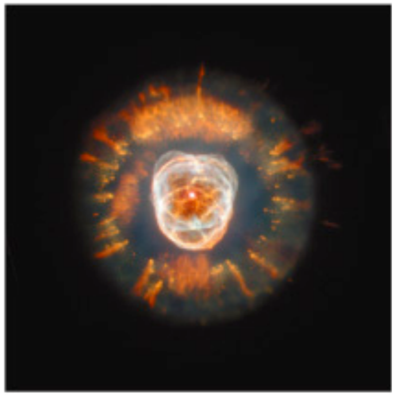
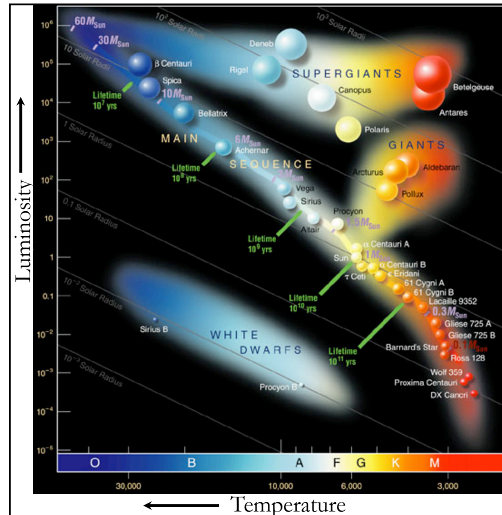
Lecture 10: Stellar Evolution

Astronomy 2020 Prof. Tom Megeath





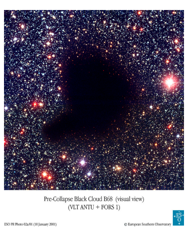
Review:
H-R diagram depicts:

X-axis: Temperature (or Color or Spectral Type)

Y-axis: Luminosity

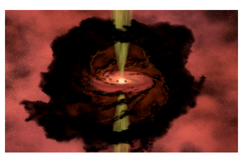
Diagonal lines: Radius

Steps of Star Formation



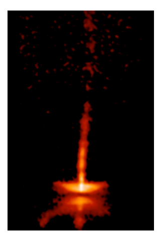
Molecular Cloud

(if you want to know what happens before a molecular cloud, take A2020)



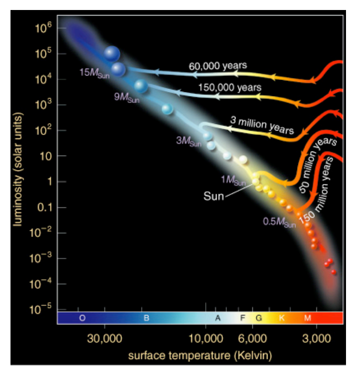
Protostar

→ 300,000 years



Star with disk

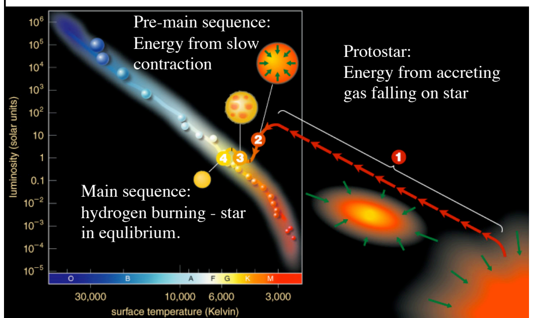
Pre-main sequence evolution and the descent to the main sequence



The amount of time a star spends in pre-main sequence contraction before it reaches the main sequence depends on its mass.

Our sun spent roughly 50 million years to get the main sequence. A star half the mass of our sun takes 150 million year. An object with mass < 0.08 solar masses never reaches the main sequence and continues to contract.

Where does the energy come from?



Luminosity =

For protostars:

G M (ΔM/Δt)/R

For pre-main sequence stars:

$G M^2 (DR/Dt)/R^2$

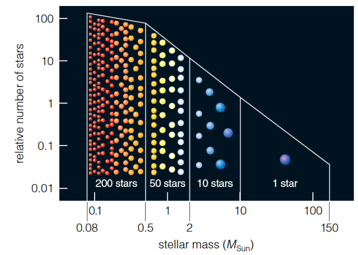
Mass of star = M
Radius of star = R
Change in mass per unit time = ΔM/Δt
Change in radius per unit time = ΔR/Δt

Masses of Stars

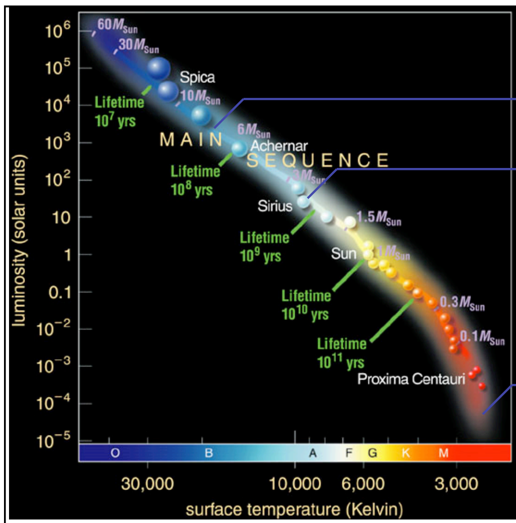
Low mass stars: 2 solar masses to 0.08 solar masses

