Astronomy 210

This Class (Lecture 31):

Stars: Spectra and the H-R Diagram

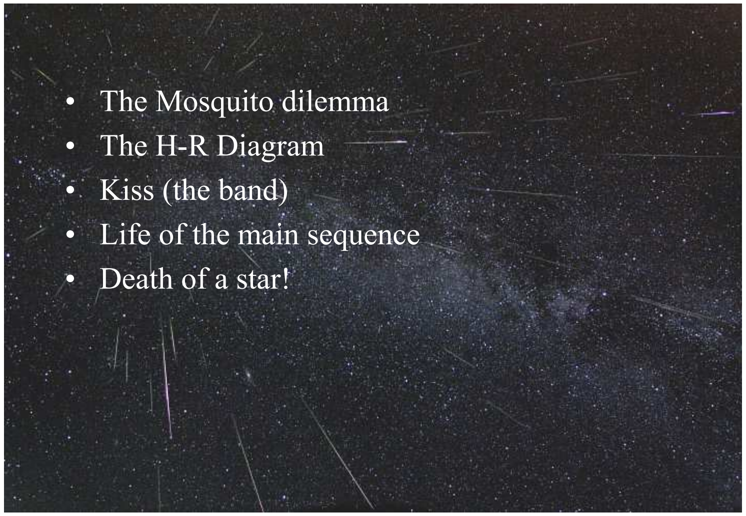
Solar Observing & HW9 due April 15th

Stardial 2 is available.

Next Class:

Life and Death of the Sun

Outline



- The Mosquito dilemma
- The H-R Diagram
- Kiss (the band)
- Life of the main sequence
- Death of a star!

Stellar Properties

- Apparent brightness – Flux or apparent magnitude
- Distance
- Masses of binary systems
- Color
- Stellar spectra

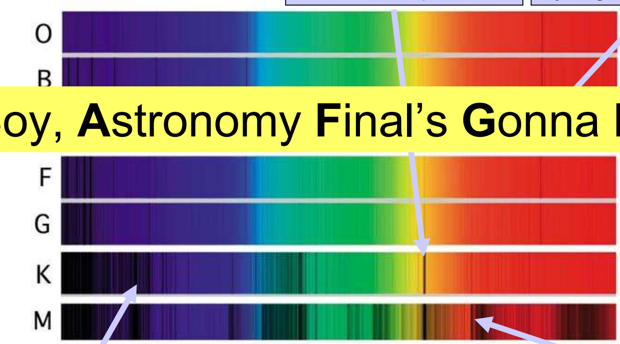
The Mosquito Dilemma

- It's like a mosquito trying to understand humans.
- They don't live long enough to watch humans be born and die, so they have to extrapolate.
- How do we understand stars that live for 10 billion+ years?

http://news.uns.purdue.edu/html3month/2004/040823.Williams.fallwnv.html

Spectral Classes

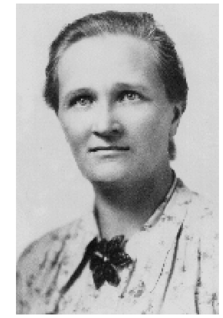
- To understand the physical nature of stars, we need to look at their spectra
- 9 classes based on spectrum lines
- Our Sun is a "G" star



"**O**h **B**oy, **A**stronomy **F**inal's **G**onna **K**ill **M**e"

What do the spectra tell us?

- The spectra tell us about both the compositions and temperatures of the stellar atmospheres
- Astronomer Cecilia Payne found that most stars' compositions are very similar to the Sun's
- The spectral sequence is due to *temperature*, not composition
  - M & K stars are 92% hydrogen, but their photospheres aren't hot enough to excite it



Cecilia Payne

Properties of Spectral Classes

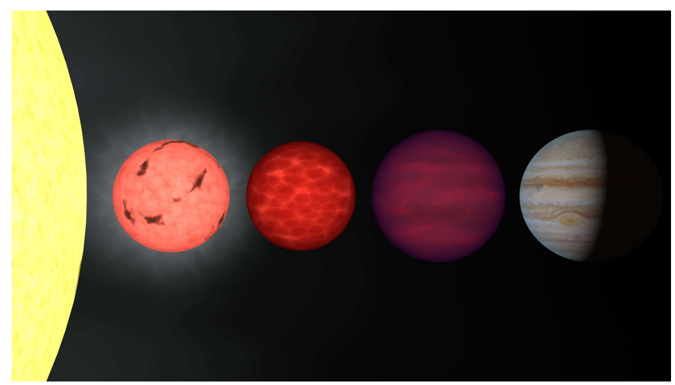
TABLE 10-1 The Spectral Sequence

Spectral class	Color	Temperature (K)	Spectral lines	Examples
O	Blue-violet	30,000–50,000	Ionized atoms, especially helium	Naos (ζ Puppis), Mintaka (δ Orionis)
B	Blue-white	11,000–30,000	Neutral helium, some hydrogen	Spica (α Virginis), Rigel (β Orionis)
A	White	7500–11,000	Strong hydrogen, some ionized metals	Sirius (α Canis Majoris), Vega (α Lyrae)
F	Yellow-white	5900–7500	Hydrogen and ionized metals such as calcium and iron	Canopus (α Carinae), Procyon (α Canis Minoris)
G	Yellow	5200–5900	Both neutral and ionized metals, especially ionized calcium	Sun, Capella (α Aurigae)
K	Orange	3900-5200	Neutral metals	Arcturus (α Boötis), Aldebaran (α Tauri)
M	Red-orange	2500-3900	Strong titanium oxide and some neutral calcium	Antares (α Scorpii), Betelgeuse (α Orionis)

