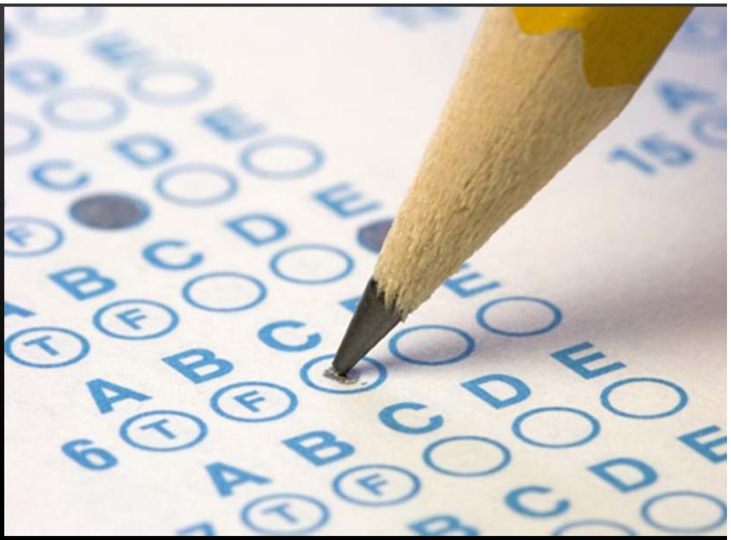
# UPCOMING TEST

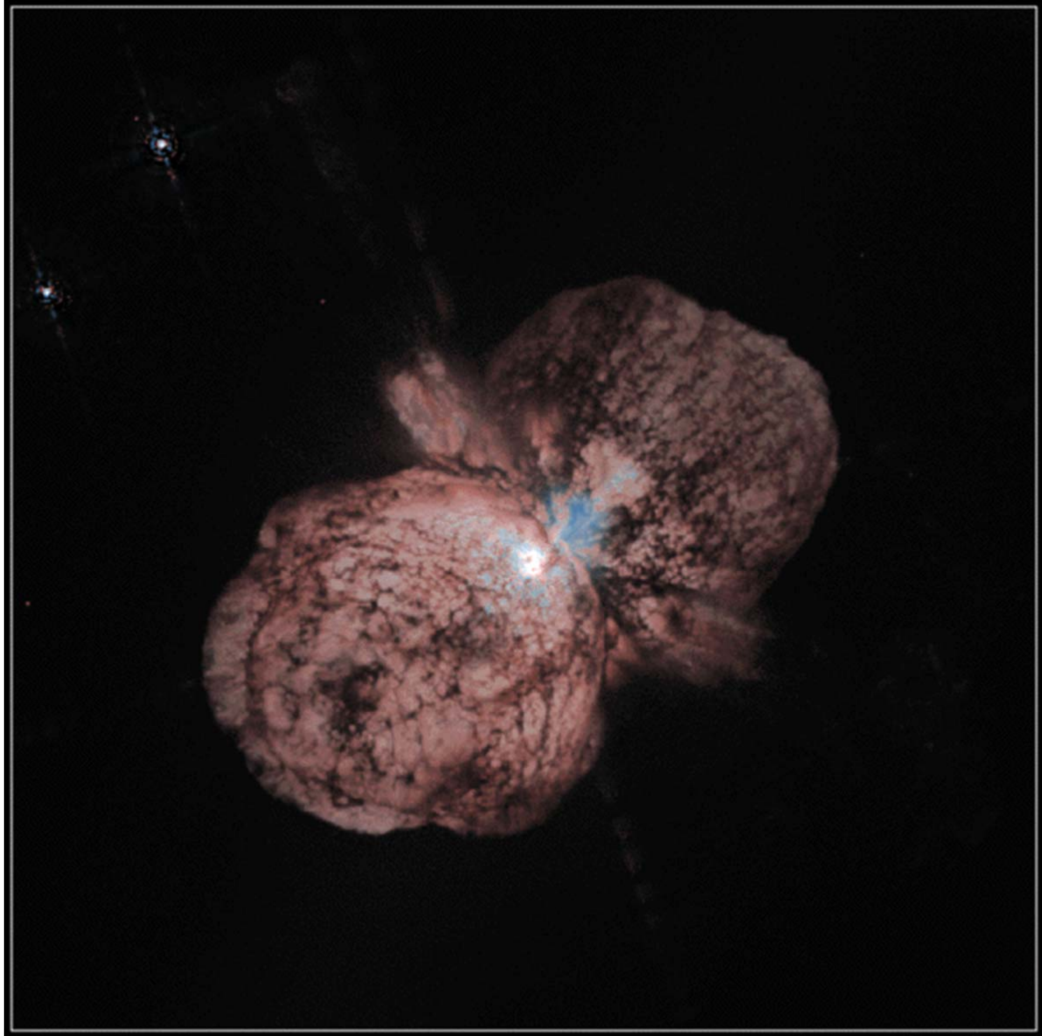


- In a week: next Friday, November 10
- Covers stars: Ch.11-14
  - Sample test has been posted for a few weeks now
  - Take advantage of the online end-of-chapter concept quizes
  - Figure out what you did right or wrong on your old tests, so you can learn not to make similar mistakes again

# HOW BIG?

- The smallest a star can be is about 80 Jupiters
  - 0.08 $M_\odot$
- There is a maximum size too –
  - Above ~100 $M_\odot$, the cloud collapses so fast that it breaks up and makes smaller stars instead
  - Plus, that large a star is so bright that pressure from the light itself blows off the star’s outer layers
    - Called the “Eddington Limit”
    - We have not observed stars more massive than this

