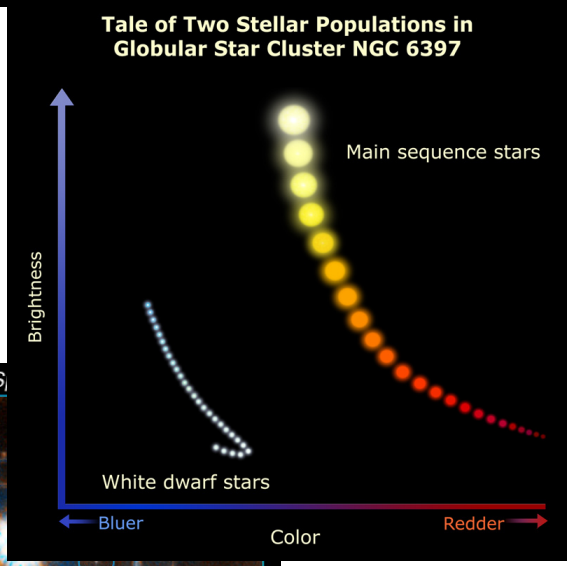


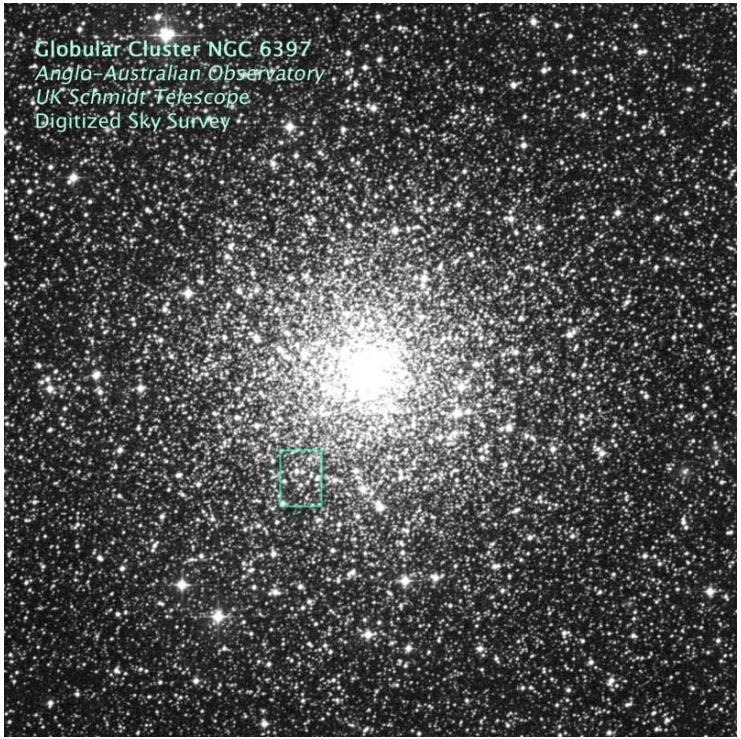


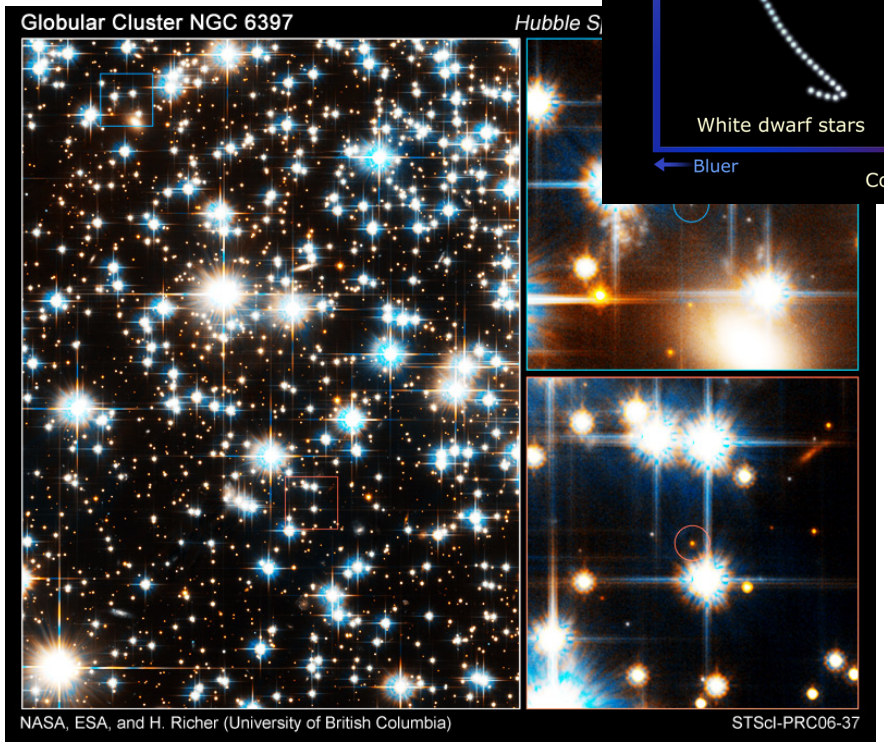
Age of Universe

- Black dwarfs found in globular cluster NGC6397
- Globular clusters have old stars
- Coolest=Oldest Black Dwarfs 12Billion years old







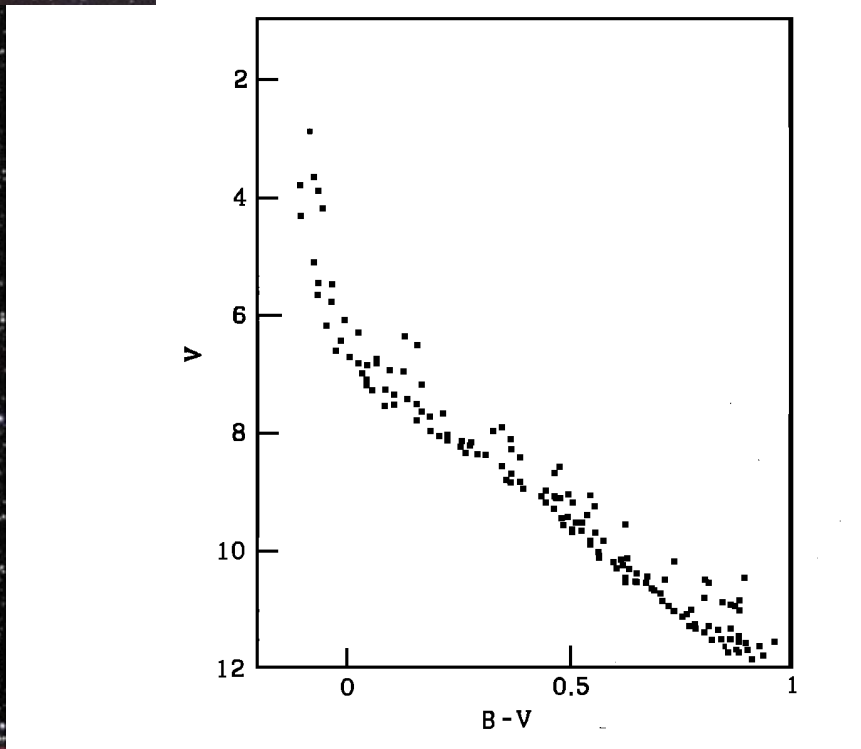


Science: Theory Predicts Observations

- Evidence of stellar evolution from Open &Globular Clusters
- All at the same distance
- All created at same time
- All have same chemical composition
- Very populous so CMD's contains examples of rare stars and short phases
- Lots of clusters of various ages
- Jewel box cluster

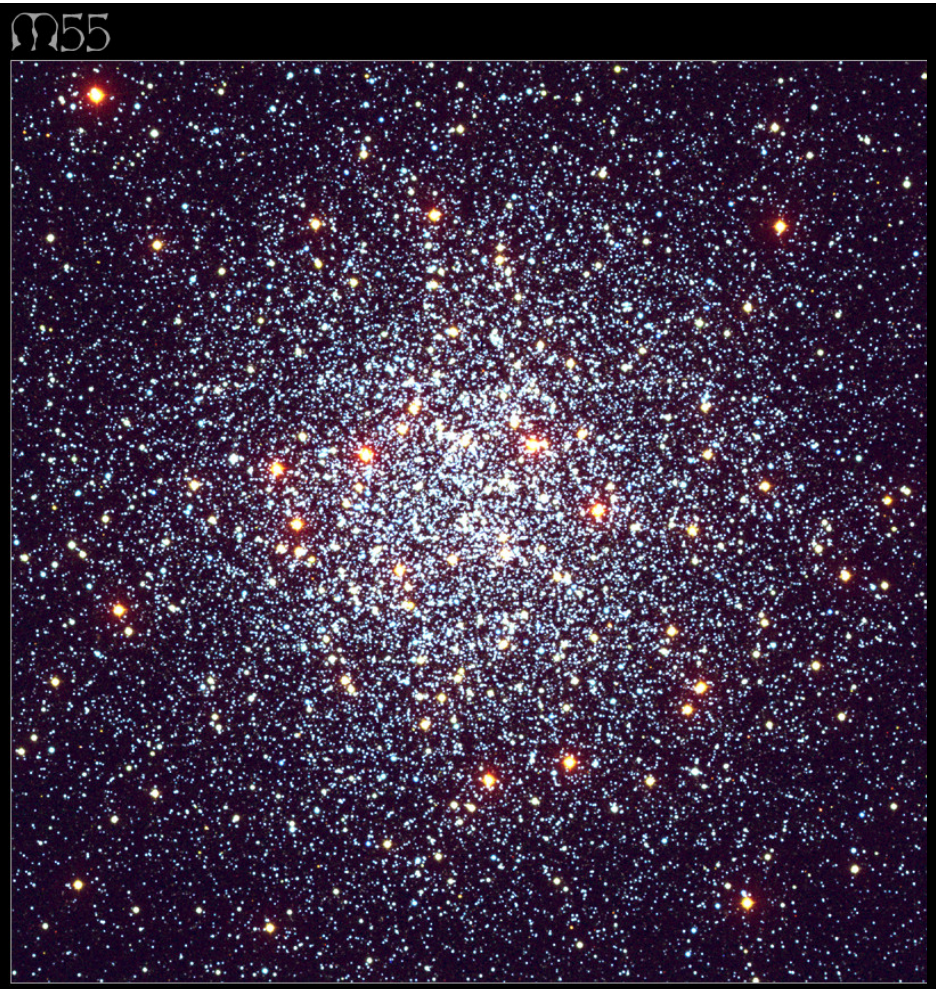
Open Clusters

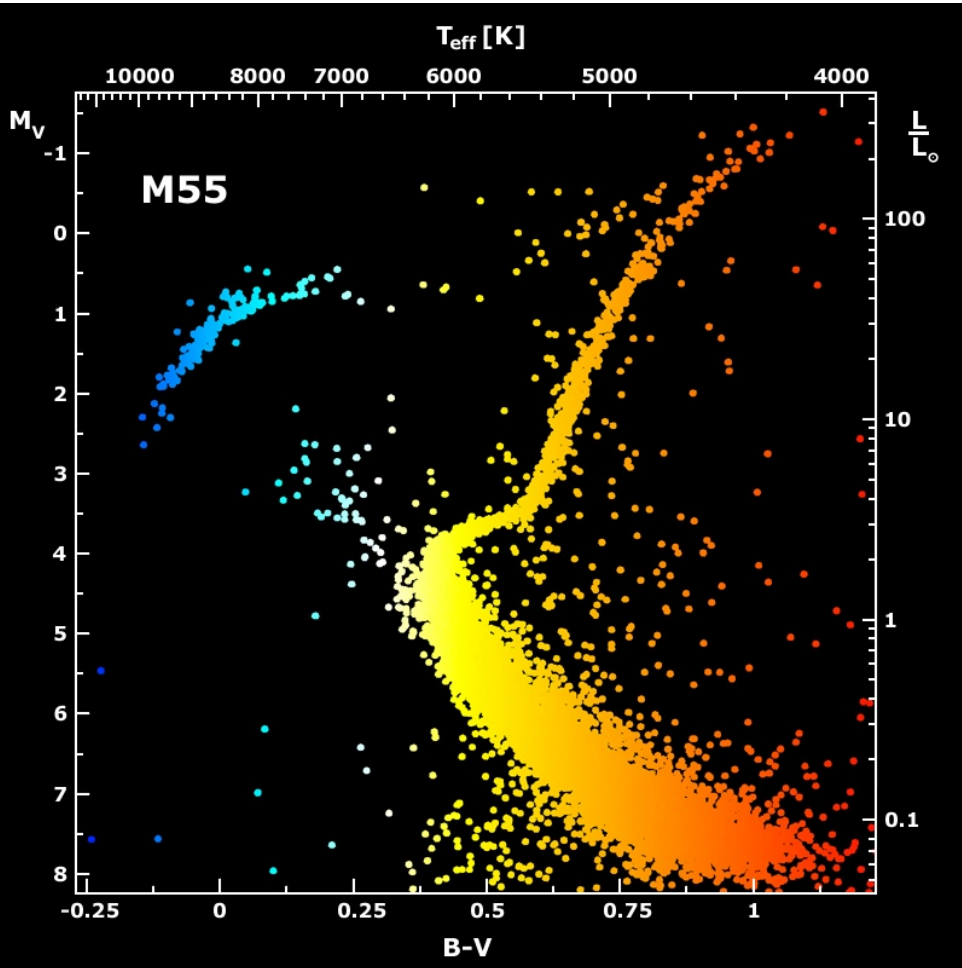
- A few thousand open clusters
- 10-10,000 stars; ~25parsecs diameter
- Irregular shape, open, transparent appearance



Globular Clusters

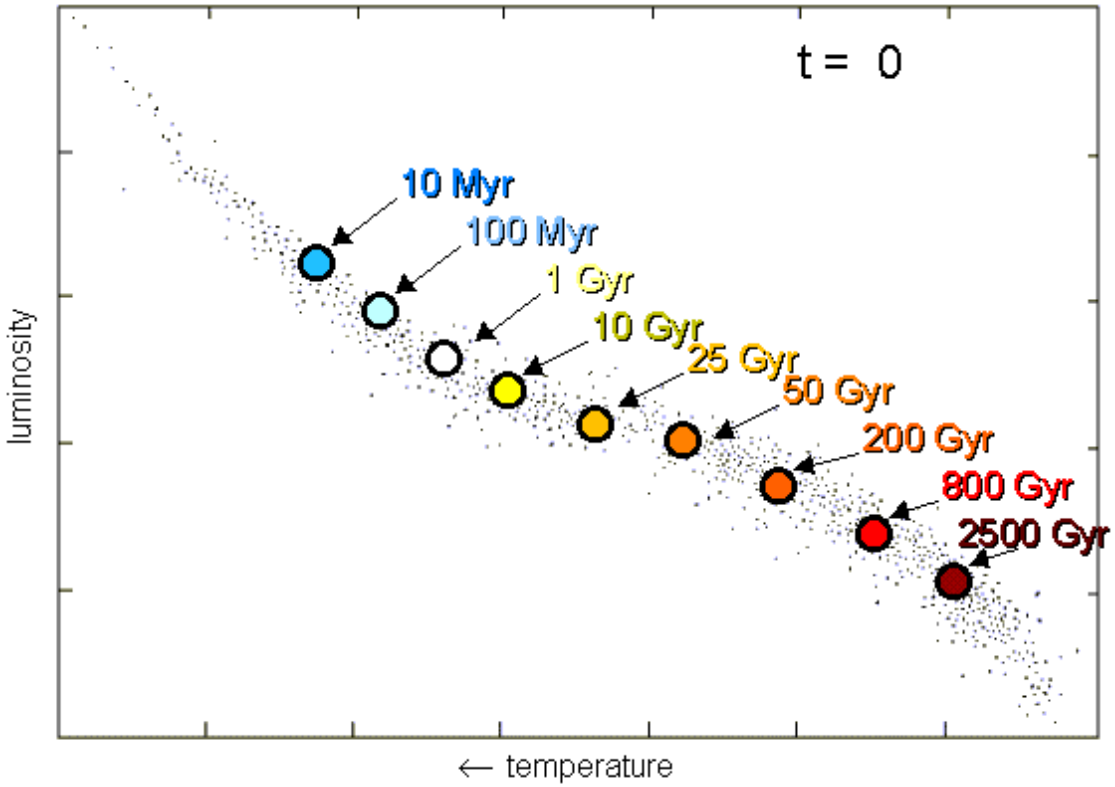
- ~100 globular clusters in Milky Way Galaxy
- 1 million stars; 10 parsecs in radius
- Old stars composed: 75% Hydrogen 25% Helium 0% rest



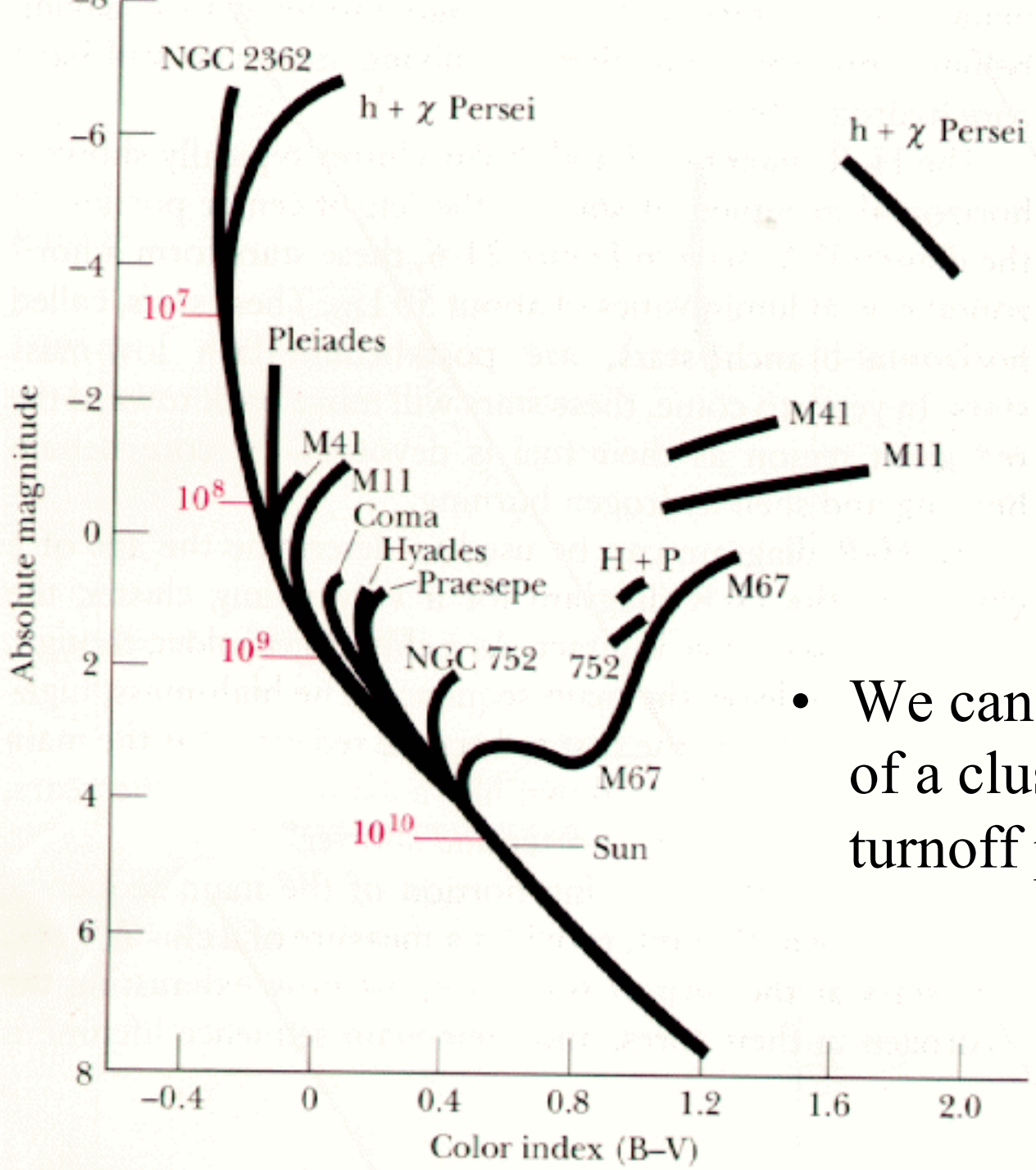


Stellar Evolution in Cluster

- **Zero Age Main Sequence = ZAMS**
- Massive Stars: Live Fast; Die Young
- As time goes on, a group of stars formed at the same time (a cluster) will loose its more massive stars