L 1500-2000

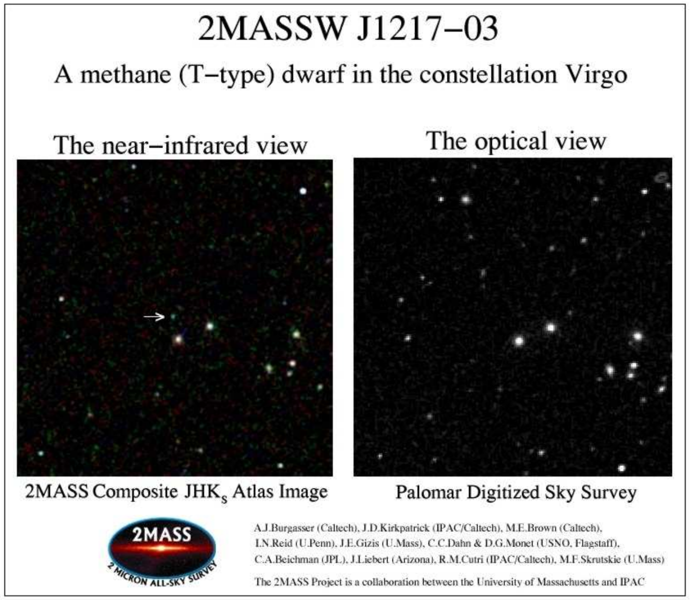
T 700-1000

Dwarves



http://spider.ipac.caltech.edu/staff/davy/ARCHIVE/

T Dwarves



.vy/ARCHIVE/

T and L

- We now have luminosity and temperatures of stars.
- How do they correlate?
- Think about it.
- If we can have any L for any T, what do we expect?
- If only one L for one T, then what?

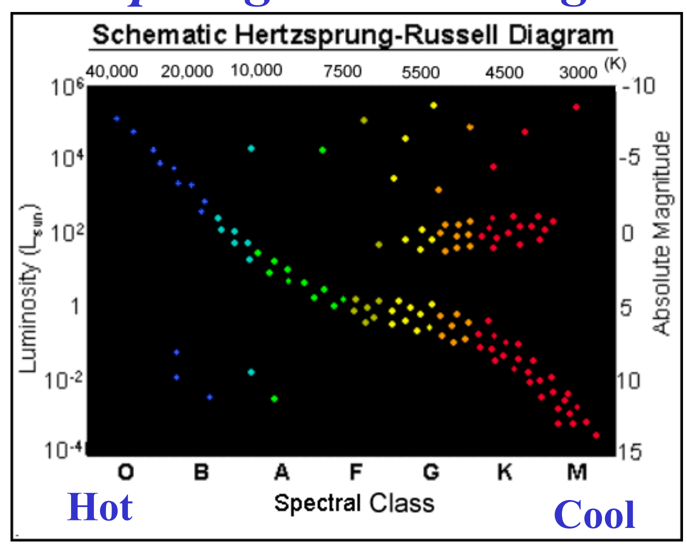
The H-R Diagram

- In the early 20th century, two astronomers plotted absolute magnitude vs. spectral class and found an interesting correlation in different regimes.
- It is not a random plot of points!
- The resulting plot is now named for them
- The **Hertzsprung-Russell Diagram**

Hertzsprung-Russell Diagram

Bright

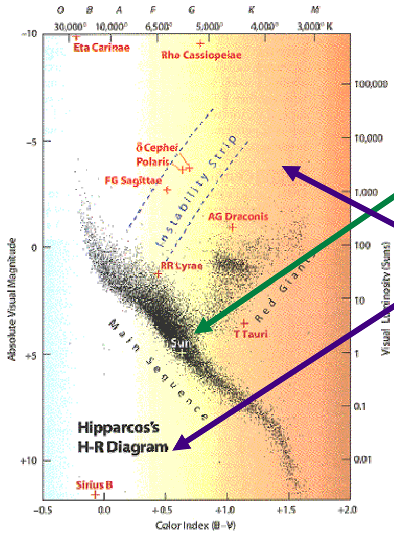
Dim



Hot

Cool

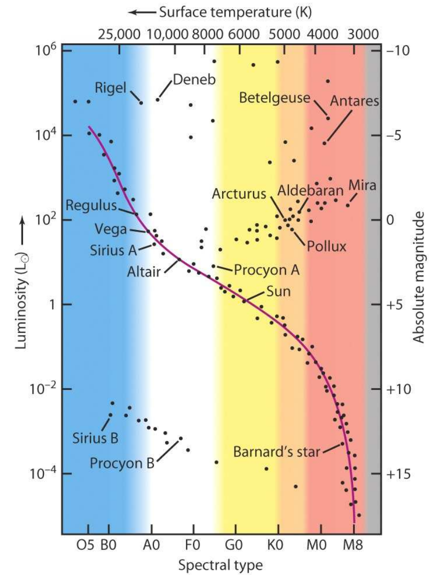
The H-R Diagram



- Stars do not have random temperatures and brightness
- 91% of all stars are on the Main Sequence.
  - Why?
- But, there are also very bright cool stars and very dim hot stars