# ETA CARINA



**Eta Carinae** HST • WFPC2

PRC96-23a • ST ScI OPO • June 10, 1996

J. Morse (U. CO), K. Davidson, (U. MN), NASA

- One (or several!) of the biggest stars known are in there, ~120 $M_\odot$

# ETA CARINA

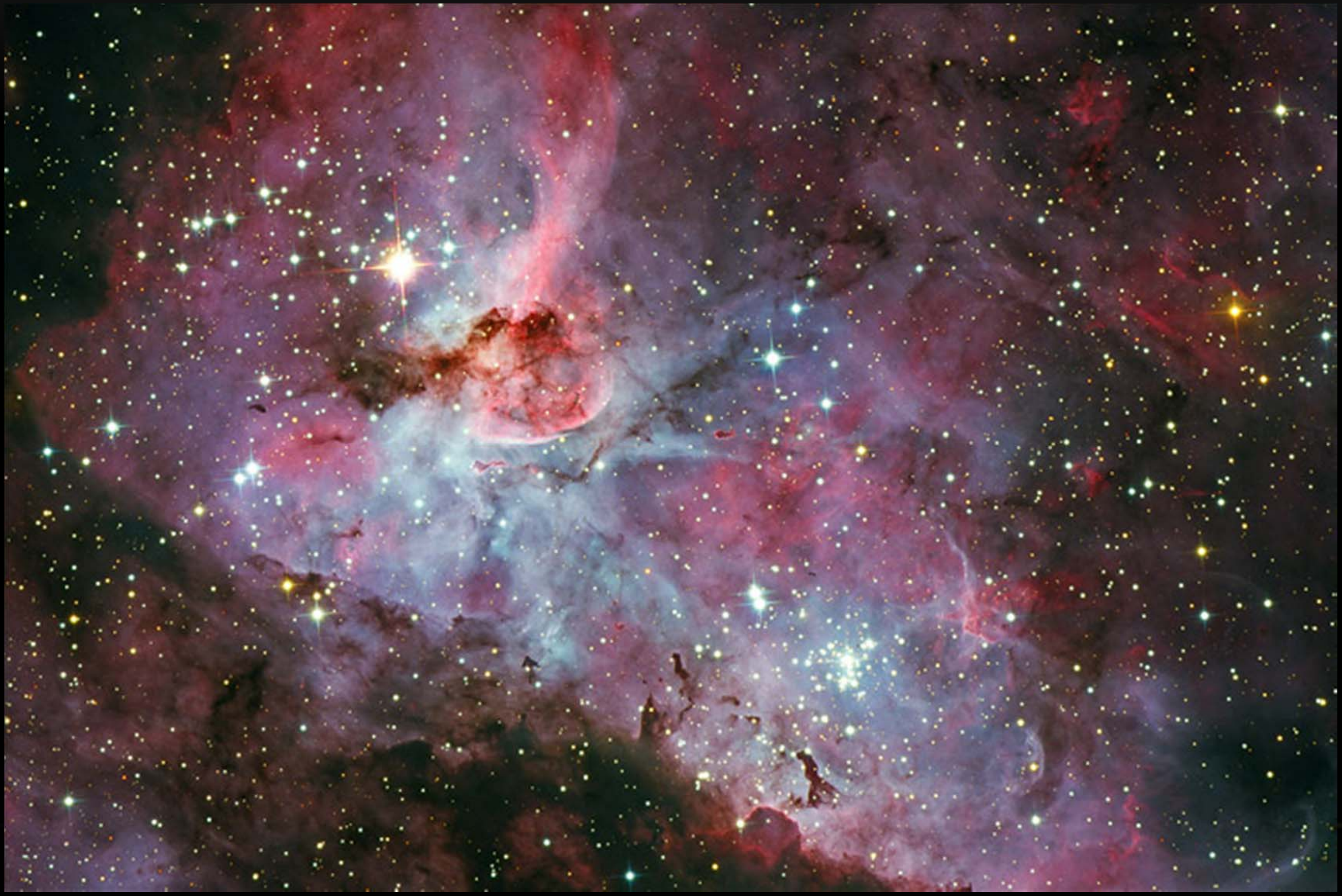


Image by
Johannes Schedler

# HOW MANY ARE BIG VS. SMALL?

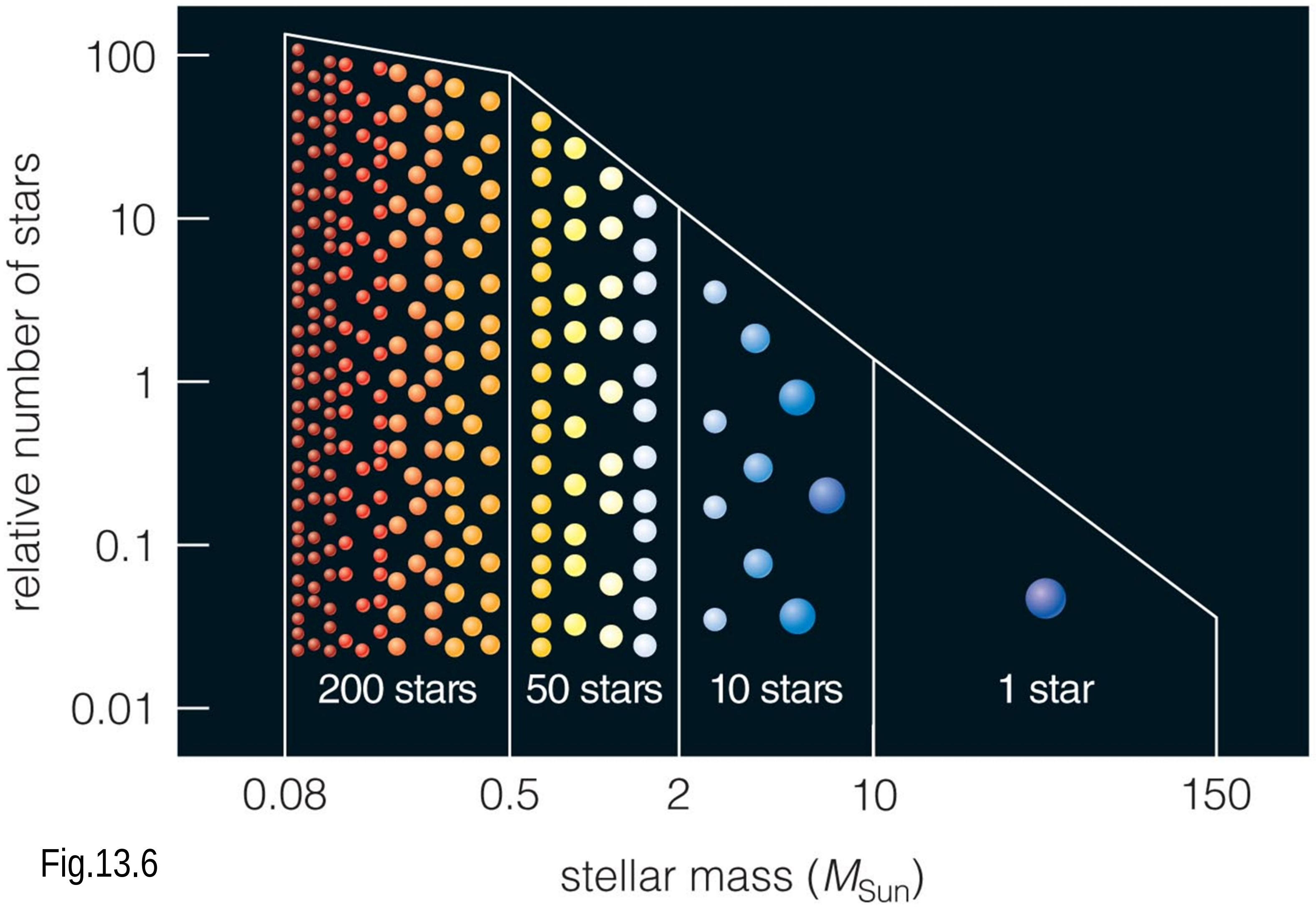


Fig.13.6

# LOTS OF BROWN DWARFS

Fig.13.7

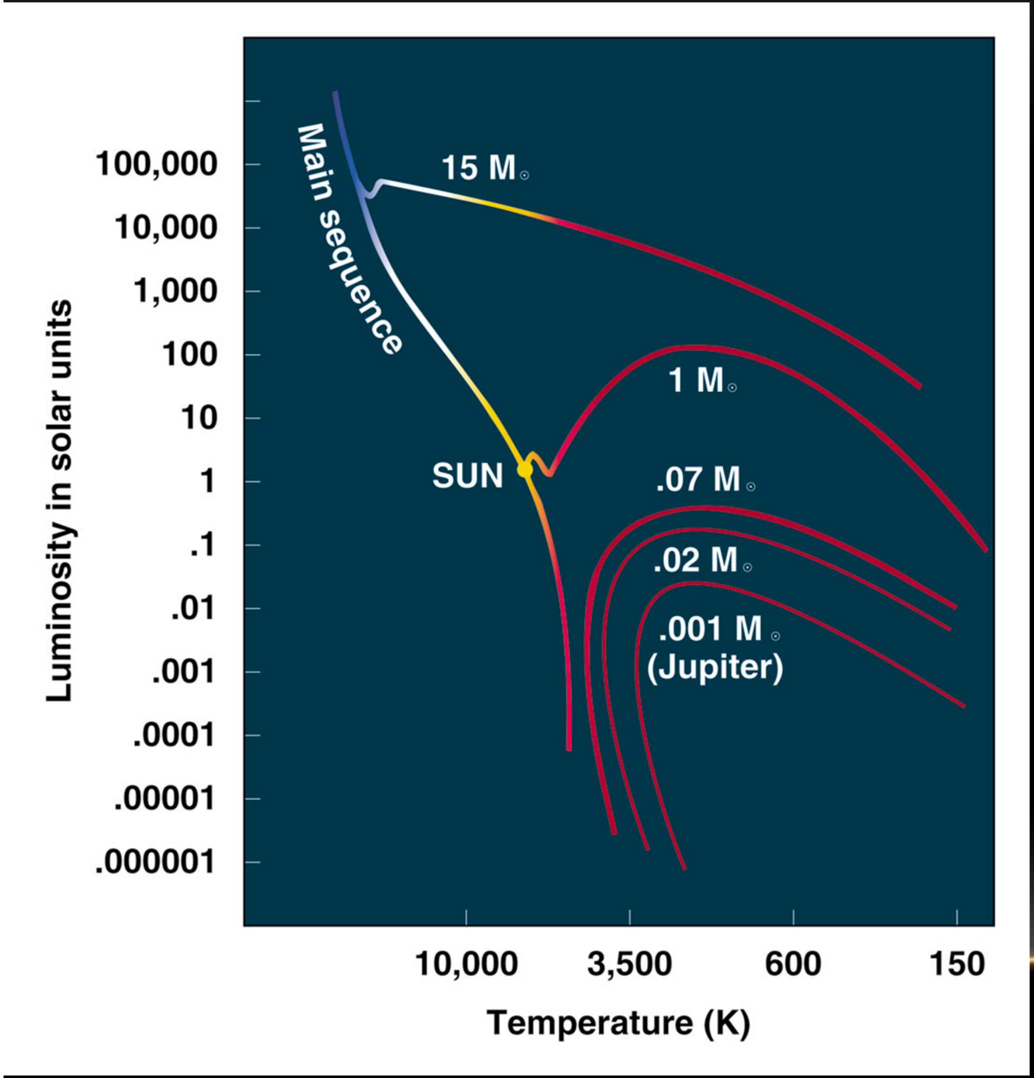
**a** Artist's conception of a brown dwarf, orbited by a planet (to its left) in a system with multiple stars. The reddish color approximates how a brown dwarf would appear to human eyes. The bands are shown because we expect brown dwarfs to look more like giant jovian planets than stars.

**b** An infrared image showing brown dwarfs (circled) in the constellation Orion. They are easier to spot in star-forming regions like this one than elsewhere in our galaxy, because young brown dwarfs still have much of the thermal energy left by the process of gravitational contraction. They therefore emit measurable amounts of infrared light.

# STELLAR EVOLUTION

## Ch.13

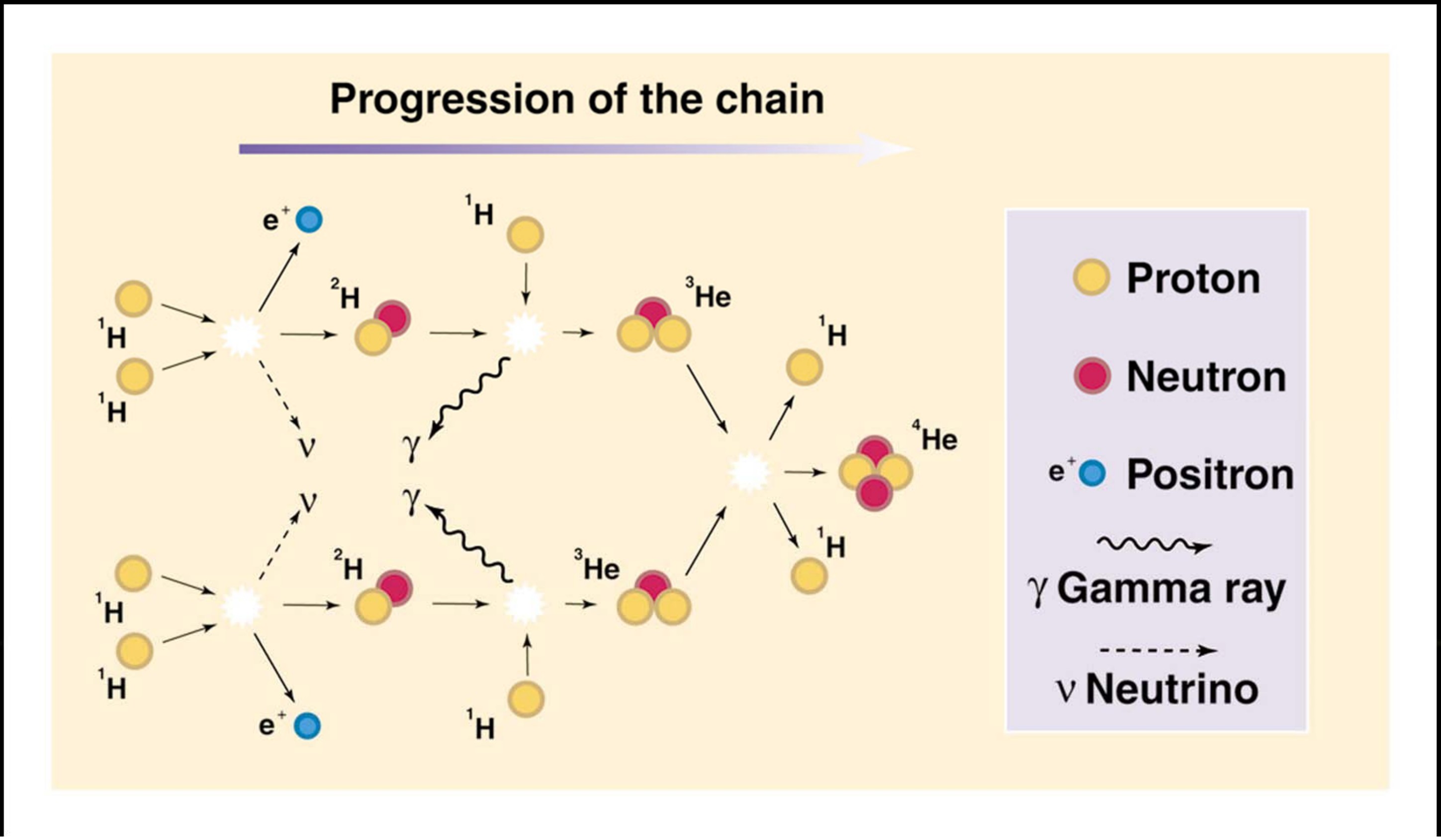
# WHAT WE KNOW SO FAR



- Star forms from gravitational collapse of glob of dust & gas
  - Compressed by gravity
  - Heats up
  - Starts fusing H to He, makes own energy
  - Is on “main sequence” when T, L plotted on the HR diagram

# THE PROTON-PROTON CHAIN

- We saw in the Sun chapter how nuclear reactions turn 4 H into 1 He:



# THE STELLAR THERMOSTAT

- The fusion process is self-regulating and stable
- If the fusion is going more rapidly than normal
  - Produces more heat, pressure
  - Core expands
  - Atoms now farther apart, fusion slows
- If the fusion slows down
  - Produces less heat, pressure
  - Core contracts
  - Atoms now closer together, fusion picks back up

# LIFE ON THE MAIN SEQUENCE

- 90% of stars we see have a T, L which when plotted on the HR diagram lies on the “main sequence”
  - Thus, stars must spend about 90% of their time doing what gives them that T and L
    - Burning H into He in their cores
- How do they change over those millions and billions of years?