Intermediate mass stars: 2 solar masses to 8 solar masses

High mass stars: 8 solar masses to 60+ solar masses



Most stars in the sky are cool M-stars



High-Mass Stars
> 8 M_{Sun}

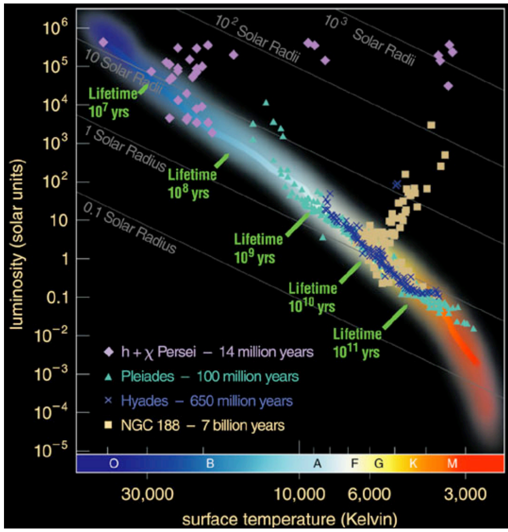
Intermediate-Mass Stars

Low-Mass Stars
< 2 M_{Sun}

Brown Dwarfs

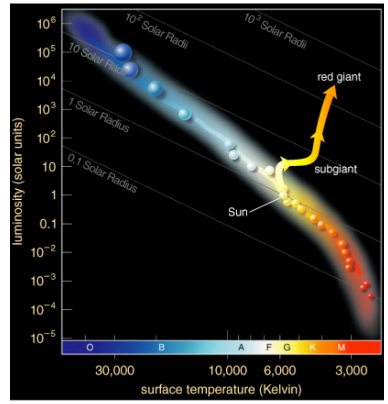
Star Clusters and Stellar Lives

- Our knowledge of the life stories of stars comes from comparing mathematical models of stars with observations
- Star clusters are particularly useful because they contain stars of different mass that were born about the same time



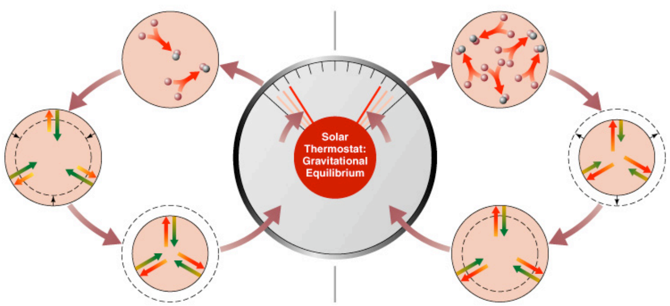
Main-sequence turnoff point of a cluster tells us its age

Life Track after Main Sequence



- Observations of star clusters show that a star becomes larger, redder, and more luminous after its time on the main sequence is over

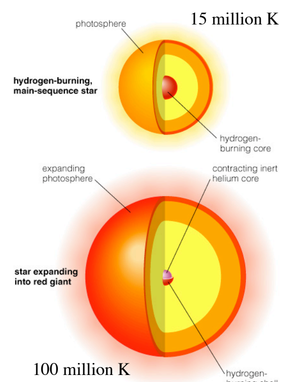
Solar Thermostat



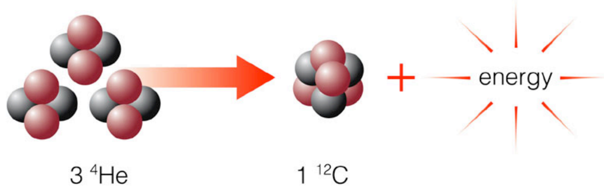
Decline in core temperature causes fusion rate to drop, so core contracts and heats up

Rise in core temperature causes fusion rate to rise, so core expands and cools down

Broken Thermostat



- As the core contracts, H begins fusing to He in a shell around the core
- Luminosity increases because the core thermostat is broken—the increasing fusion rate in the shell does not stop the core from contracting



Helium fusion does not begin right away because it requires higher temperatures (200 million K!!) than hydrogen fusion — the larger charge leads to greater repulsion

Fusion of two helium nuclei doesn't work, so helium fusion must combine three He nuclei to make carbon

Degeneracy Pressure

Normal *thermal* pressure depends on temperature (Pressure = nkT where n is density, T is temperature, and k is Boltzman's constant).

Electrons resists being compressed.

