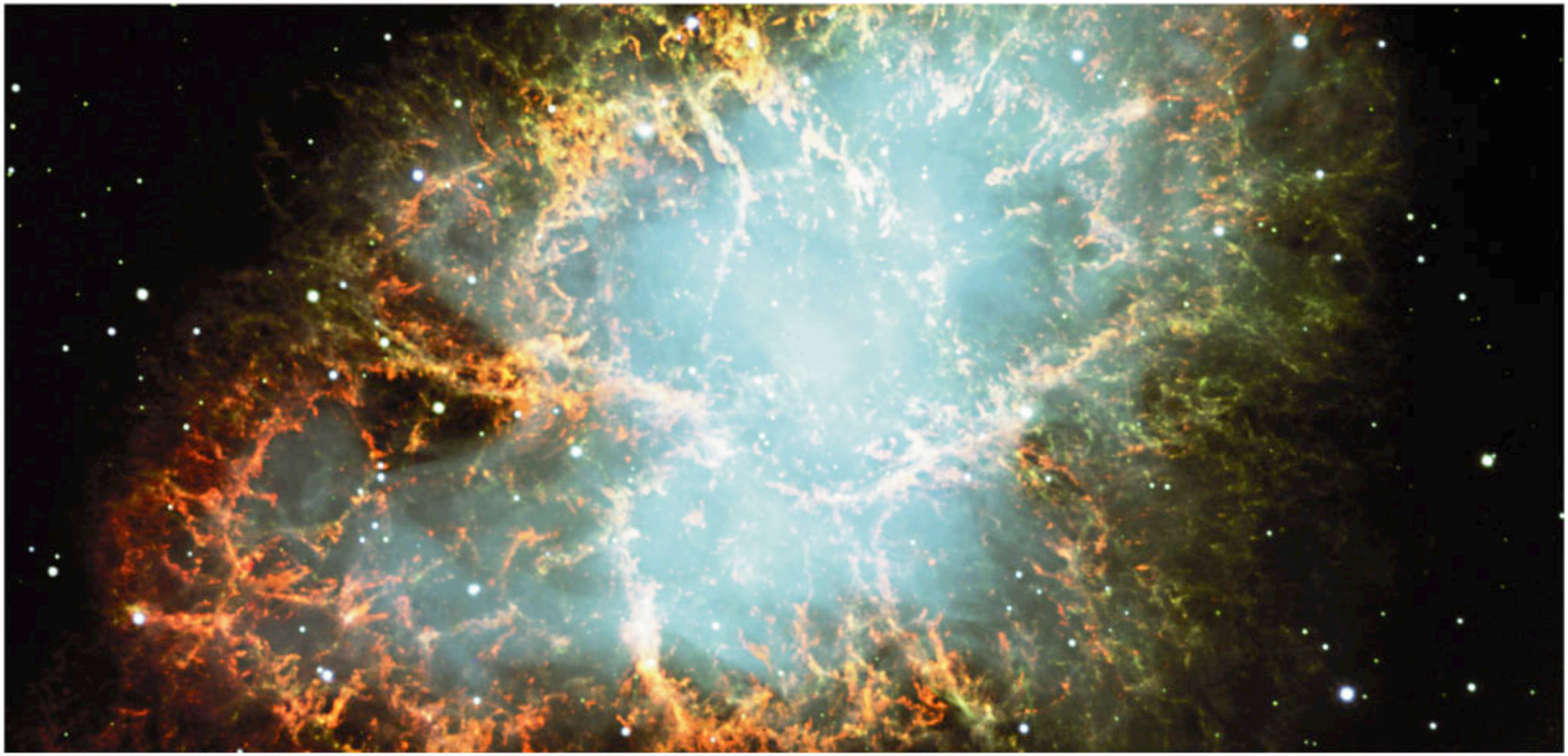
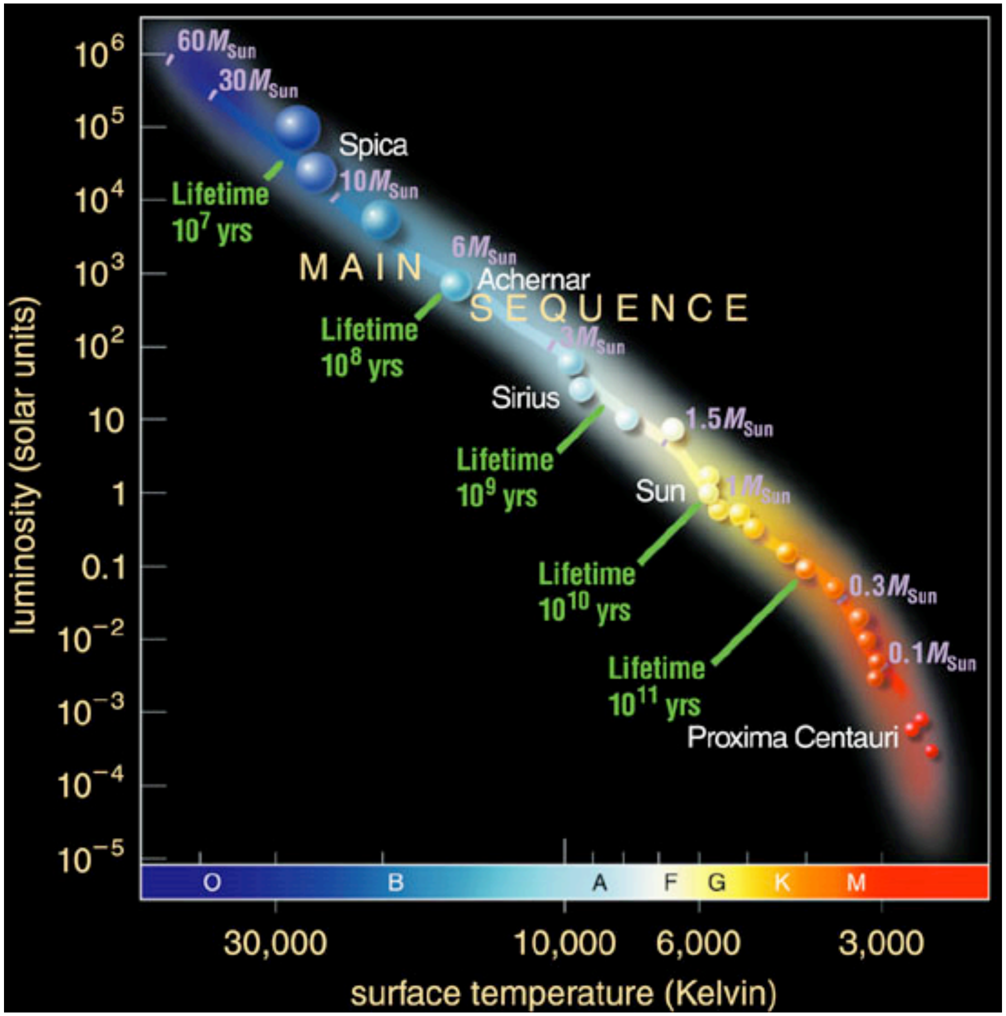
Evolution of High Mass Stars

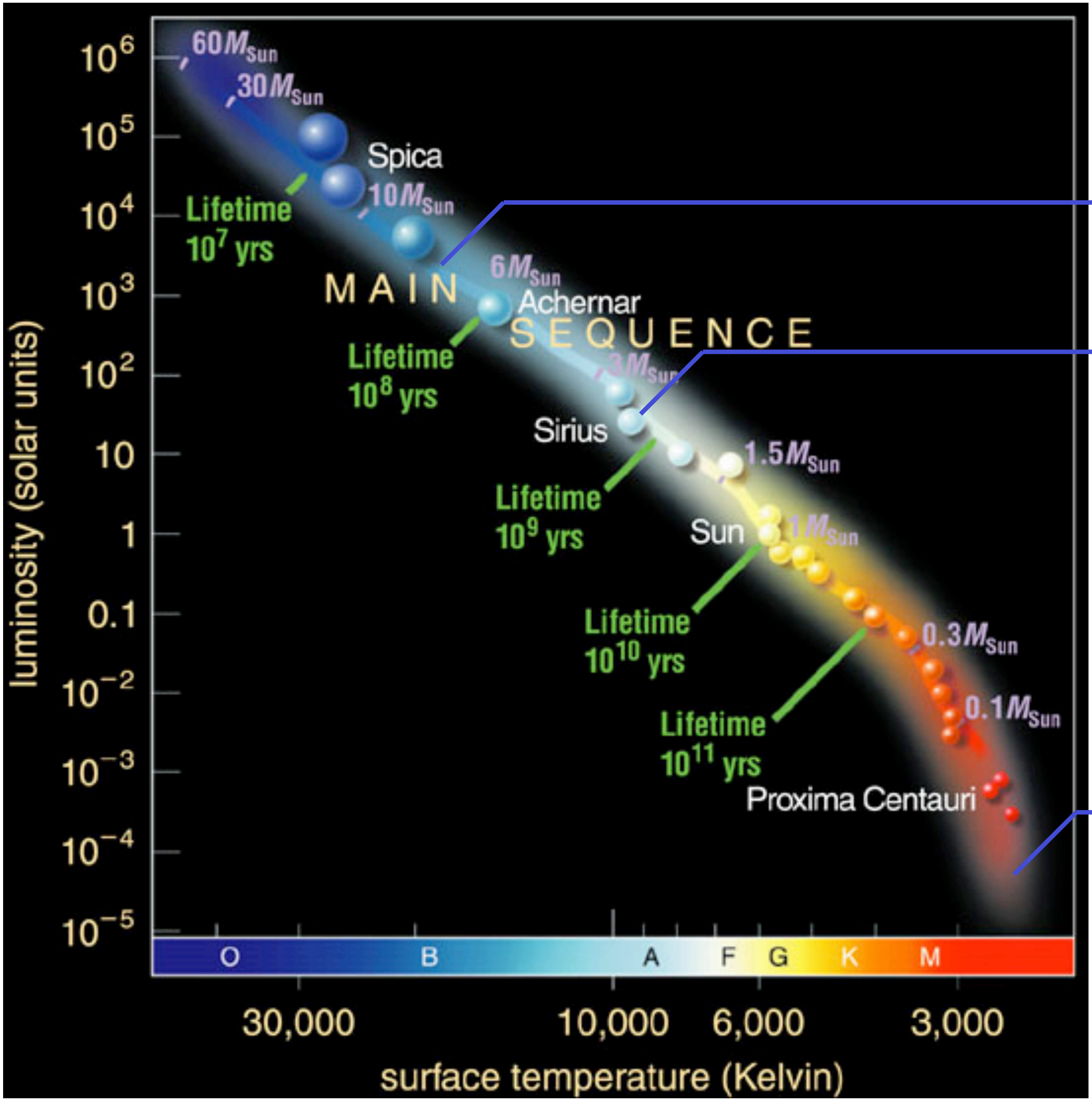


Stellar Mass and Fusion



- The mass of a main sequence star determines its core pressure and temperature
- Stars of higher mass have higher core temperature and more rapid fusion, making those stars both more luminous and shorter-lived
- Stars of lower mass have cooler cores and slower fusion rates, giving them smaller luminosities and longer lifetimes