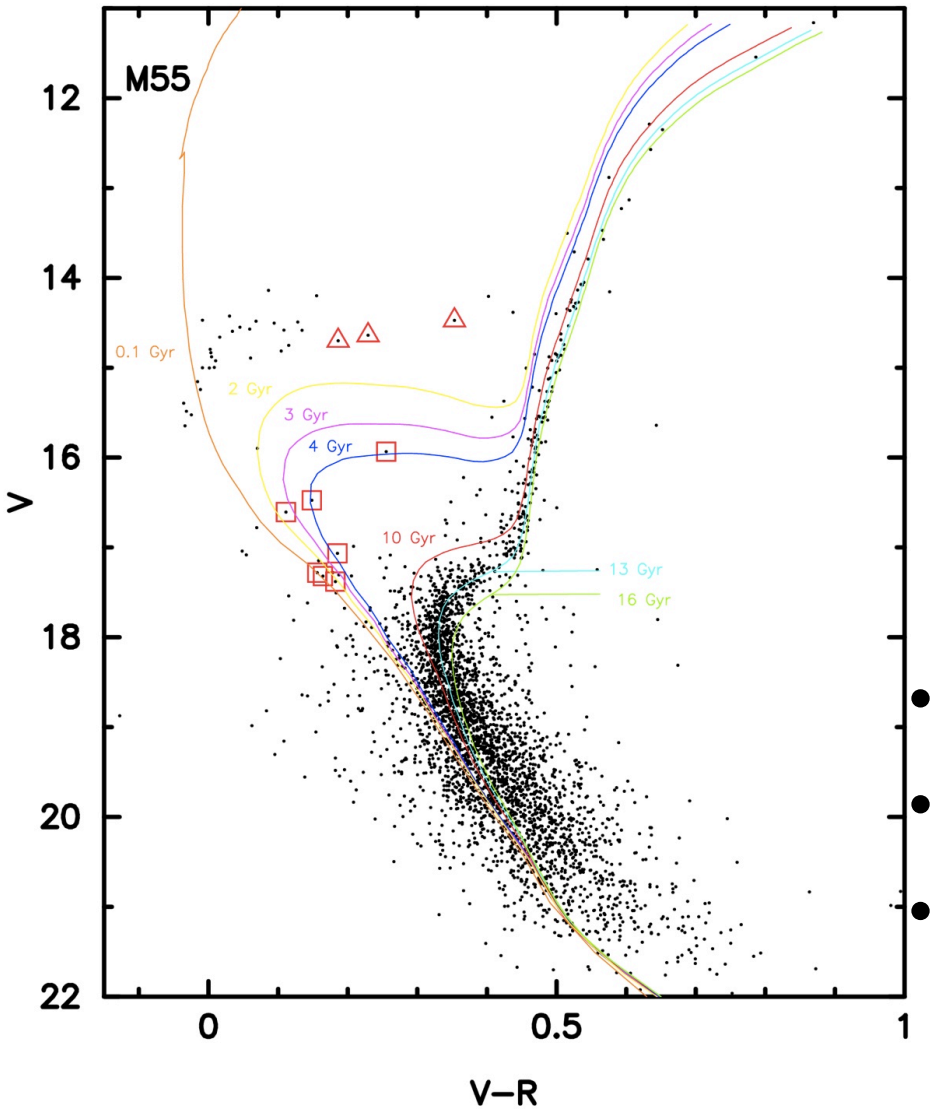


Turn Off Points



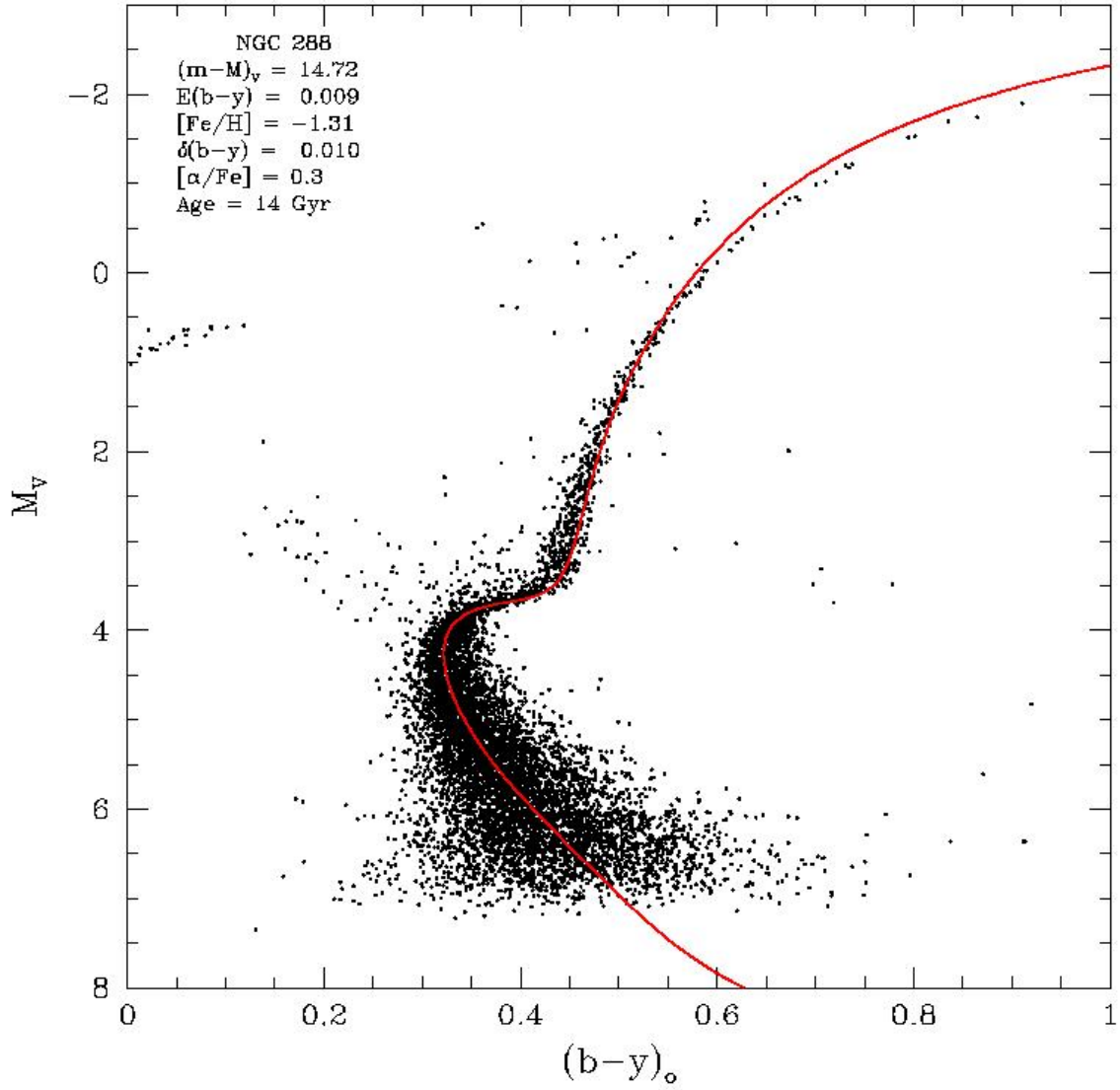
- We can estimate the age of a cluster from the turnoff point

Isochrones



- Theory calculates Isochrones
- Iso=same chron = time
- Stars of various masses at a certain time (age)

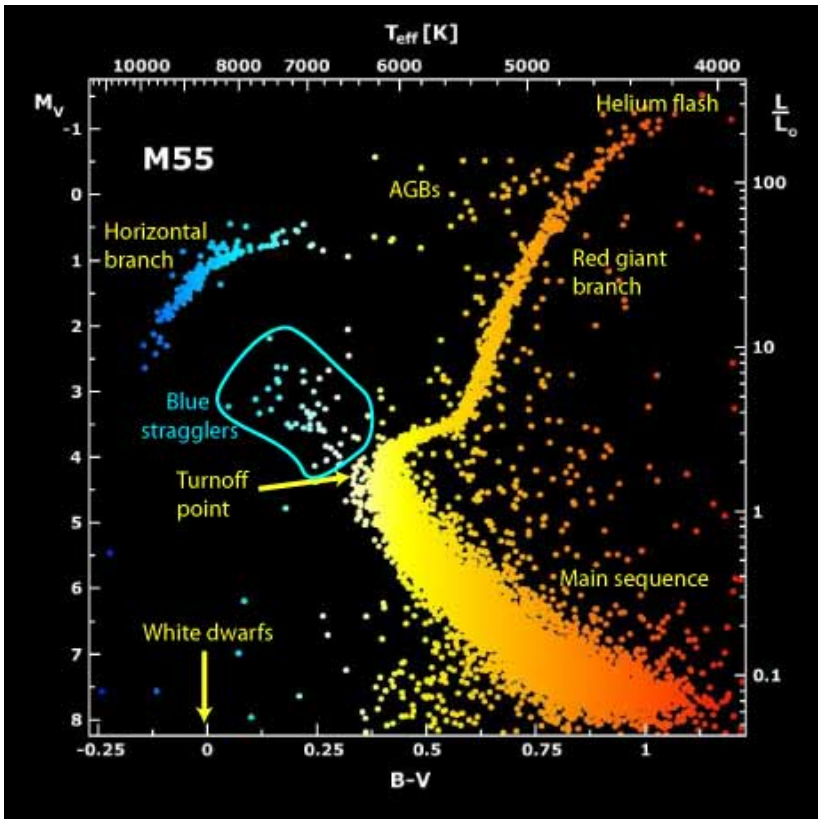
Theory Agrees with Observations. Isochrones Fit Cluster CMD

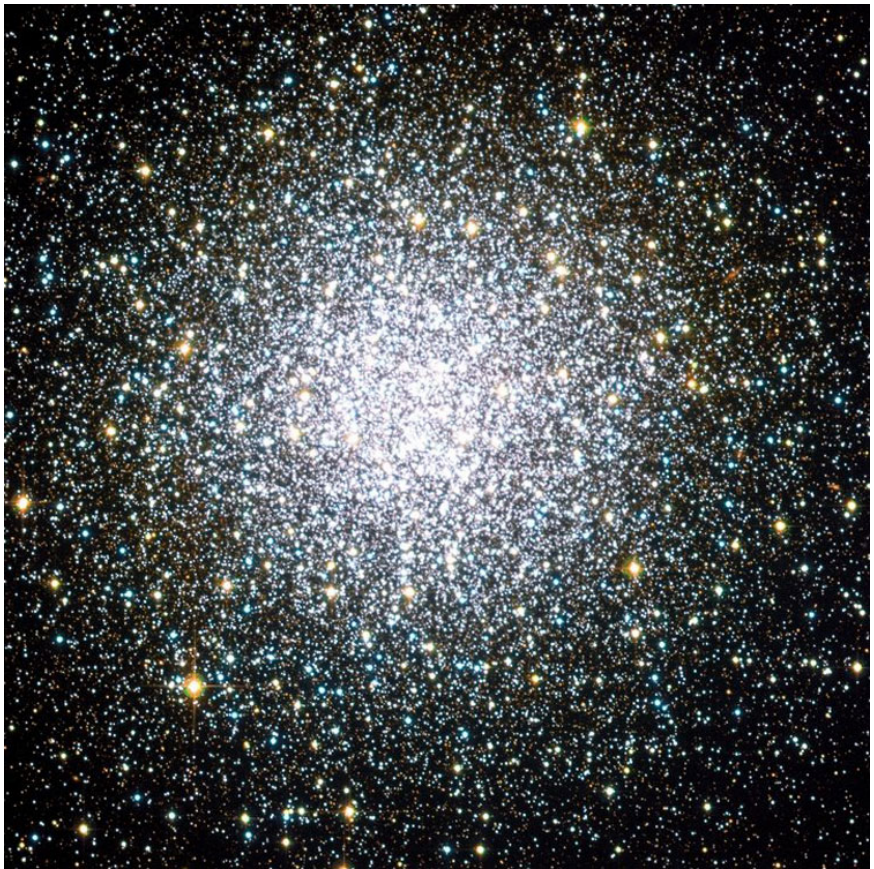


- Distance
- Reddening
- Metalicity
- Age
- NGC 288 J. Clem

Blue Stragglers

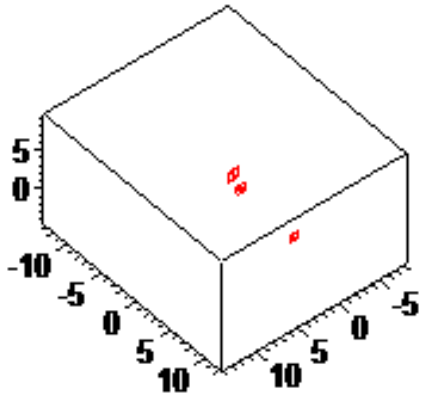
- But not all stars fit! Some beyond the turnoff
- Mergers? Binary stars or collisions?
- Within 30 light years a million stars





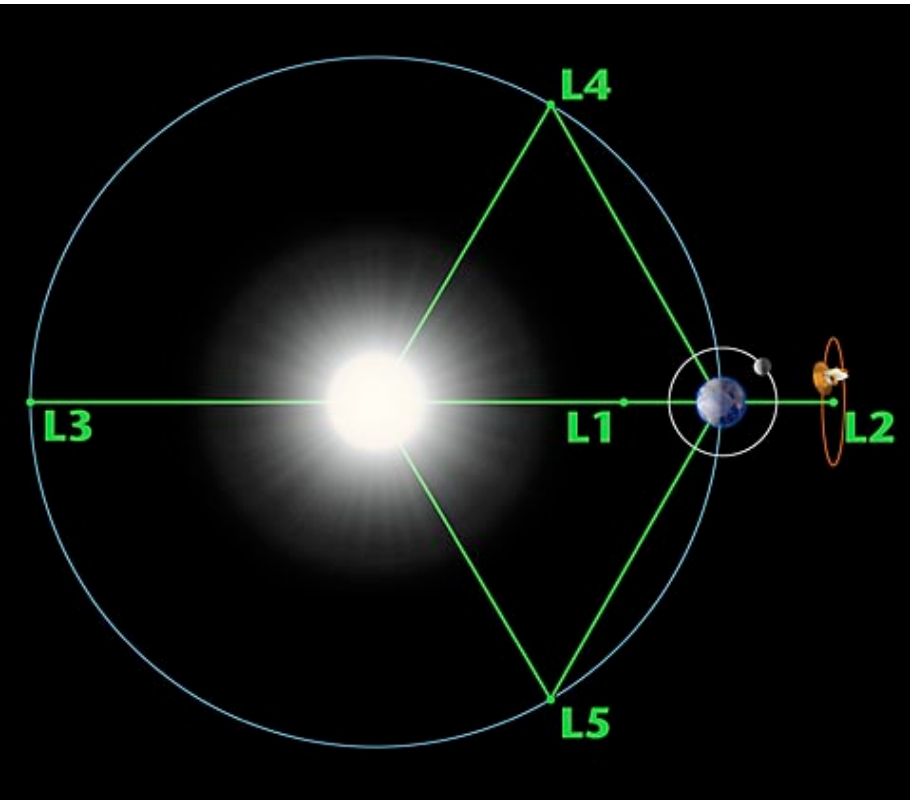
Lagrange 1736-1813

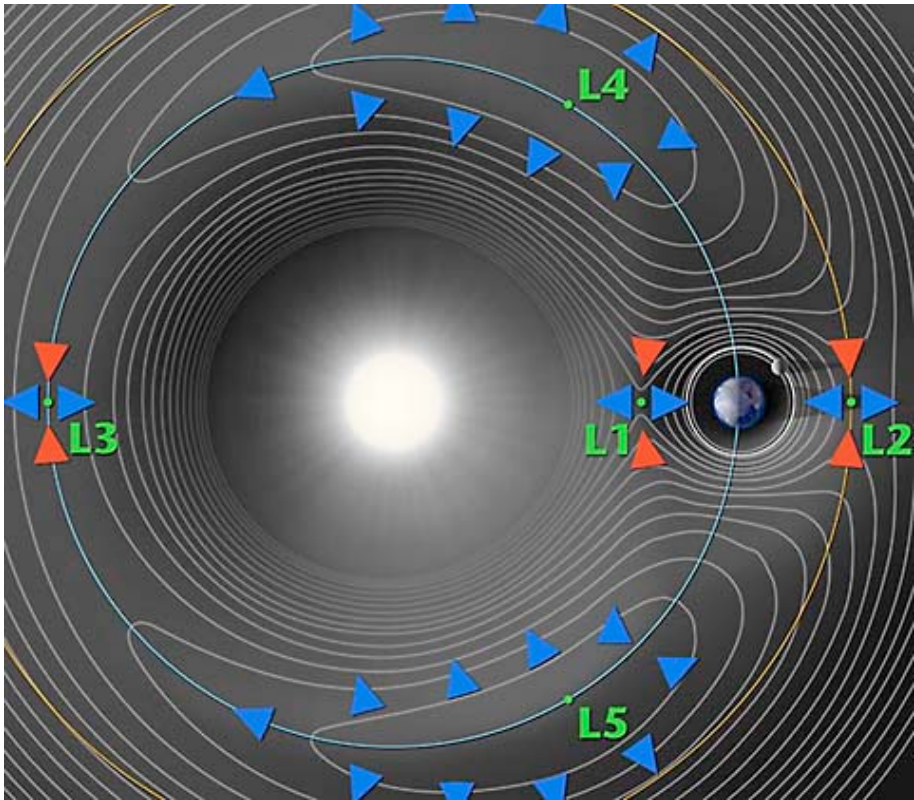
- One of the greatest mathematicians of the 18th century
- Survived the French Revolution
- Newton solved two body problem
- Lagrange solved restricted three body problem



Lagrangian Points

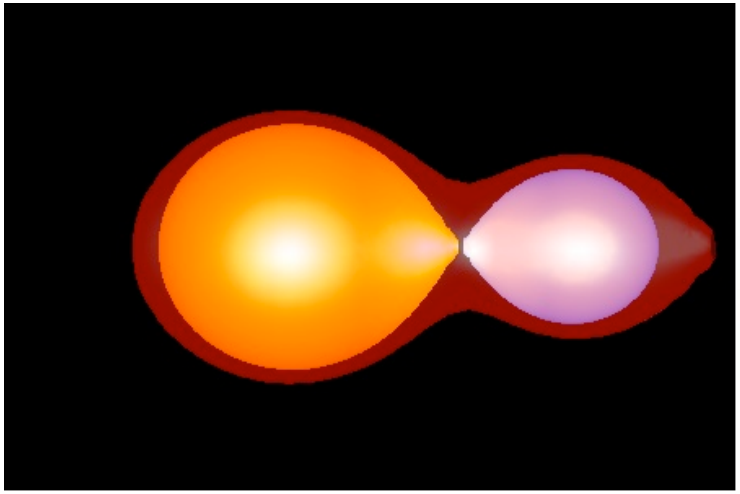
- Lagrange Points are where gravitational forces of two stars balance
- L1, L2, L3 are unstable but L4&L5 are stable
- SOHO at L1 and at L2 is WMAP and maybe JWST

