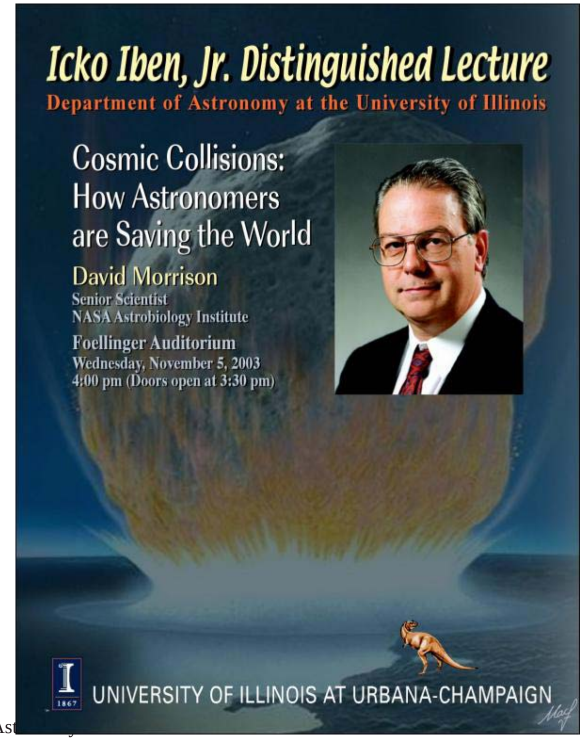
- Next homework is #7– due Friday at 11:50 am– last one before exam.
- Exam #2 is less than two weeks! Friday, November 14th!
- Let's vote for exam style.
- Don't forget the Icko Iben Lecture on Wednesday.



# Want some extra credit?

- Download and print report form from course web site
- Attend the Iben Lecture on November 5th
- Obtain my signature *before* the lecture and answer the questions on form. Turn in by Nov. 14th
- Worth 12 points (1/2 a homework)

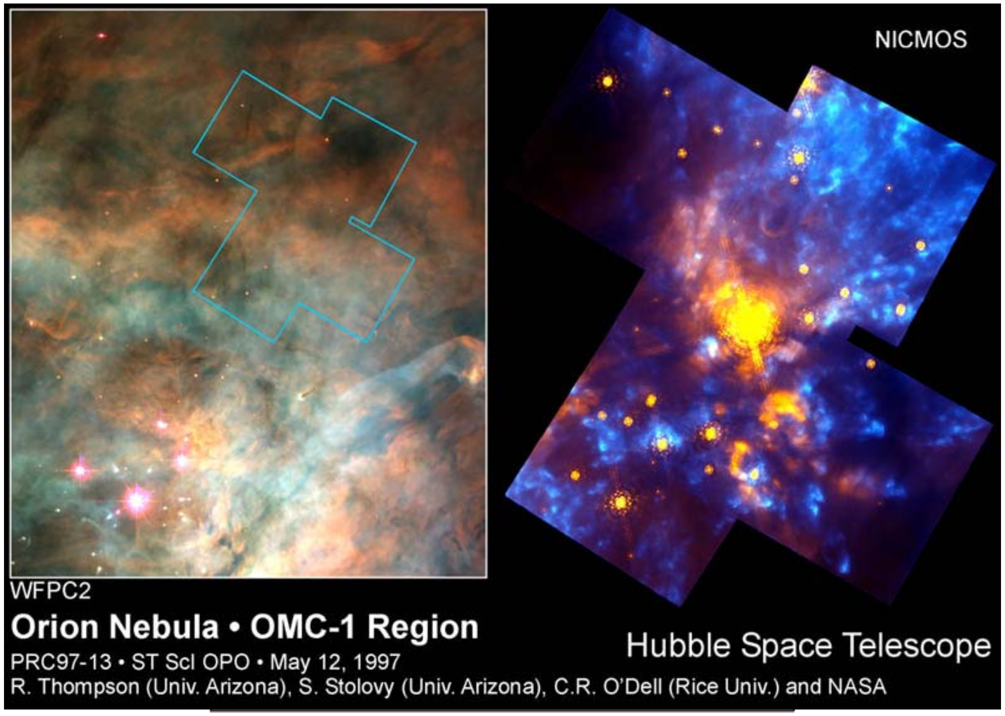





# Outline

- Finish up summary of star birth.
- Birth of a star onto the HR diagram.
- Stellar demise depends on the stellar mass.
- Higher mass stars– live fast, die hard!
- The end of a 1 solar mass star
  - Main sequence
  - Red Giant
  - Planetary nebula and white dwarf