Quantum mechanical effect based on Heisenberg Uncertainty Principle:

$\Delta X \, \Delta P > h/2\pi$

Where P is momentum (mass x velocity)

Means that the more precisely you know the position of a particle, the less well you know the momentum. Only important for subatomic particle.

As you compress particles ΔX goes down and ΔP must go up.

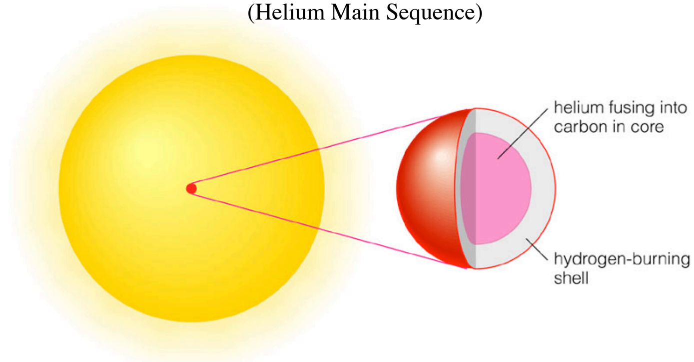
As ΔP goes up, pressure goes up!

Higher momentum implies higher pressure independent of temperature.

Helium Flash

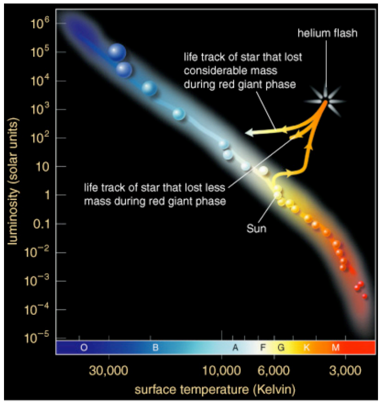
- Thermostat is broken in low-mass red giant because degeneracy pressure supports core
- Core temperature rises rapidly when helium fusion begins
- Helium fusion rate skyrockets until thermal pressure takes over and expands core again
- In about 1 minute, 60-80% of the helium in "burned"

After the Helium Flash: the horizontal branch (Helium Main Sequence)



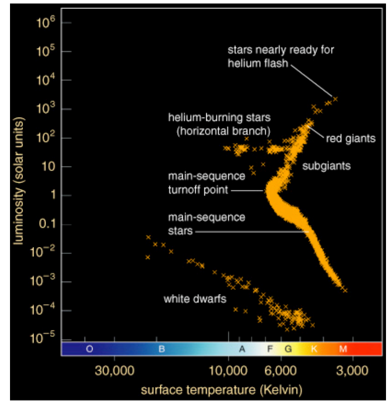
Helium burning stars neither shrink nor grow because core thermostat is temporarily fixed.

Life Track after Helium Flash



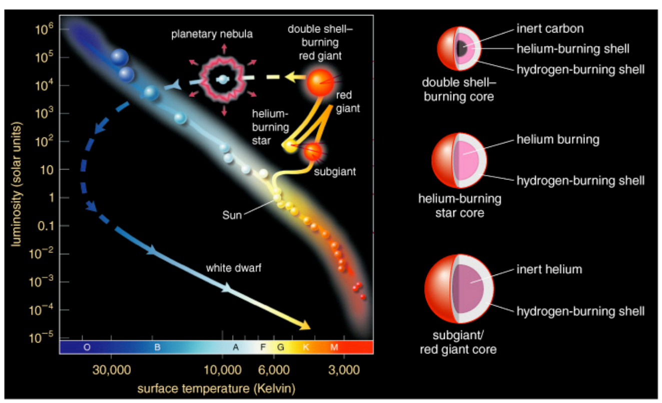
- Models show that a red giant should shrink and become less luminous after helium fusion begins in the core

Life Track after Helium Flash

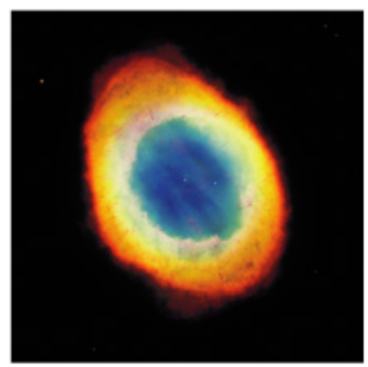


- Observations of star clusters agree with those models
- Helium-burning stars are found in a *horizontal branch* on the H-R diagram

Life Track of a Sun-Like Star

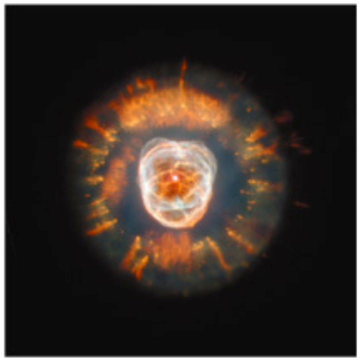


Planetary Nebulae



- Double-shell burning ends with a pulse that ejects the H and He into space as a *planetary nebula*
- The core left behind becomes a white dwarf