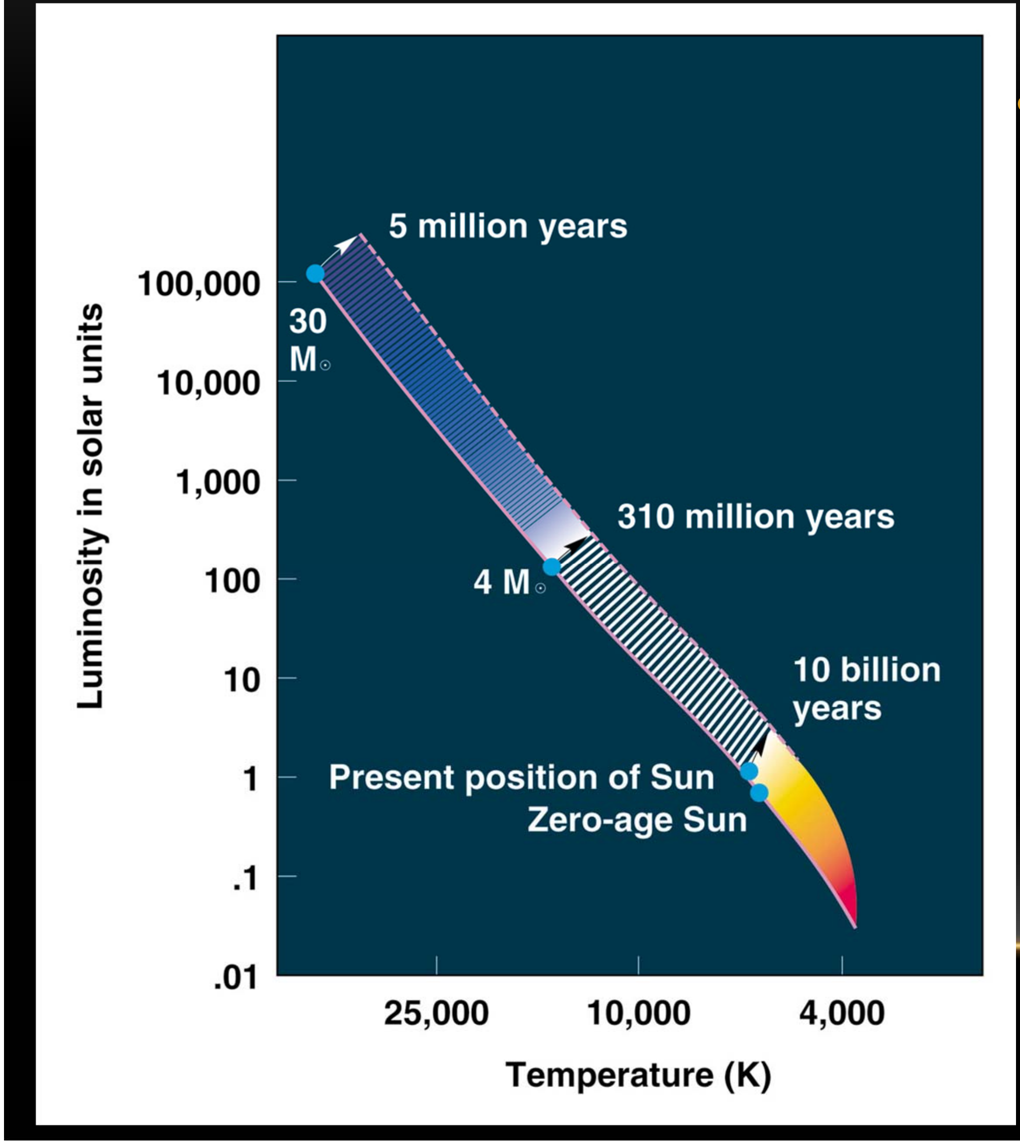
# ZERO-AGE MAIN SEQUENCE

- Just after fusion starts and the star settles into equilibrium, its position on the main sequence is called the ZAMS
- Composition is like the universe in general
  - 74% H, 25% He, 1% everything else
- But the star turns 4 H into 1 He in its core over time, so…
  - fewer atoms in there, less pressure
  - thus the core contracts, heats up
  - hotter makes for faster fusion – more energy

# AGING ON THE MAIN SEQUENCE

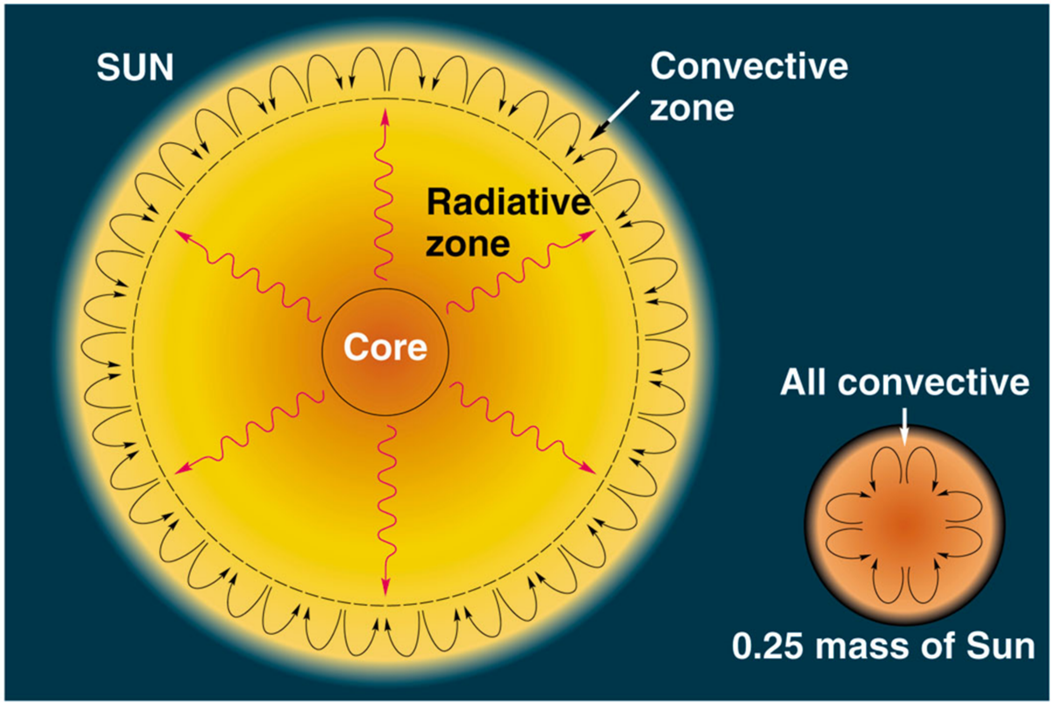
- Fewer atoms, core shrinks, heats up
- Hotter increases fusion rate, more energy produced
- Star becomes more luminous
- Outer parts of star pushed outwards, expand
  - Surface cools
- Brighter, cooler – that’s up and to the right on the HR diagram

# AGING ON THE MAIN SEQUENCE



- Sun is ~4.5 billion years old
  - Has about 64% He, 35% H in core right now
  - Is 40% brighter than when it turned on
  - Has another 5 billion years or so of H left
  - Will continue to get brighter, bigger, and cooler
  - Will raise the Earth’s temperature by another ~20 $^{o}$C

# VERY LOW-MASS STARS



- $<0.4\ M_\odot$
- Low luminosity, last a very long time
- Plus – completely convective, keeps mixing fresh H into core
  - Lots of extra fuel

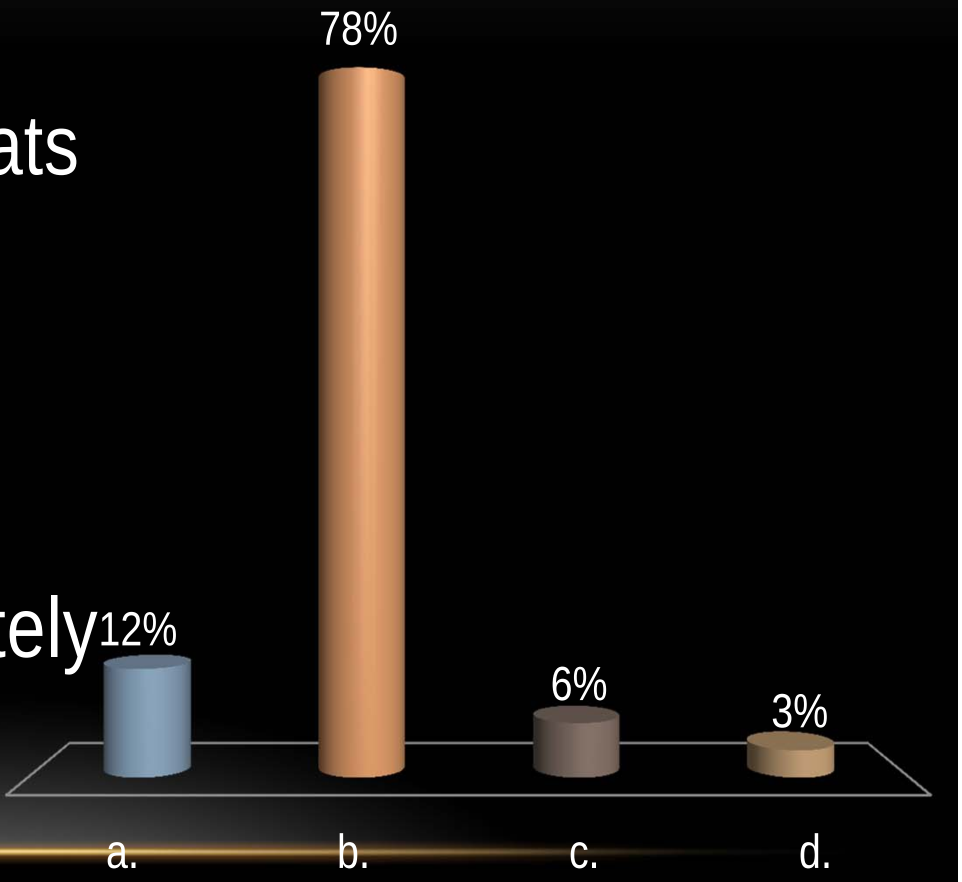
# WHAT HAPPENS WHEN A STAR CAN NO LONGER FUSE HYDROGEN TO HELIUM IN ITS CORE??

a. Its core cools off.

b. [✓ Its core shrinks and heats up.]

c. Its core expands and heats up.