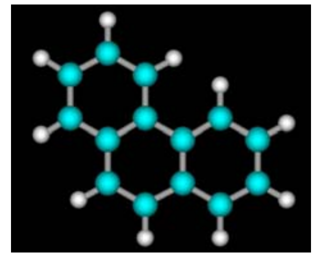




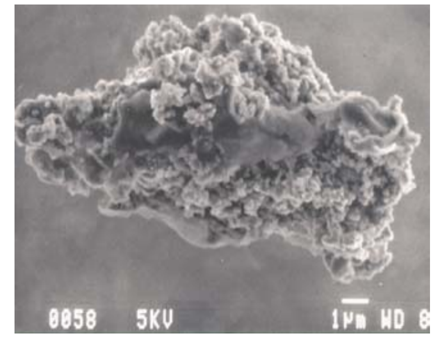

## Other Things Besides Hydrogen in Molecular Clouds

- Molecules (e.g.)
  - Carbon monoxide (CO)
  - Water ($H_2O$)
  - Ammonia ($NH_3$)
  - Formaldehyde ($H_2CO$)
  - Ethyl alcohol ($CH_3CH_2OH$)
  - Glycine ($NH_2CH_2COOH$)
  - Acetic Acid ($CH_3COOH$)
  - Urea [$(NH_2)_2CO$]
- Dust particles
  - Silicates, sometimes ice-coated
  - Soot molecules





Polycyclic aromatic hydrocarbons (PAH)

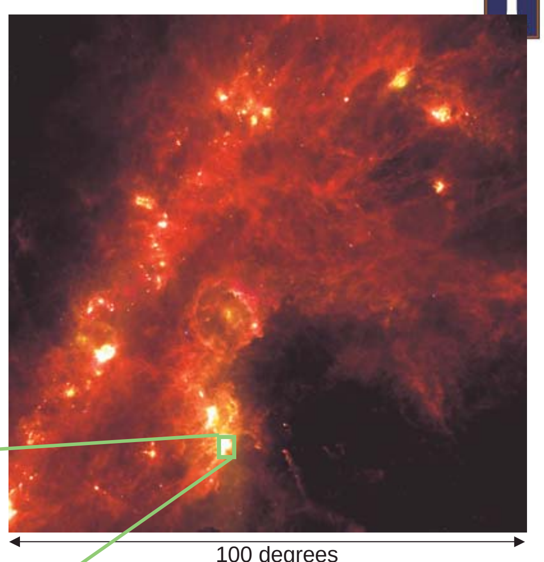



Dust particle (interplanetary)



# Giant Molecular Clouds

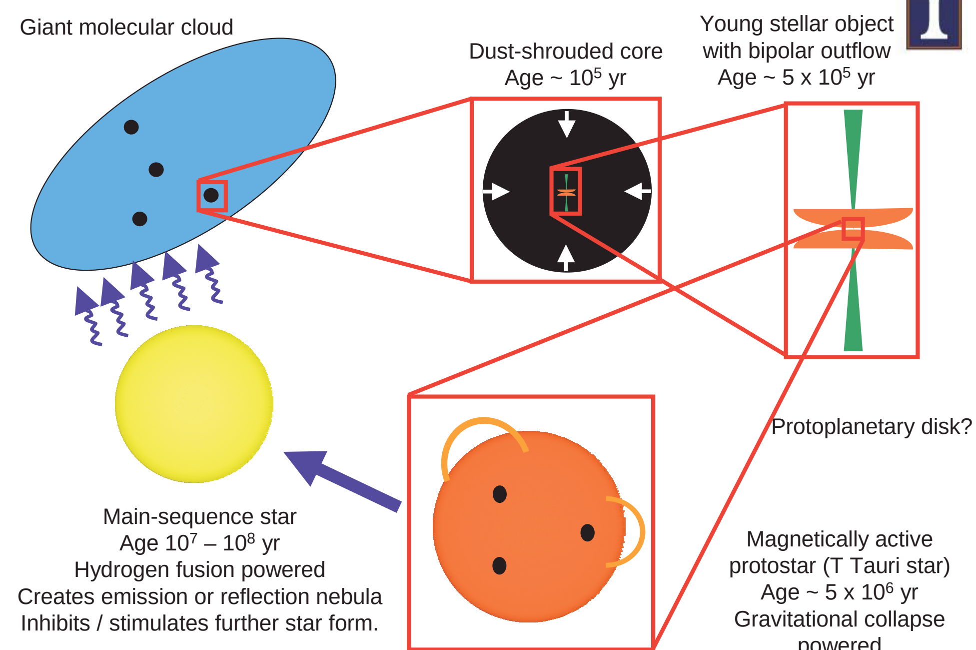
- Cool: < 100 K
- Dense: $10^2 – 10^5$ $H_2$ molecules/$cm^3$
- Huge: 10 – 100 pc across, $10^5 – 10^6$ solar masses
- CO molecular emission & dust emission trace structure