Russel-Vogt Theorem: *Stellar Mass determines Stellar Evolution*



High-Mass Stars

$> 8\ M_{Sun}$

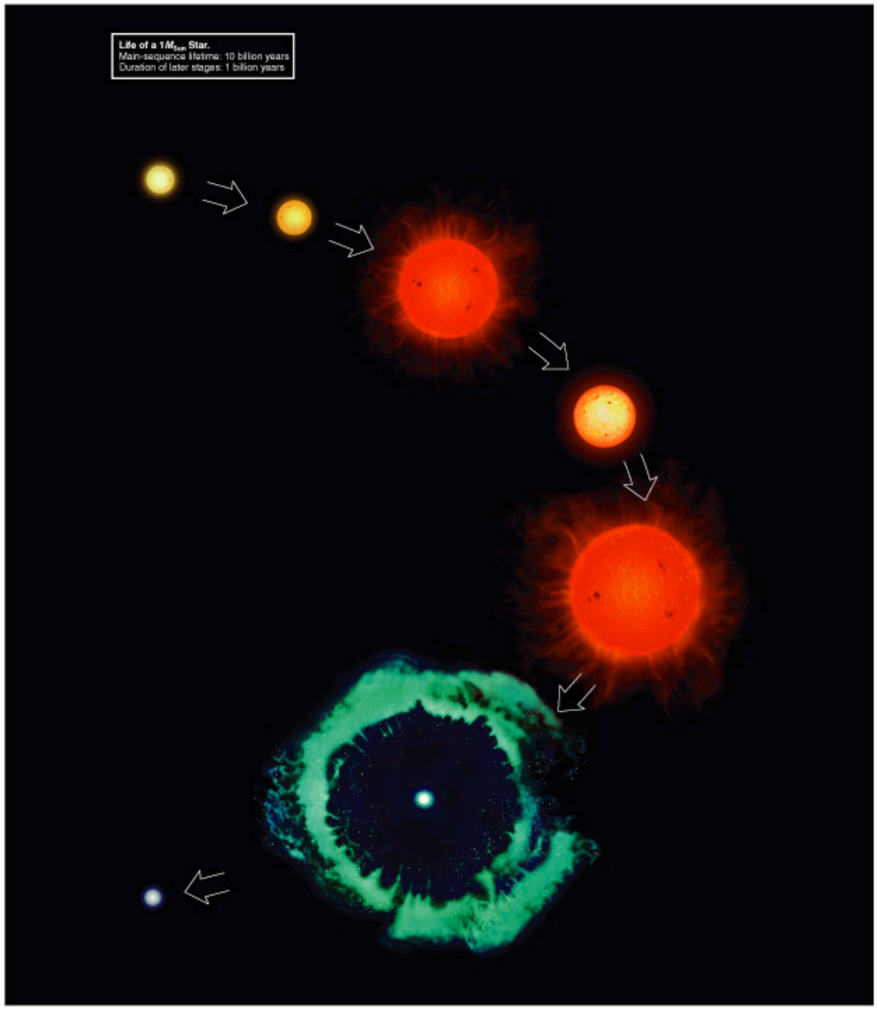
Intermediate-Mass Stars

Low-Mass Stars

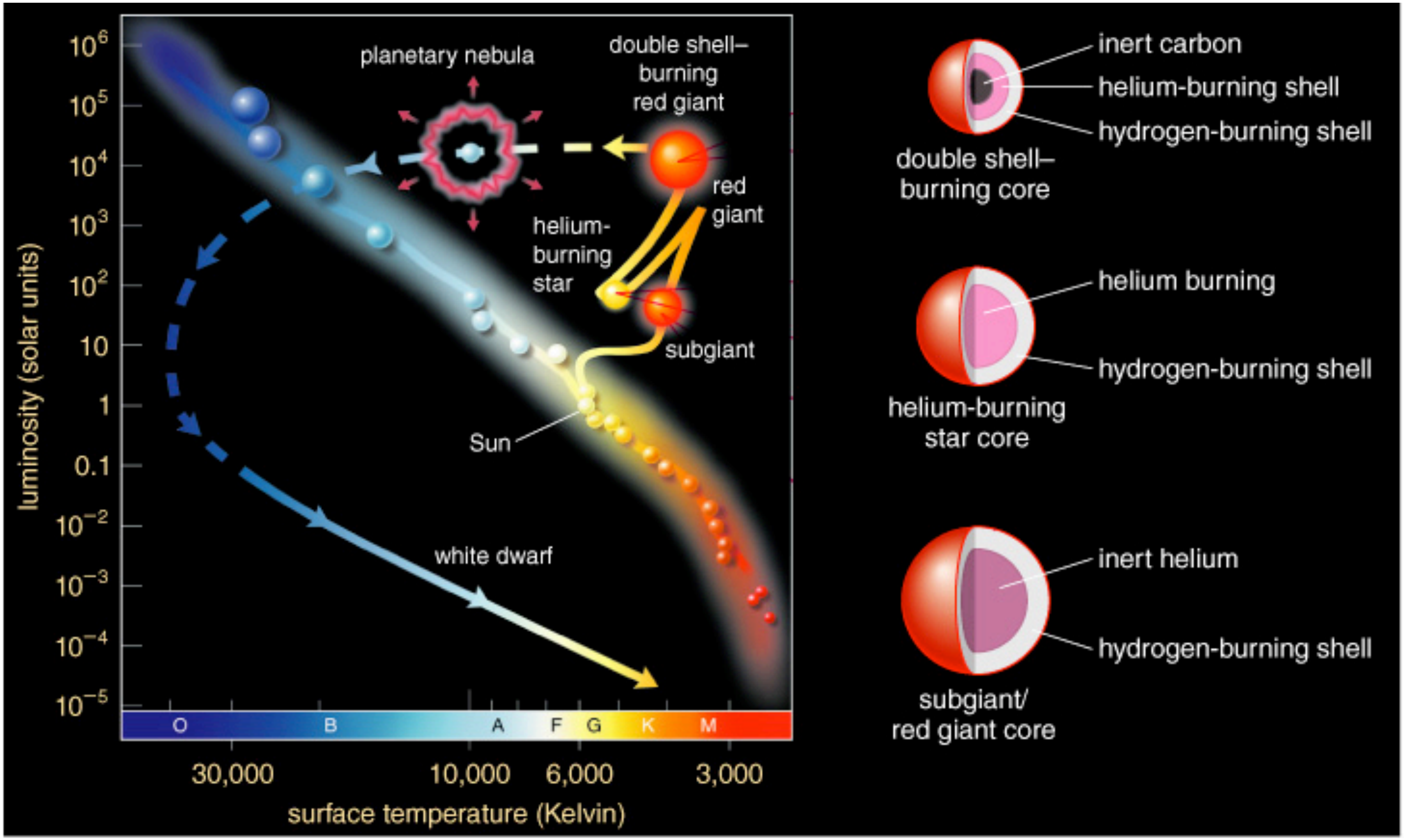
$< 2\ M_{Sun}$

Brown Dwarfs

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



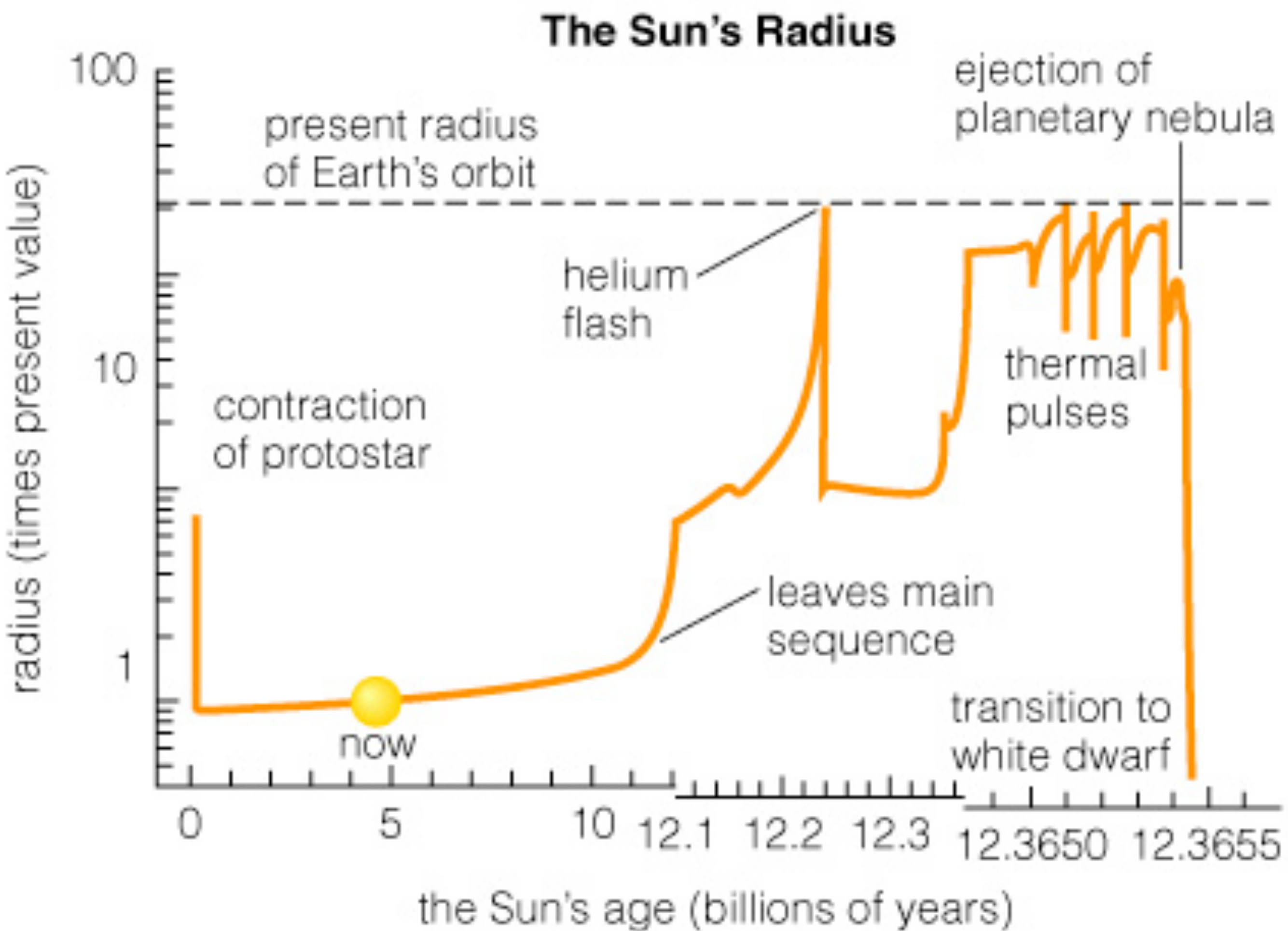
Life Track of a Sun-Like Star



Life Stages

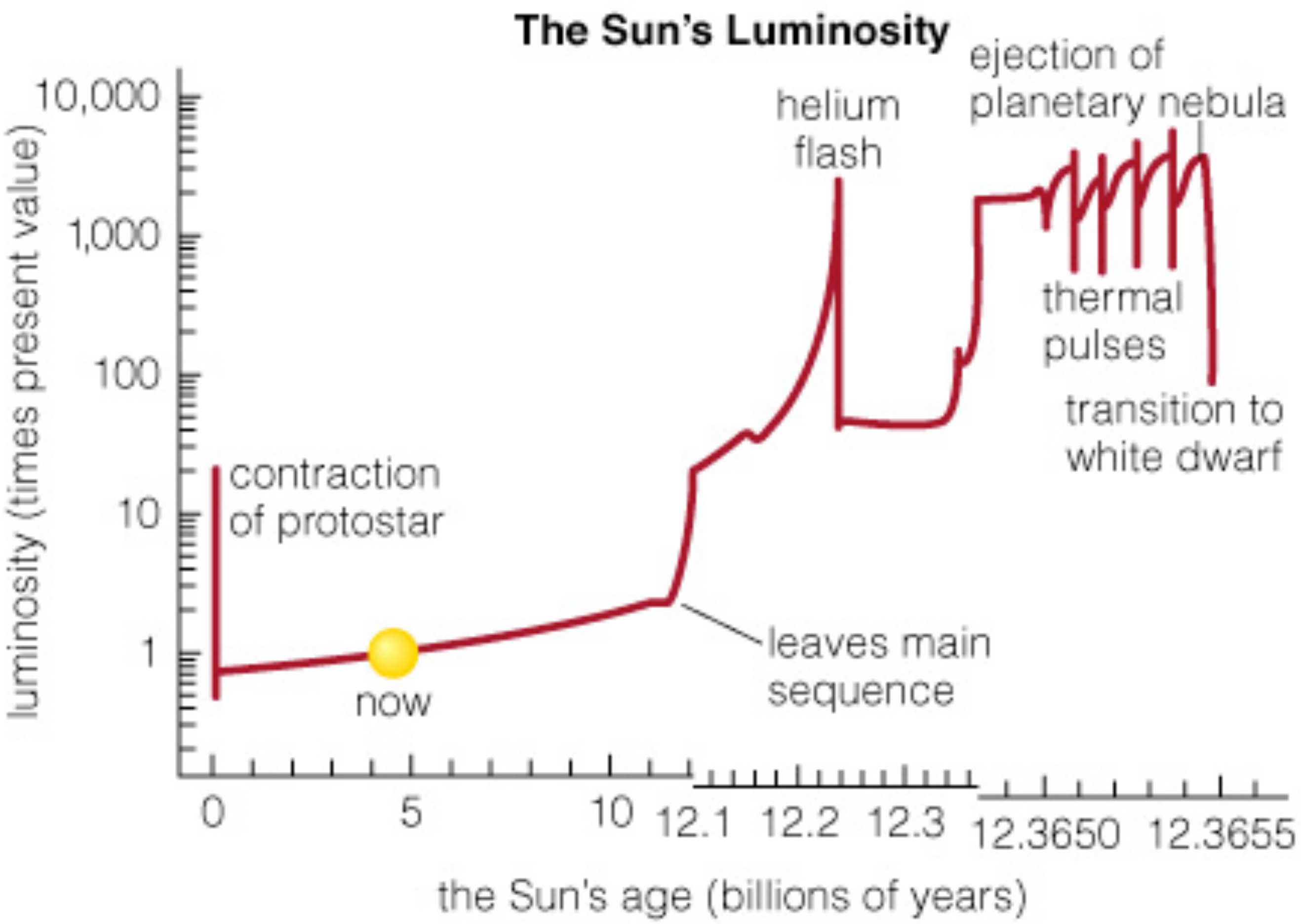
1. *Protostar*: gravitational contraction
2. Onset of Nuclear Reactions: gravity plus nukes
3. *Main Sequence*: ^{1}H --> ^{4}He fusion (p-p chain) in core
4. End of M/S - 10 billion yrs
5. *Red Giant*: ^{1}H -->^{4} He fusion in shell around contracting core (leading to He Flash)