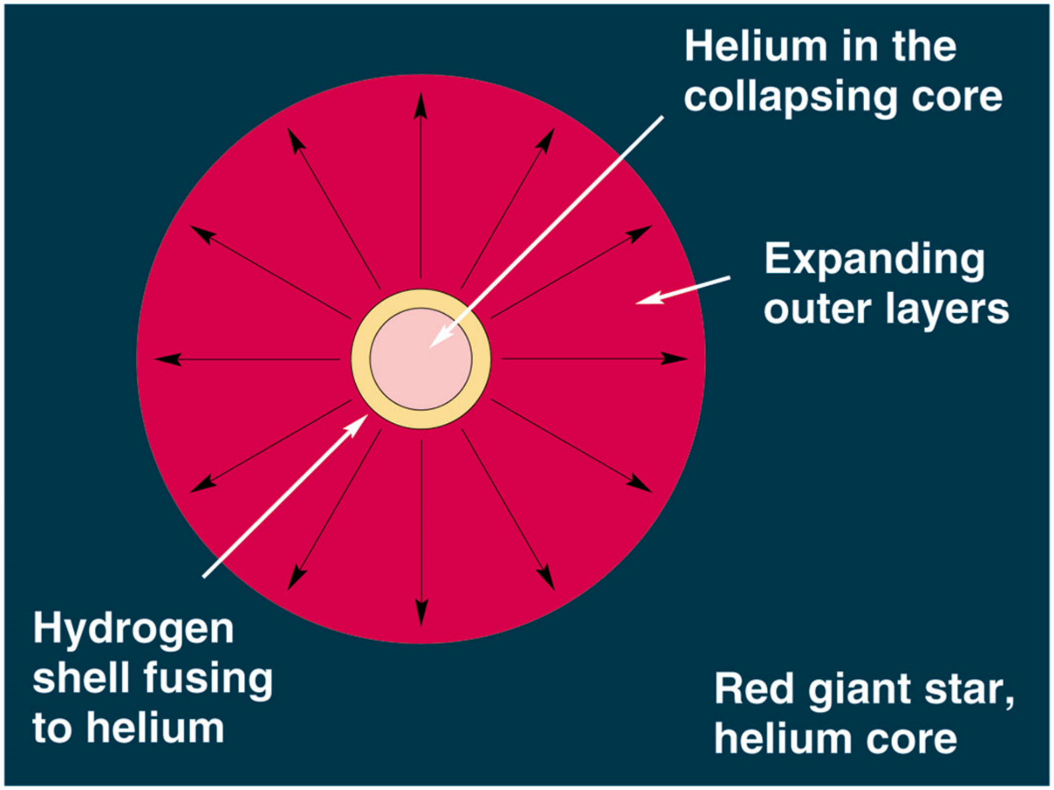
d. Helium fusion immediately begins.



# FADE AWAY…

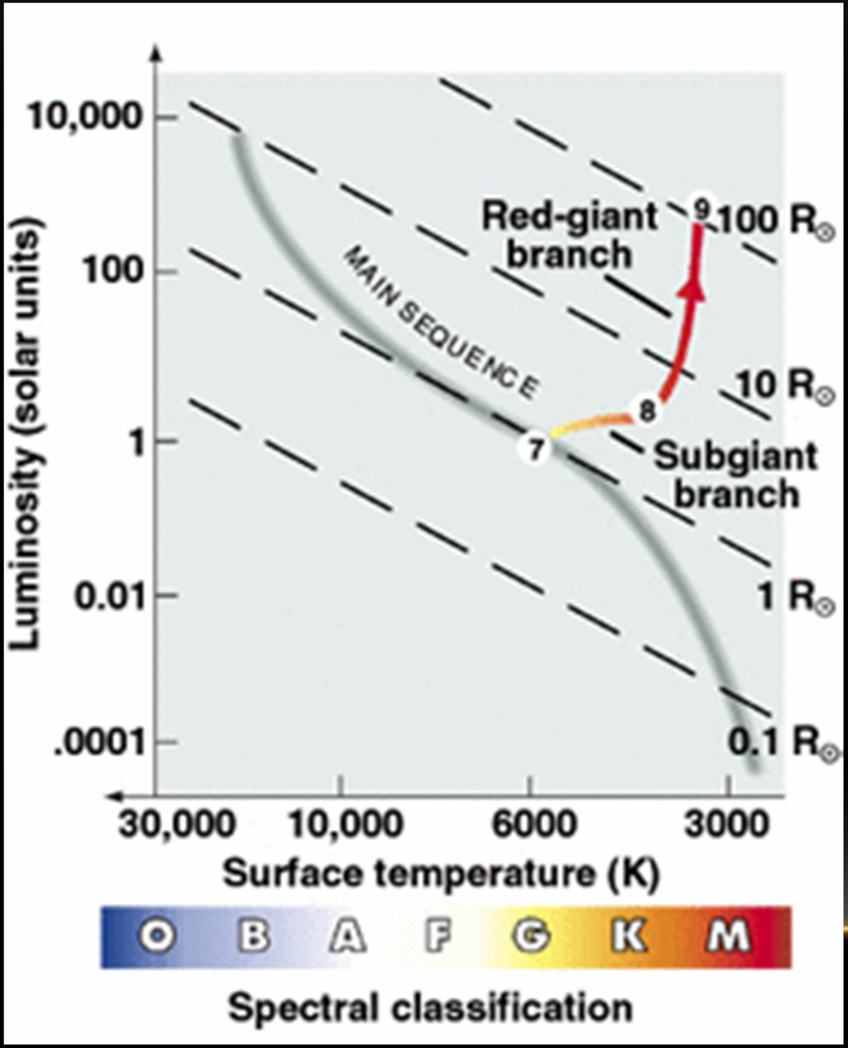
- When these light stars eventually run out of fuel, there will be no energy to provide pressure to hold them up
  - Collapse!
- This makes them very dense, very hot
  - A White Dwarf
    - Hot, small, not very luminous
  - Not enough gravity to crush the degenerate matter of a white dwarf down further
  - White dwarf slowly cools, fades out, becomes a black dwarf cinder

# LARGER STARS



- Have radiative cores (like the sun)
  - No fresh H gets mixed in
- Run out of H in core
  - He core contracts, gets very hot
  - H fusion ignites in a shell around core

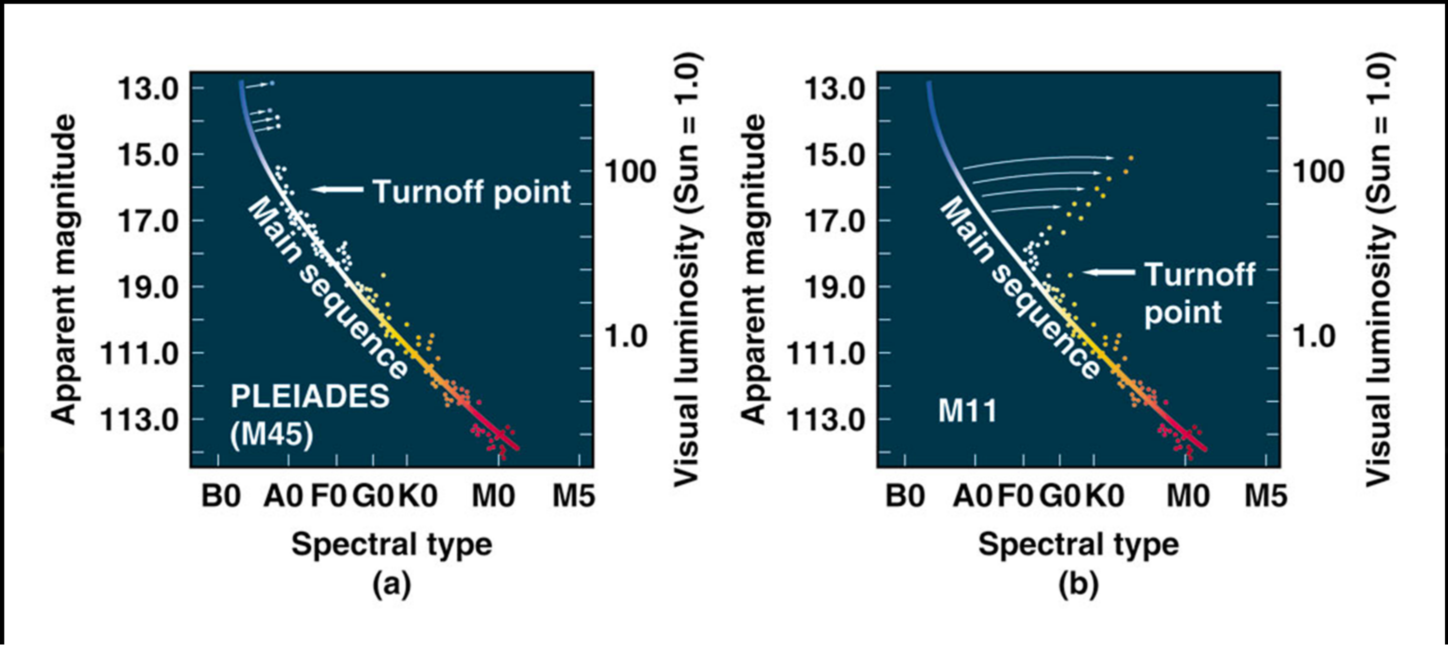
# LEAVING THE MAIN SEQUENCE



- Contraction energy + H shell burning makes star expand
  - Brighter, cooler “Red Giant”
- Grows to ~100 $R_\odot$
  - About Mercury’s orbit
- Luminosity is ~500 $L_\odot$
- Photosphere cools to ~3500 K, expansion makes it much less dense

# TURNOFF POINT

- Brighter, cooler changes a star’s place on the HR diagram – moves off Main Sequence
- More massive stars run out of H first
- HR plots for clusters show this happening, tell us the cluster’s age

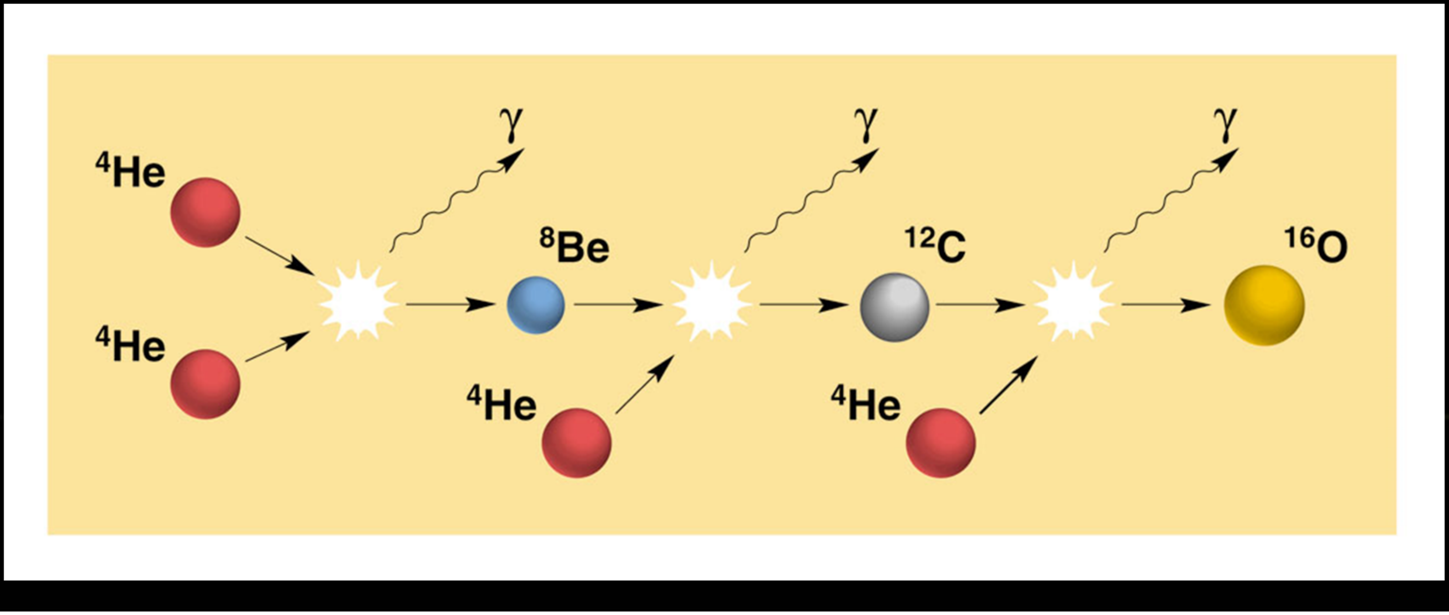


(a)