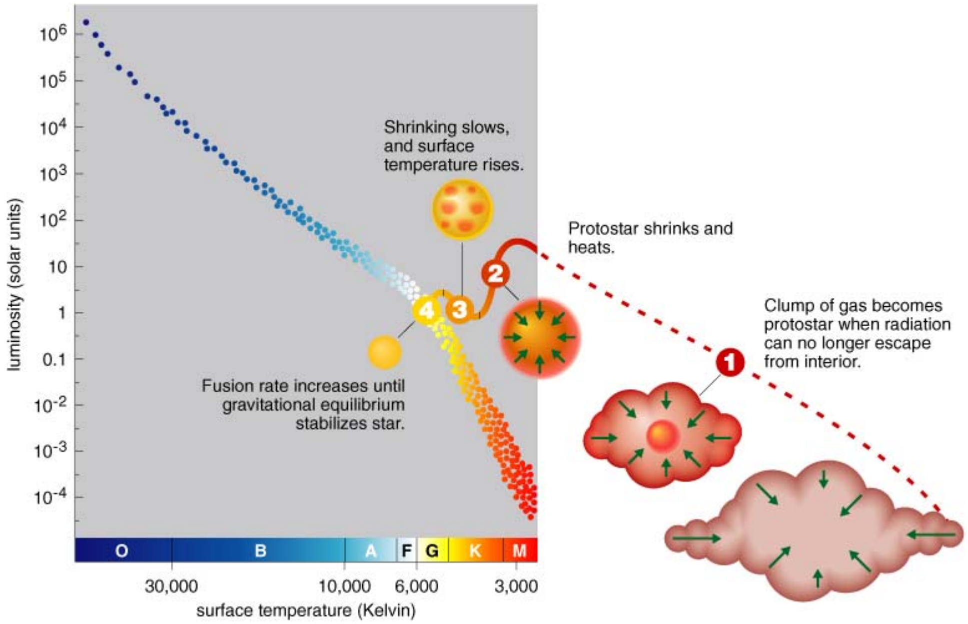

Infrared image from *IRAS*



## Low-Mass Star Formation - Summary

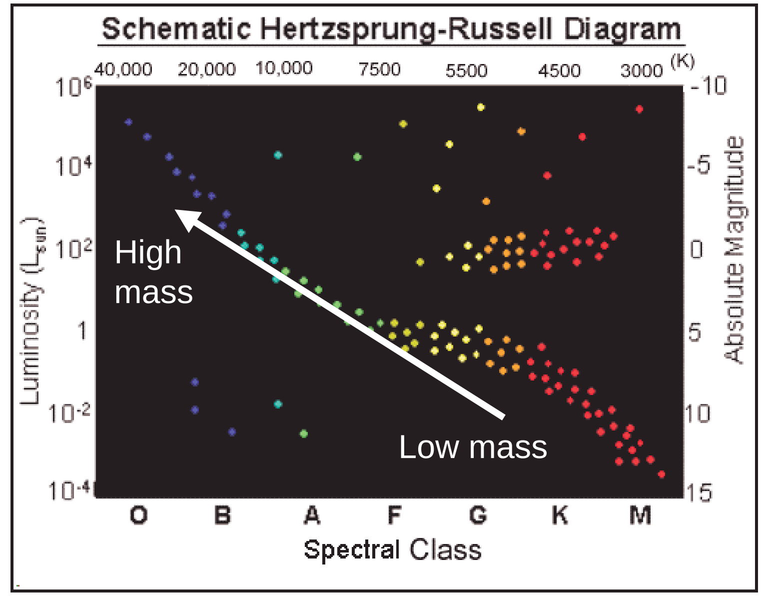


# Movement onto the Main Sequence

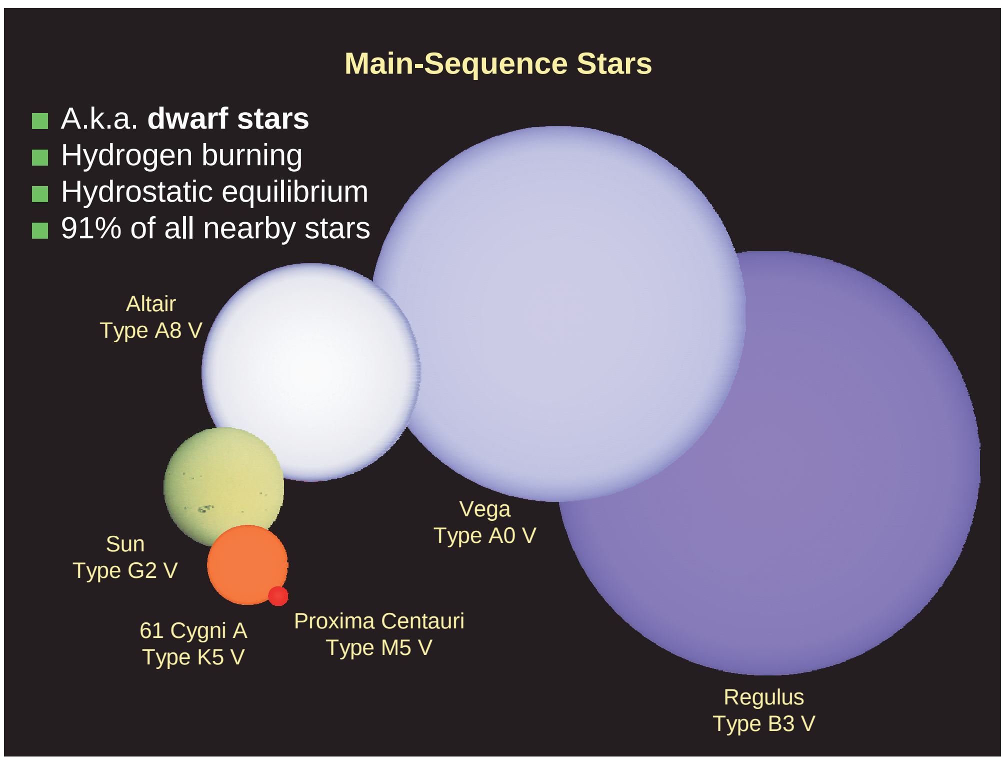





# Main Sequence Mass Relation



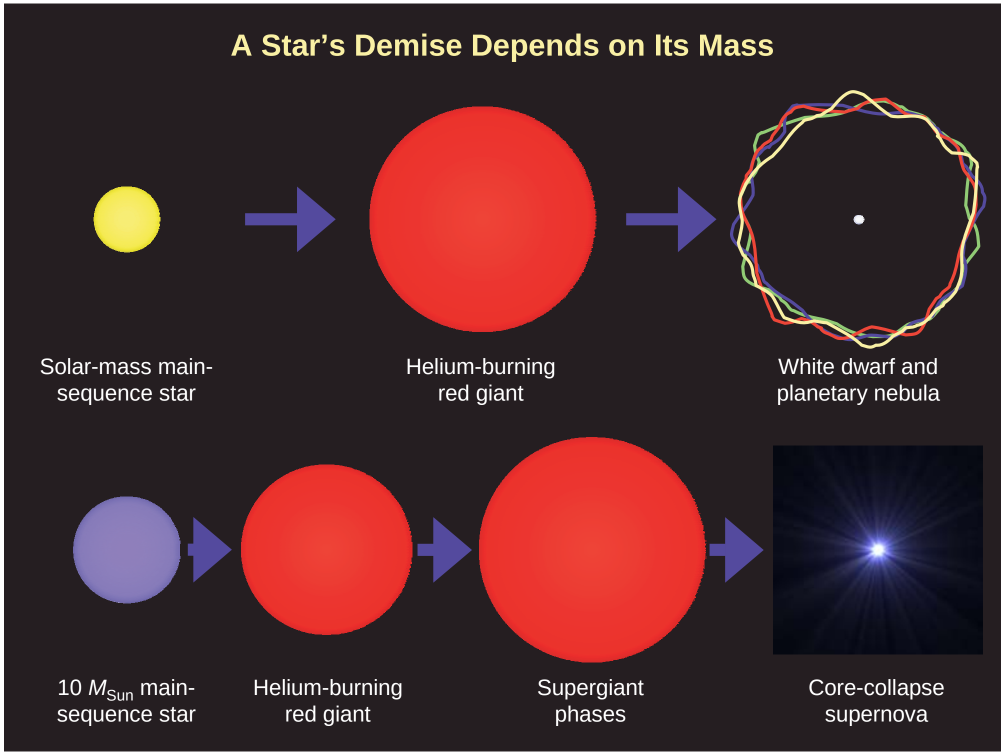


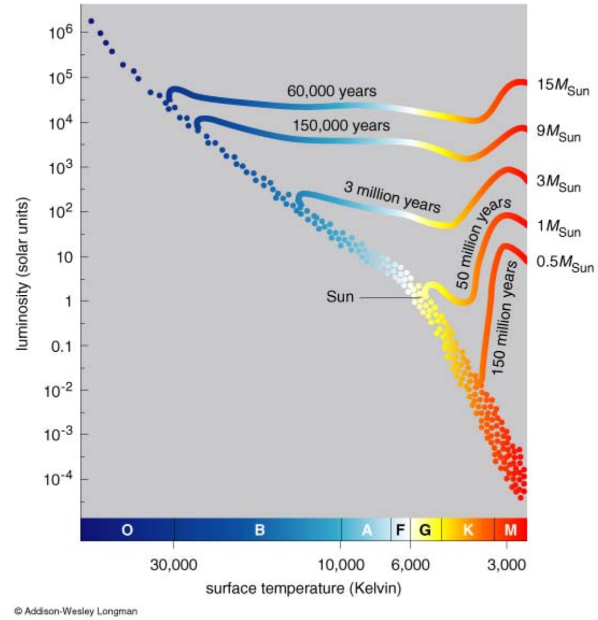

## Stellar Middle Age

Stars like the Sun

Massive stars