6. *He Main Sequence*: He fusion in core (horizontal branch)
   - 2 billion years
7. Double-shell (^{4}He --> ^{12}C; ^{1}H --> ^{4}He) burning (red giant)
8. Ejection of H and He in a *Planetary Nebula* reveals hot (100,000K) stellar core
9. Leaving behind an inert *White Dwarf* (radiates store of thermal energy)

Earth's Fate



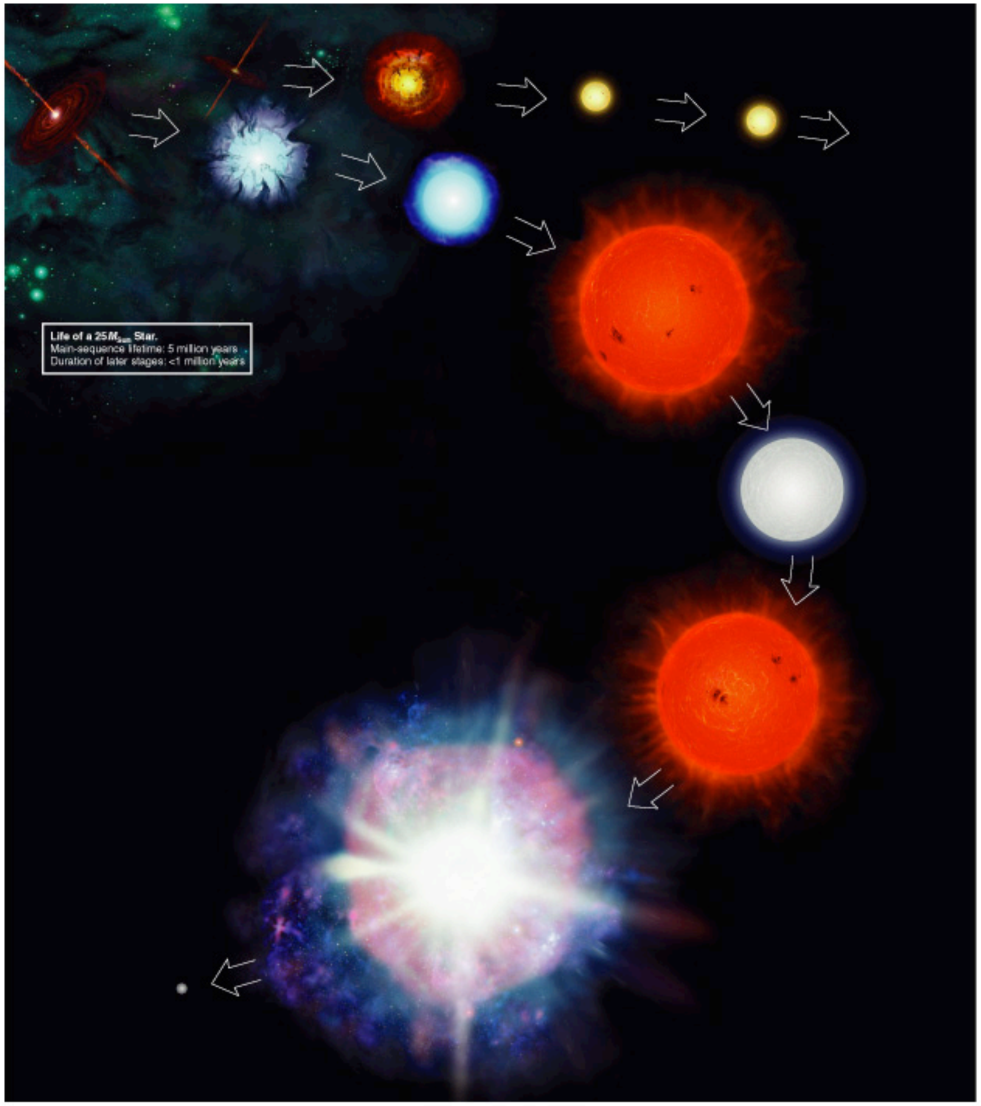
- Sun's radius will grow to near current radius of Earth's orbit

Earth’s Fate



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

High Mass Stars



1. L ∝ M^3; Fuel ∝ M
   ⇒ Lifetime ∝ $1/M^2$ (M/M^3)
   Massive stars live fast, die young
   (shorter lifetimes in all phases)