http://www.kosmologika.net/Stars/HR-fordelning_av_samplade_stjarnor.gif

The H-R Diagram

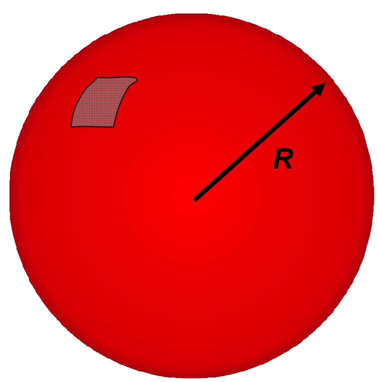


How does the size of a star near the top left of the H-R diagram compare with a star of the same brightness near the top right of the H-R diagram?

- They are the same size
- The star near the top left is larger
- The star near the top right is larger

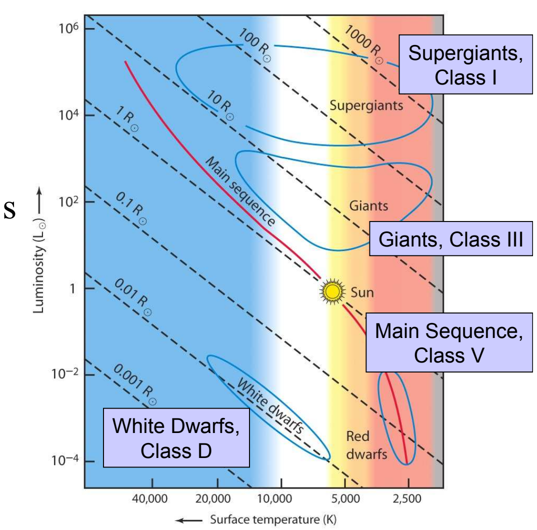
Luminosity

- Energy radiated per second
- Depends on
  - Temperature – luminosity per area proportional to T^4
  - Radius – surface area proportional to R^2
- Bright cool stars must be large
  - **Giants & Supergiants**
- Dim hot stars must be small
  - **White dwarfs**



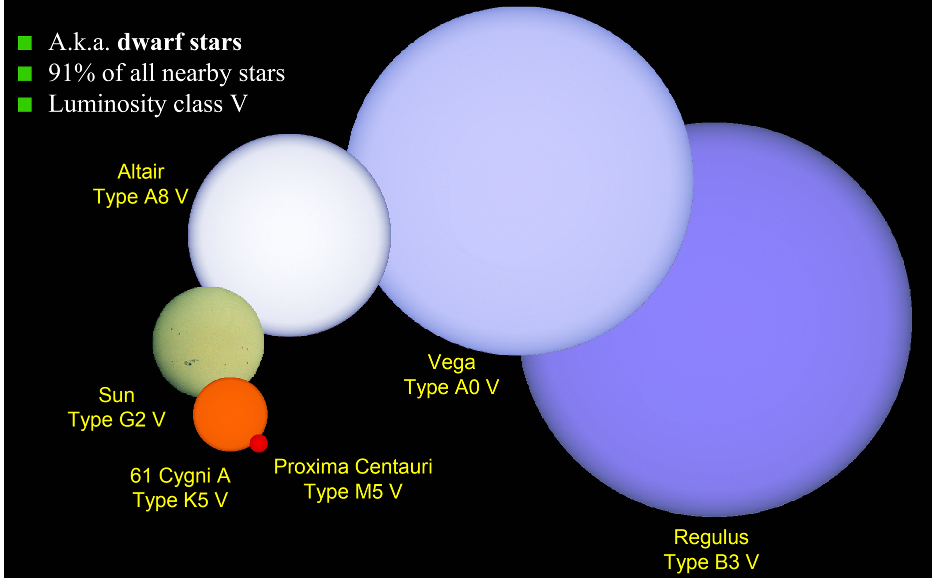
Luminosity Classes

- Stars on the H-R diagram are also divided into **luminosity classes**
- Appended to a star's spectral class
- The Sun is a class "G V" star