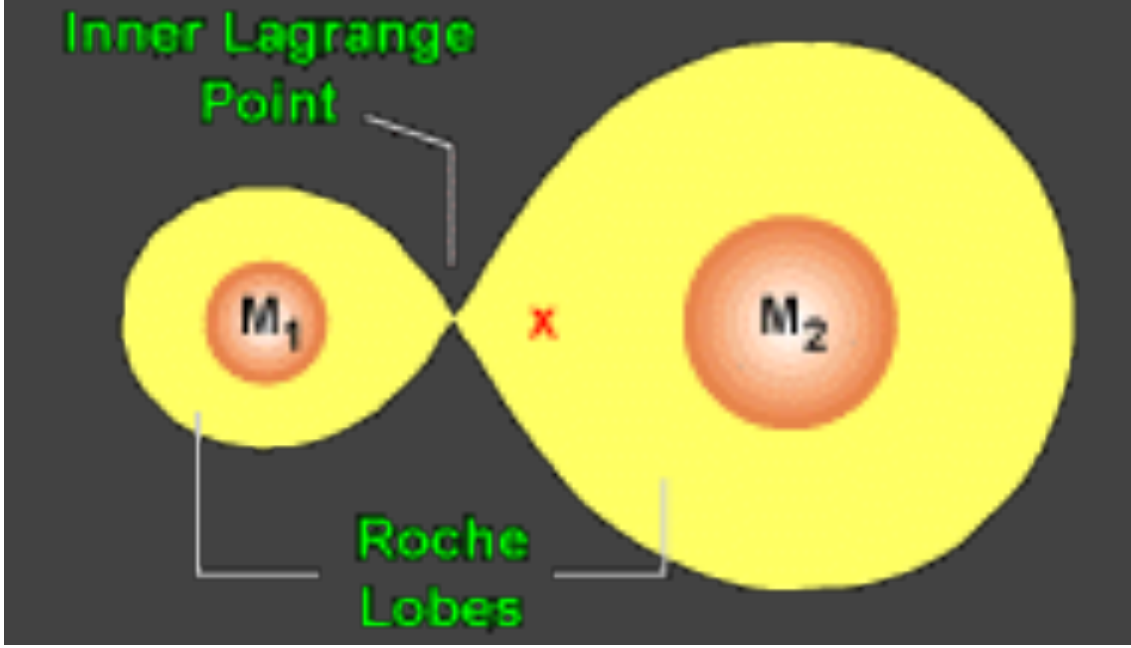


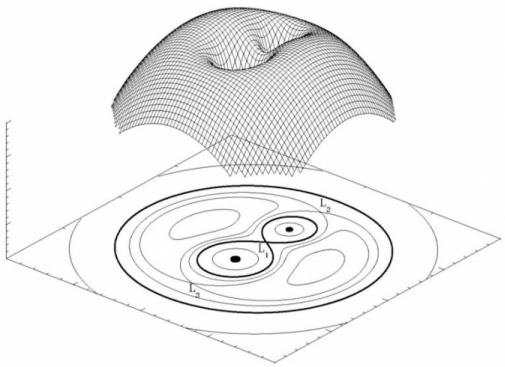


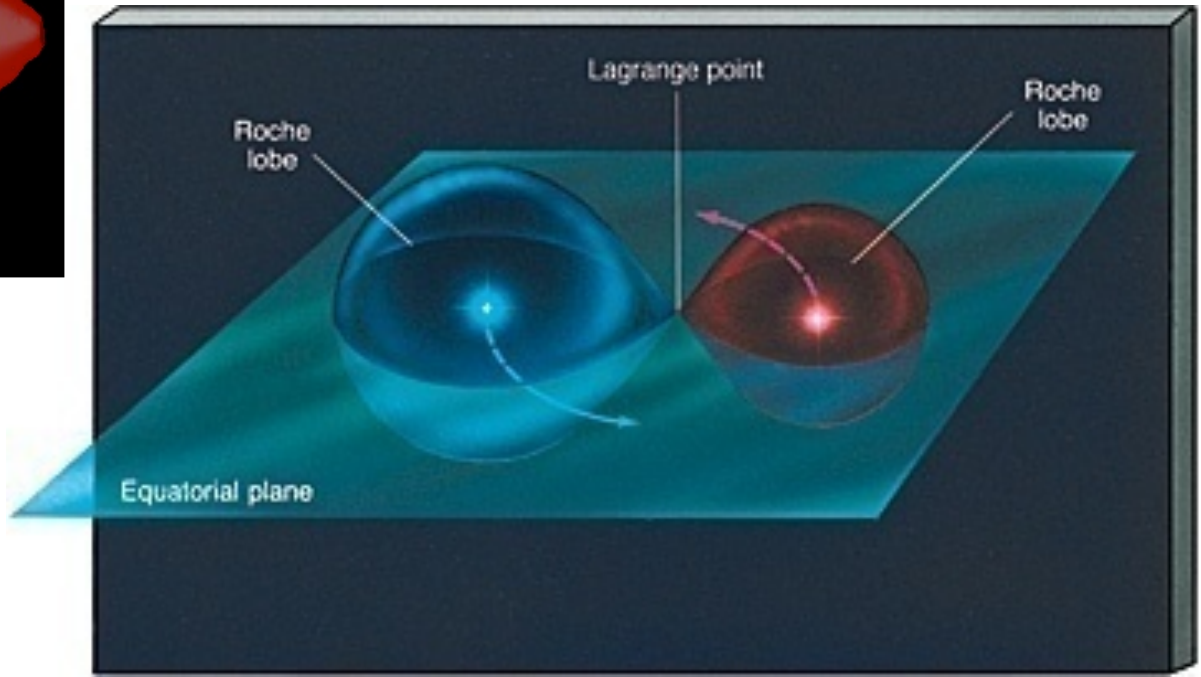
Roche Lobes

- Roche Lobes are the regions of gravitational influence of each star



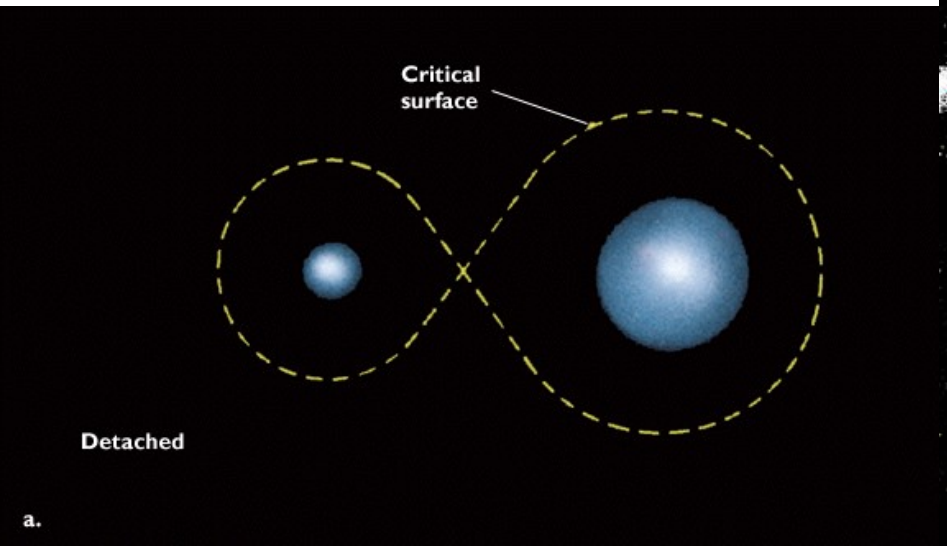


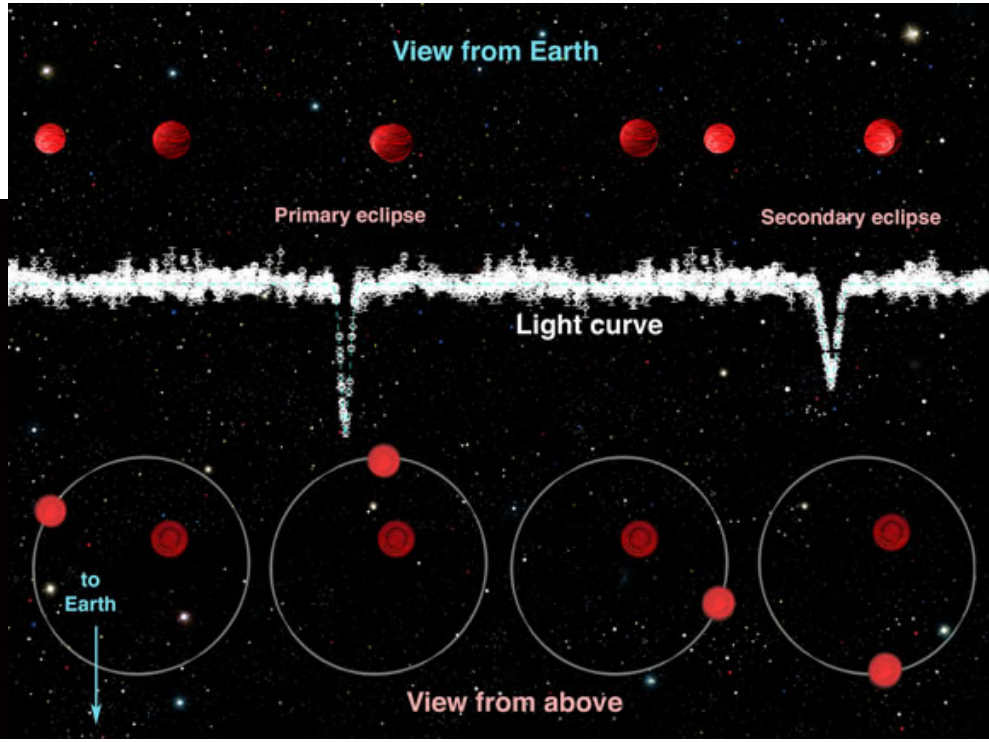




Detached Binary

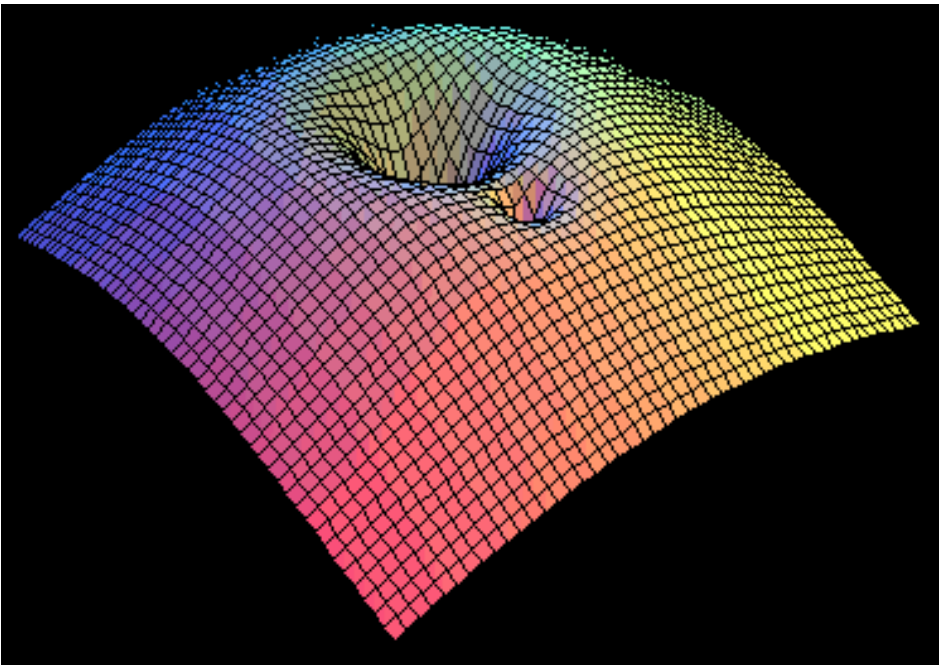
- If the star is well separated from its Roche Lobe then it is spherical and evolves like a single star
- Eclipsing pair of brown dwarfs

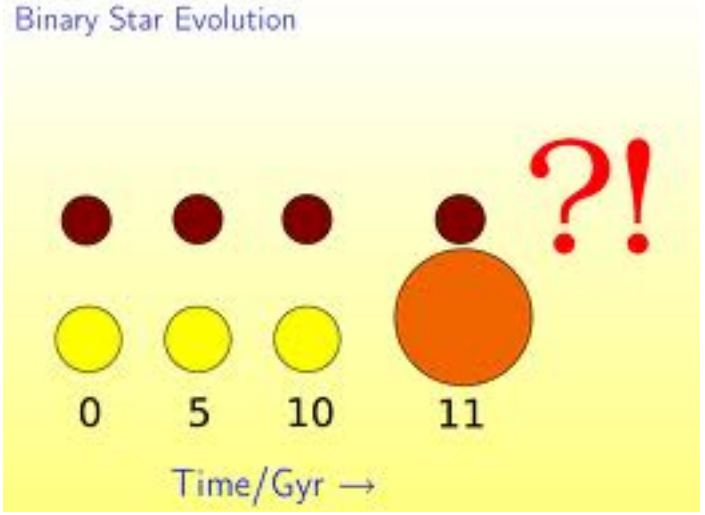




Mass Transfer

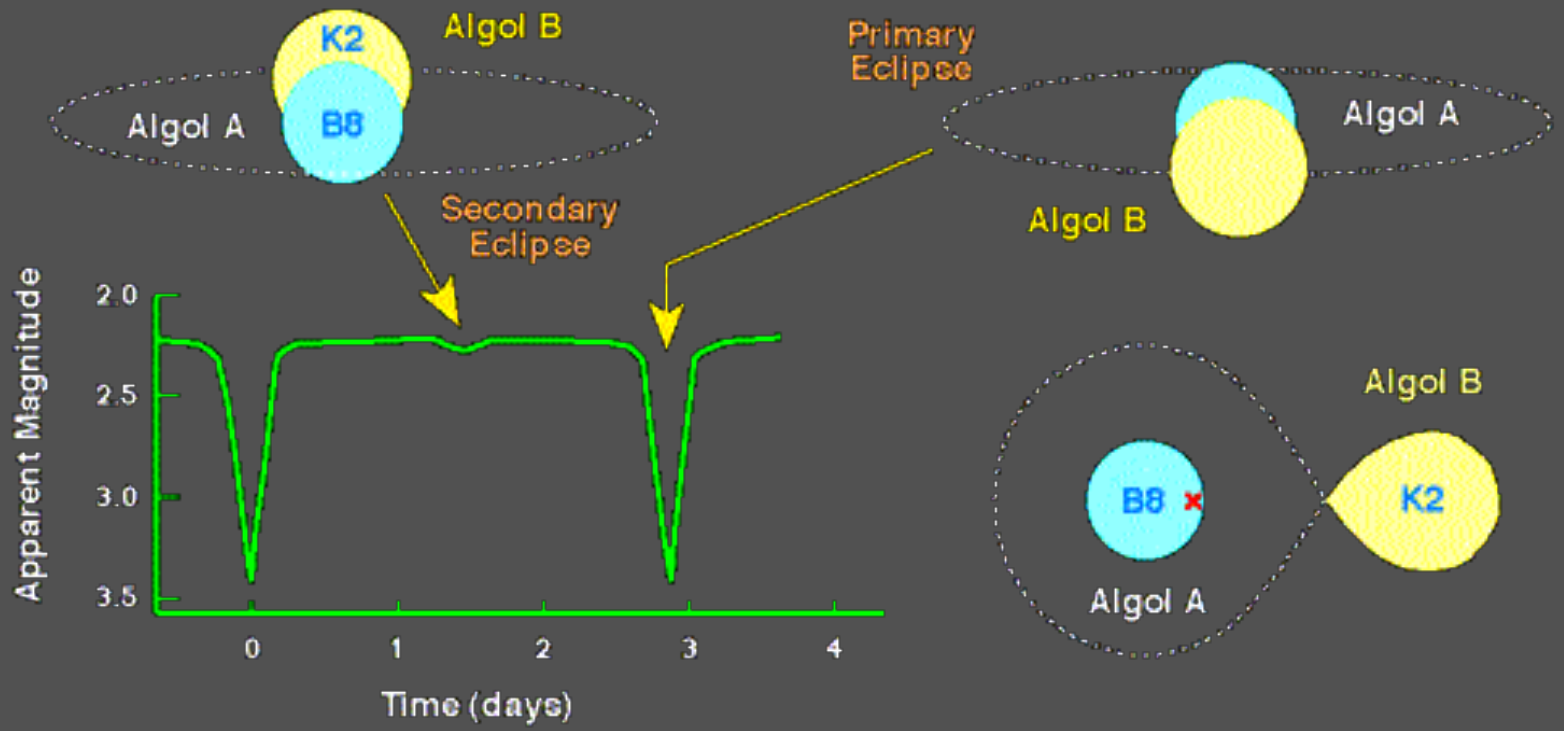
- Massive star makes big dent and small star makes small dent
- When more massive star becomes red giant
- It overflows its Roche lobe & transfers mass through L1 point





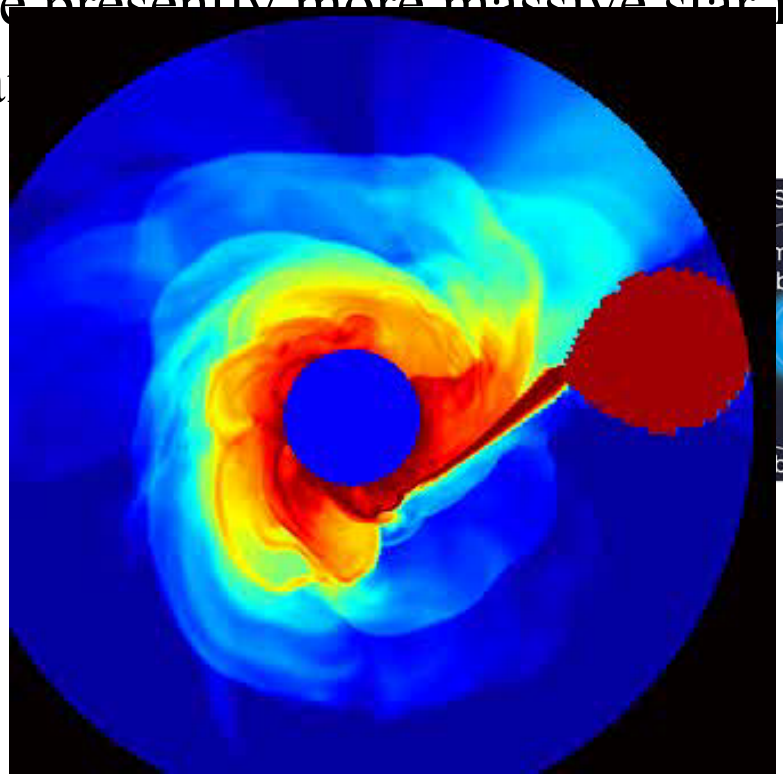
Semi Detached = Algol

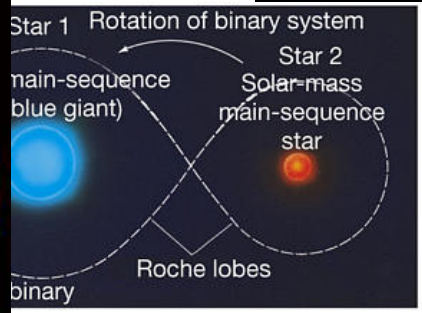
- One of the stars fills its Roche Lobe
- Mass transfers onto other star