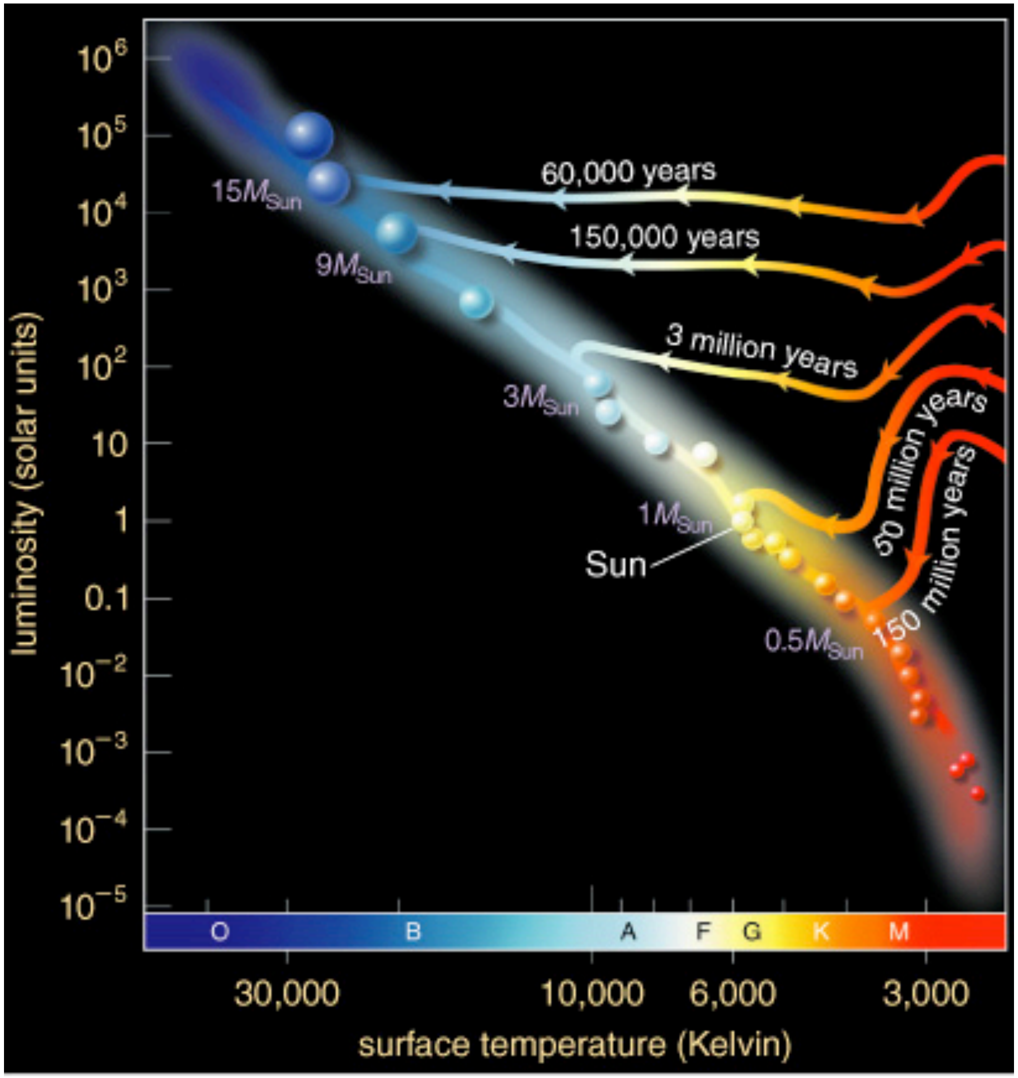
2. Higher T ⇒ CNO Cycle on M/S

3. No core degeneracy (higher T ⇒ higher P) means no helium flash

4. Higher T ⇒ more nuclear burning stages (it is the high mass stars that make the elements heavier than C,N,O and even most of the C,N,O that goes into the ISM.

5. Massive stars will have very different evolutionary endpoints (remnants: neutron star or black hole vs white dwarf)

Life Tracks for Different Masses

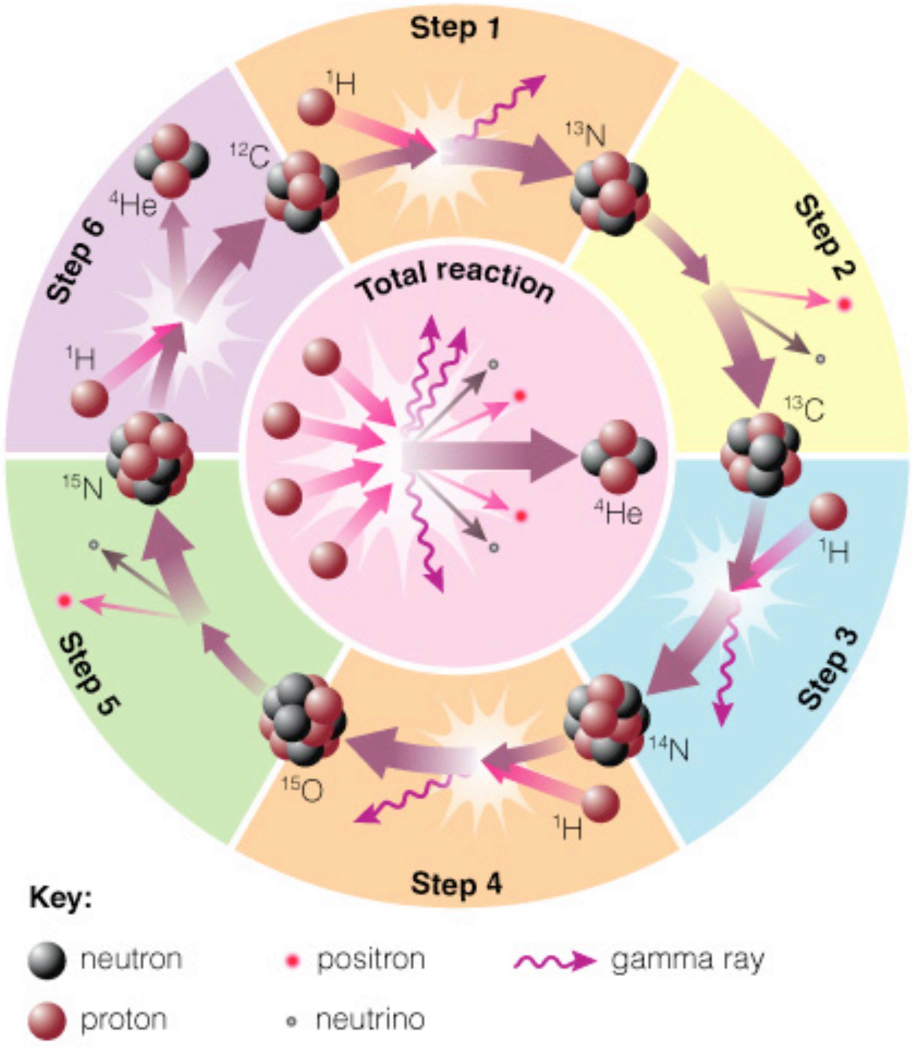


- Models show that Sun required about 30 million years to go from protostar to main sequence

- Higher-mass stars form faster

- Lower-mass stars form more slowly

CNO Cycle



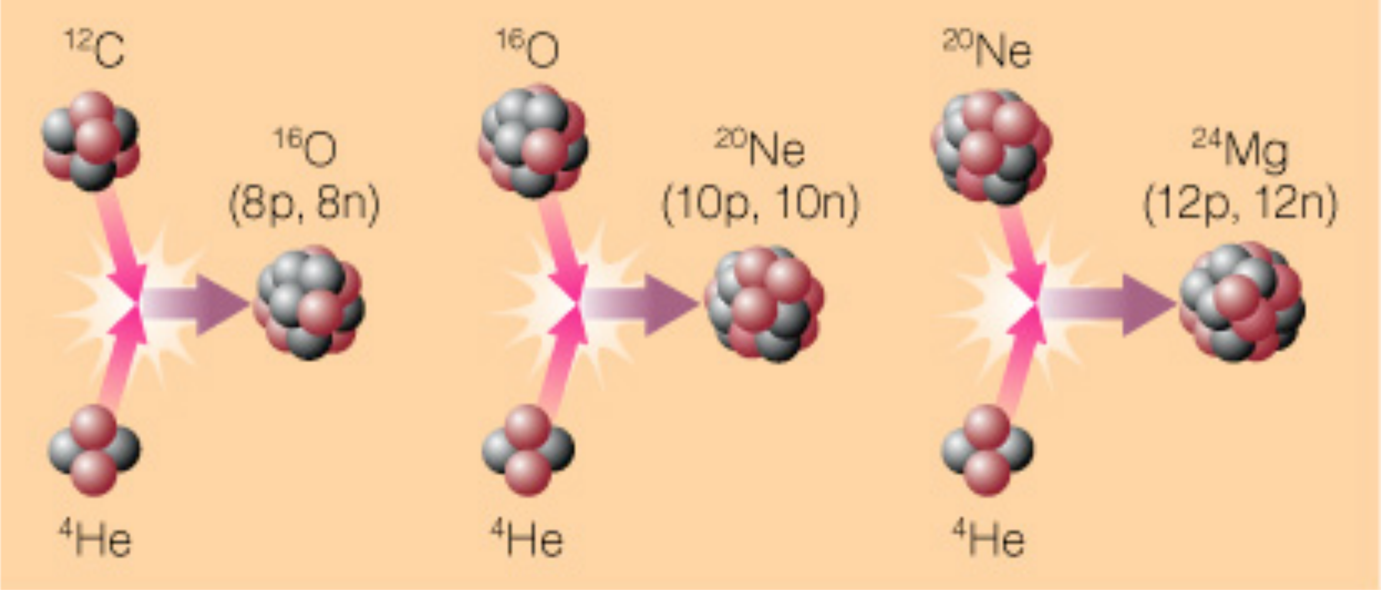
- High-mass main sequence stars fuse H to He at a higher rate using carbon, nitrogen, and oxygen as catalysts