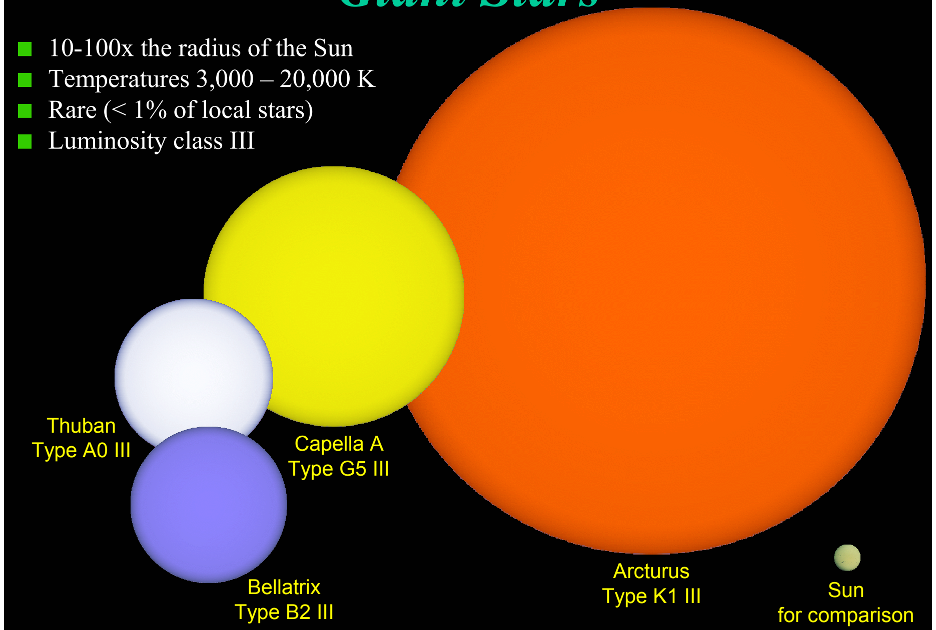
Main Sequence Stars

- A.k.a. **dwarf stars**
- 91% of all nearby stars
- Luminosity class V



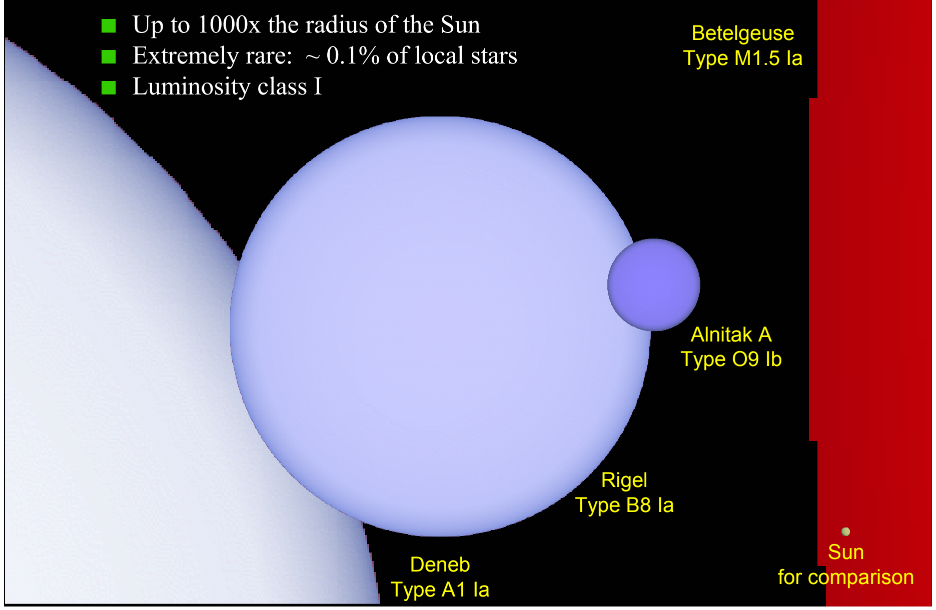
Giant Stars

- 10-100x the radius of the Sun
- Temperatures 3,000 – 20,000 K
- Rare (< 1% of local stars)
- Luminosity class III



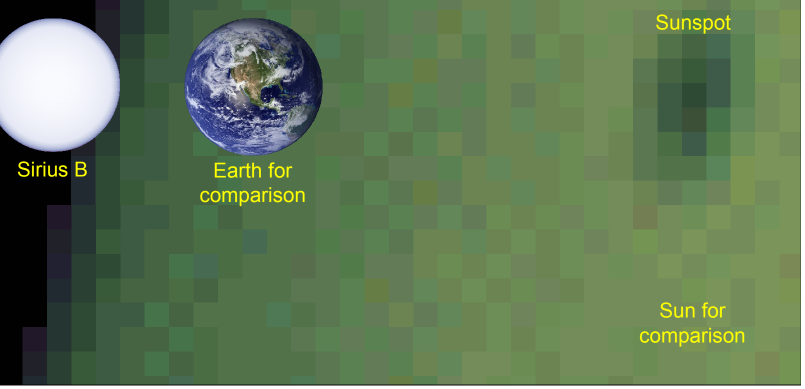
Supergiant Stars

- Up to 1000x the radius of the Sun
- Extremely rare: ~ 0.1% of local stars
- Luminosity class I