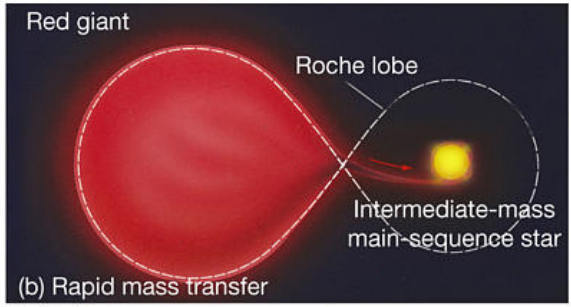


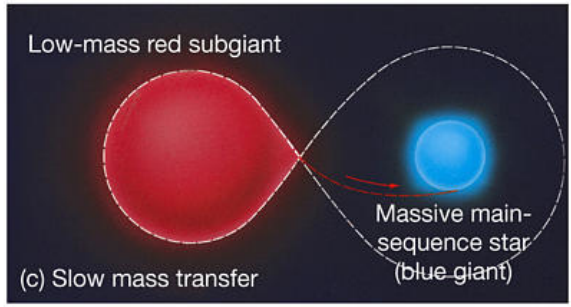
Algol

- Can peel off outer layers of star and transfer them to the companion
- Algol- originally more massive star is now the less massive but it's a red giant
- The presently more massive star is a ma



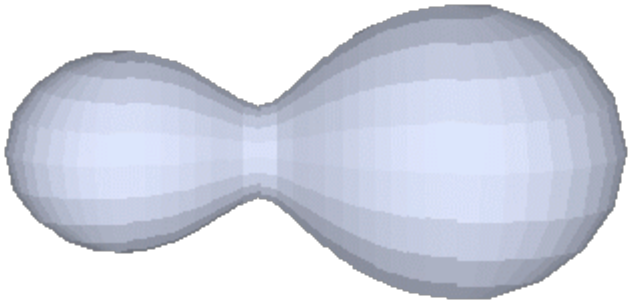


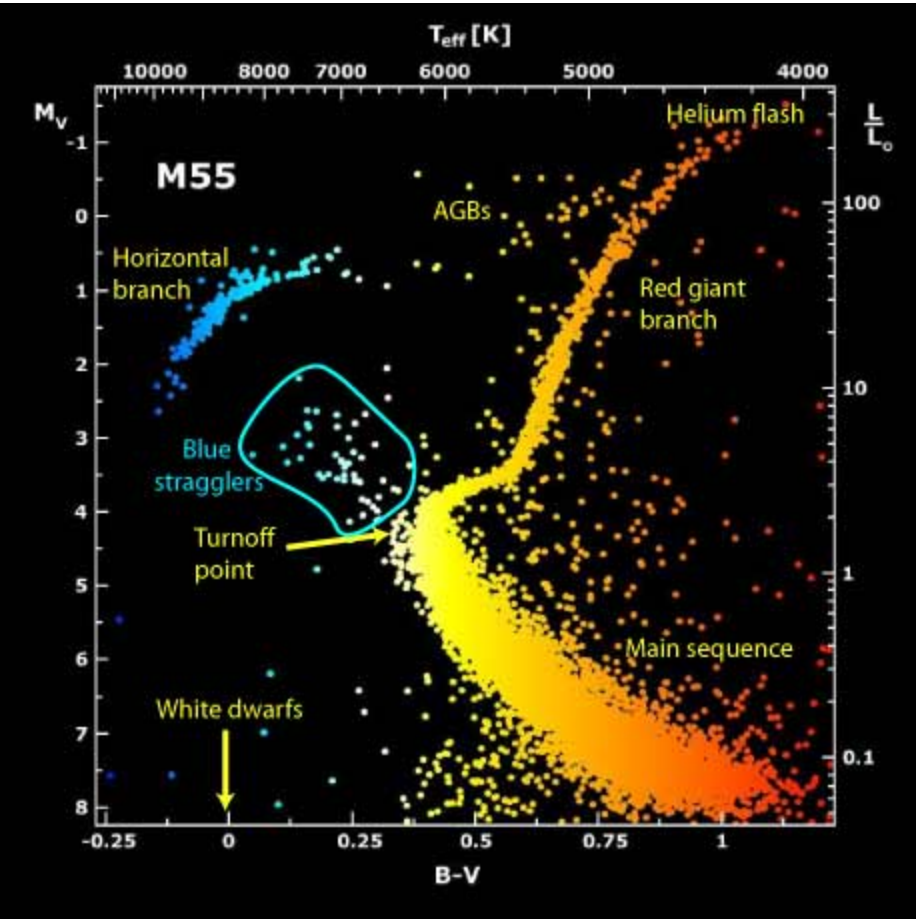


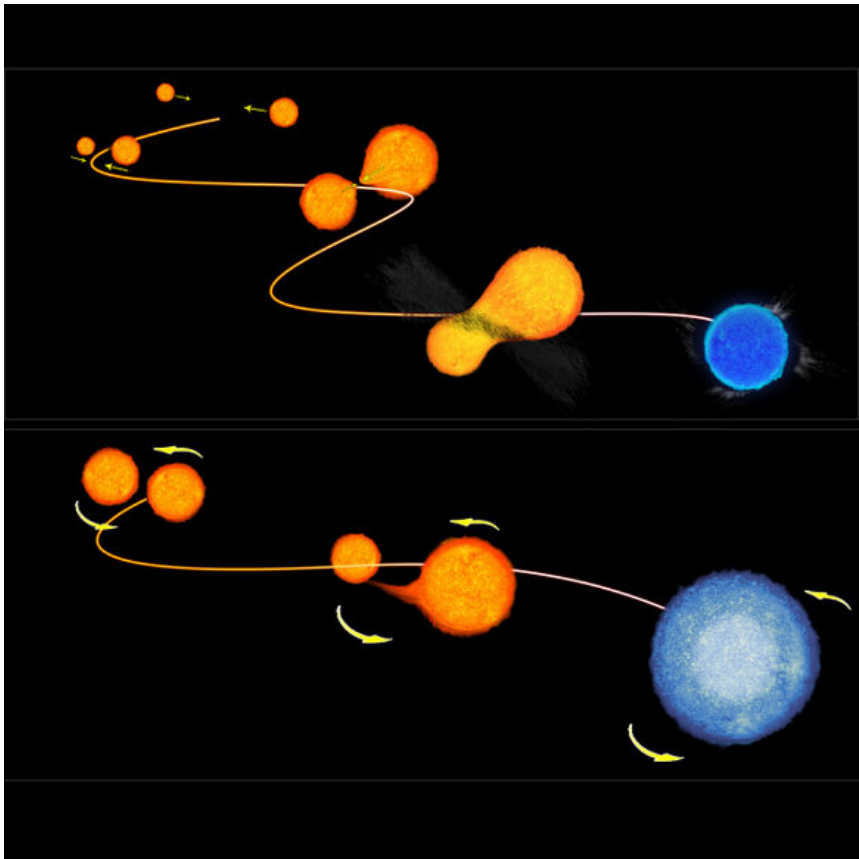


Contact Binary

- Two stars can touch
- Overflow = Overcontact
- Forming Blue Straggler Or Rapidly rotating giant





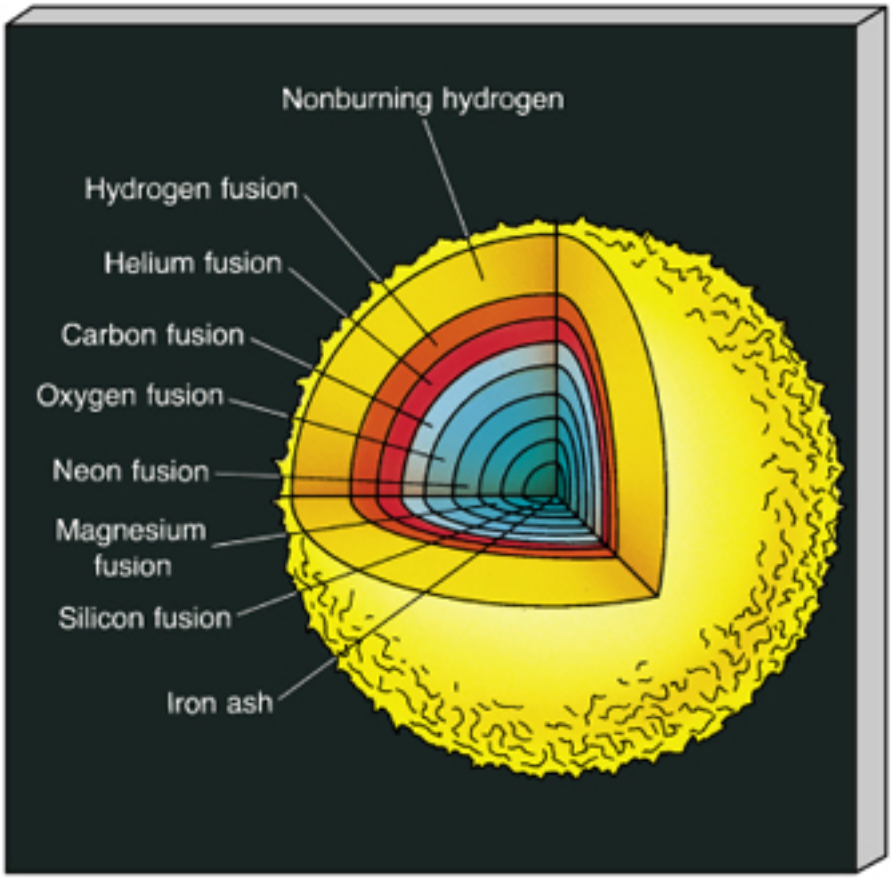


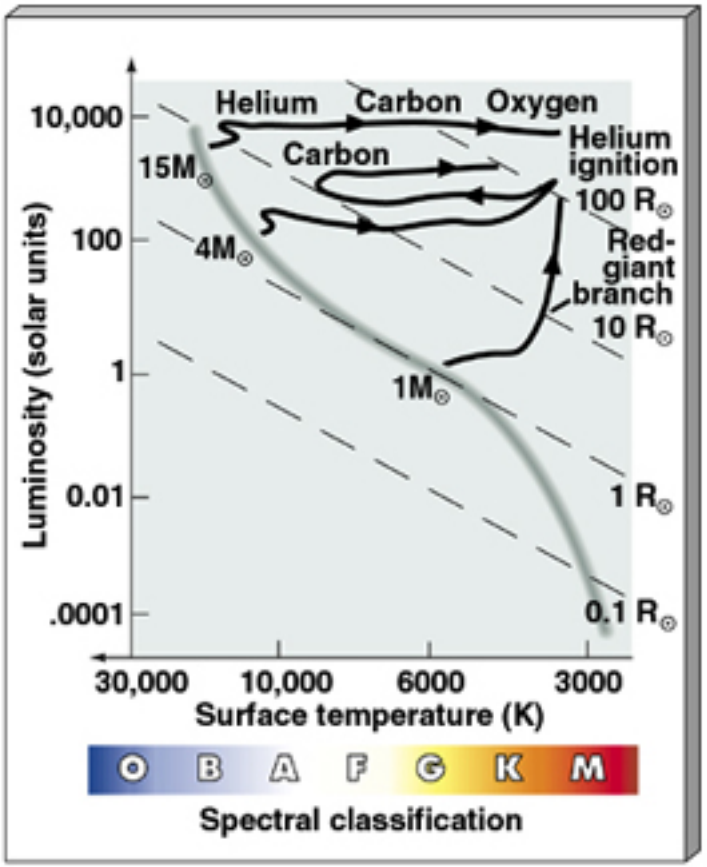
The end of the Earth will occur when the sun:

a. Becomes a red giant and expands to be bigger than the Earth's orbit
b. Becomes a Planetary Nebula
c. Overflows its Roche Lobe
d. Becomes a cool Black Dwarf
e. Core becomes electron degenerate & has a Helium flash and moves on to the Horizontal Branch

Formation of Heavier Elements

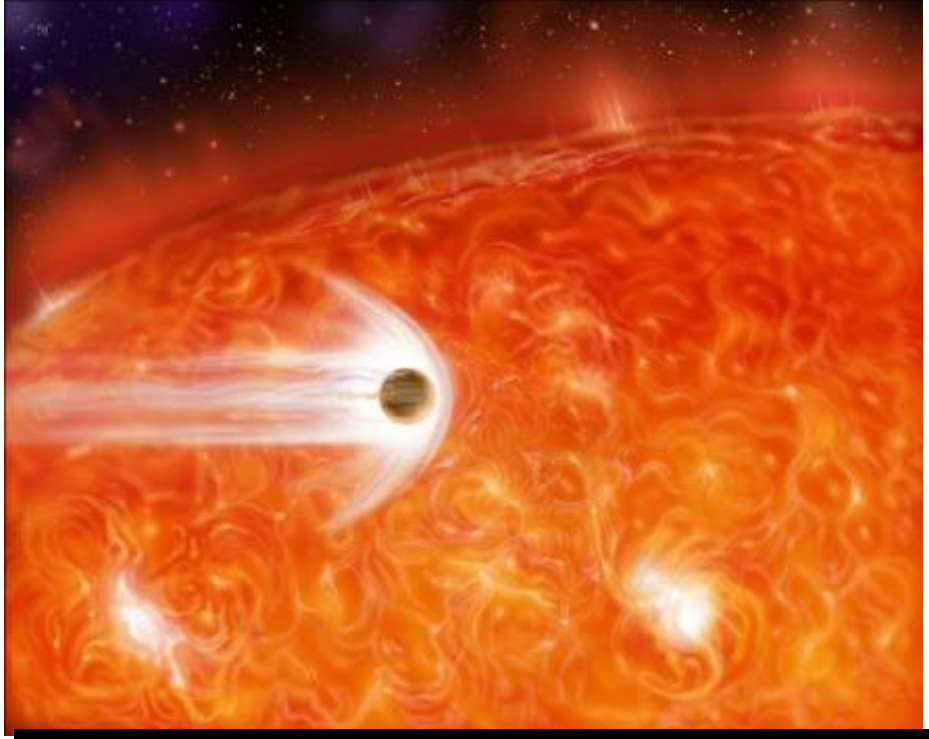
- After each element fuses in core, the core contracts
- The temperature rises and a new element begins to fuse
- Super giants can make many crossings of HR Diagram

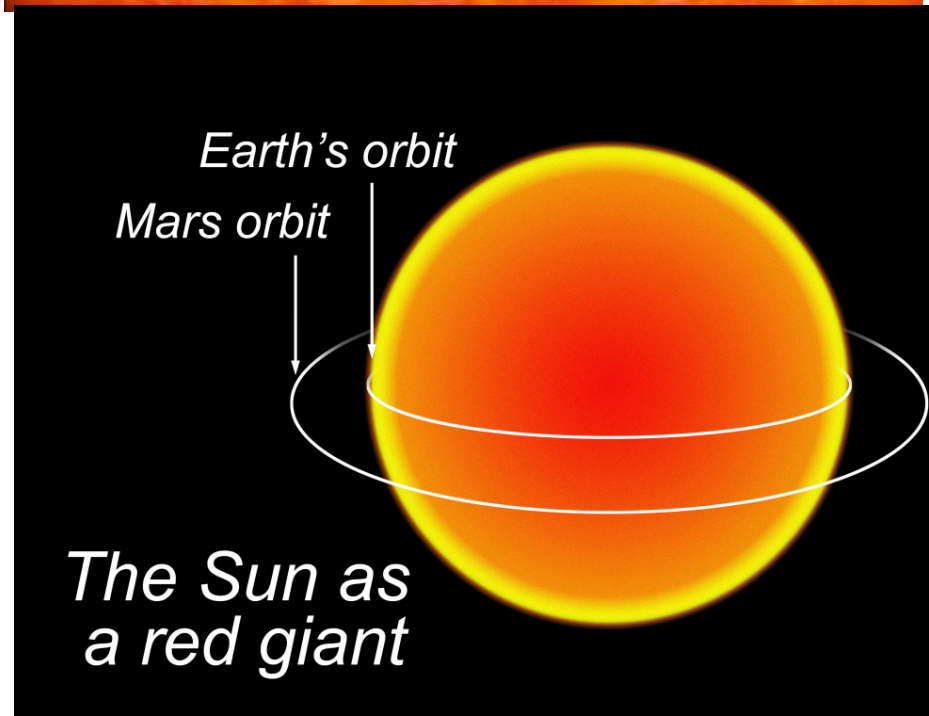




End of the Earth

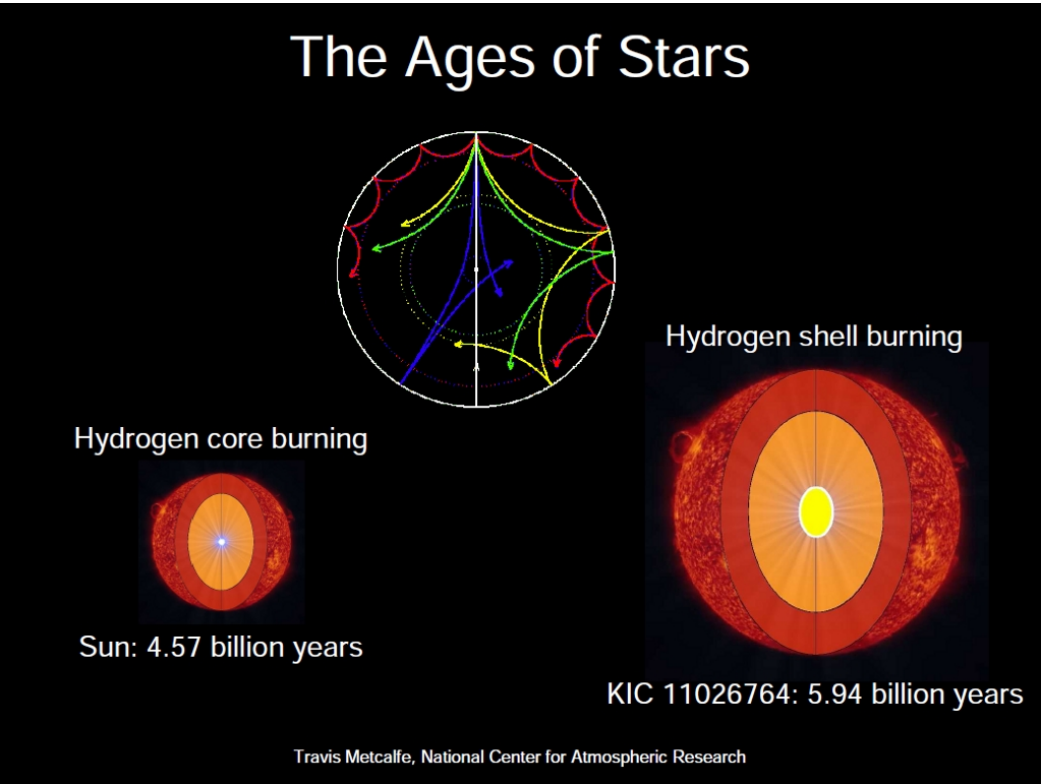
- In 10Billion years
- Surface of Sun will/ may engulf Earth
- Tides & mass loss: Earth recedes, but
- Earth may spiral in and evaporate
- Did it happen to BD +48 740??