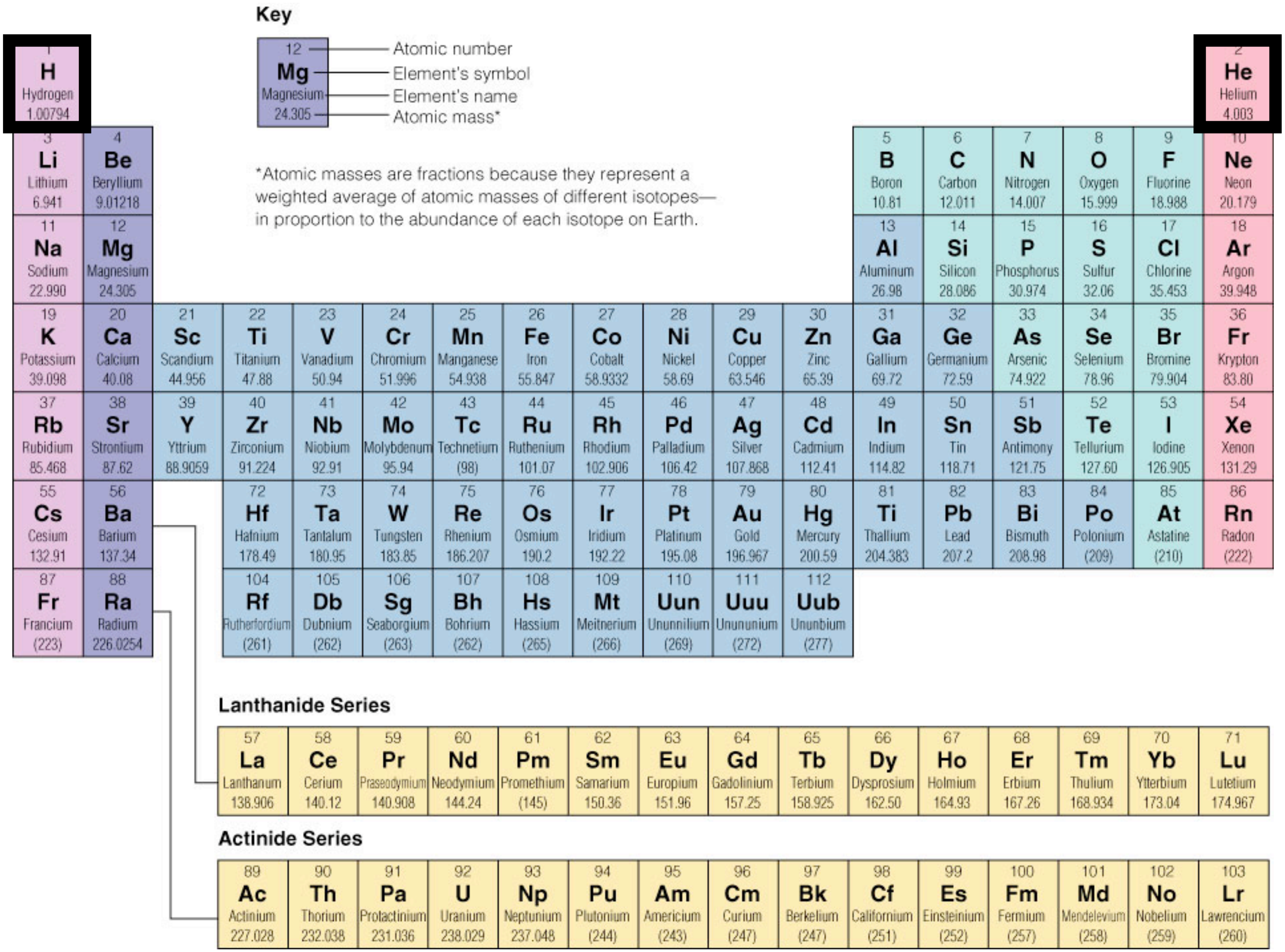
- Greater core temperature enables H nuclei to overcome greater repulsion

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)
- But continue with further stages:
  - Helium capture
  - Advanced nuclear stages to creation of Iron

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





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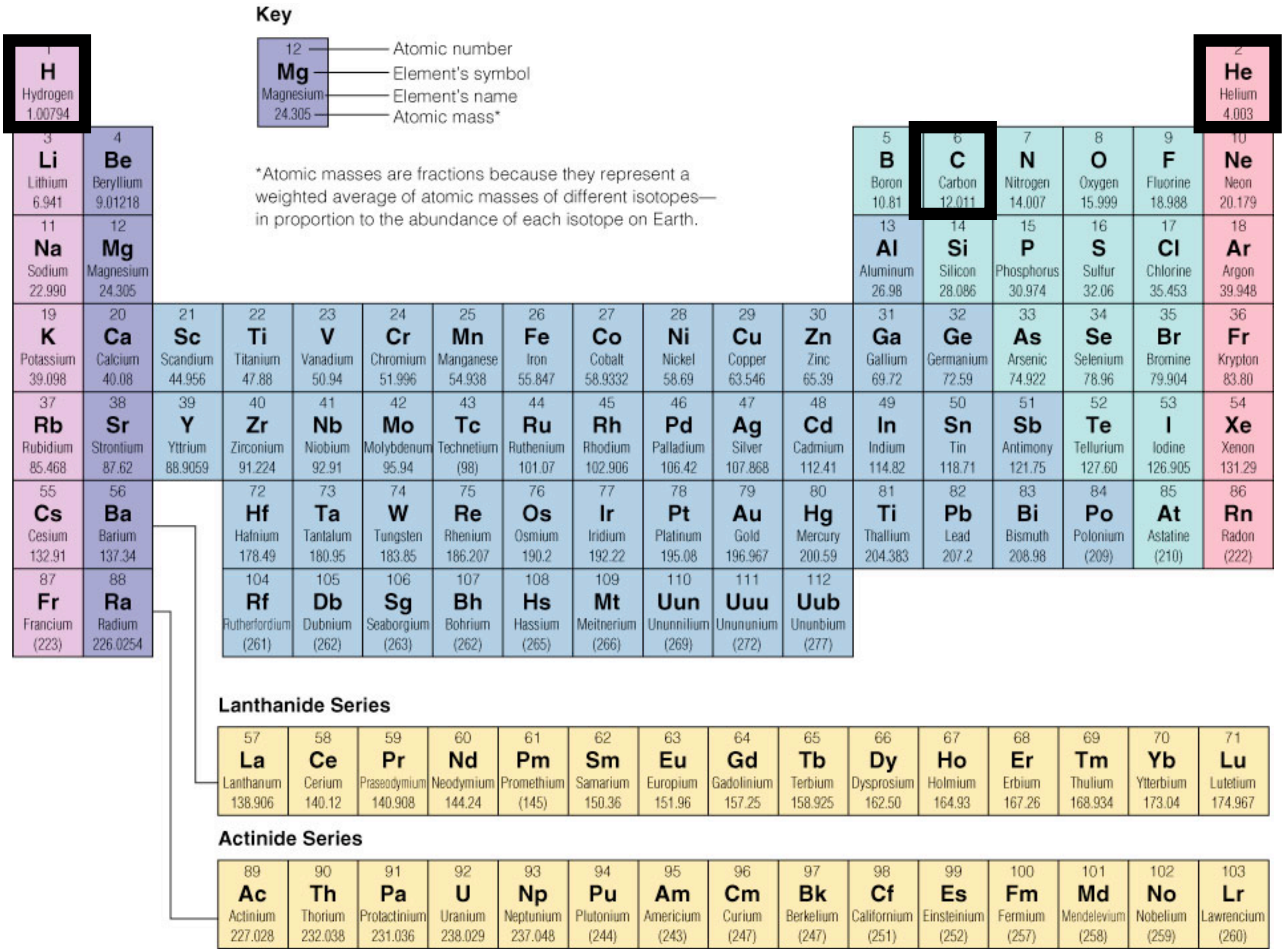
Big Bang made 75% H, 25% He – stars make everything else



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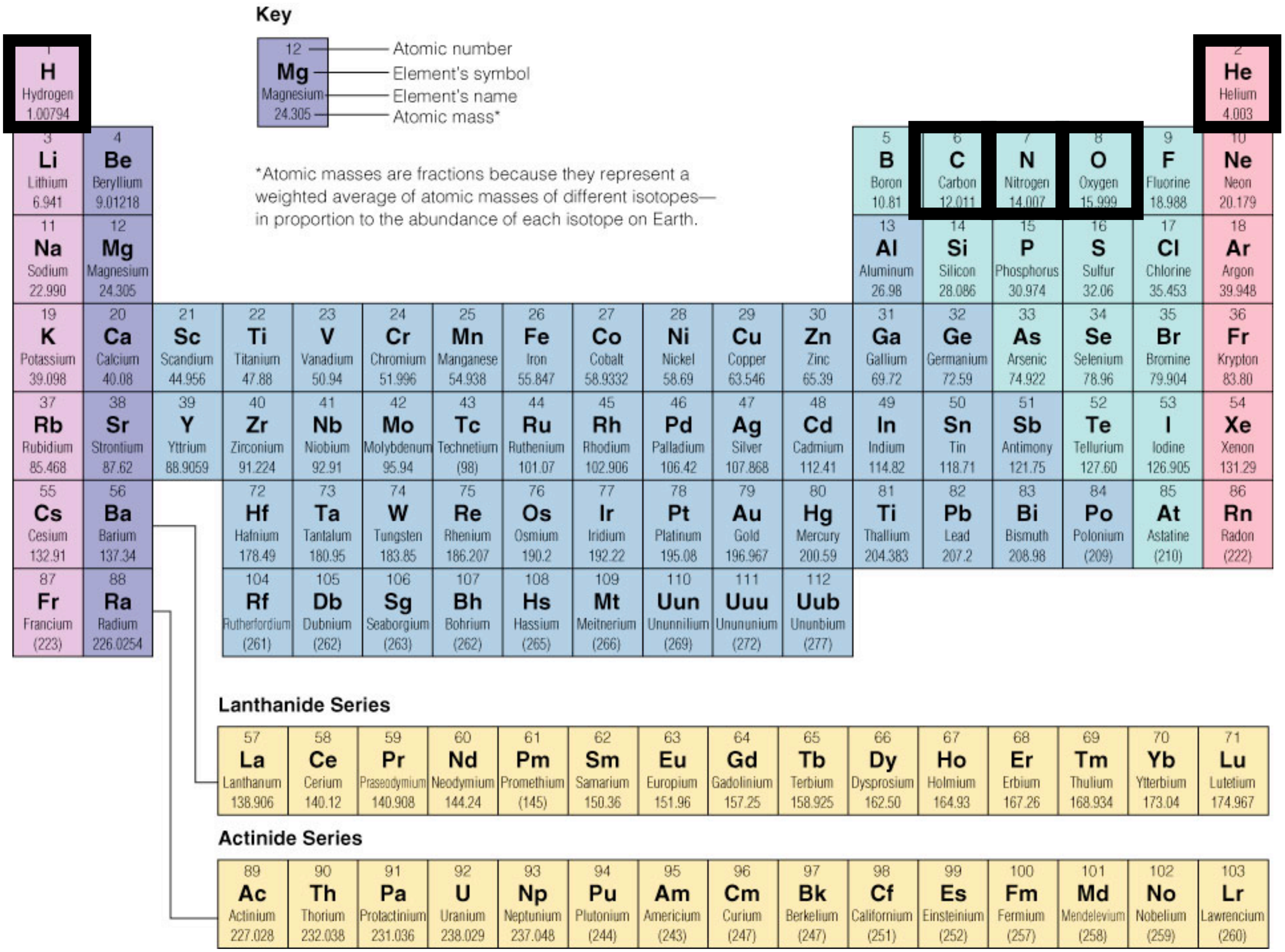
Helium fusion can make carbon in low-mass stars