# Movement off the Main Sequence






# Movement off the Main Sequence

**TABLE 11-1** Main-Sequence Lifetimes

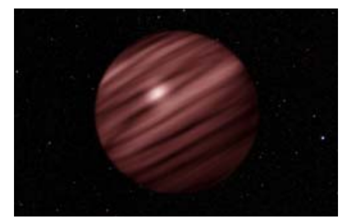
| Mass ($M_\odot$) | Surface temperature (K) | Luminosity ($L_\odot$) | Time on main sequence ($10^6$ years) | Spectral class |
|---|---|---|---|---|
| 25 | 35,000 | 80,000 | 3 | O |
| 15 | 30,000 | 10,000 | 15 | B |
| 3 | 11,000 | 60 | 500 | A |
| 1.5 | 7,000 | 5 | 3 ,000 | F |
| 1.0 (Sun) | 6,000 | 1 | 10,000 | G |
| 0.75 | 5,000 | 0.5 | 15,000 | K |
| 0.50 | 4,000 | 0.03 | 200,000 | M |

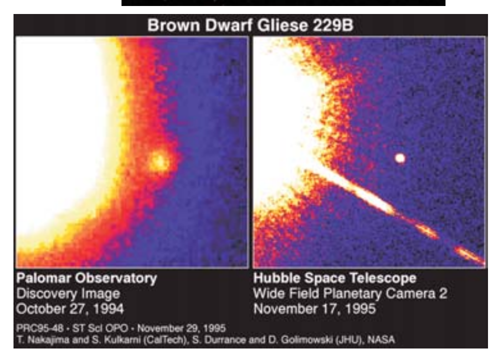
Luminosity = rate at which fuel is being consumed
Mass = amount of fuel available



# Brown Dwarves: M < 0.08 $M_{sun}$

- These are objects that are below 80 Jupiter masses.
- The central density and temperature do not get large enough for nuclear fusion to occur.
- These failed stars, gradually cool down and contract.
- Recently, there have been a number of discovered brown dwarves.