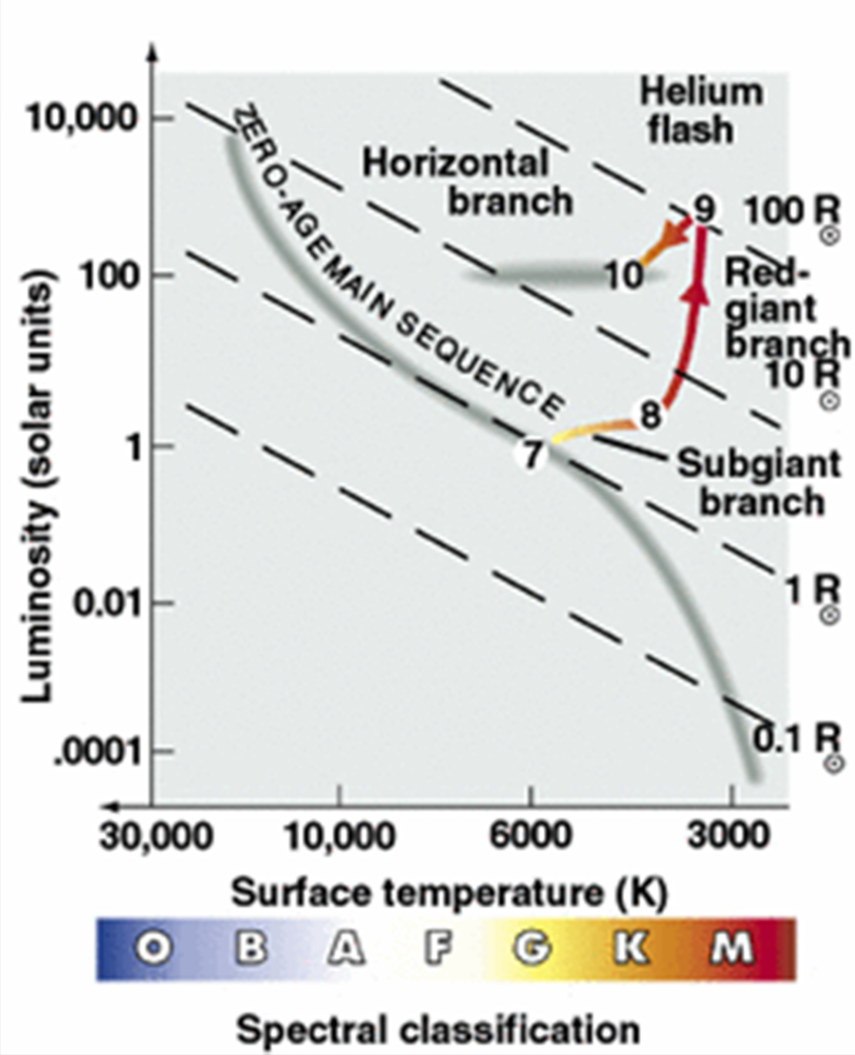
(b)

# HELIUM BURNING

- He can be fused to form heavier elements, releasing energy
- Needs even hotter, denser conditions than H fusion
  - Why? Each He has two protons, more electrostatic repulsion



# HELIUM FLASH



- Eventually He core gets hot and dense enough
- In medium-sized stars, this happens all at once
  - Due to "electron degeneracy"
- He burning then proceeds regularly
- More centralized energy source moves star back towards main sequence a bit, ends up on "horizontal branch"
- Still fusing H in shell

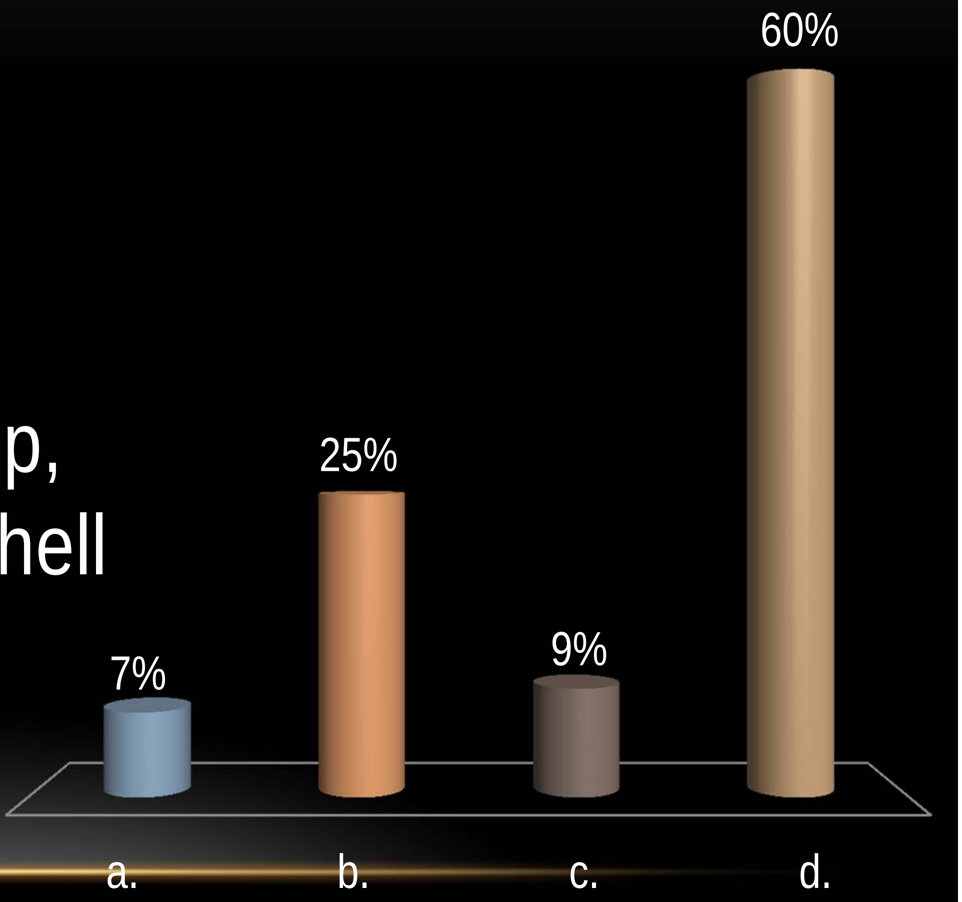
# WHAT HAPPENS WHEN A STAR'S CORE RUNS OUT OF HELIUM?

a. The star explodes.

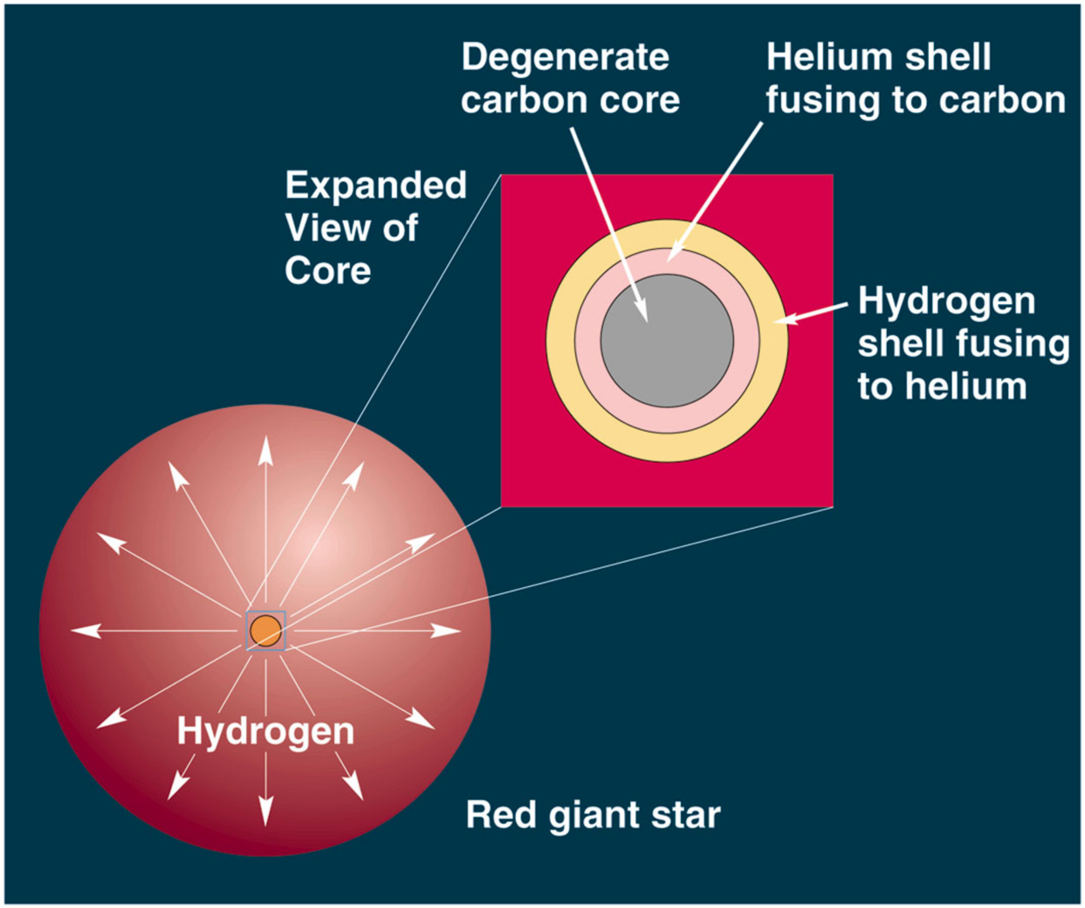
b. Carbon fusion begins.

c. The core cools off.

✓ d. Core contracts, heats up, and helium fuses in a shell around the core.