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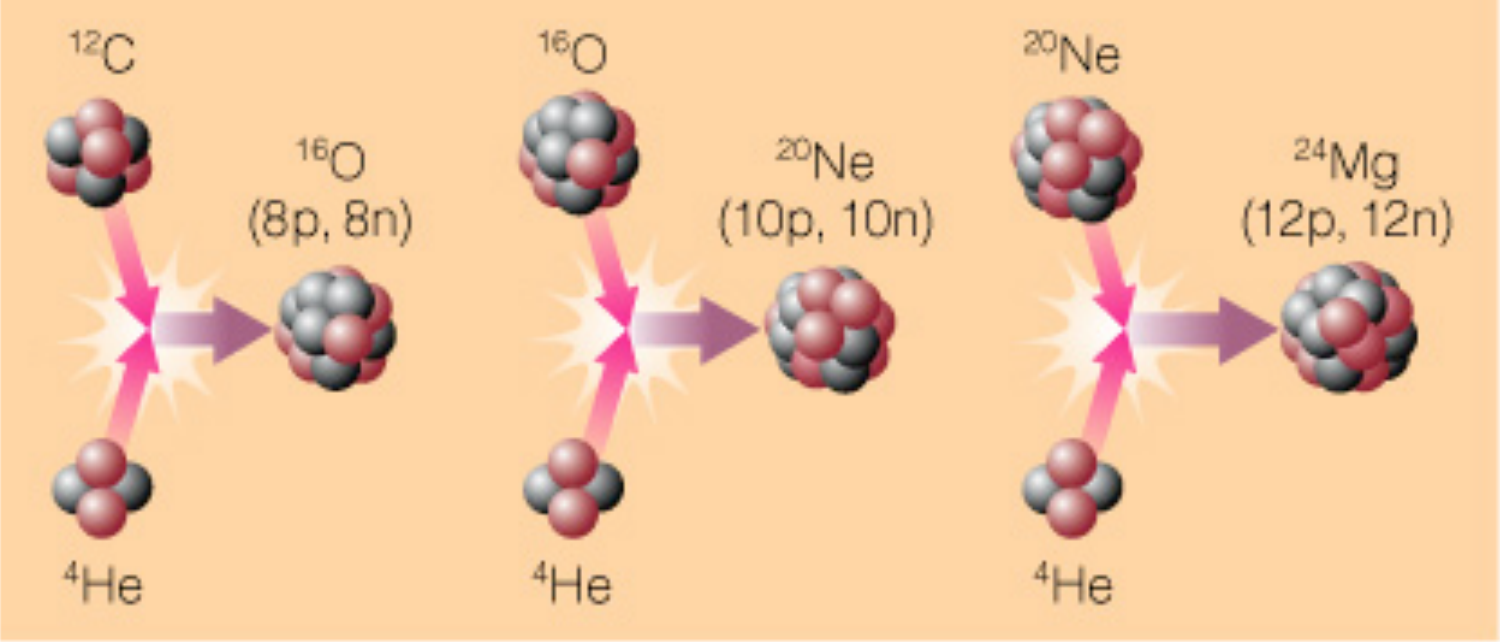
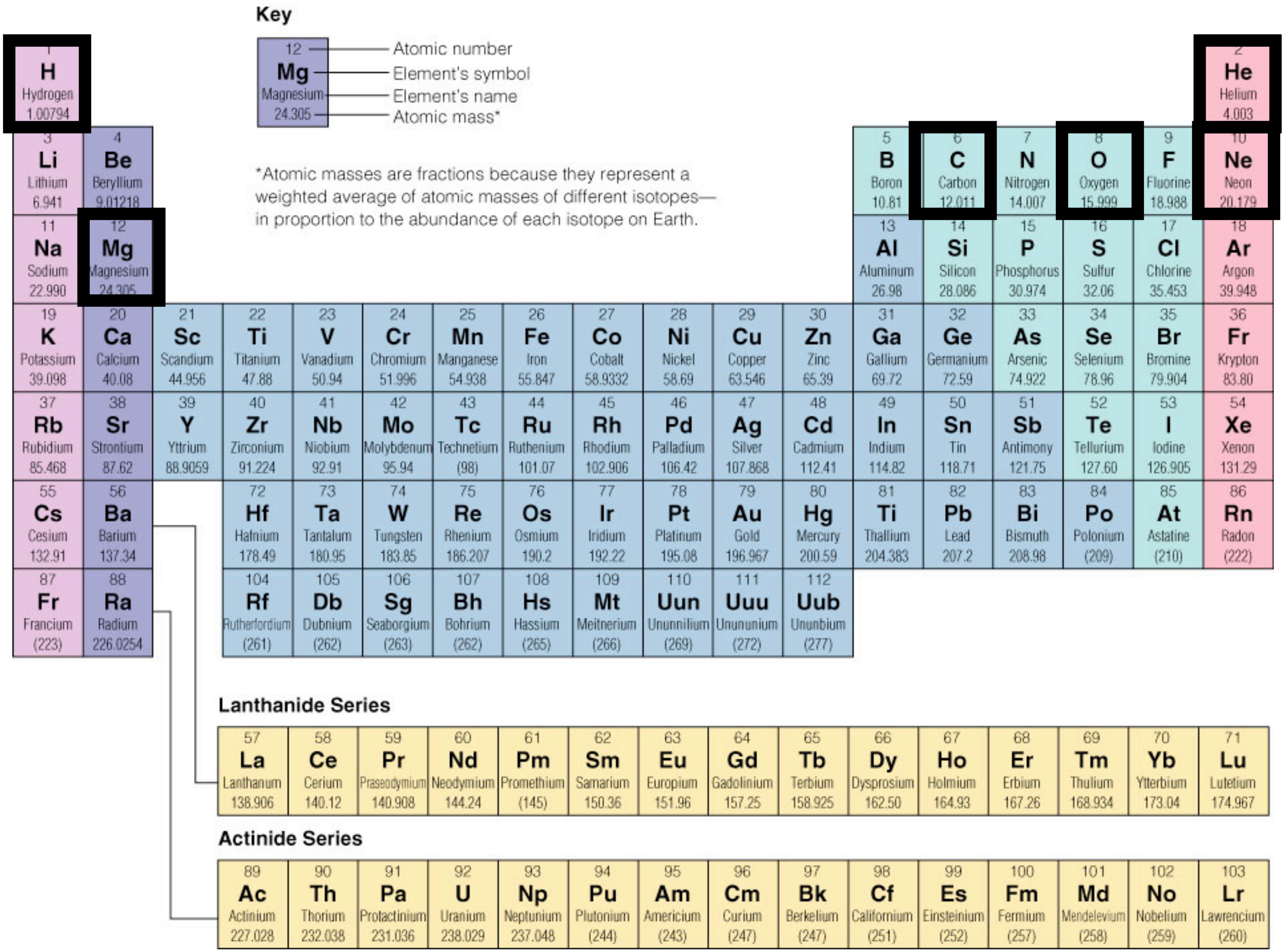
CNO cycle can change C into N and O