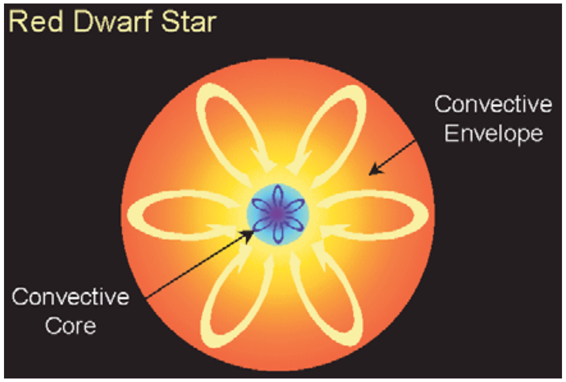





http://www.ast.cam.ac.uk/HST/press/gl229b.html

# Red Dwarves:
# 0.08 $M_{sun}$ < M < 0.4 $M_{sun}$

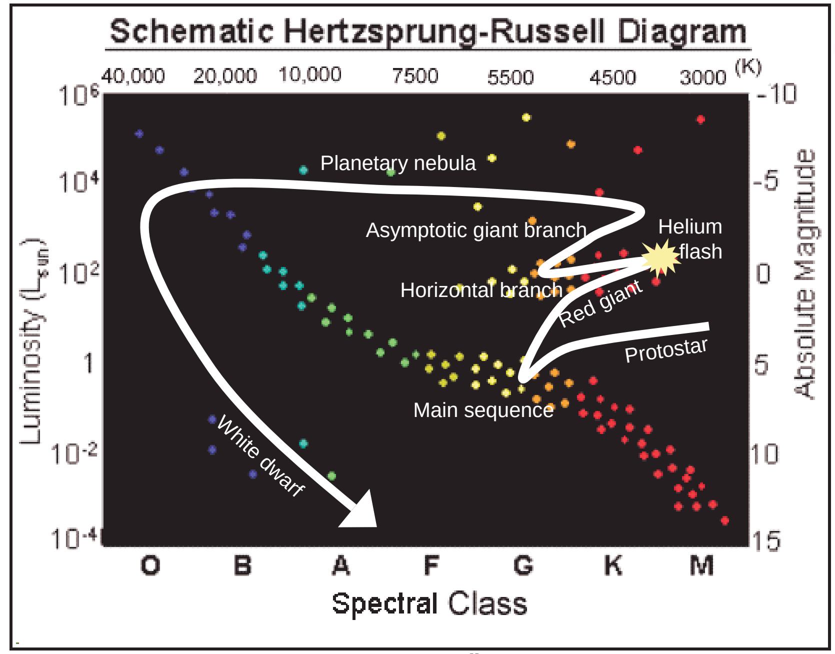
- Fully convective interior, so helium produced in fusion gets evenly spread.
- The star turns all of its hydrogen to helium, then all fusion would stop.
- These stars live an incredibly long time – hundreds of billions of years. As the Universe is thought to only be about 14 billion years old, none of these stars have yet made it to the end of their life.




http://www-astronomy.mps.ohio-state.edu/~pogge/Ast162/Unit2/RedDwarf.gif



# Evolutionary Path of a Solar-Mass Star





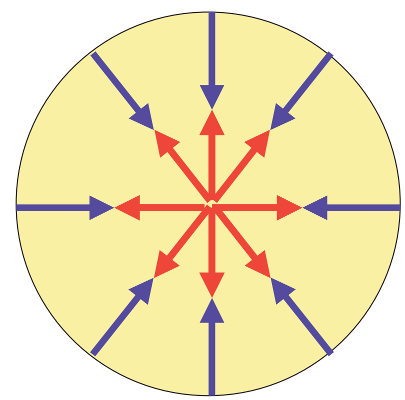

# The Life of a 1 Solar Mass Star:
# 0.4 $M_{Sun}$ < M < 4 $M_{Sun}$

Example of how low mass stars will evolve on the HR Diagram– http://rainman.astro.uiuc.edu/ddr/stellar/archive/suntrackson.mpg

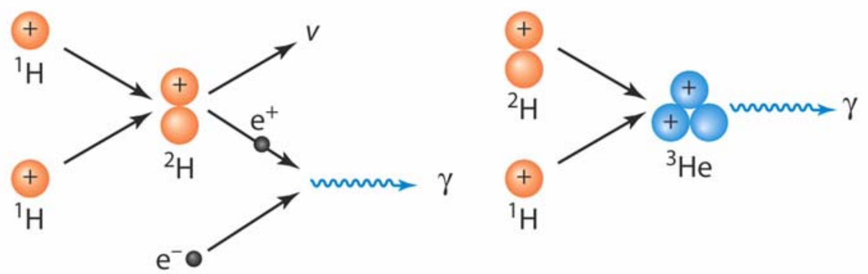


# Hydrostatic Equilibrium:
## The Battle between Gravity and Pressure

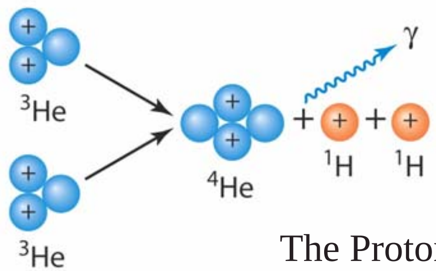
- Pressure pushes out and gravity pulls in– *an equilibrium*
- This is why a main sequence star isn't shrinking even though it's a big ball of gas.
- A star's life is all about this battle!



# What keeps it up?




The pressure comes from fusion. Gravity squeezes hydrogen, until fusion starts. Then, the fusion creates a back pressure.

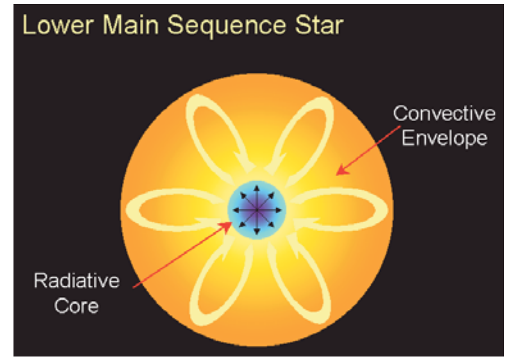



The Proton-Proton Cycle



# And when the Hydrogen Runs out?

- The low mass stars have radiative cores.
- First the hydrogen is burned in the core– not hot enough to burn helium
- Then the core starts to shrink a little– hydrogen shell burning (around the inert helium core) starts.
- This stops the collapse, and actually the outer envelope expands quickly.
- As the envelope expands, it cools– so it becomes a Red Giant