White Dwarf Stars

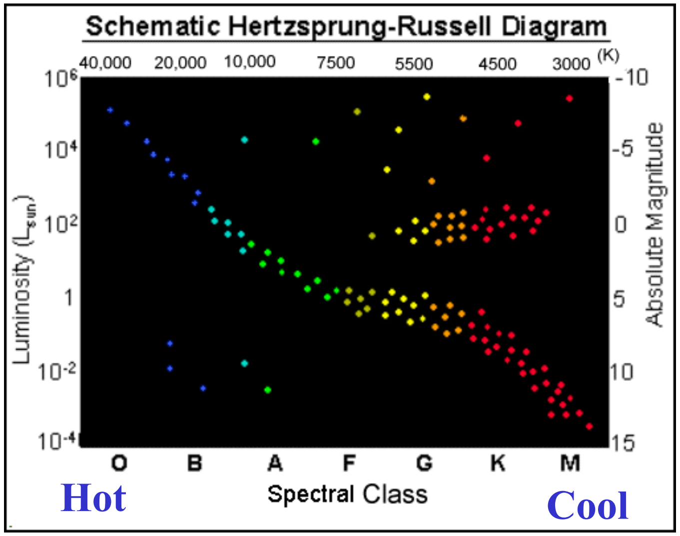
- About the size of the Earth
- Very hot: 5,000 – 20,000 K
- About 8% of local stars
- Luminosity class D



Hertzsprung-Russell Diagram

Bright

Dim



What do the regions of the H-R Diagram mean?

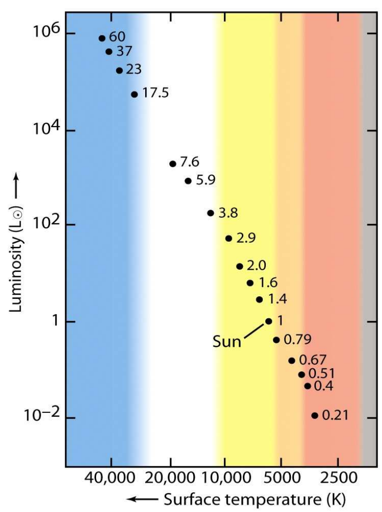
- One big question - What are the differences between stars in the regions of the H-R diagram?
- The regions of the H-R diagram reflect different states of stellar evolution (aging)
  - Main sequence stars are "adult stars"
  - Giants and supergiants are "aged stars" (nearing the end of their lives)
  - White dwarfs are "dead stars"

The Mass-Luminosity Relationship

- Luminosity is proportional to Mass

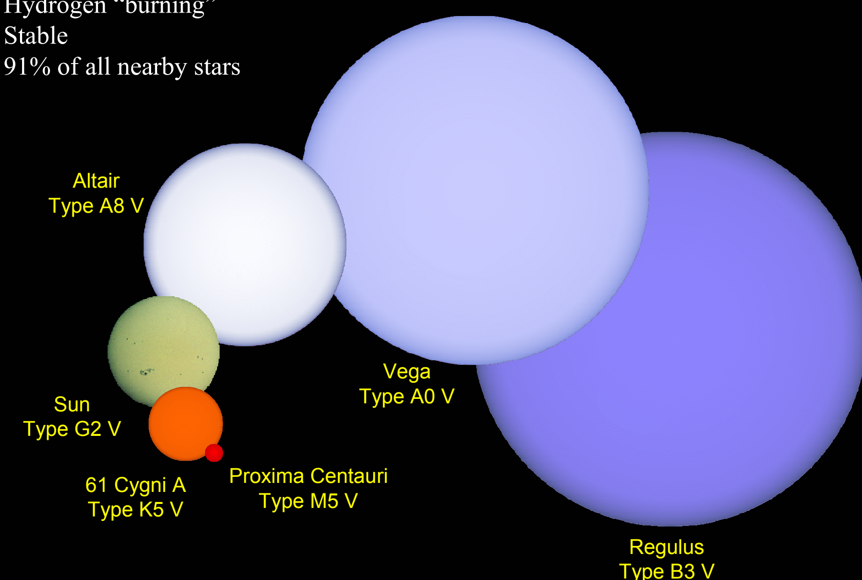
$$L \propto M^{\alpha} \quad \text{where} \quad \alpha = \begin{cases} 2.3 & M < 0.43 M_{\odot} \\ 4.0 & 0.43 < M < 10 M_{\odot} \\ 3.0 & M > 10 M_{\odot} \end{cases}$$

- Much larger range in luminosity than in mass
- Non-main sequence stars deviate from this relationship



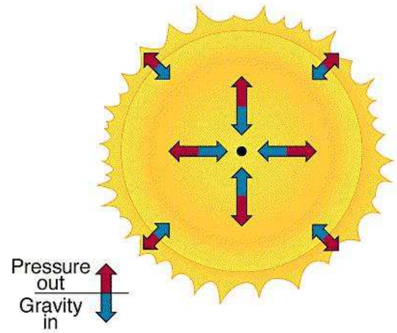
Main-Sequence Stars

- Hydrogen "burning"
- Stable
- 91% of all nearby stars



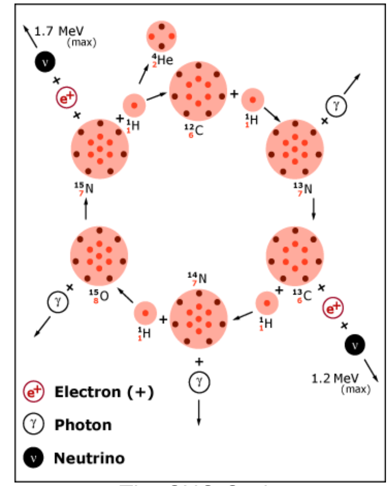
Hydrostatic Equilibrium

- The battle between Gravity and Pressure is a draw for these stars.
- 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!