Helium Capture



- High core temperatures allow helium to fuse with heavier elements



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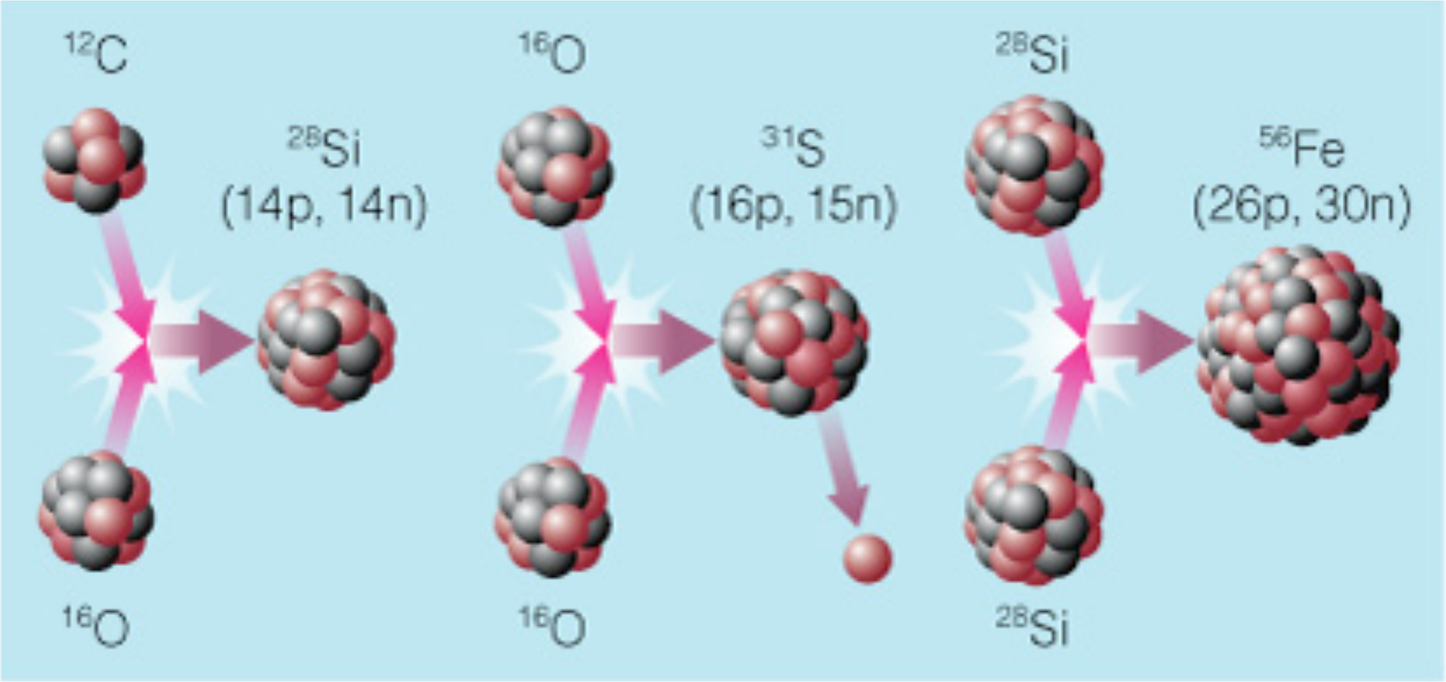
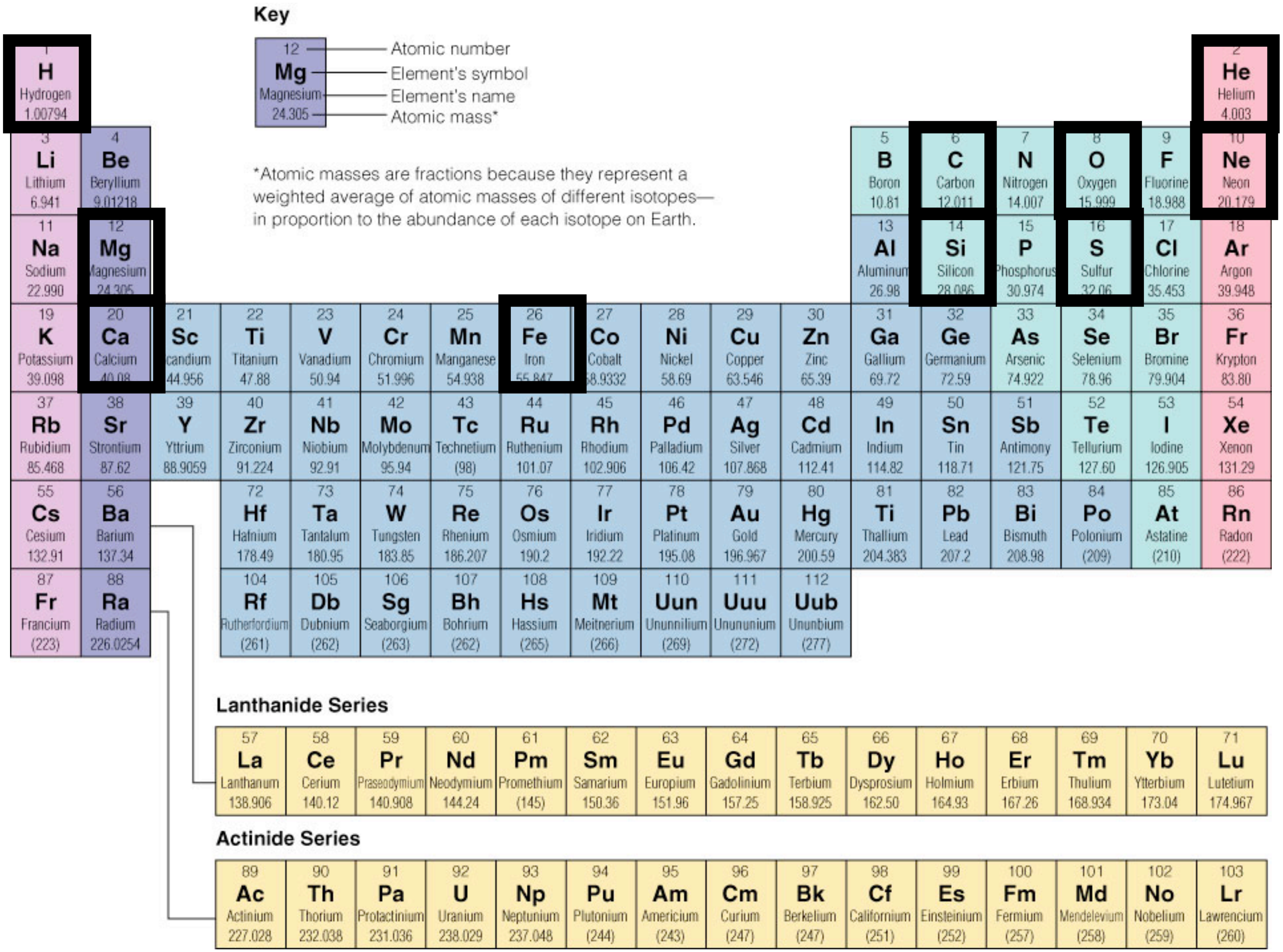
Helium capture builds C into O, Ne, Mg, …

Advanced Nuclear Burning



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



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11 **Na** Sodium 22.990	12 **Mg** Magnesium 24.305											13 **Al** Aluminum 26.98	14 **Si** Silicon 28.086	15 **P** Phosphorus 30.974	16 **S** Sulfur 32.06	17 **Cl** Chlorine 35.453	18 **Ar** Argon 39.948
19 **K** Potassium 39.098	20 **Ca** Calcium 40.08	21 **Sc** candium 44.956	22 **Ti** Titanium 47.88	23 **V** Vanadium 50.94	24 **Cr** Chromium 51.996	25 **Mn** Manganese 54.938	26 **Fe** Iron 55.847	27 **Co** Cobalt 8.9332	28 **Ni** Nickel 58.69	29 **Cu** Copper 63.546	30 **Zn** Zinc 65.39	31 **Ga** Gallium 69.72	32 **Ge** Germanium 72.59	33 **As** Arsenic 74.922	34 **Se** Selenium 78.96	35 **Br** Bromine 79.904	36 **Fr** Krypton 83.80
37 **Rb** Rubidium 85.468	38 **Sr** Strontium 87.62	39 **Y** Yttrium 88.9059	40 **Zr** Zirconium 91.224	41 **Nb** Niobium 92.91	42 **Mo** Molybdenum 95.94	43 **Tc** Technetium (98)	44 **Ru** Ruthenium 101.07	45 **Rh** Rhodium 102.906	46 **Pd** Palladium 106.42	47 **Ag** Silver 107.868	48 **Cd** Cadmium 112.41	49 **In** Indium 114.82	50 **Sn** Tin 118.71	51 **Sb** Antimony 121.75	52 **Te** Tellurium 127.60	53 **I** Iodine 126.905	54 **Xe** Xenon 131.29
55 **Cs** Cesium 132.91	56 **Ba** Barium 137.34		72 **Hf** Hafnium 178.49	73 **Ta** Tantalum 180.95	74 **W** Tungsten 183.85	75 **Re** Rhenium 186.207	76 **Os** Osmium 190.2	77 **Ir** Iridium 192.22	78 **Pt** Platinum 195.08	79 **Au** Gold 196.967	80 **Hg** Mercury 200.59	81 **Ti** Thallium 204.383	82 **Pb** Lead 207.2	83 **Bi** Bismuth 208.98	84 **Po** Polonium (209)	85 **At** Astatine (210)	86 **Rn** Radon (222)
87 **Fr** Francium (223)	88 **Ra** Radium 226.0254		104 **Rf** Rutherfordium (261)	105 **Db** Dubnium (262)	106 **Sg** Seaborgium (263)	107 **Bh** Bohrium (262)	108 **Hs** Hassium (265)	109 **Mt** Meitnerium (266)	110 **Uun** Ununnilium (269)	111 **Uuu** Unununium (272)	112 **Uub** Ununbium (277)						

Lanthanide Series

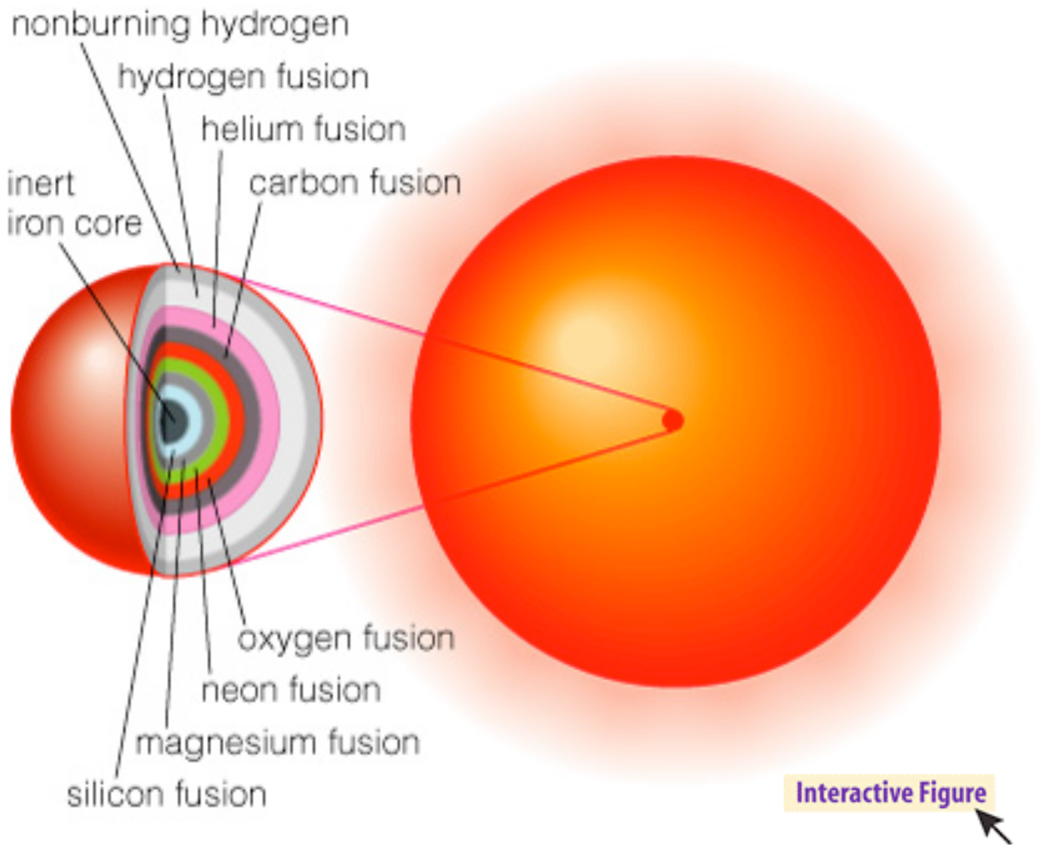
57 **La** Lanthanum 138.906	58 **Ce** Cerium 140.12	59 **Pr** Praseodymium 140.908	60 **Nd** Neodymium 144.24	61 **Pm** Promethium (145)	62 **Sm** Samarium 150.36	63 **Eu** Europium 151.96	64 **Gd** Gadolinium 157.25	65 **Tb** Terbium 158.925	66 **Dy** Dysprosium 162.50	67 **Ho** Holmium 164.93	68 **Er** Erbium 167.26	69 **Tm** Thulium 168.934	70 **Yb** Ytterbium 173.04	71 **Lu** Lutetium 174.967