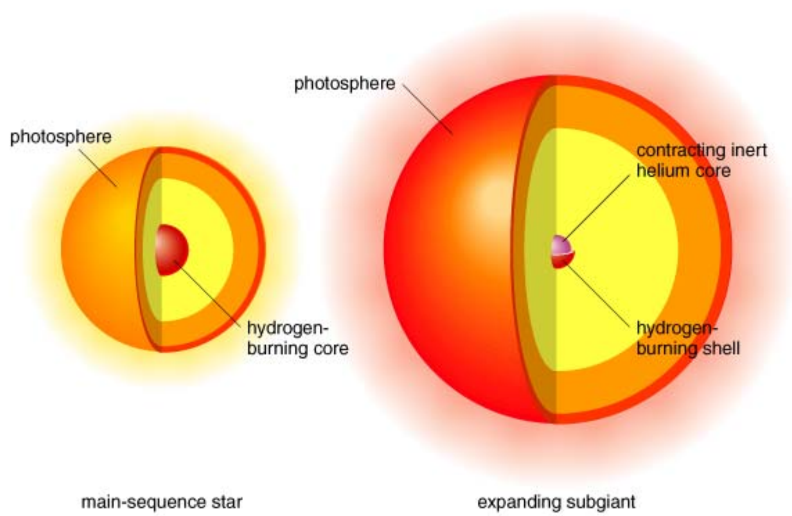



Our Sun has about 5 billion more years left on the main sequence.

http://www-astronomy.mps.ohio-state.edu/~pogge/Ast162/Unit2/LowerMS.gif



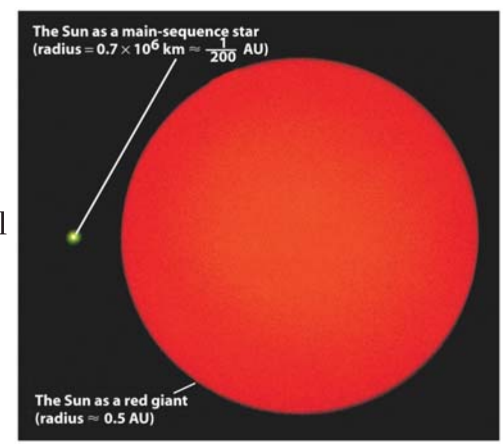
# The Interior of the Red Giant






# And then?

- So, we have a low mass star that has:
  1) H fusing into He in the core
     - Main sequence
  2) H fusing into He in a shell around the core
     - Red giant (100 times larger, radius of 0.5 AU), turning the Earth to cinders…
- What next? A Helium Flash!



# Helium Flash

- In the giant phase, the core temperature rises
- When temperature of the core reaches 100 million K, helium begins to fuse into carbon (C). Three Helium atoms fuse into Carbon and photons.

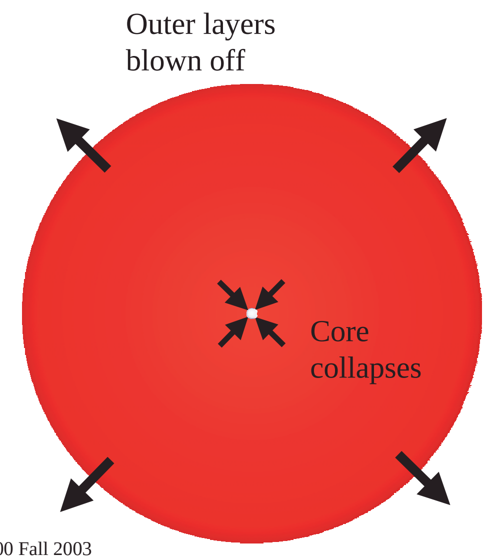
$$^{4}He + {}^{4}He + {}^{4}He \rightarrow {}^{12}C + \gamma$$

  - The star gets bigger again
  - Outer layers cool off
- .Helium burning happens suddenly and explosively



# Planetary Nebula– Ejection

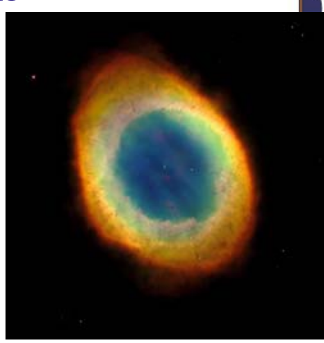
- Fusion slows down– the helium has burned into carbon and oxygen, not enough pressure to fuse anything else.
- Stellar core collapses to high densities– heats up
- The outer layers are pushed out by the hot radiation pressure of the core.
- The outer layers are almost all ejected
- The core (a white dwarf!) is made of "ash" from helium fusion – carbon & oxygen.