More than one way to fuse

- High-mass stars do fusion by a second process
- Called the *CNO cycle*
  - Still converts 4 hydrogens into 1 helium
  - Uses a carbon nucleus as a catalyst
- Requires very high temperatures in the core
  - More than low-mass stars (like the Sun) can produce



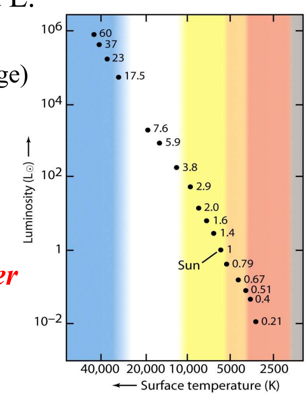
The CNO Cycle

Important Questions

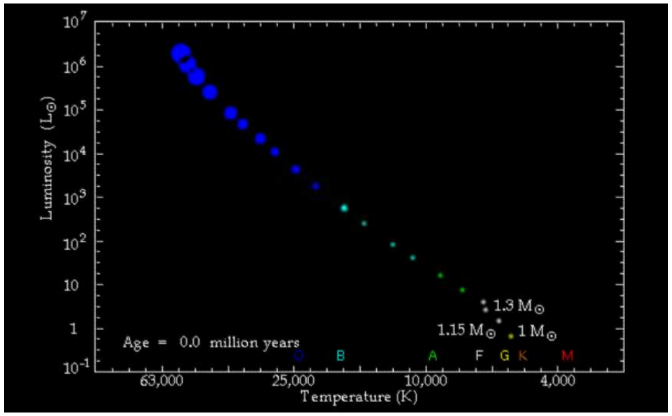
- A star remains stable and on the main sequence as long as it has hydrogen to fuse in the core…
- **How long will the fuel last?**
- **What happens when the fuel runs out?**

Main Sequence Lifetimes

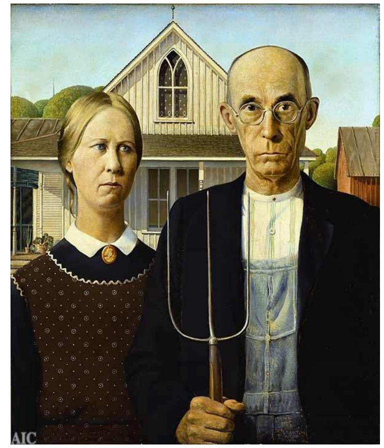
- For main sequence stars, we have an M and L.
- We know $E = L\tau$
  - energy supply (fuel) = energy lost (burn rate x age)
- So, $\tau = E/L$ and $E \propto M$ and $L \propto M^4$
- $\tau = 1/M^3$
- Using solar values, we get
- $\tau = 10^{10} (M_{\odot}/M)^3$
- **High-mass stars have dramatically *shorter* lifespans!**



Main Sequence Lifetimes



Stellar Lifestyles



Low-mass stars

Massive stars

Life Fast, Die Young

- High-mass stars: “gas guzzlers”
  - Very bright
  - Live short lives, millions of years
- Low-mass stars: “fuel efficient”
  - Dim
  - Long-lived, tens to hundreds of billions of years

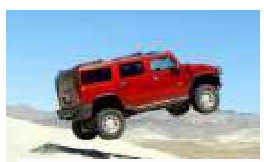
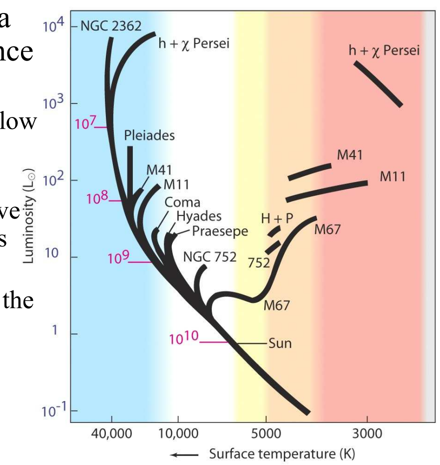