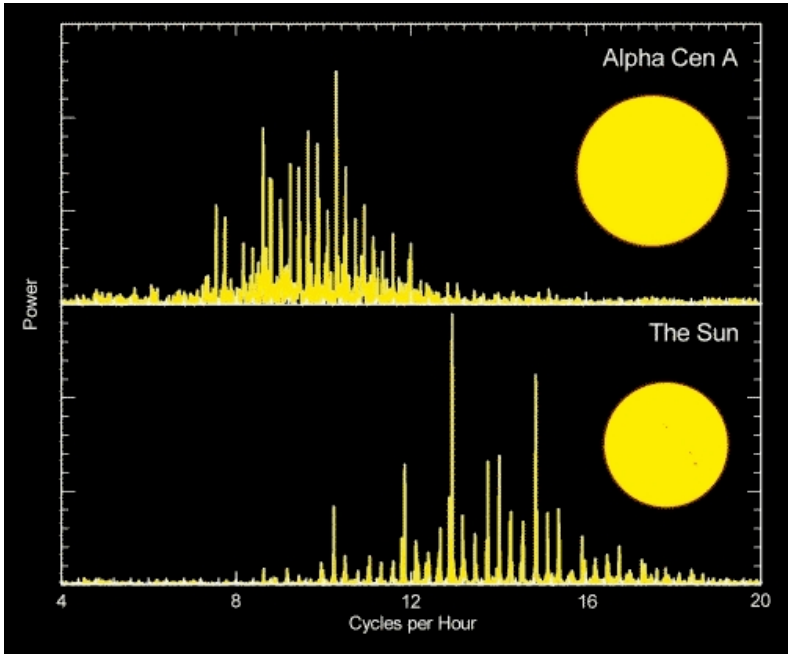




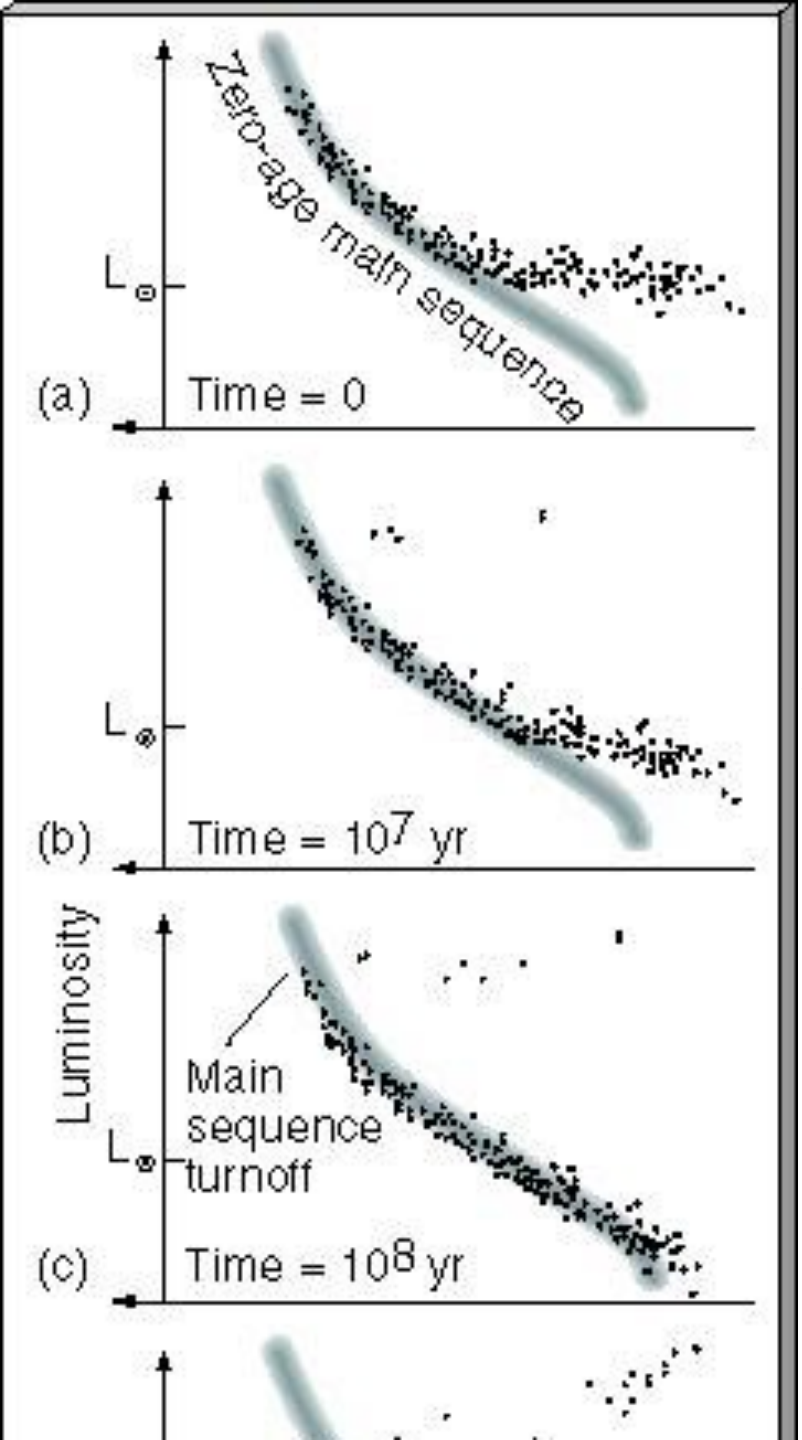
Core of **Asymptotic Giant Branch Star**

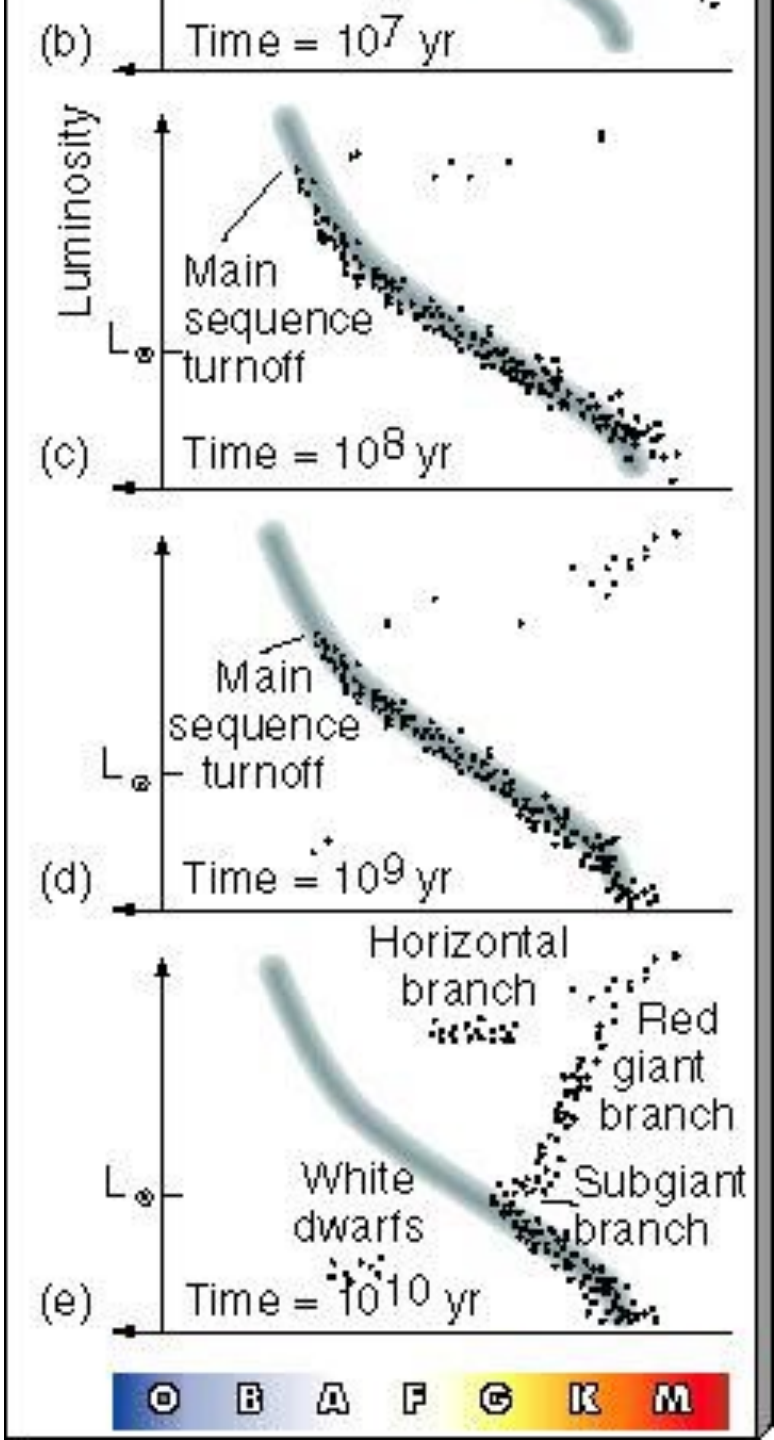
- Core is size of the Earth
- from Kepler asteroseismology data: Core spins faster than envelope and can now distinguish AGB from red giant stars





Evolution of a Cluster

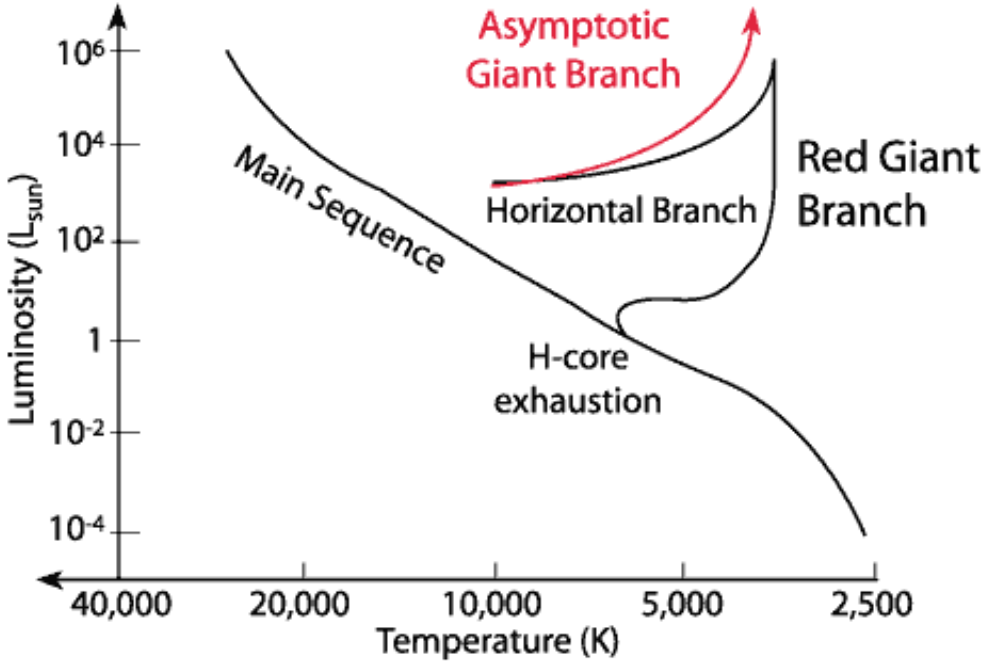


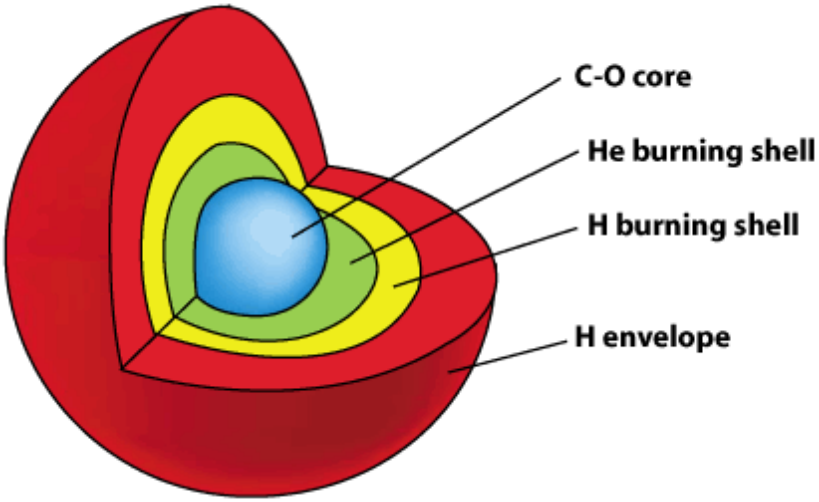


- Note: no stars beyond **turn-off point**

Asymptotic-Giant Branch

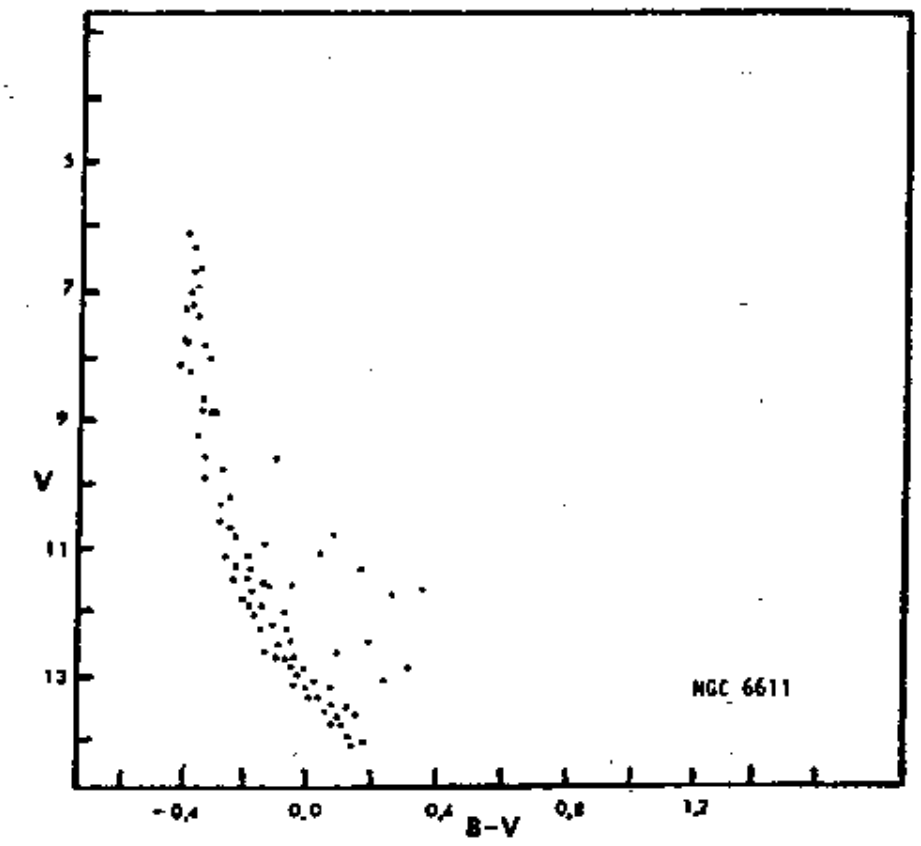
- Carbon ash builds up – Helium burns in shell
- Core contracts, core temperature increases, star expands becomes Red Giant again





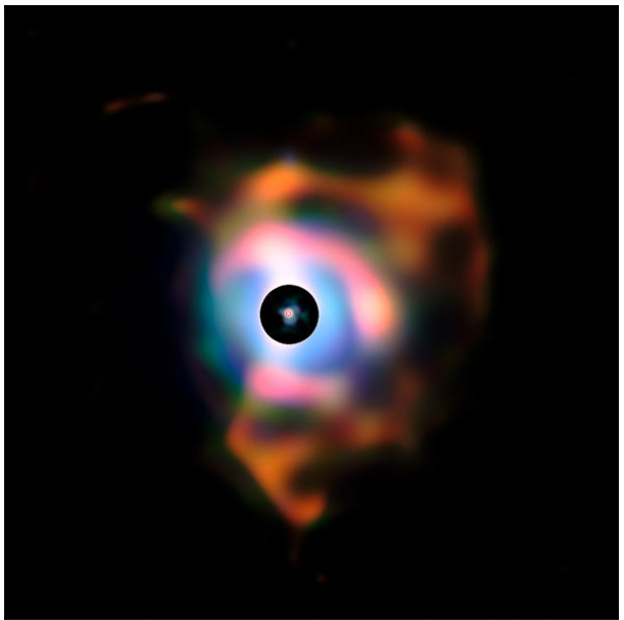
ColorMagnitudeDiagram of NGC 6611

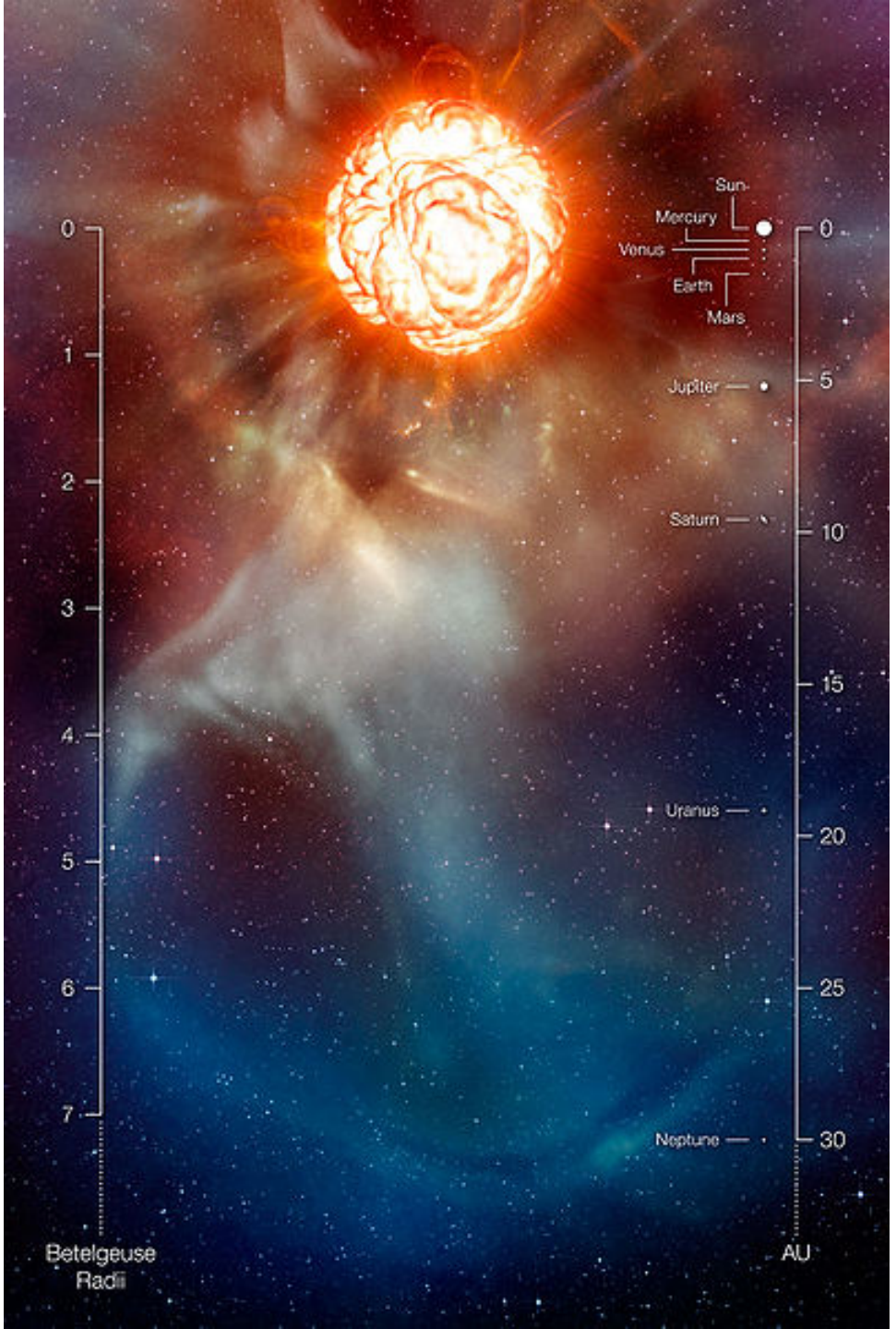
- CMD shows stars a few million years old still approaching the **Zero Age Main Sequence = ZAMS**