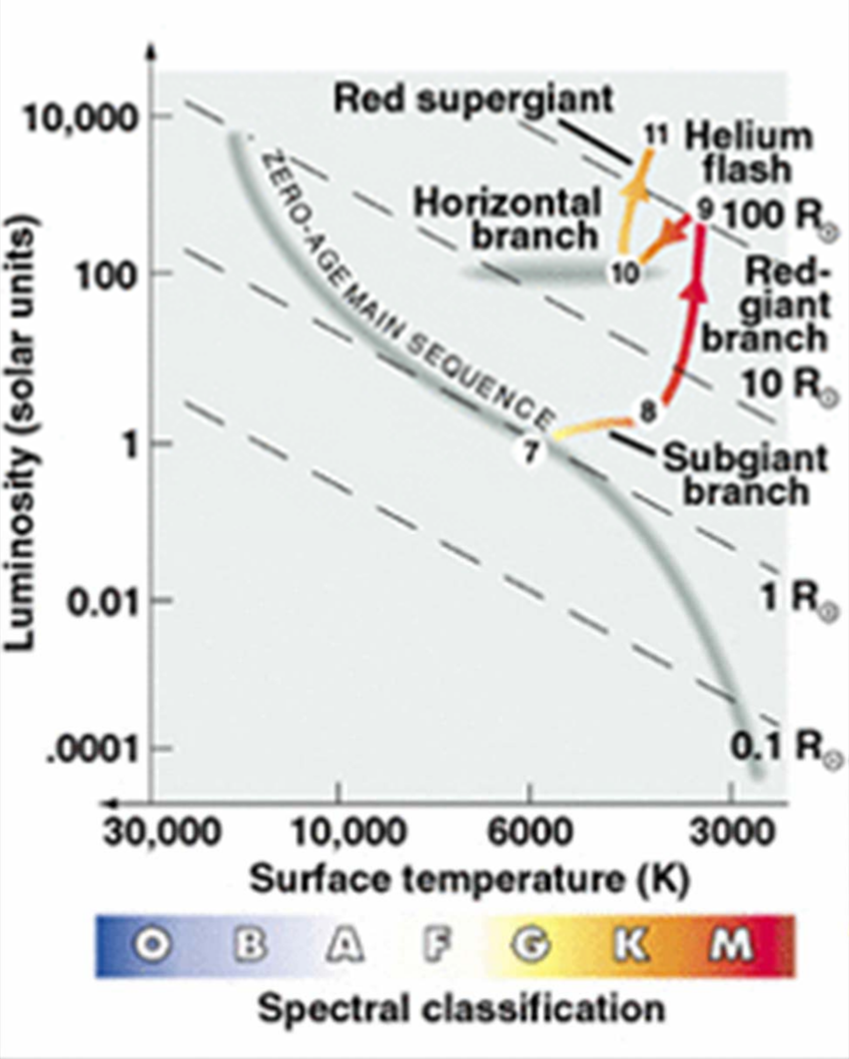


# RUNNING OUT OF HELIUM

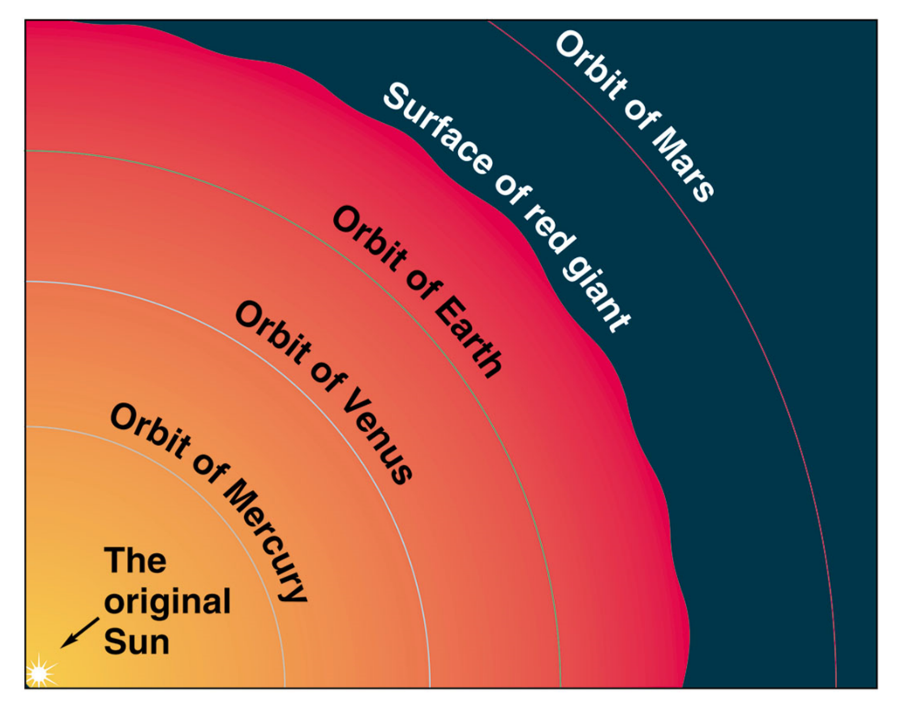


- The star runs out of He
  - After ~100 million years for the Sun
- Carbon core contracts, heats up, ignites He shell burning
- Extra contraction energy plus shell burning again!

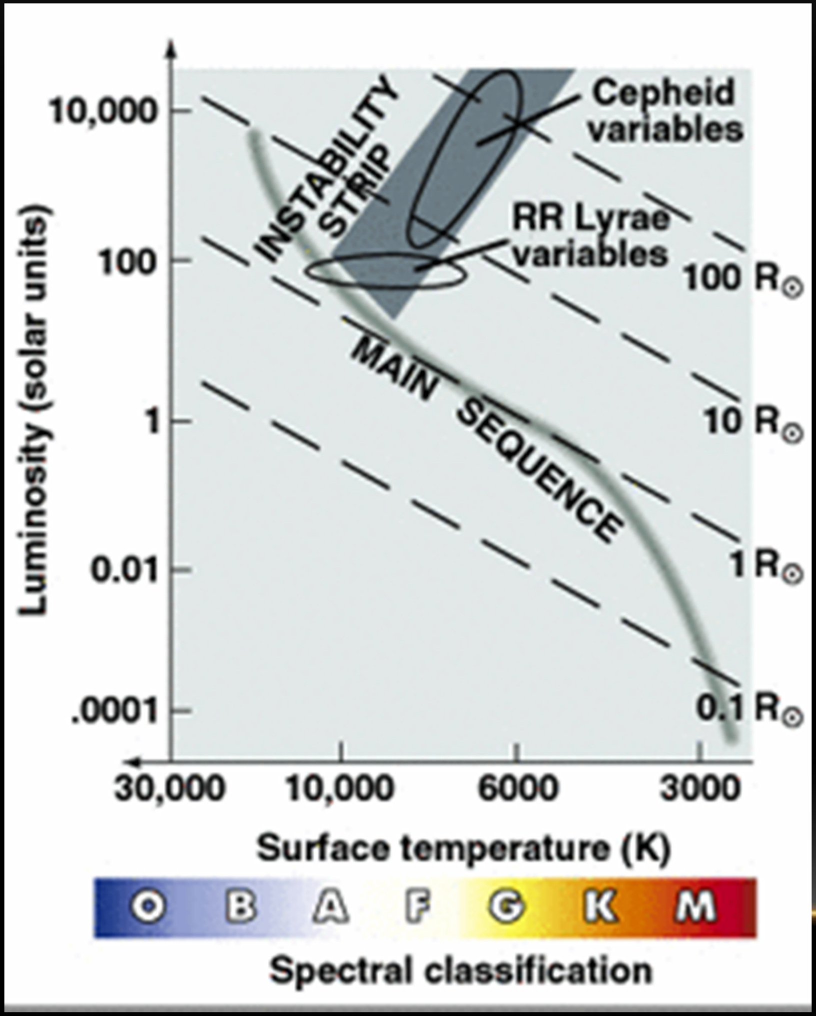
# RED SUPERGIANT



- Star expands greatly, becomes much brighter and cooler
  - Radius almost to Mars!
  - 10,000x as luminous



# INSTABILITY STRIP



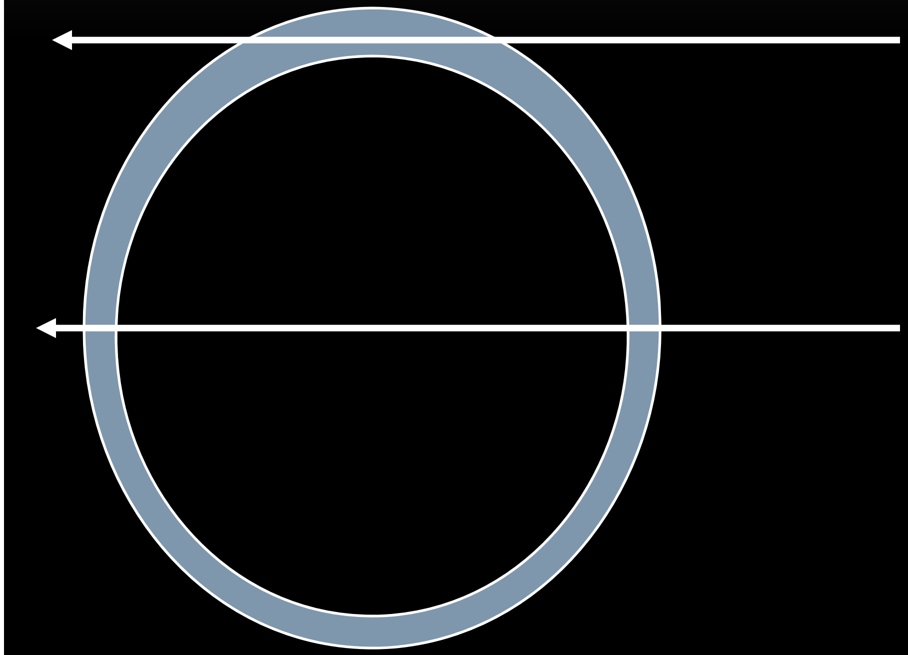
- As star's cross this area of the HR diagram late in life, they pulsate
- The pulsation is related to their absolute brightness
- Called Cepheids, RR Lyrae
- These stars are extremely useful to find distances!
  - Bright, can see from far away
  - Measure period, learn their distance

# MASS LOSS

- These very bloated stars have much less gravity at their surfaces
  - Plus star is pulsing
- The star boils away
  - Strong stellar wind
  - What's left is hotter core, blows harder
- Forms a planetary nebula
- Leaves core as a white dwarf