Planetary Nebulae



- Double-shell burning ends with a pulse that ejects the H and He into space as a *planetary nebula*
- The core left behind becomes a white dwarf

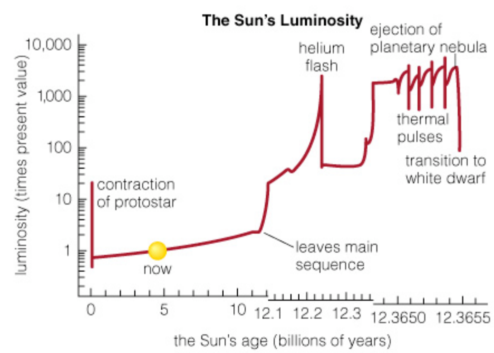
Planetary Nebulae

- Double-shell burning ends with a pulse that ejects the H and He into space as a *planetary nebula*
- The core left behind becomes a white dwarf

Planetary Nebulae

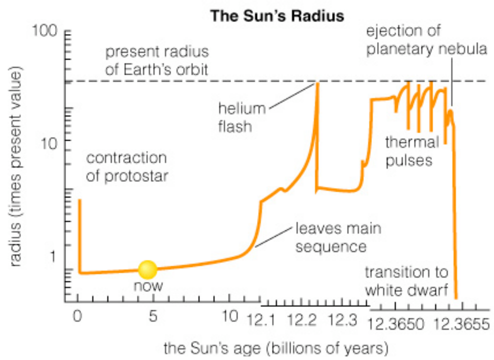
- Double-shell burning ends with a pulse that ejects the H and He into space as a *planetary nebula*
- The core left behind becomes a white dwarf

Earth's Fate



- Sun's luminosity will rise to 1,000 times its current level—too hot for life on Earth

Earth's Fate



- Sun's radius will grow to near current radius of Earth's orbit

How hot would the Earth get?

Energy balance:

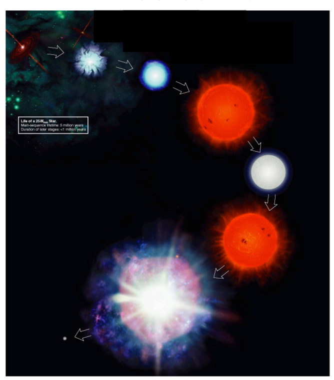
$4 \pi R_{earth}^2 \sigma T_{earth}^4 = (1-q) L_{sun} R_{earth}^2 / 2 D_{earth\_sun}^2$

T_{earth} proportional to $L^{0.5}$

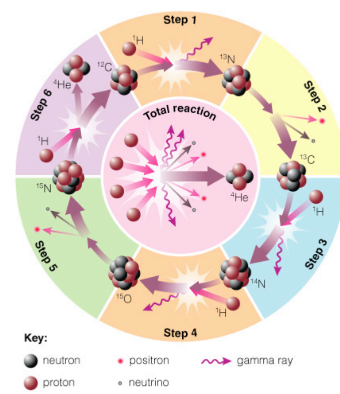
$L_{sun} = 2 \times 10^{33}$ erg s^{-1} T= 263 K

$L_{sun} = 2 \times 10^{36}$ erg s^{-1} T=1480 K

What are the life stages of a high-mass star?



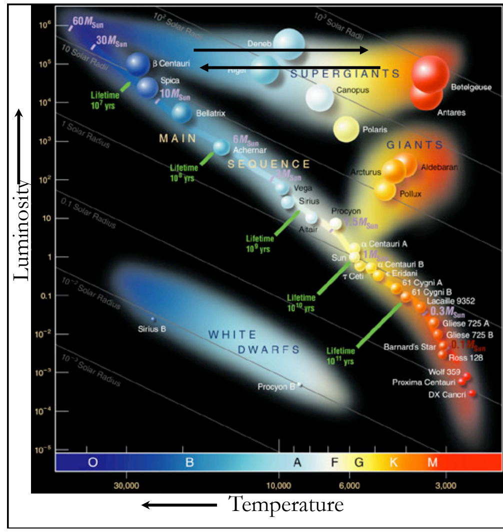
CNO Cycle



- High-mass main sequence stars fuse H to He at a higher rate using carbon, nitrogen, and oxygen as catalysts
- Greater core temperature enables H nuclei to overcome greater repulsion

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 burning (supergiant)
  - Helium core fusion (supergiant)