Mass Loss

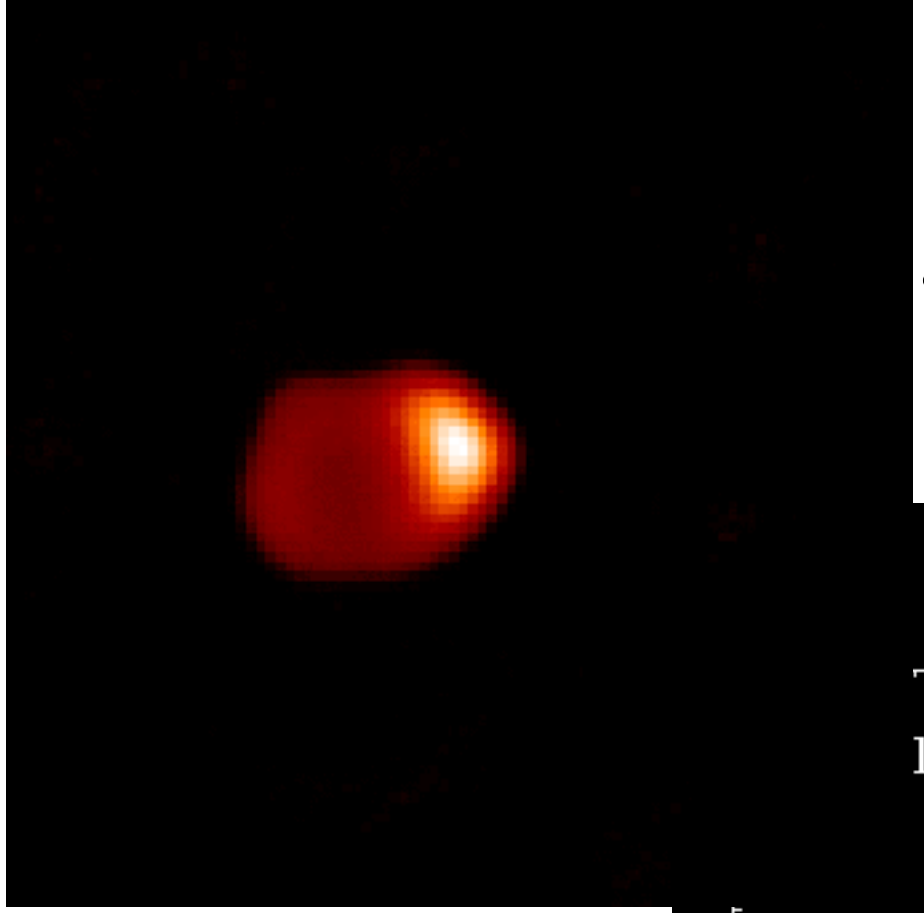
- VLT image of Betelgeuse
- Artistic conception
- Even $8M_{\odot}$ star may loose enough mass to become a white dwarf

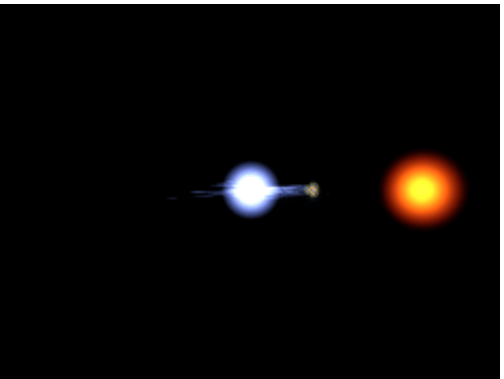


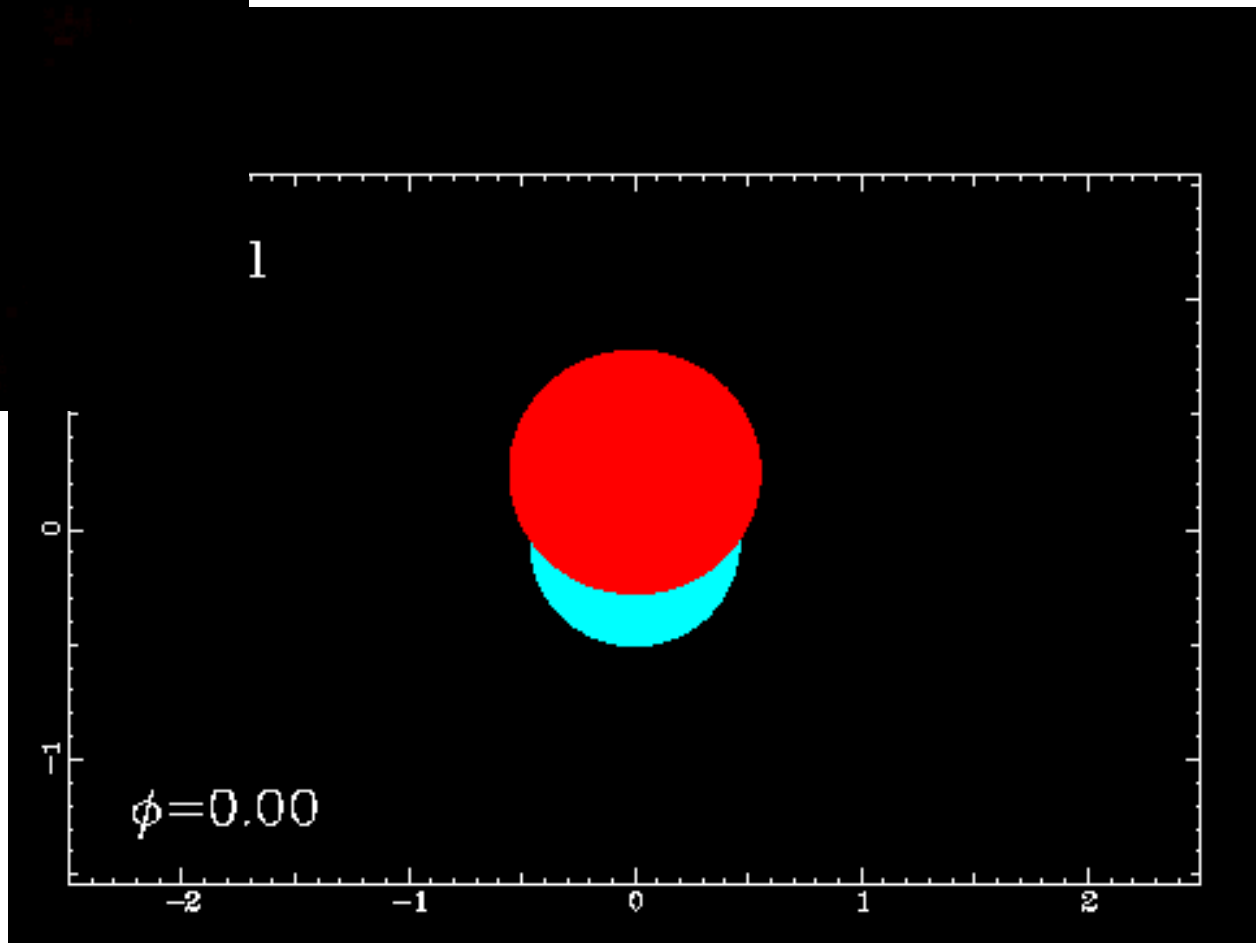


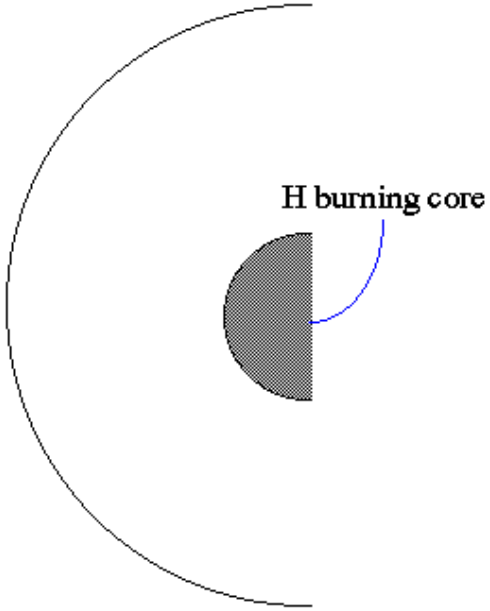
Algol Movies

- CHARA observations & animations

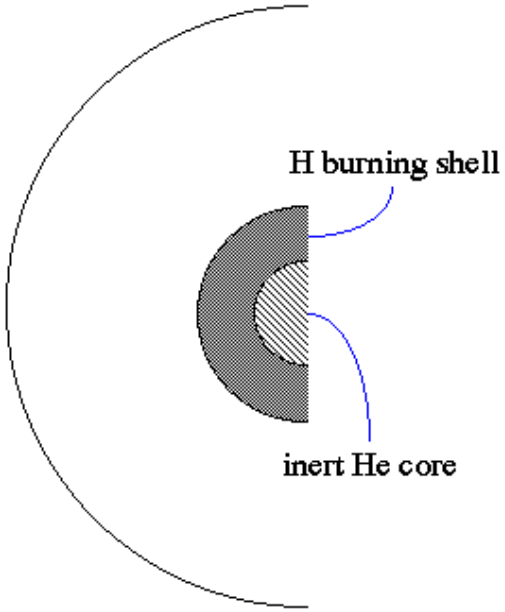




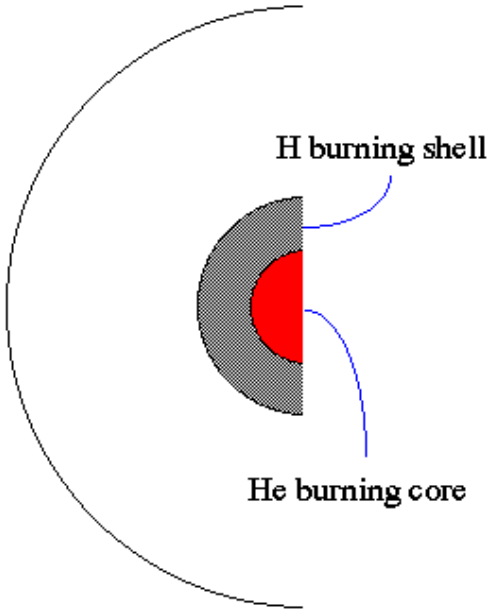




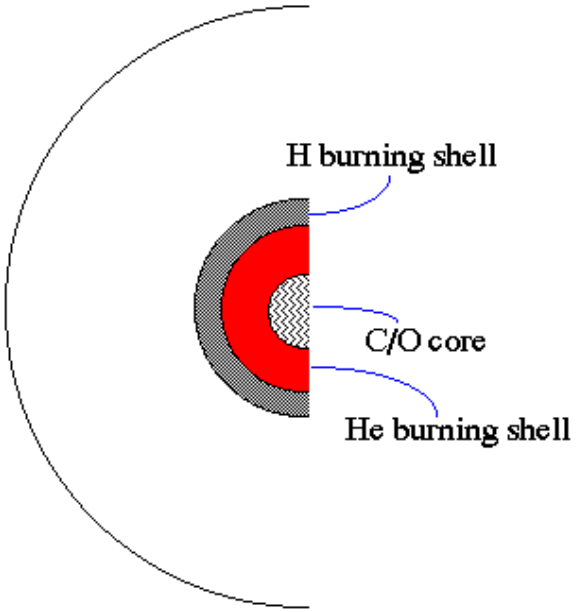
Main Sequence Star



Red Giant Star



Horizontal Branch Star

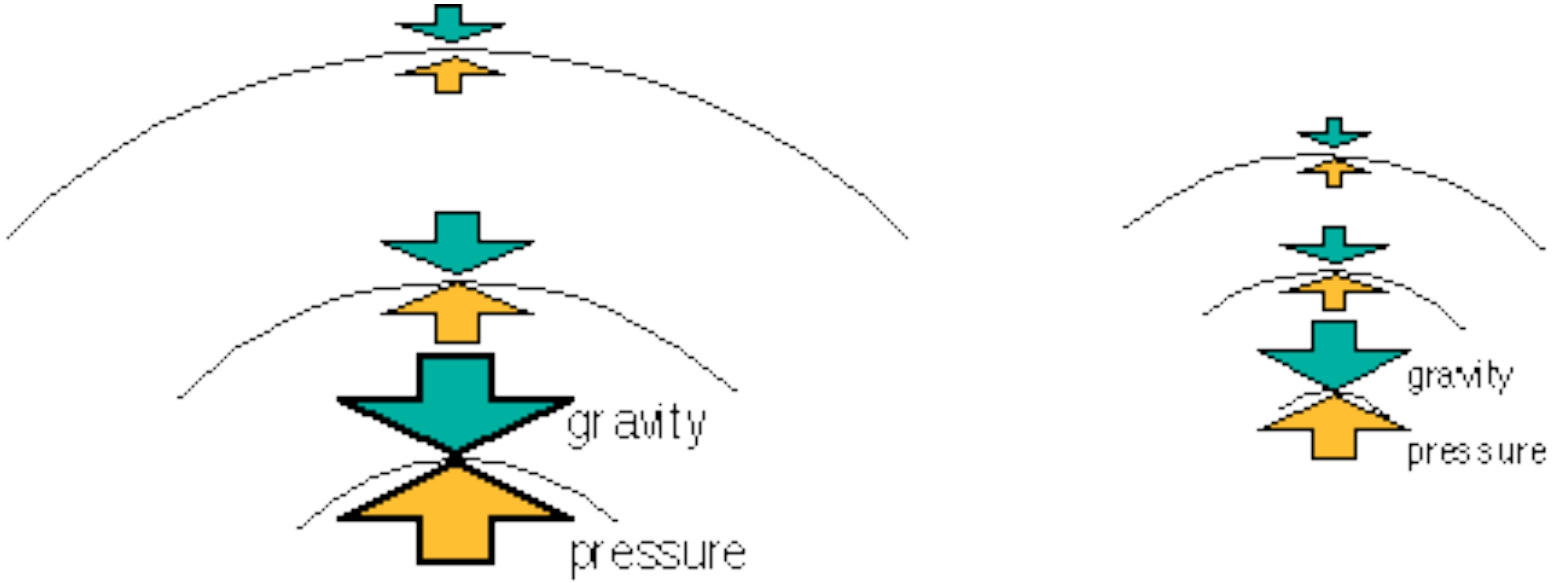


Asymptotic Giant Branch Star

Summary: Solar Post Main-Sequence Evolution

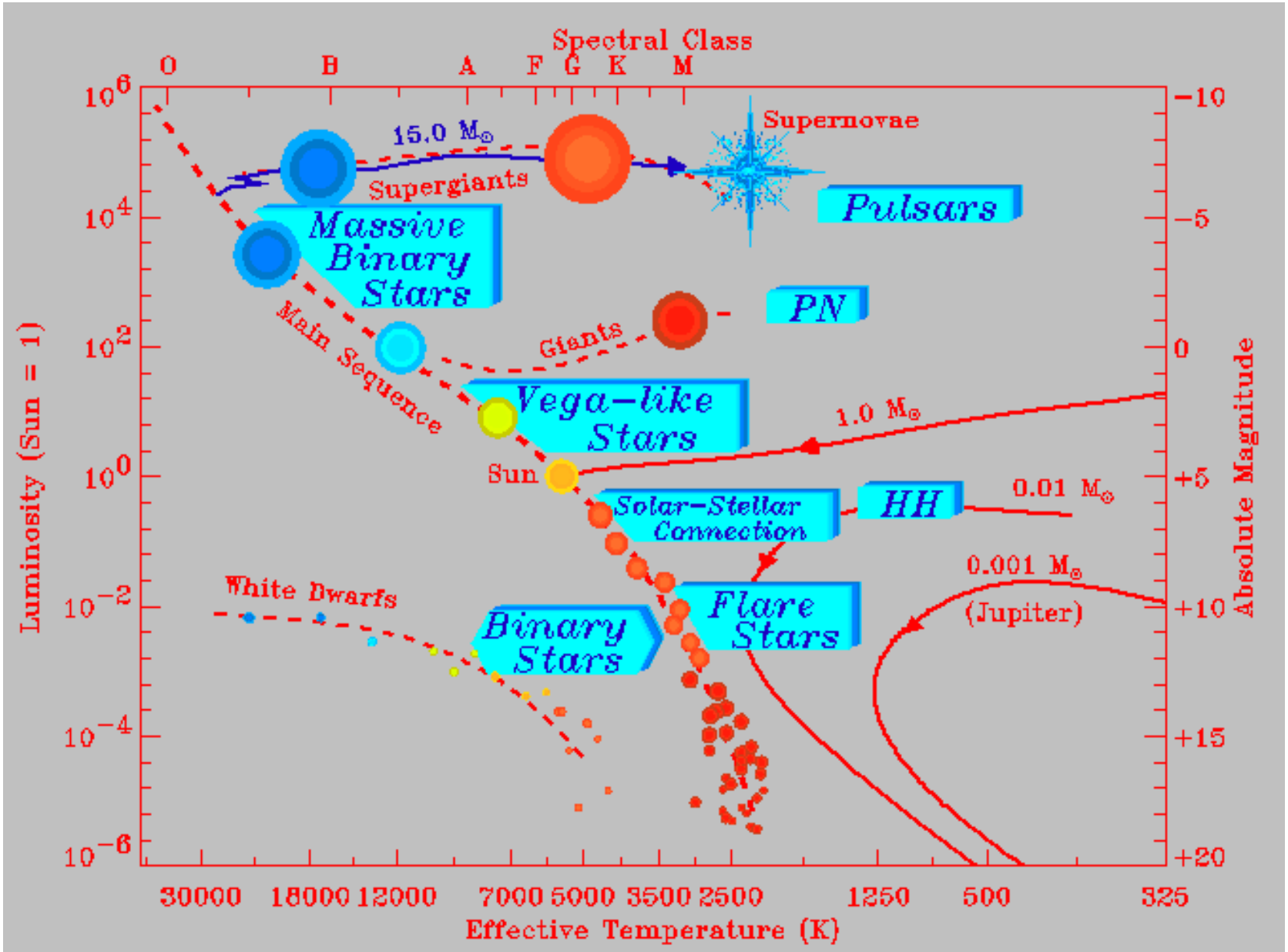
Hydrostatic Equilibrium = Mass-Luminosity Relation

- At surface star needs lower pressure & temp to support small mass
- In the center: higher weight/mass, higher pressure, higher temperature
- The faster the protons go - the more fusion reactions
- More reactions - the brighter the star = Mass-Luminosity Relation