## Planetary Nebulae


Hourglass Nebula

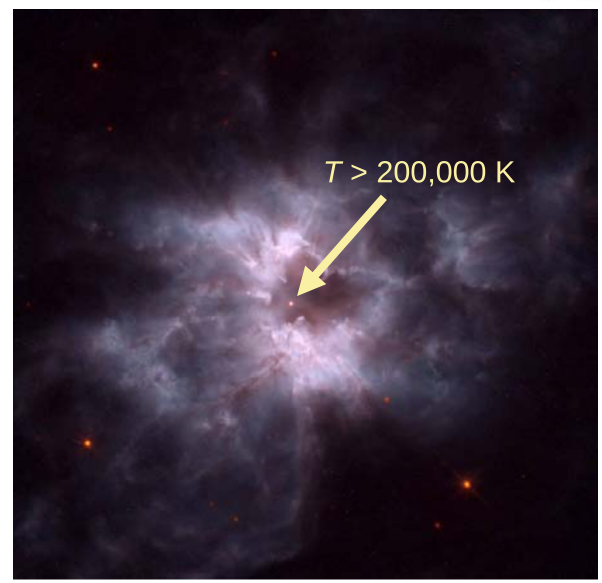

Ring Nebula


Cat's Eye Nebula



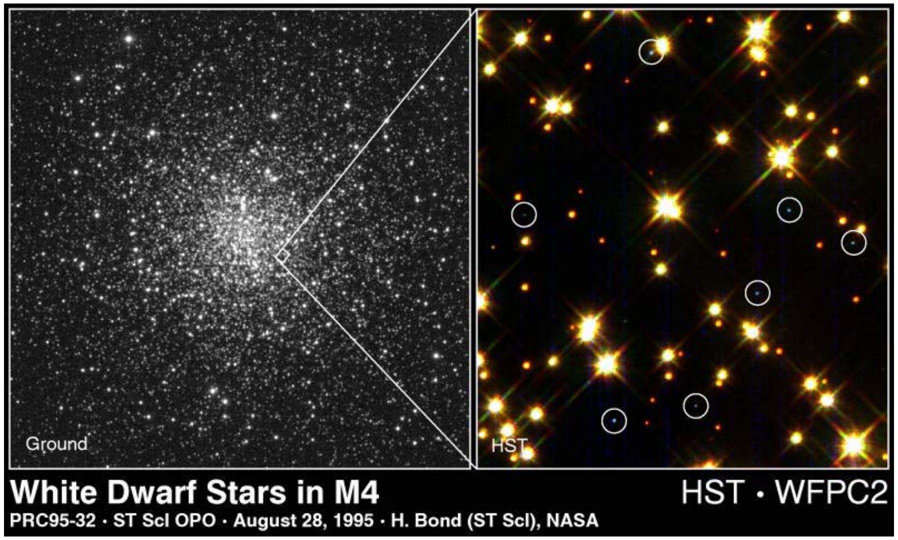
## White Dwarfs and Planetary Nebulae

- Outer layers of the red giant star are blown away by radiation from the hot new white dwarf
- As they expand, they are lit from within by the white dwarf
- Distortions appear as expanding shell hits interstellar medium



NGC 2440

# White Dwarves!




http://oposite.stsci.edu/pubinfo/jpeg/M4WD.jpg



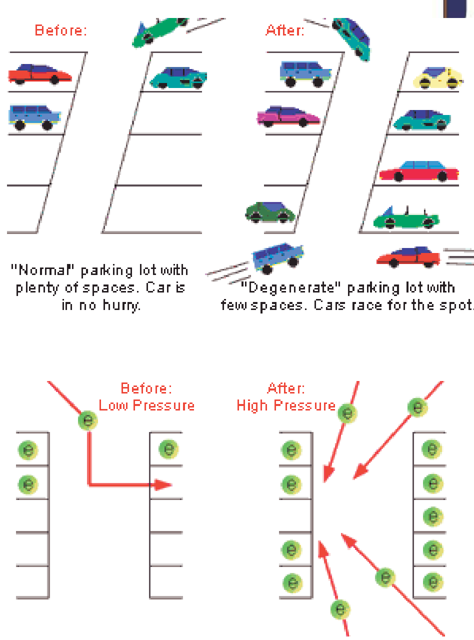
# What Keeps a White Dwarf up?

- The nuclear fusion stopped, and gravity begun to win the battle.
- Then, the electrons got so squashed together that they get pushed into degenerate states.
- Nearby electrons can not occupy the same energy states.
- This electron degeneracy causes pressure to counteract gravity



## Degeneracy Pressure

- Electrons are forced into higher energy levels than normal – all of the lower levels are taken
- Effect manifests itself as pressure




NASA