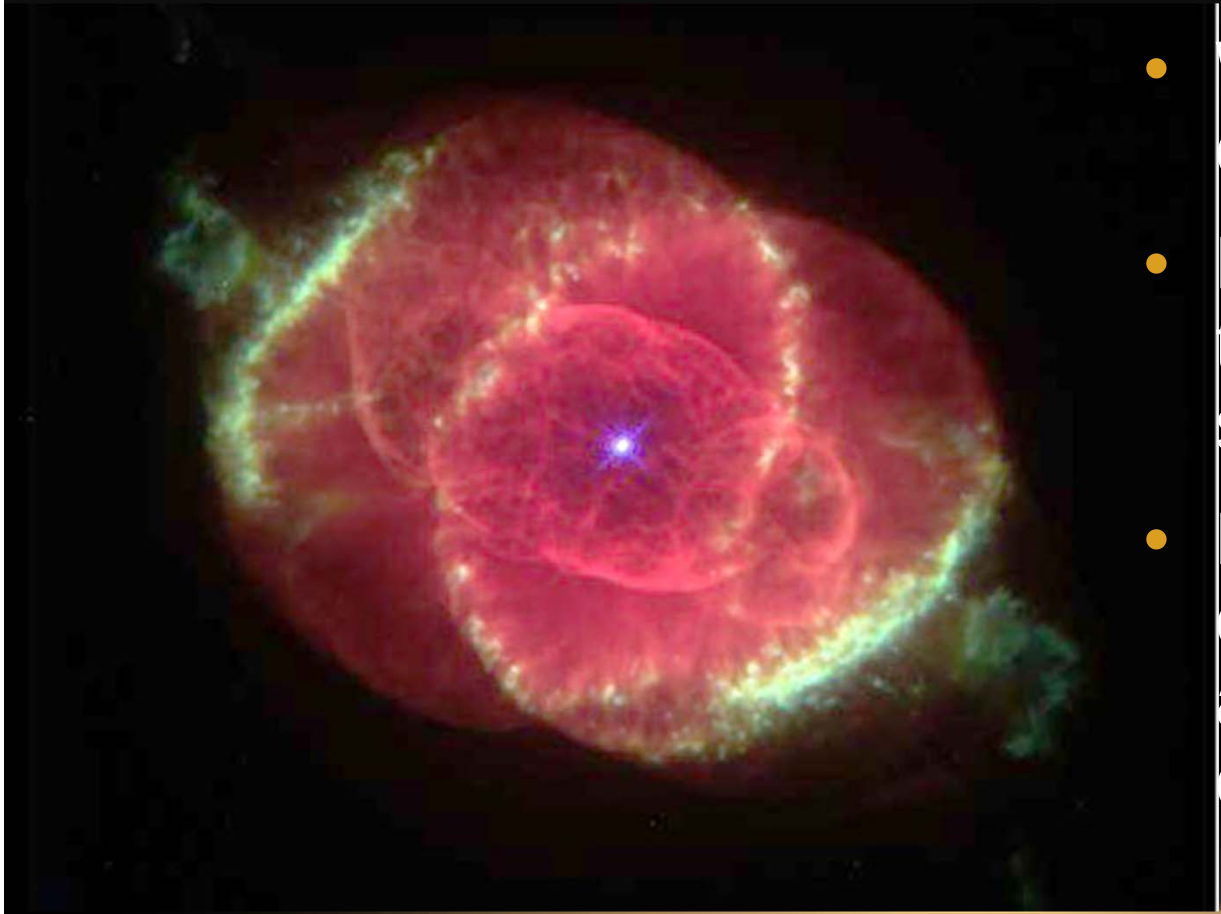
M57 ("Ring Nebula") by
H. Bond *et al*, HST

# PLANETARY NEBULA



- Why a ring?
- Gas forms a spherical shell
- At the edges, we look through more stuff so it is brighter
- Looks to us ring-like

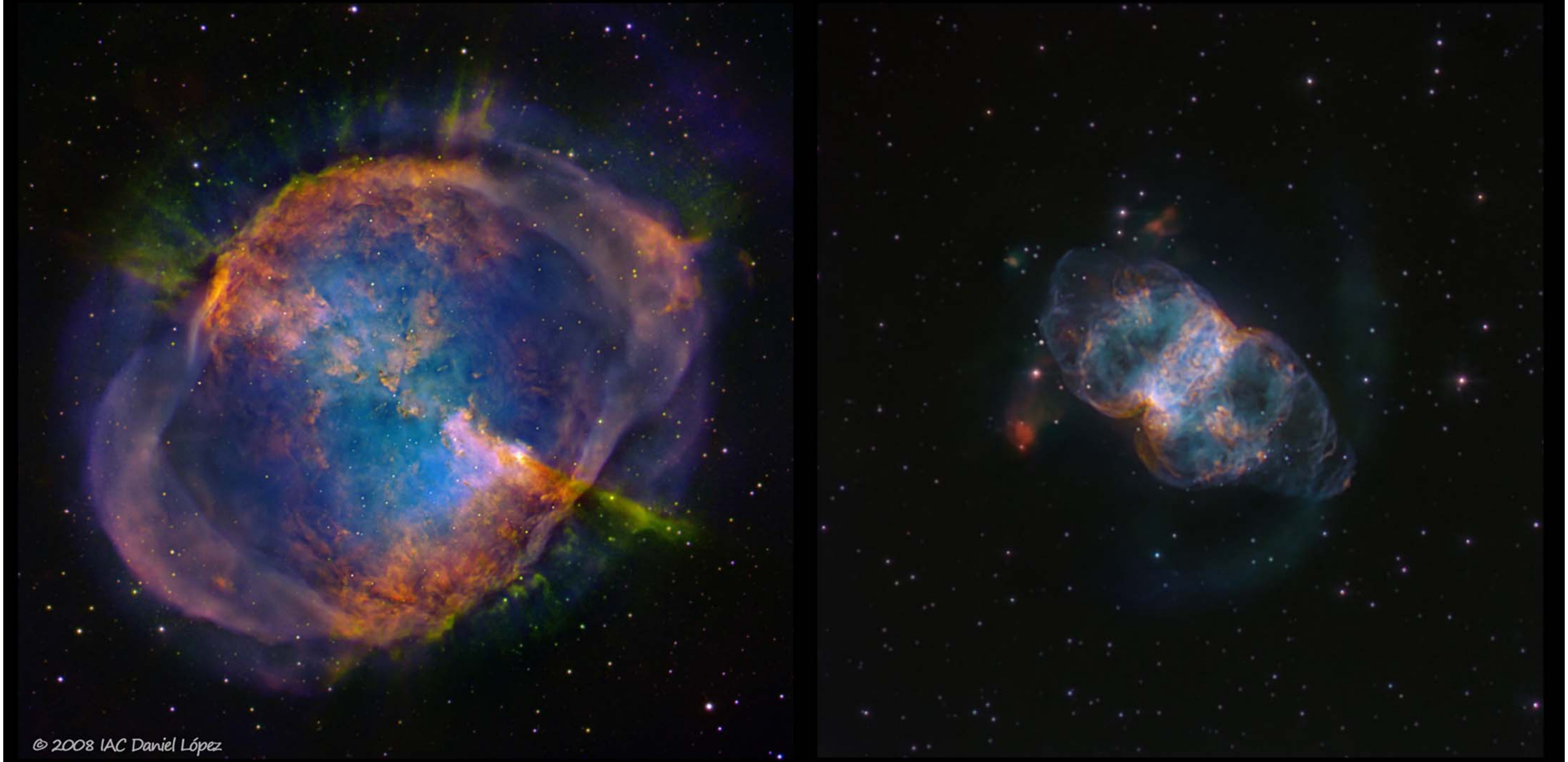
# “CAT’S EYE” NEBULA



- Why something more complicated?
- Perhaps a binary star throwing stuff off like a sprinkler
- Perhaps later expulsions catching up and crashing into earlier ones

J.P. Harrington and K.J. Borkowski, with the HST

# DUMBBELL NEBULA



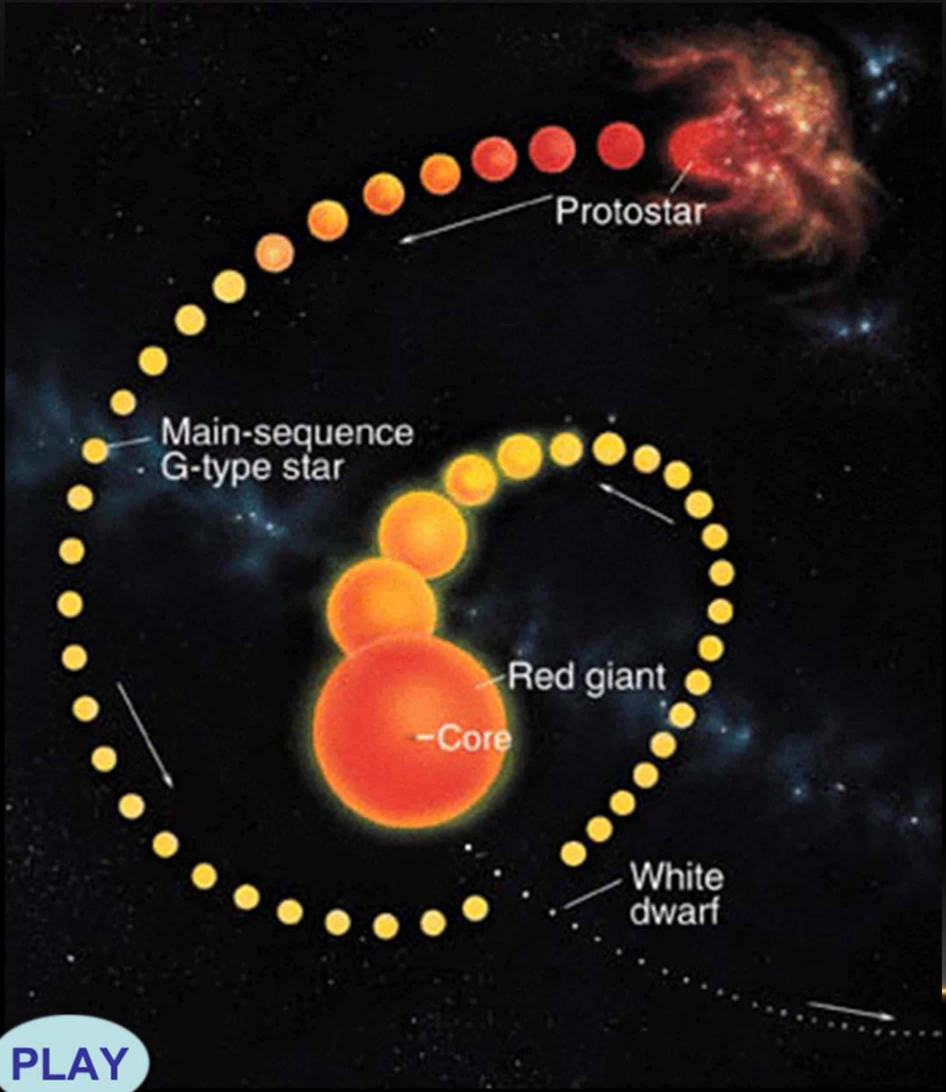
M-27 “Dumbbell” and M-76 “Little Dumbbell”
by Daniel Lopez, IAC

# WHITE DWARF

- The leftover core is a hot, dense, small thing
- Cools over time
- Star to left is one of the hottest known
  - Youngest
  - See its atmosphere dispersing