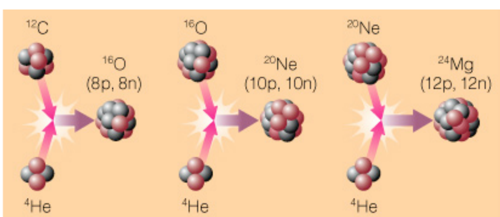
Supergiants

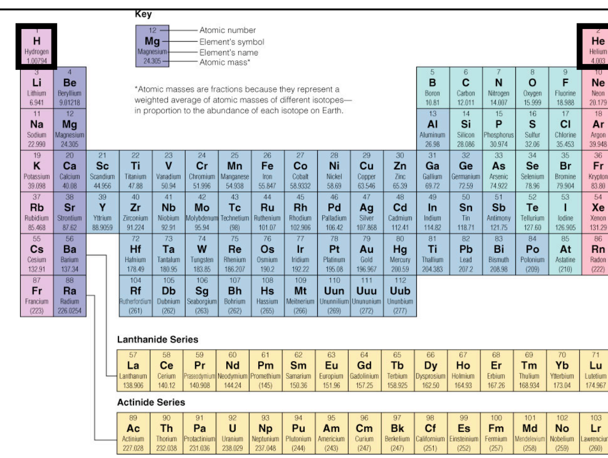
Supergiants do not show helium flash.

Evolve at roughly constant luminosity.

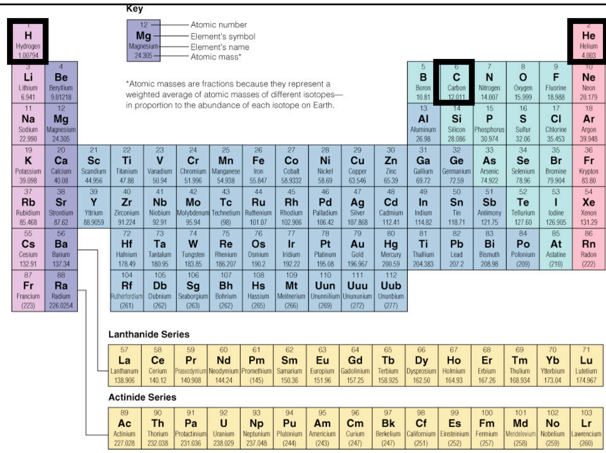
Stars expand and cools as core burning stops and then contracts and heats up as core burning stars up.

How do high-mass stars make the elements necessary for life?

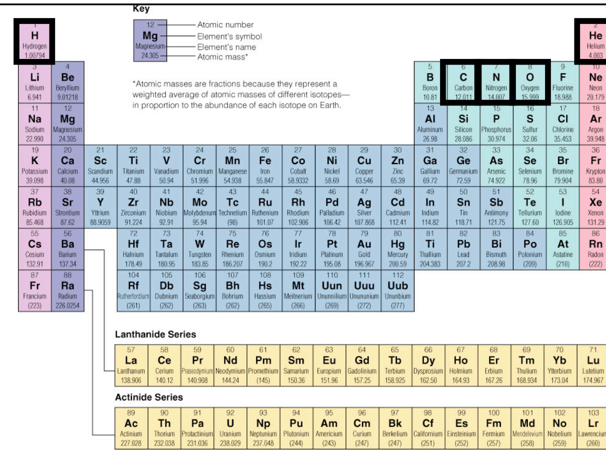




Big Bang made 75% H, 25% He – stars make everything else

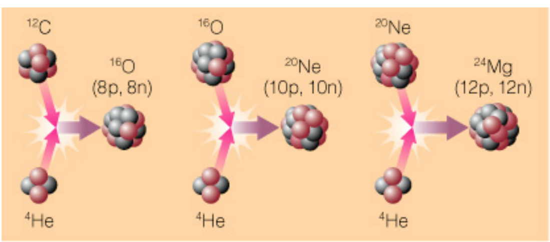


Helium fusion can make carbon in low-mass stars

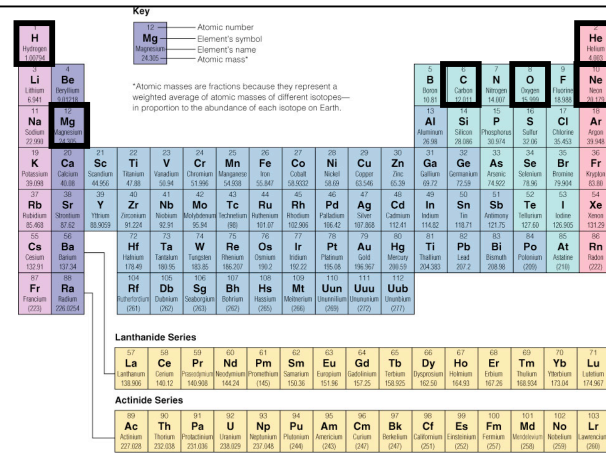


CNO cycle can change C into N and O

Helium Capture

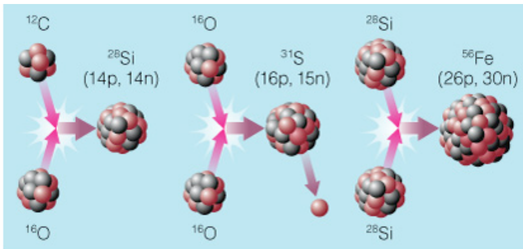


- High core temperatures (> 600 million K!!) allow helium to fuse with heavier elements