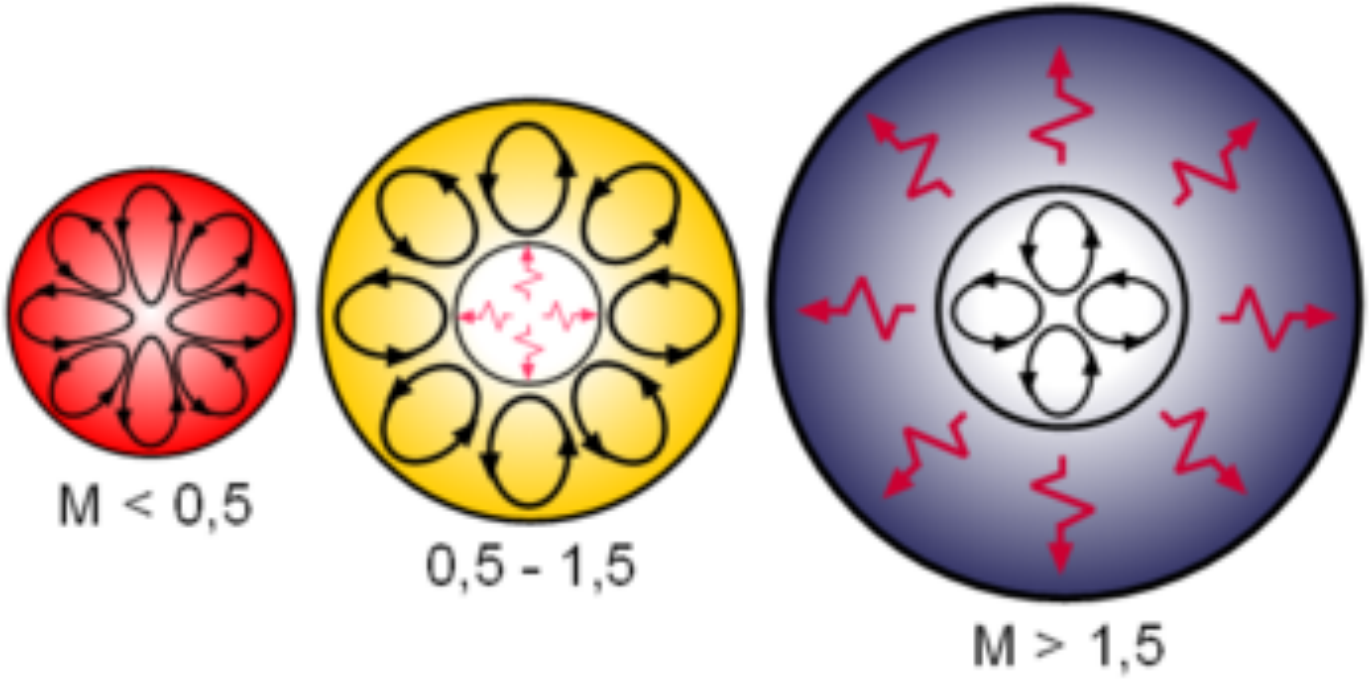
More massive stars have greater gravity compression. They need higher core temperatures to be stable and have very many more nuclear reactions. A slight change in mass produces a large change in luminosity.

Labeled HR Diagram



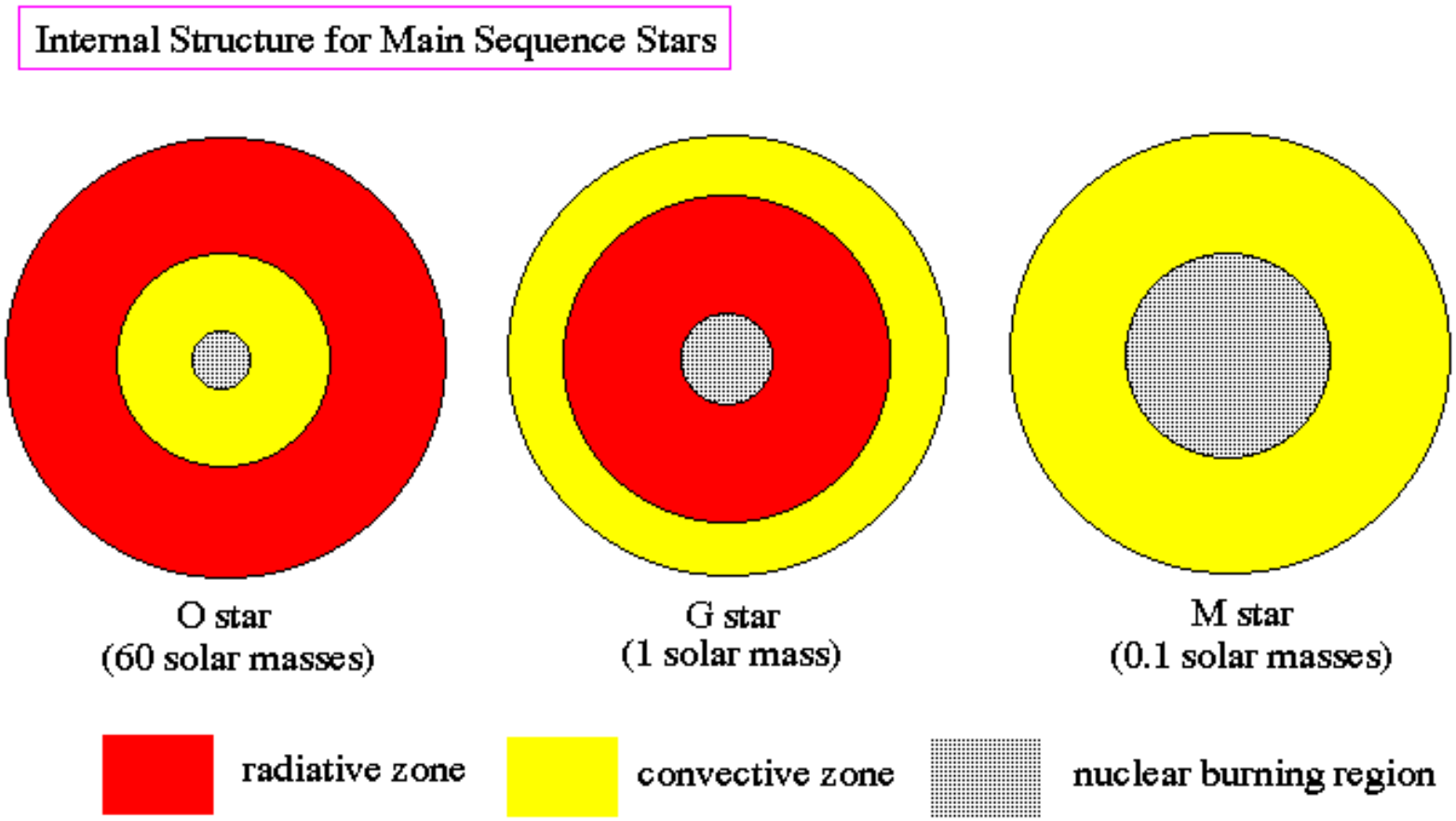
Energy Transportation on ZAMS

- **ZAMS = Zero Age Main Sequence**
- Size of nuclear burning region ~ Earth
- Stars more massive than 1.1X sun produce too much energy (CNO) in very small hot core for radiation to carry it away so convection starts
- Low mass stars are fully convective = mixed



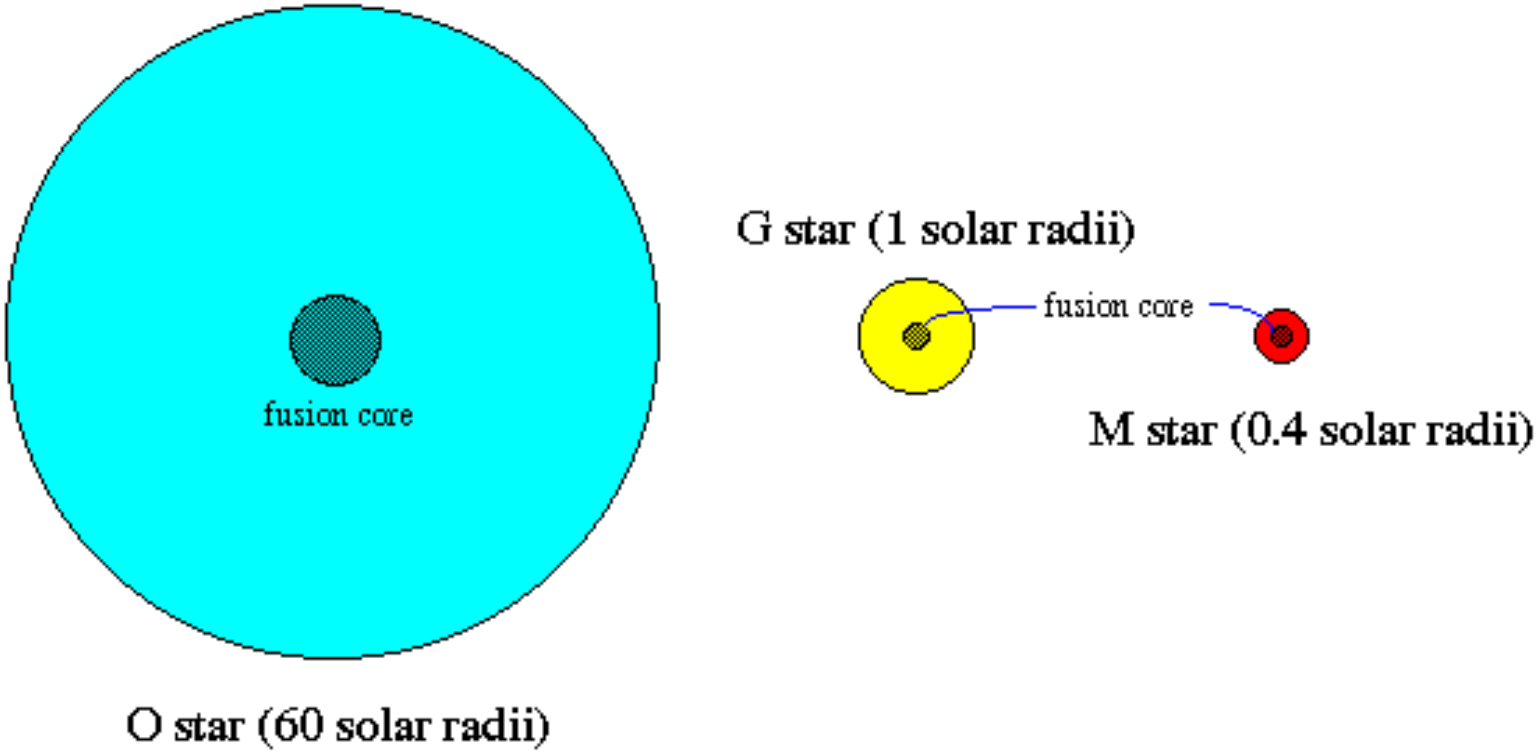
Internal Structure of ZAMS Stars

- Size of nuclear burning region ~ Earth
- Stars more massive than 1.1X sun produce too much energy (CNO) in very small hot core for radiation to carry it away so convection starts
- Low mass stars are fully convective = mixed

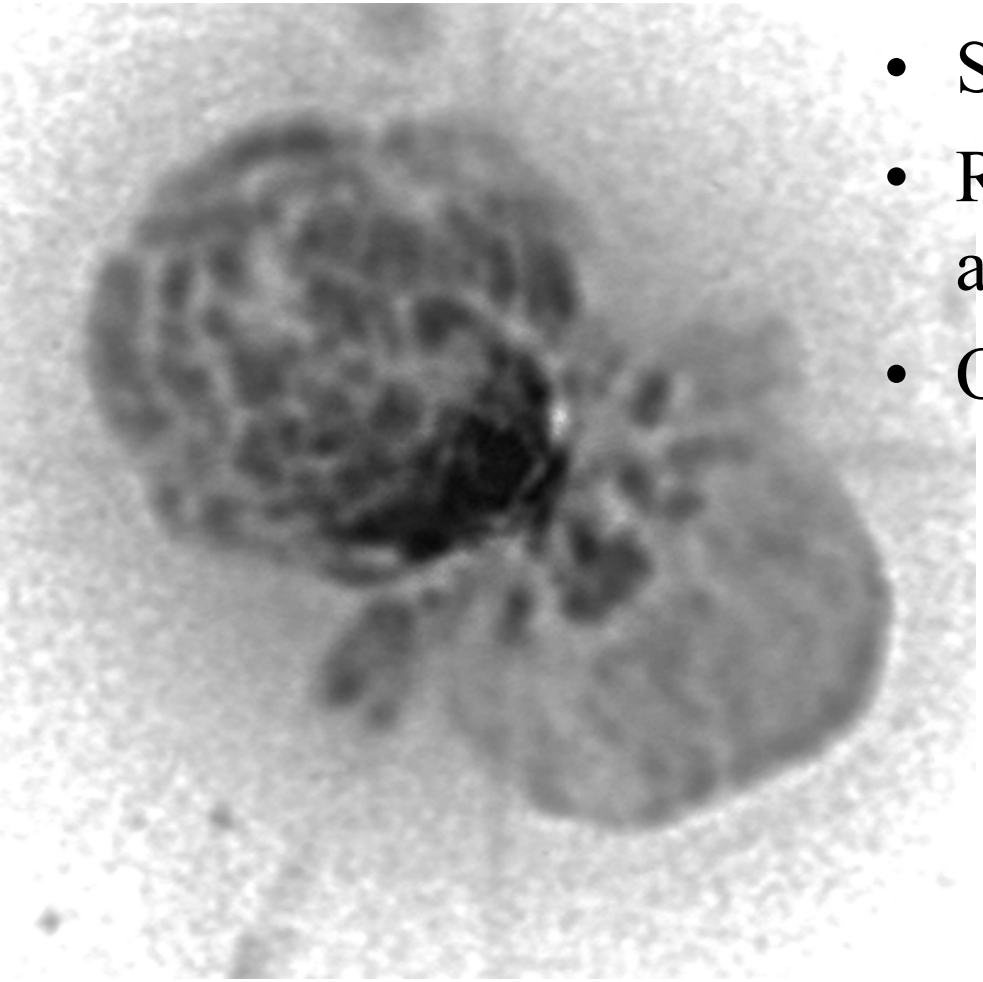


Relative Sizes of Main Sequence Stars

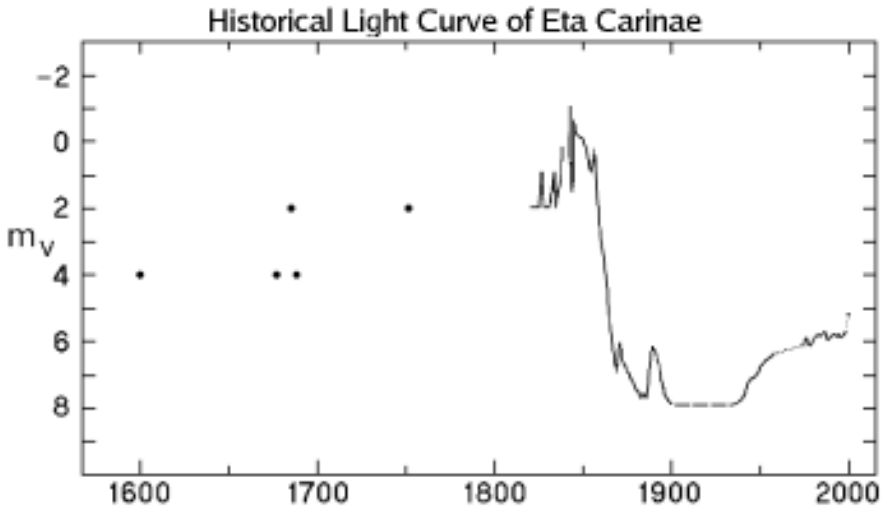
- Stellar models requires lots of physics:
- Nuclear reaction rates, opacity/ionization, energy transport
- All at temperatures we do not have on Earth



Most Massive Star=Eta Carinae?

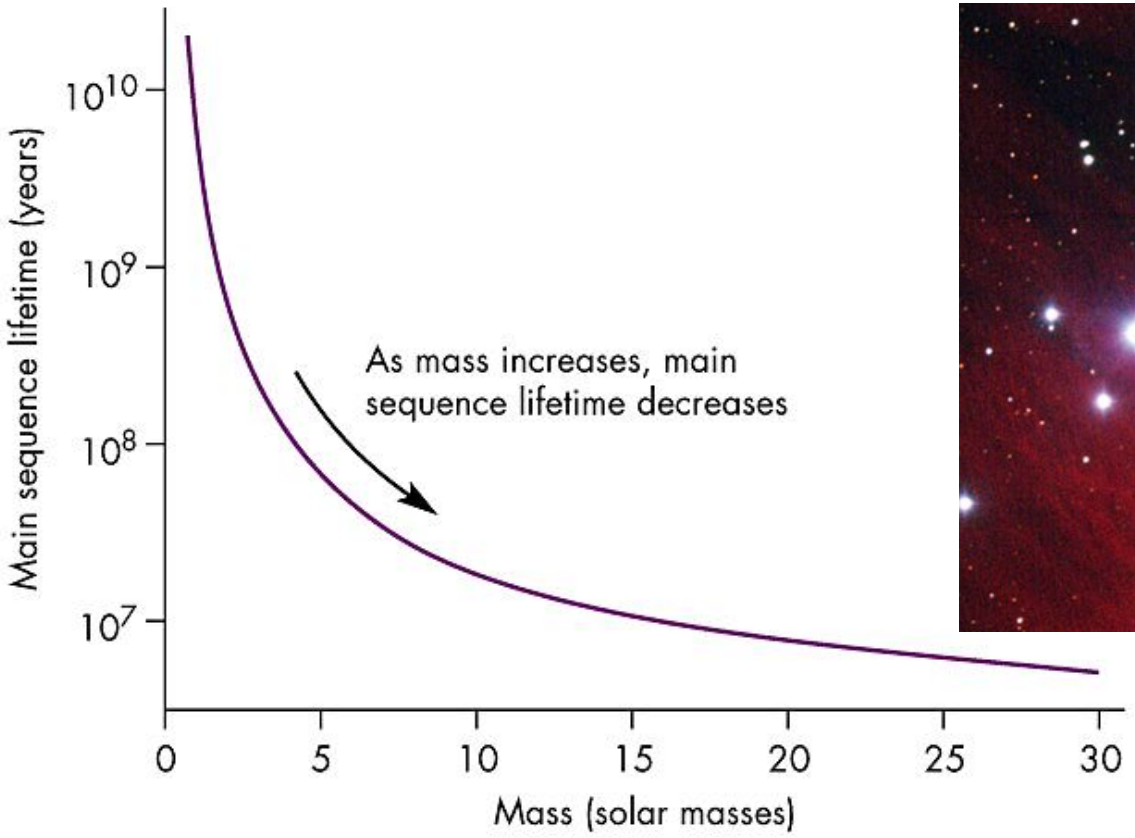


- Maybe 100 solar masses
- 5 million solar luminosities
- Size limited by:
- Radiation pressure will blow away surface layers
- Original cloud would fragment