TABLE 11-1 Main-Sequence Lifetimes

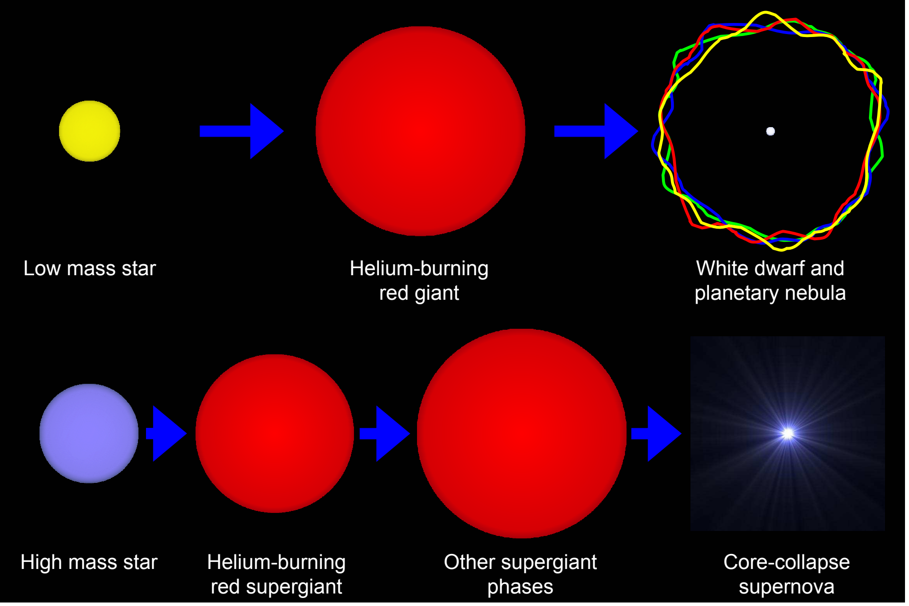
Mass ($M_\odot$)	Surface temperature (K)	Luminosity ($L_\odot$)	Time on main sequence (10^6 years)	Spectral class
25	35,000	80,000	3	O
15	30,000	10,000	15	B
3	11,000	60	500	A
1.5	7,000	5	3 ,000	F
1.0 (Sun)	6,000	1	10,000	G
0.75	5,000	0.5	15,000	K
0.50	4,000	0.03	200,000	M

Guess The Cluster’s Age!

- We can estimate the age of a cluster from its main sequence stars
  - Massive stars age faster than low mass stars
  - The cluster can’t be any older than its most massive stars’ main sequence lifetimes
  - We call the point where a cluster’s main sequence ends the *main sequence turnoff*



Stellar Demise!

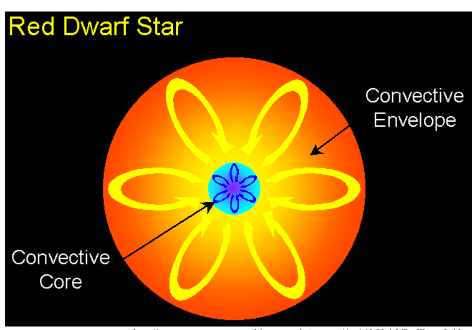


The Evolution of Stars

- A star's evolution depends on its mass
- We will look at the evolution of three general types of stars
  - Red dwarf stars (less than 0.4 M_{Sun})
  - Low mass stars (0.4-8 M_{Sun})
  - High mass stars (more than 8 M_{Sun})
- We can track the evolution of a star on the H-R diagram
  - From main sequence to giant/supergiant and to its final demise

Red Dwarf Stars

- 0.08 M_{Sun} < Mass < 0.4 M_{sun}
- Fully convective interior
- The star turns all of its hydrogen to helium, then all fusion will stop
- Live hundreds of billions to trillions of years
- The Universe is only about 14 billion years old, so none of these stars have yet made it to the end of their life



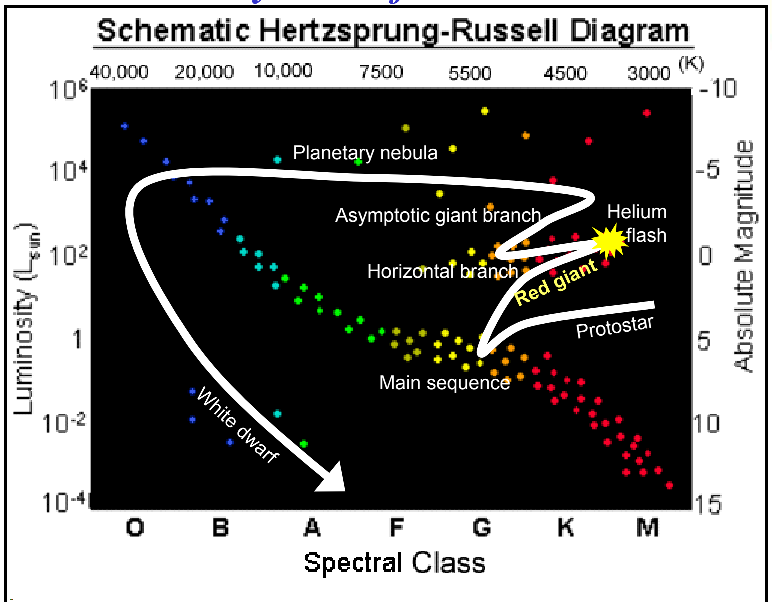
http://www-astronomy.mps.ohio-state.edu/~pogge/Ast162/Unit2/RedDwarf.gif