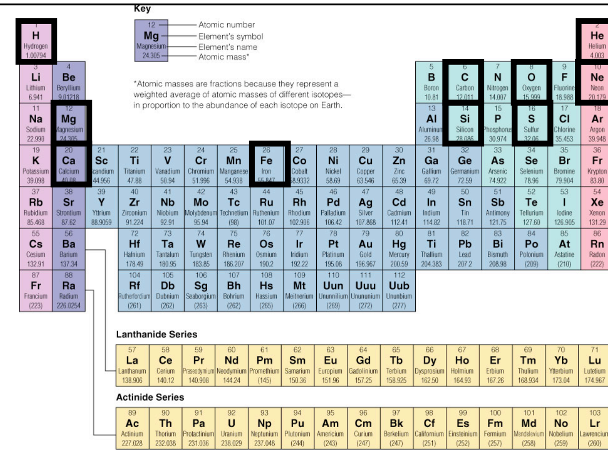


Helium capture builds C into O, Ne, Mg, …

Advanced Nuclear Burning

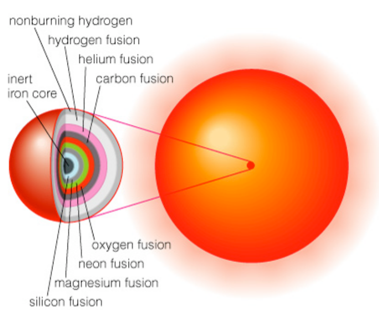


- Core temperatures in stars with $>8M_{\text{Sun}}$ allow fusion of elements as heavy as iron

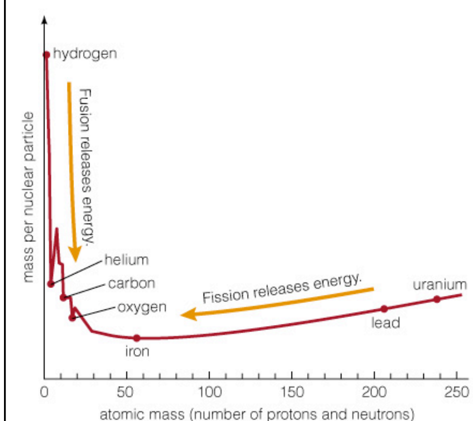


Advanced reactions in stars make elements like Si, S, Ca, Fe

Multiple Shell Burning

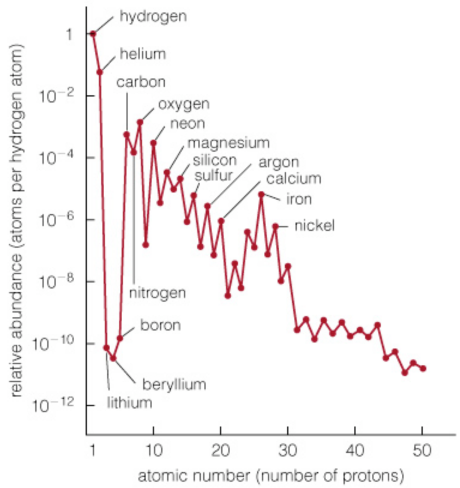


- Advanced nuclear burning proceeds in a series of nested shells
- Temperatures of 600 million Kelvin needed to fuse carbon.
- H fusion 7 million years
- He fusion 500,000 years
- C fusion 600 years
- Ne fusion 1 year
- O fusion 6 months
- Si fusion 1 day



Iron is dead end for fusion because nuclear reactions involving iron do not release energy

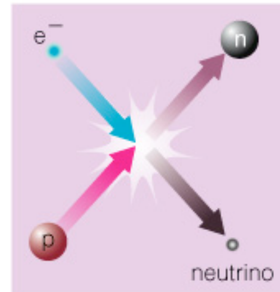
(Fe has lowest mass per nuclear particle)



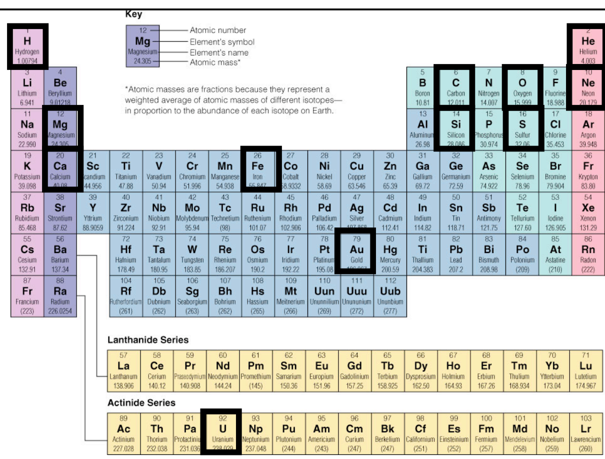
Evidence for helium capture:

Higher abundances of elements with even numbers of protons

Supernova Explosion



- Core degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos
- Neutrons collapse to the center, forming a **neutron star**

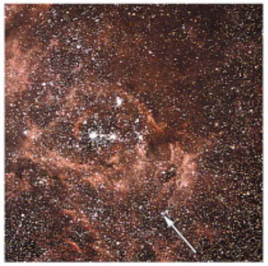


Energy and neutrons released in supernova explosion enable elements heavier than iron to form, including Au and U

Supernova Remnant

- Energy released by collapse of core drives outer layers into space
- The Crab Nebula is the remnant of the supernova seen in A.D. 1054 by Chinese astronomers.
- Other supernova seen in 1006, 1572 and 1604
- The 1006 supernova could be seen in the day and would cast shadows at night

Supernova 1987A




- The closest supernova in the last four centuries was seen in 1987

How Bright is a Supernova?

Energy in a supernova is 10^{51} ergs

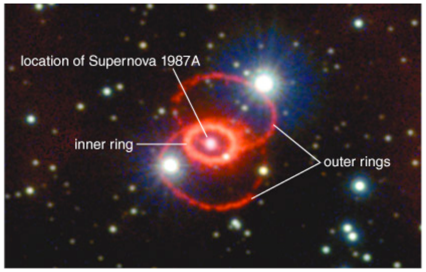
Sun radiates 10^{33} ergs s^{-1}

Sun radiates one supernova of energy in 10^{18} seconds

10^{18} seconds = 3×10^{10} years

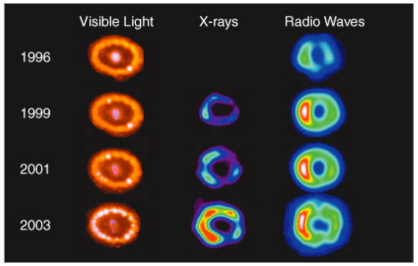
The 10^{11} stars in our galaxy radiate approximate 10^{44} erg s^{-1} - thus supernova same as energy radiated by the entire galaxy in 9 years.

Rings around Supernova 1987A

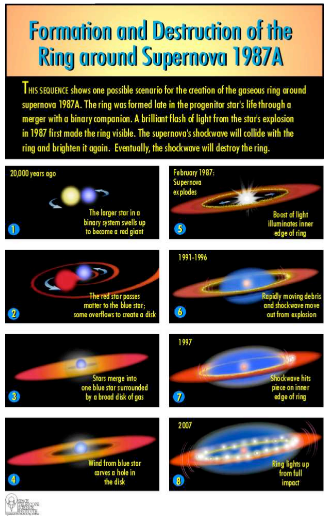


- The supernova's flash of light caused rings of gas around the supernova to glow

Impact of Debris with Rings



- More recent observations are showing the inner ring light up as debris crashes into it



Intermediate Mass Stars

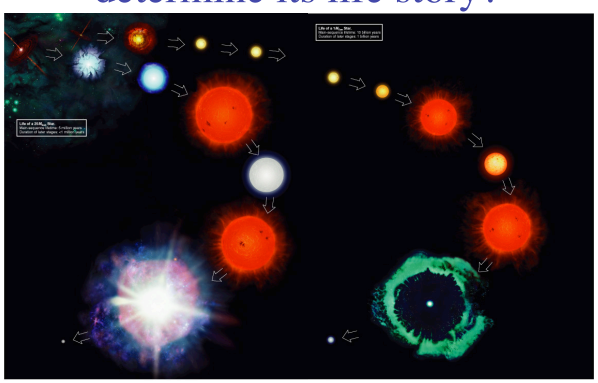
Intermediate mass stars also have CNO cycle.

Like high mass stars, expands in to supergiant.

However temperatures never high enough to fuse carbon into heavier elements.

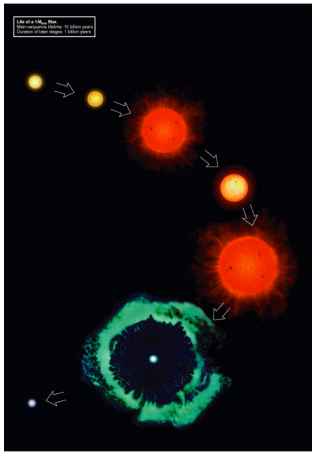
Like low mass stars, blow off outer layers and die as white dwarfs.

How does a star's mass determine its life story?