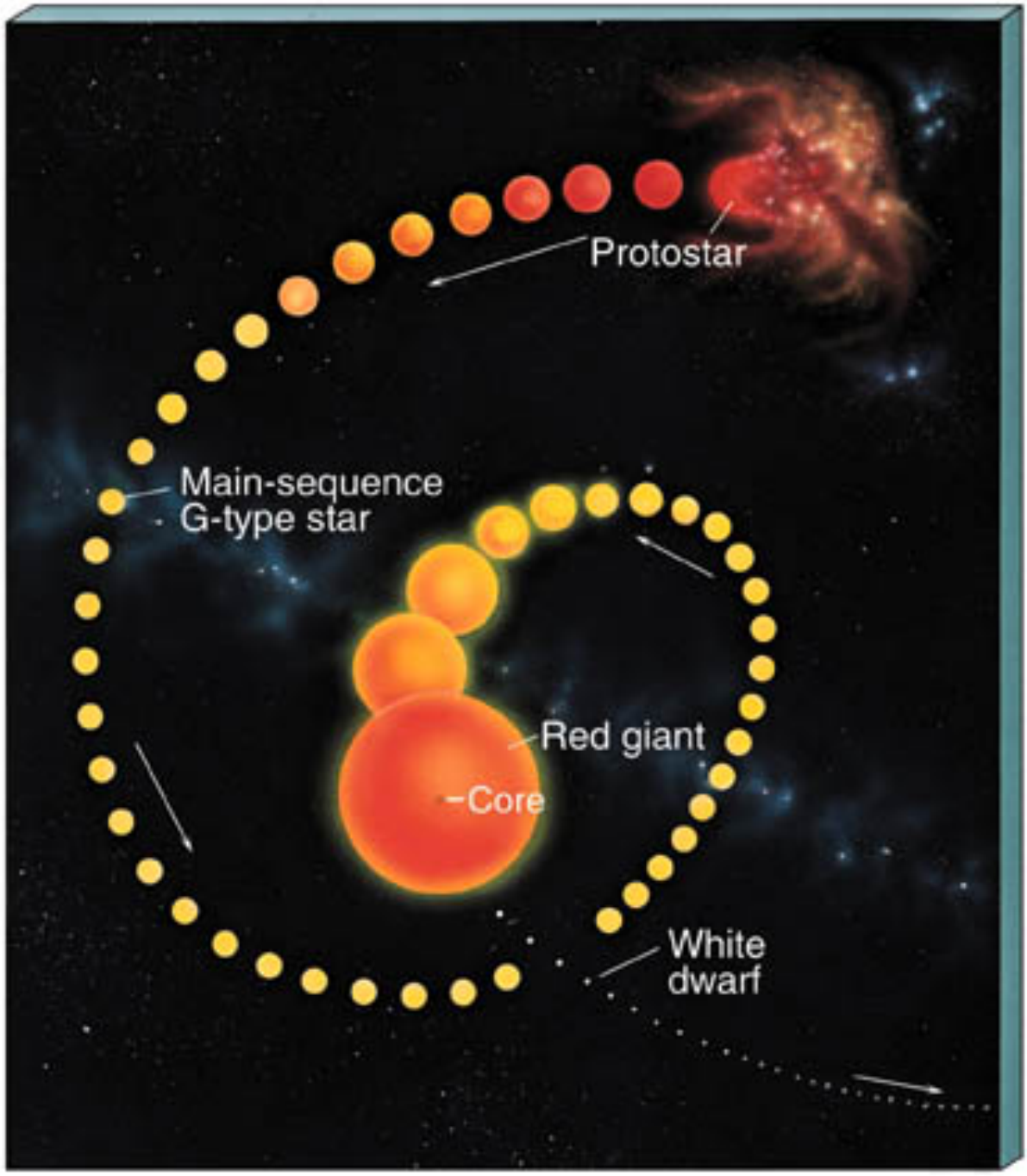
Lifetime of a Star

- Lifetime = Fuel / Consumption
- Fuel is fraction of Mass
- Time=Mass/Luminosity
- Luminosity=Mass $^{3.5}$
- Time=1/Mass $^{2.5}$ of a solar lifetime = 10Billion yr
- Stars live millions to billions to trillions of years



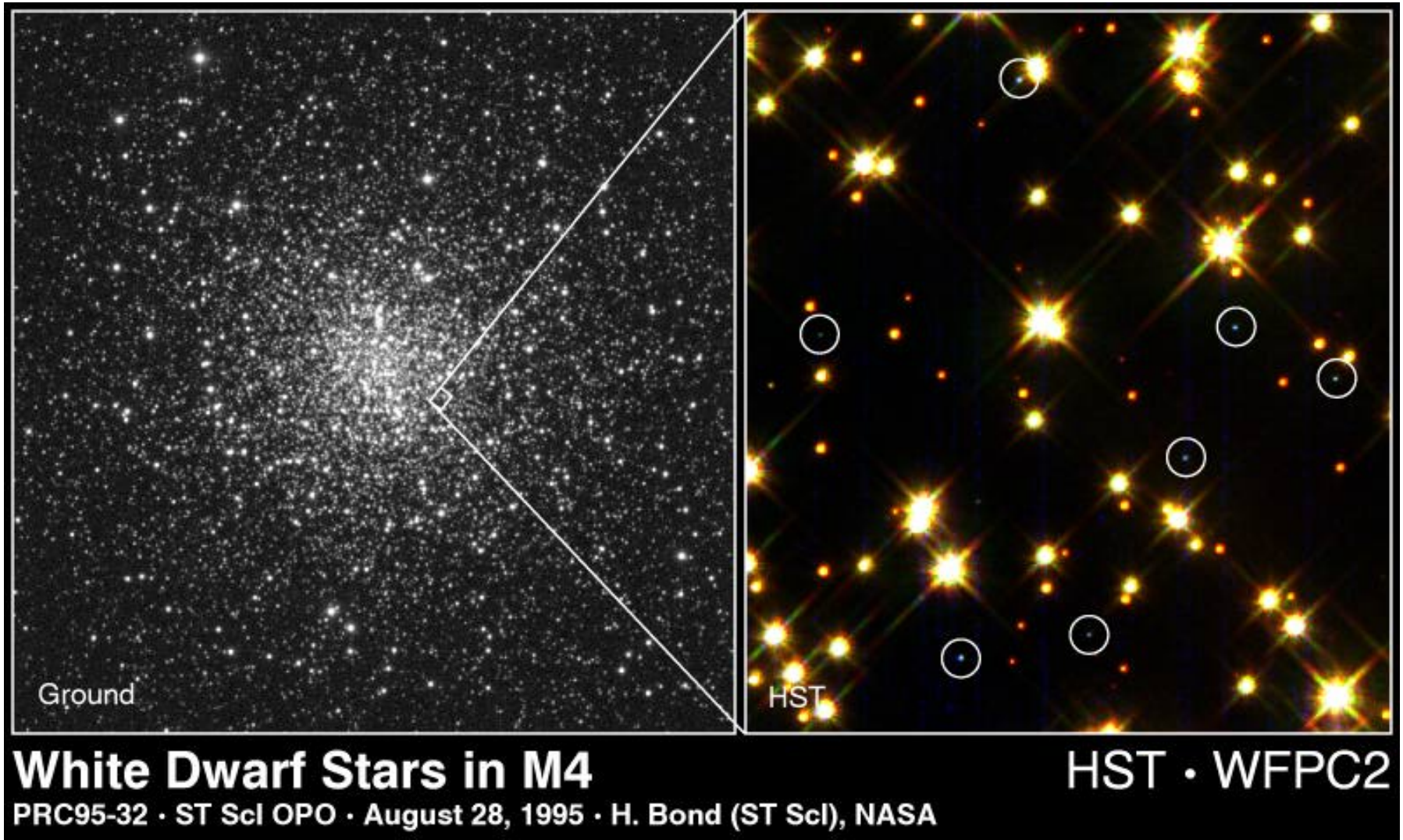
Main Sequence Evolution

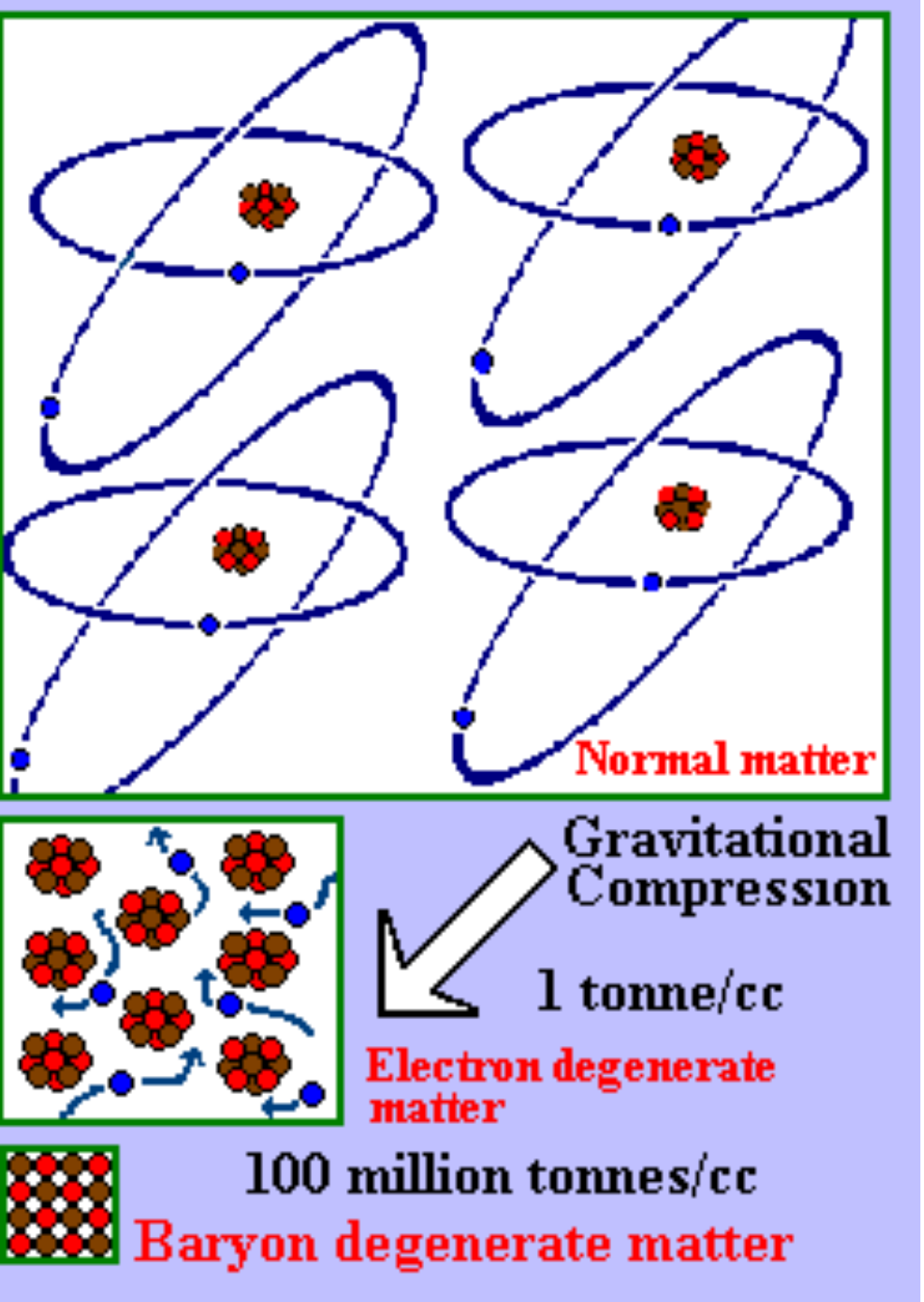
- "Stars join the main sequence when they begin hydrogen fusion in their cores. They leave the main sequence and become red giants when the core hydrogen is depleted"



White Dwarfs in M4

- Lots of white dwarfs
- So there are billions in our galaxy, but they are faint





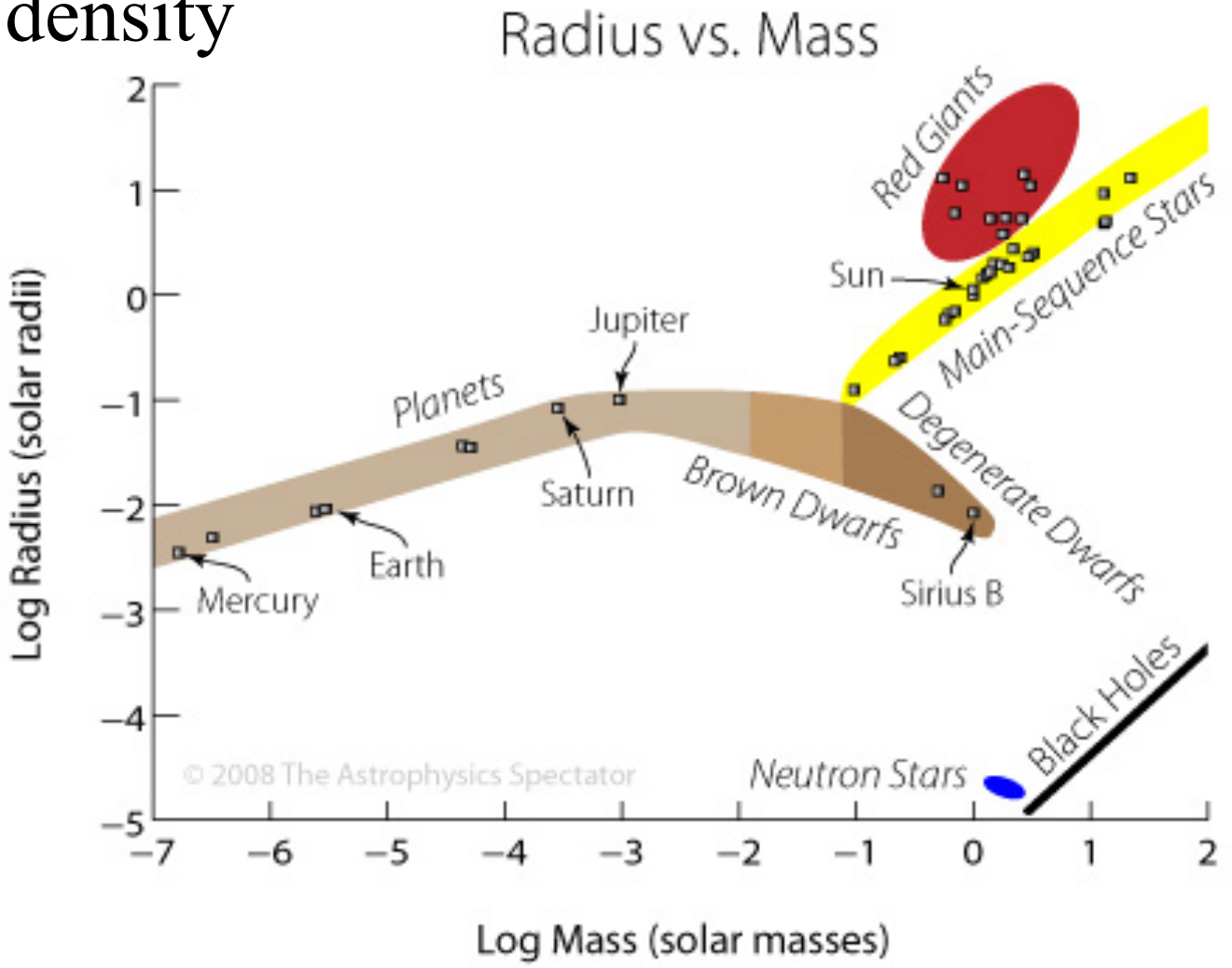
Density of Degenerate Matter

White Dwarf's density is 3,000kg/cm^3 (teaspoon=semi)

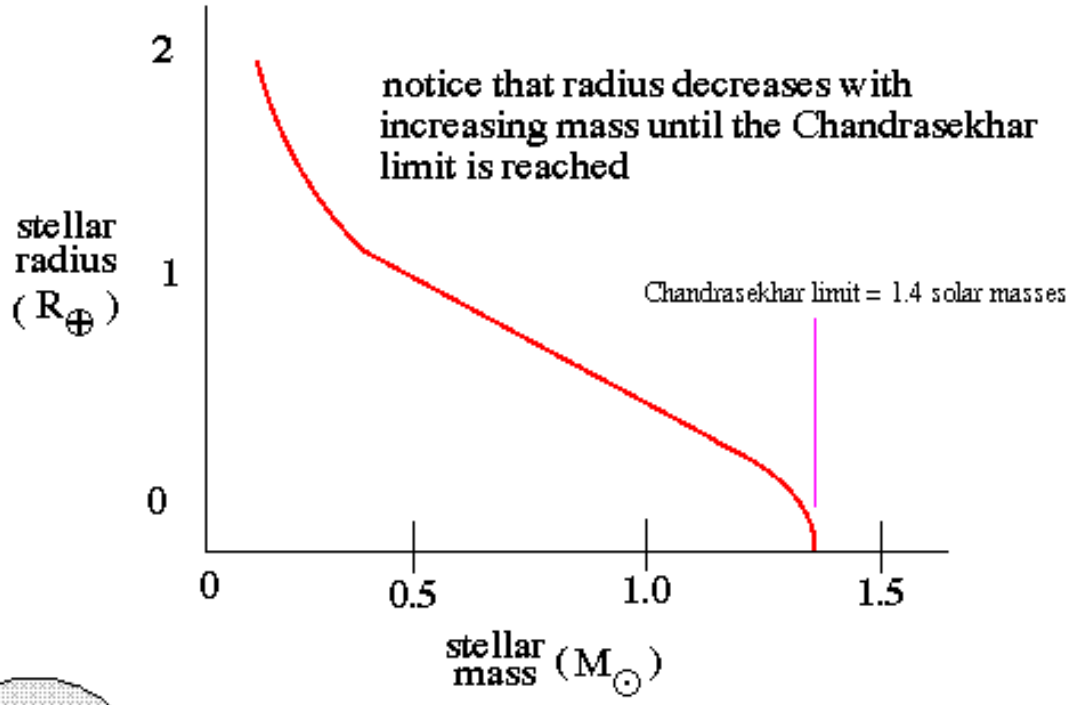
Pressure resisting gravity is given by degenerate electrons

Compact Objects / Stars

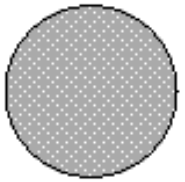
- Small radius & Large mass =
- High density



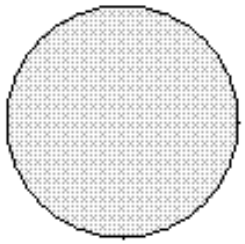
Mass-Radius Relation for White Dwarf Stars



Regular star:
More mass => larger size.

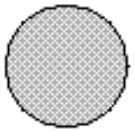


M = 0.5 solar mass



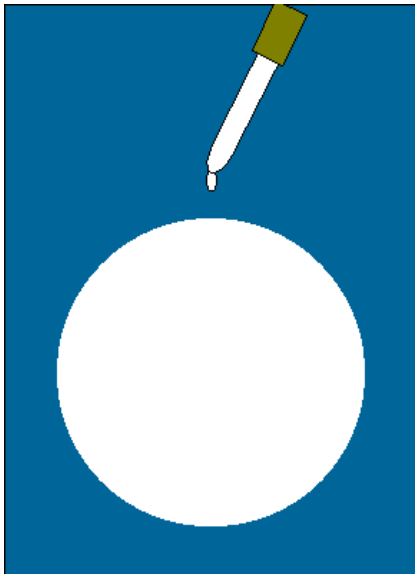
M = 1.0 solar mass

Degenerate star:
More mass => *smaller* size.



M = 0.5 solar mass

M = 1.0 solar mass



Chandrasekhar Limit

- An electron degenerate star can not be more massive than 1.4 solar masses
- Mass loss can be so large that even 7 or 8 solar mass stars may become this small
- But what about bigger stars?