Life of a Low Mass Star

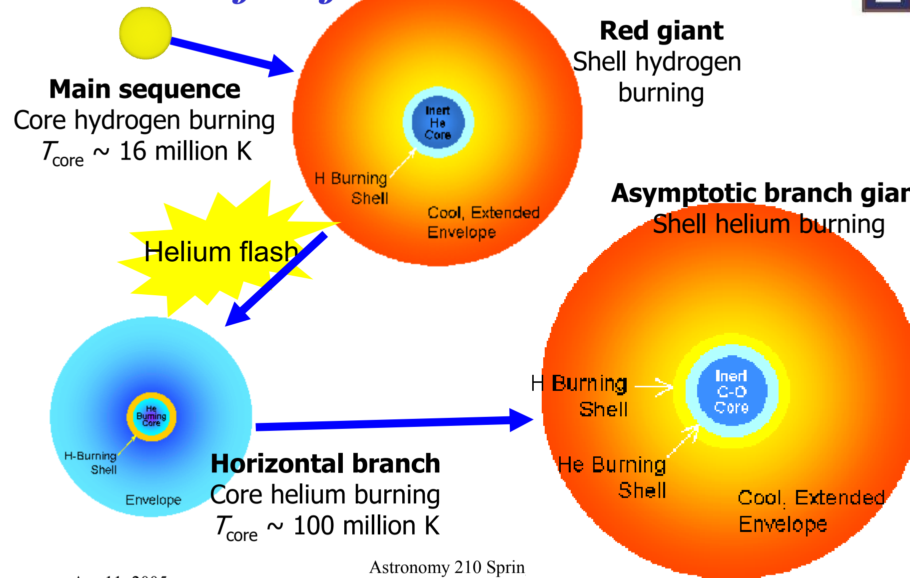
- Most of its life is spent in the happy pursuit of burning H ⇒ He
- With time L and T evolve gradually in response
- The Sun is now 30% brighter than zero age MS
- At 10 Byr will be 2x as bright as now
- This alone will cause a Greenhouse effect on earth!
- But in fact, oceans boil⇒ runaway greenhouse when $L = 1.1L_{\odot}$, which happens in about 1 Byr. So this is when things may hit the fan, not in 5 Byr.
- Model dependent, but still….

http://wings.avkids.com/Book/Myth/Images/ocean_sun.gif

Evolutionary Path of a Solar-Mass Star

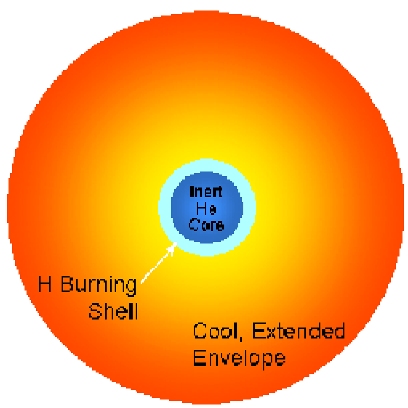


Life of a Low Mass Star



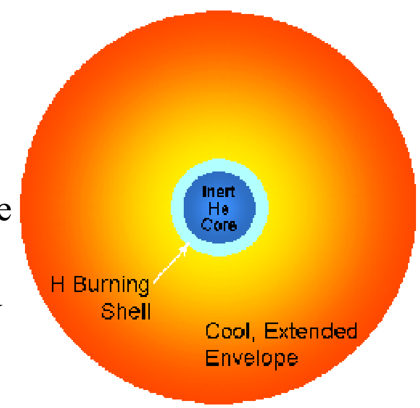
The Red Giant Phase

- When the hydrogen is gone in the core, fusion stops
- Core starts to contract under its own gravity
- This contracting heats the core, and hydrogen fusion starts in the shell around the core
- Energy is released, expands envelope ⇒ Lum increases!
- As the envelope expands, it cools – so it becomes a red giant



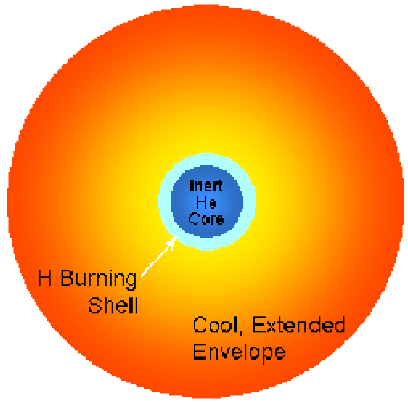
Contraction Junction

- In core, contraction increases ρ
- Contraction slowed by Pauli exclusion principle: can't put 2e's in same state
- Quantum "degeneracy" pressure (same as in solid bodies!)
- $P = K\rho^{5/3}$ K const: depends only on ρ, not T (≠ ideal gas!)



Contraction Junction

- Degenerate core and H burning shell
- Core heats ⇒ He fusion ignites
- In a normal gas: T ↑, P ↑ so it expands & cools
- In a degen. gas: T ↑, P const so no expansion & no cooling
- So the reaction speeds up ⇒ explosion!
- Helium Flash (few min)
- Note: explosion energy trapped in outer layers so don't see anything special from the outside



Helium Burning

- When the core of the star reaches 100 million degrees, it can start to fuse helium into carbon
- Called the Triple-Alpha Process
  - Converts 3 heliums into one carbon + energy