Role of Mass

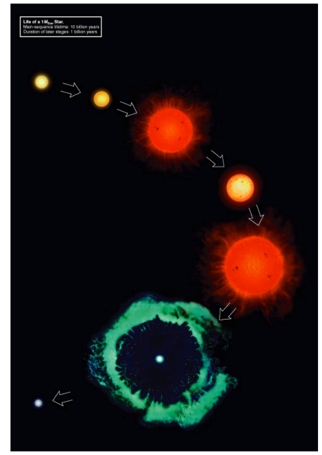
- A star's mass determines its entire life story because it determines its core temperature
- High-mass stars with $>8M_{Sun}$ have short lives, eventually becoming hot enough to make iron, and end in supernova explosions
- Low-mass stars with $<2M_{Sun}$ have long lives, never become hot enough to fuse carbon nuclei, and end as white dwarfs
- Intermediate mass stars can make elements heavier than carbon but end as white dwarfs



Not to scale!

Low-Mass Star Summary

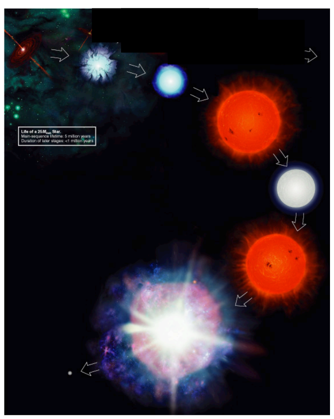
1. Main Sequence: H fuses to He in core
2. Red Giant: H fuses to He in shell around He core
3. Helium Core Burning: He fuses to C in core while H fuses to He in shell
4. Double Shell Burning: H and He both fuse in shells
5. Planetary Nebula leaves white dwarf behind



Not to scale!

Reasons for Life Stages

- Core shrinks and heats until it's hot enough for fusion
- Nuclei with larger charge require higher temperature for fusion
- Core thermostat is broken while core is not hot enough for fusion (shell burning)
- Core fusion can't happen if degeneracy pressure keeps core from shrinking

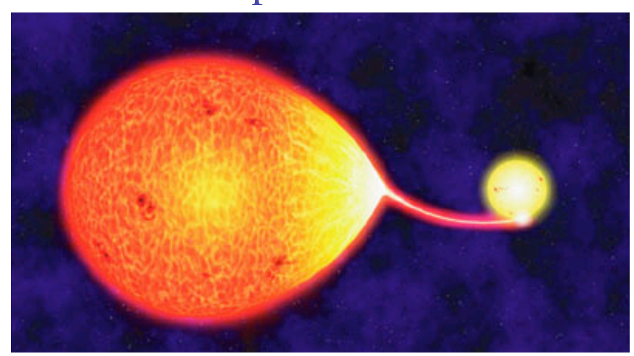


Not to scale!

Life Stages of High-Mass Star

1. Main Sequence: H fuses to He in core
2. Red Supergiant: H fuses to He in shell around He core
3. Helium Core Burning: He fuses to C in core while H fuses to He in shell
4. Multiple Shell Burning: Many elements fuse in shells
5. Supernova leaves neutron star behind

How are the lives of stars with close companions different?

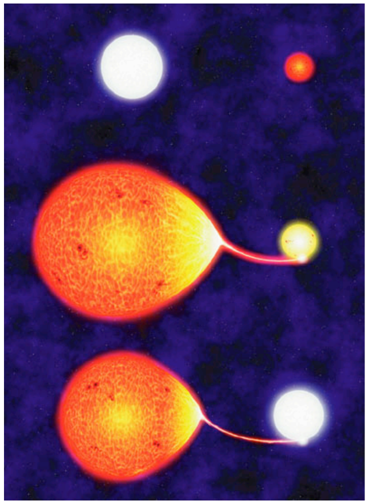


Thought Question

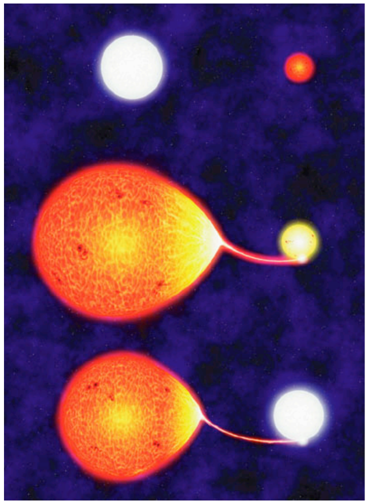
The binary star Algol consists of a 3.7 M_{Sun} main sequence star and a 0.8 M_{Sun} subgiant star.

What's strange about this pairing?

How did it come about?



Stars in the Algol system are close enough that matter can flow from subgiant onto main-sequence star



Star that is now a subgiant was originally more massive

As it reached the end of its life and started to grow, it began to transfer mass to its companion (*mass exchange)*

Now the companion star is more massive

Brief Summary

The evolution of low mass stars

The evolution of high mass stars

Production of carbon by low mass stars

Production of heavy elements by high mass stars

How binaries can transfer mass