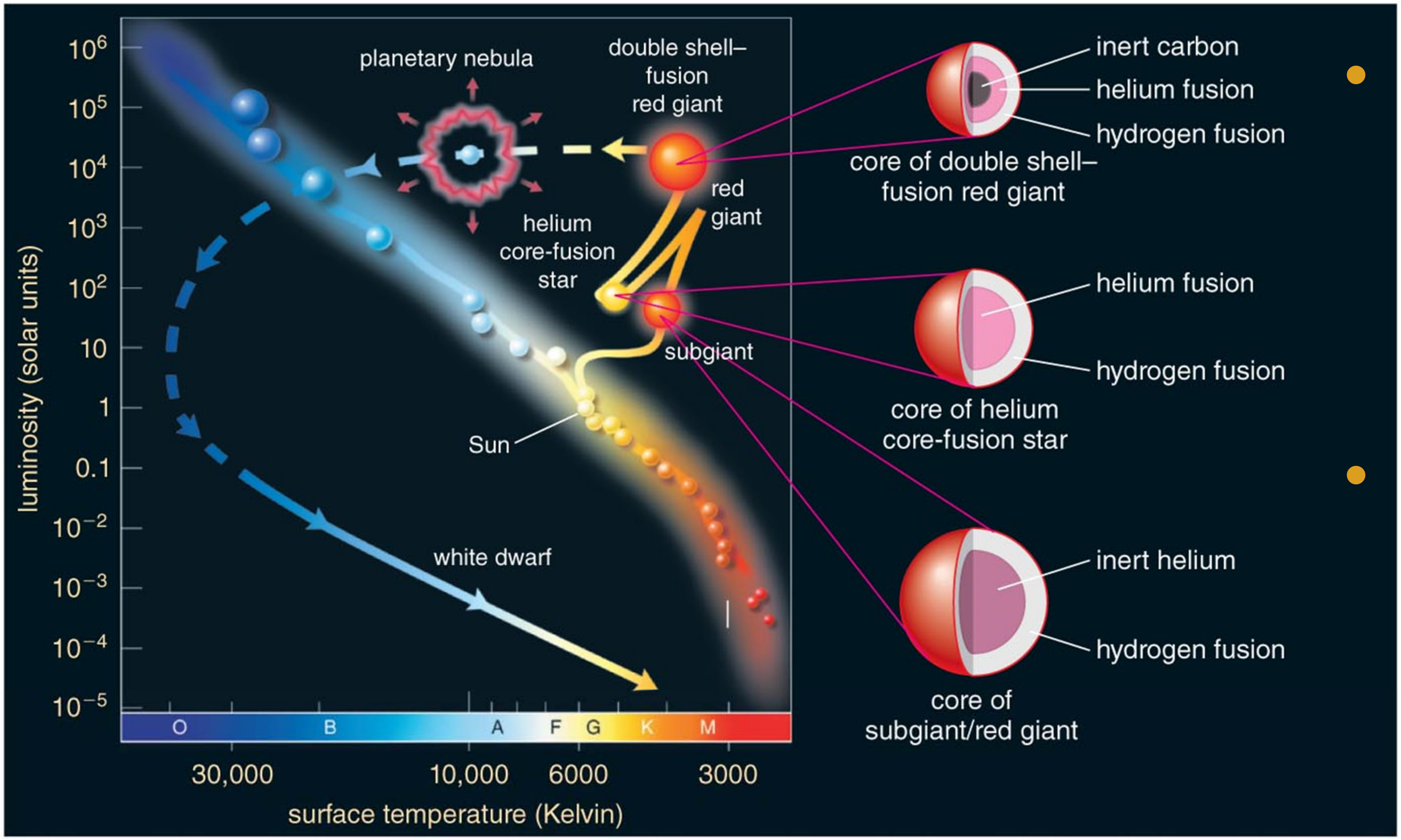
NGC 2440 by H. Bond (STScI),
R. Ciardullo with HST

# THE SUN’S STORY



- This evolution over time is typical for a star of 0.4 to 2.0 $M_{\odot}$
- Lower mass, fully convective stars eventually just fade away into white dwarfs
- Higher mass stars – next bit

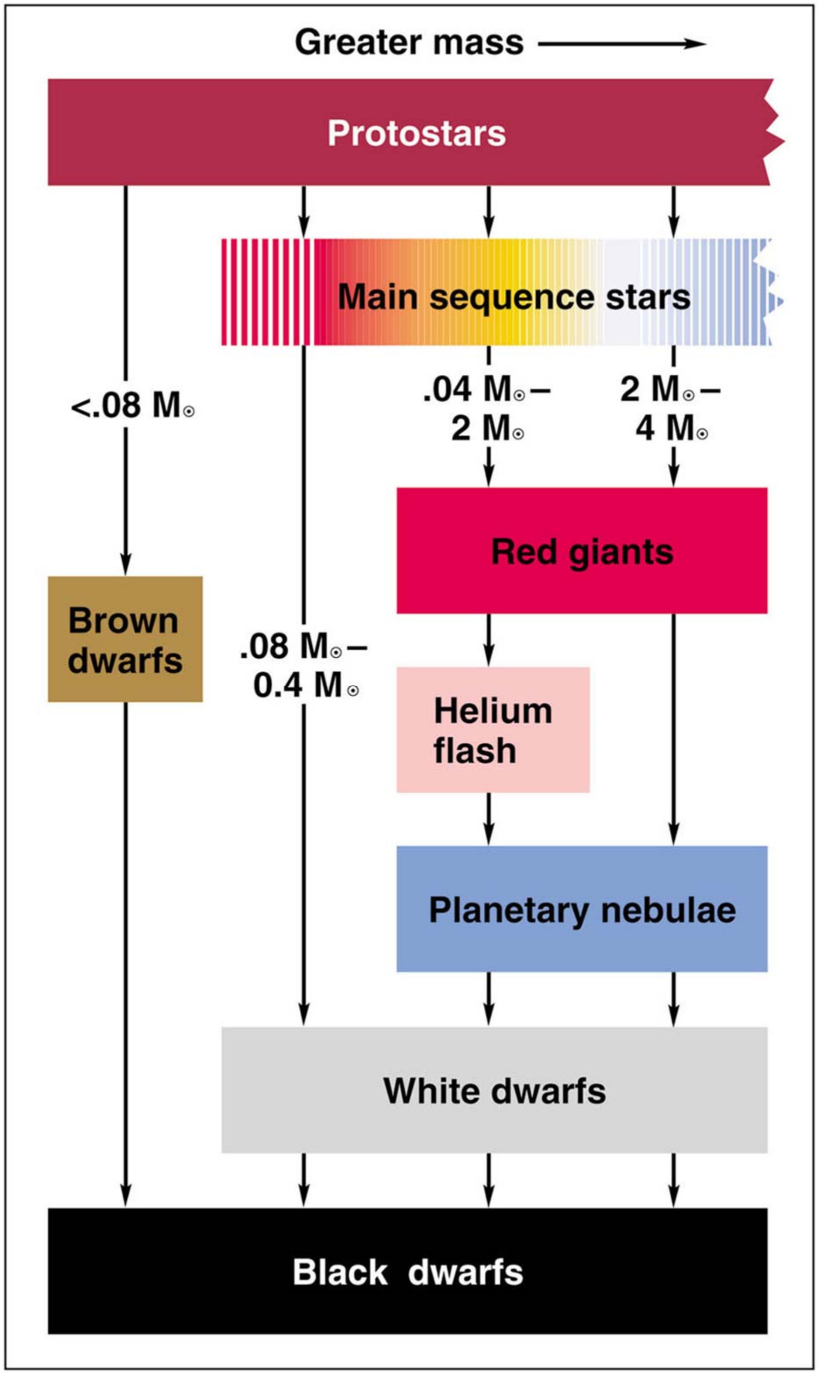
# ON THE HR DIAGRAM



- Plot L vs. T as time goes on for one star
- Get “post main sequence evolutionary tracks”

Fig.13.13

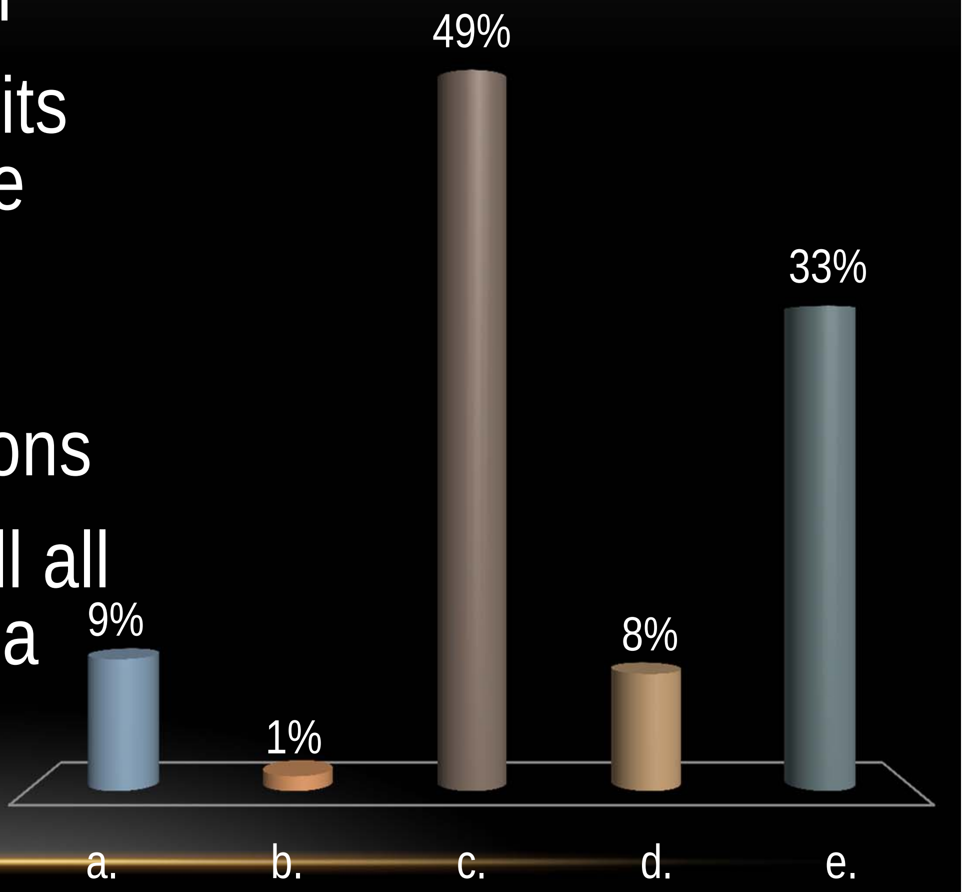
# LOW MASS STAR SUMMARY



- The things that happen to Low Mass Stars takes different steps depending upon how massive they were to start
- More massive stars run through this more quickly

# AFTER THE SUN BECOMES A RED GIANT STAR AND MAKES CARBON IN ITS CORE, WHY WILL IT NOT MAKE HEAVIER ELEMENTS?

a. It will have run out of fuel
b. It will be near the end of its life and doesn't have time
✓ c. It will not be massive enough to make it hot enough for further reactions
d. The heavier elements will all go into a planetary nebula
e. A and B



# MORE MASSIVE STARS

- How do they differ? ($M > 4\ M_{\odot}$)
- More massive – larger temperatures, pressures in core
  - Run on CNO cycle rather than pp for H fusion
  - Can fuse heavier things than H, He later in life
- Convective, radiative layers switched
  - Convection just above core, radiative from there to surface

# THE CNO CYCLE

- Another way to fuse 4 H into 1 He
  - More complicated
  - Works better at higher temperatures: more charge, more repulsion!
  - So is more important in larger stars with hotter cores
- The sequence uses ${}^{12}C$ as a catalyst:
  - ${}^{1}H + {}^{12}C \longmapsto {}^{13}N$ plus $\gamma$
  - ${}^{13}N \longmapsto {}^{13}C + e^{+} + \nu$
  - ${}^{1}H + {}^{13}C \longmapsto {}^{14}N + \gamma$
  - ${}^{1}H + {}^{14}N \longmapsto {}^{15}O + \gamma$
  - ${}^{15}O \longmapsto {}^{15}N + e^{+} + \nu$
  - ${}^{1}H + {}^{15}N \longmapsto {}^{12}C + {}^{4}He$

Still 4 ${}^{1}H$

built into 1 ${}^{4}He$

(${}^{12}C$ unchanged in the end)

See Fig.13.14 in the book for a graphical version of this

# LIFE STAGES OF HIGH-MASS STARS

- Late life stages of high-mass stars are similar to those of low-mass stars:
  - Hydrogen core fusion (main sequence)
  - Hydrogen shell fusion (giant)
  - Helium core fusion (horizontal branch)
  - Double-shell burning (supergiant)