Actinide Series

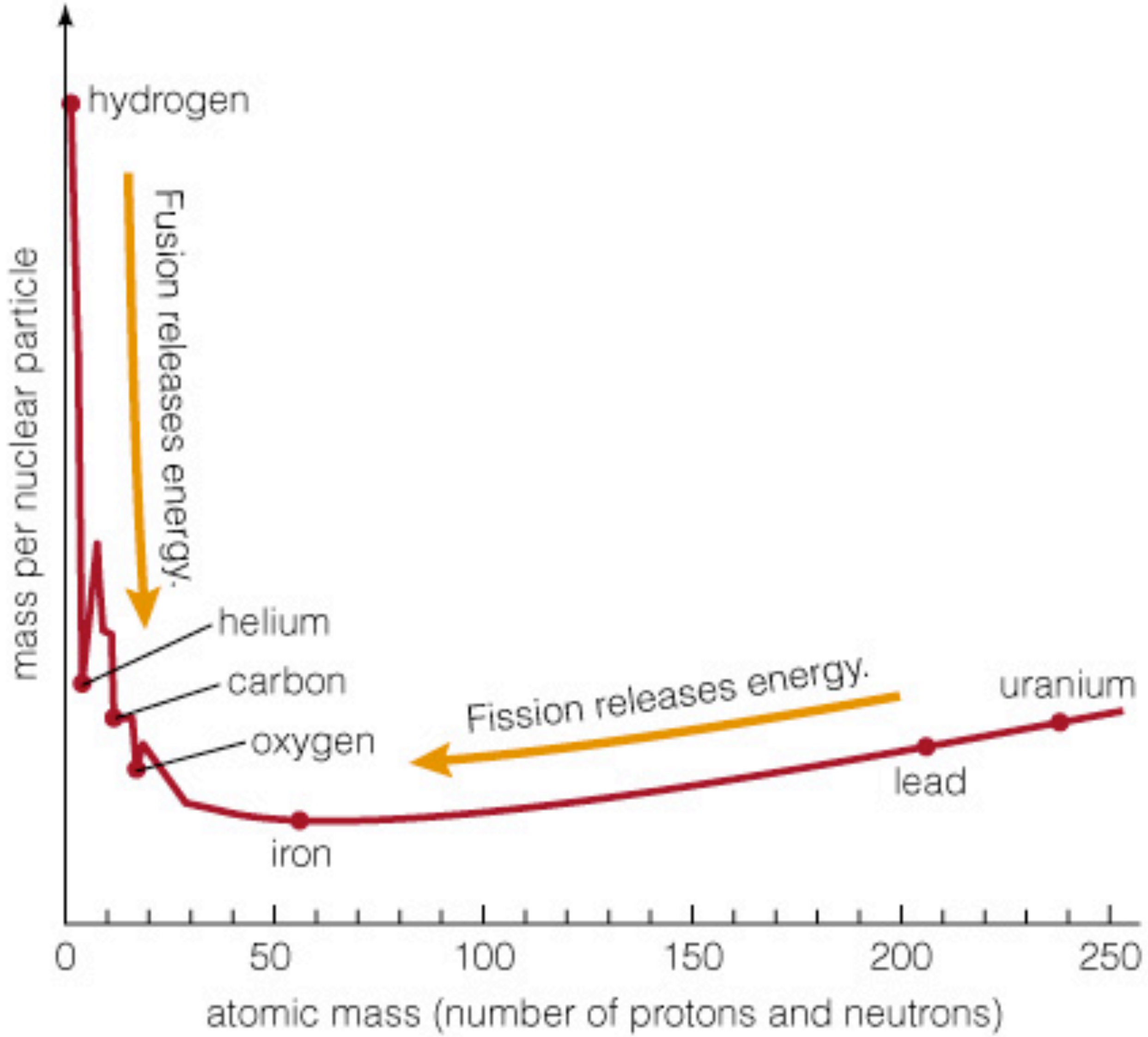
89 **Ac** Actinium 227.028	90 **Th** Thorium 232.038	91 **Pa** Protactinium 231.036	92 **U** Uranium 238.029	93 **Np** Neptunium 237.048	94 **Pu** Plutonium (244)	95 **Am** Americium (243)	96 **Cm** Curium (247)	97 **Bk** Berkelium (247)	98 **Cf** Californium (251)	99 **Es** Einsteinium (252)	100 **Fm** Fermium (257)	101 **Md** Mendelevium (258)	102 **No** Nobelium (259)	103 **Lr** Lawrencium (260)

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

Multiple Shell Burning

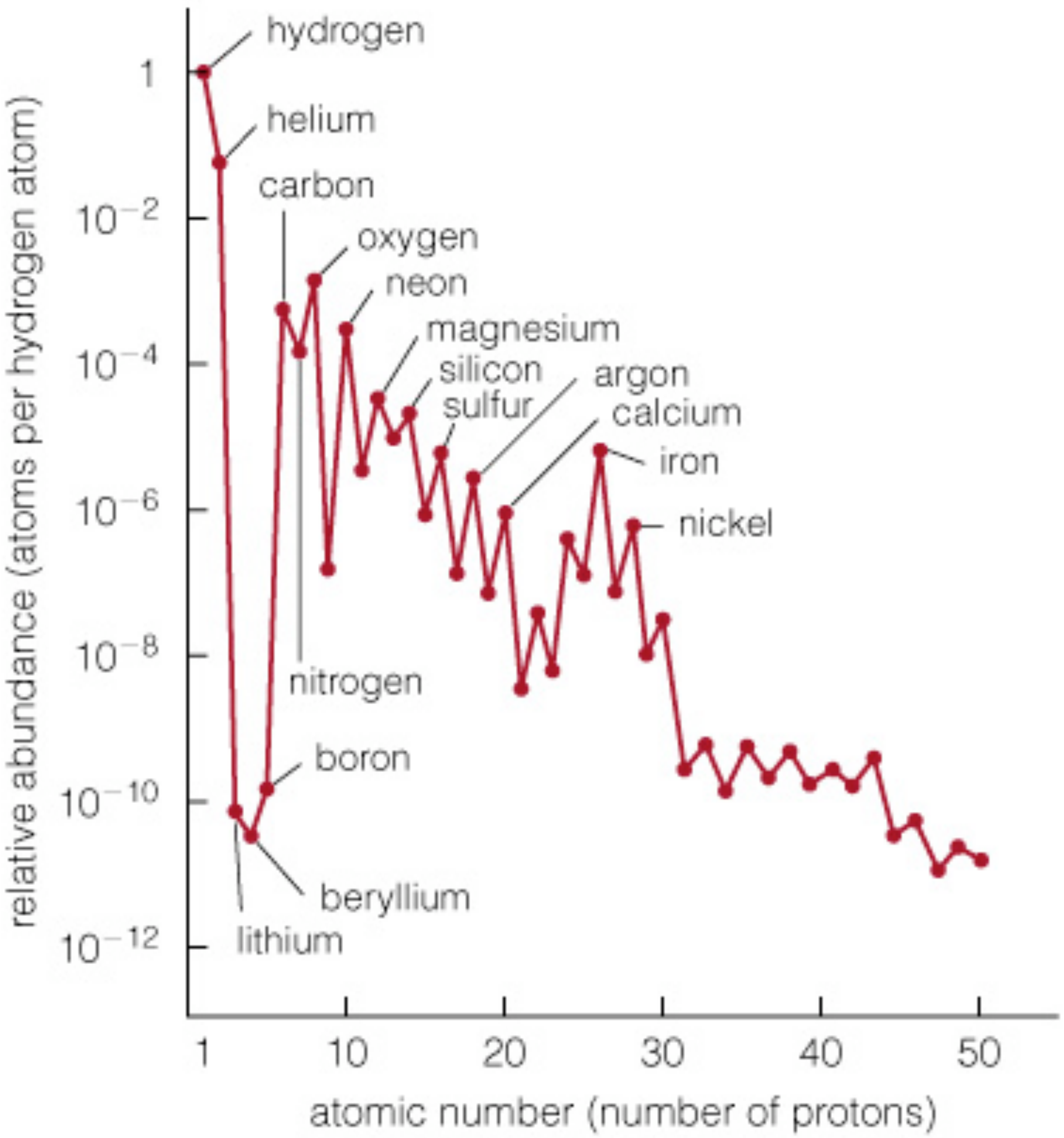


- Advanced nuclear burning proceeds in a series of nested shells



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

(Fe has lowest mass per nuclear particle)



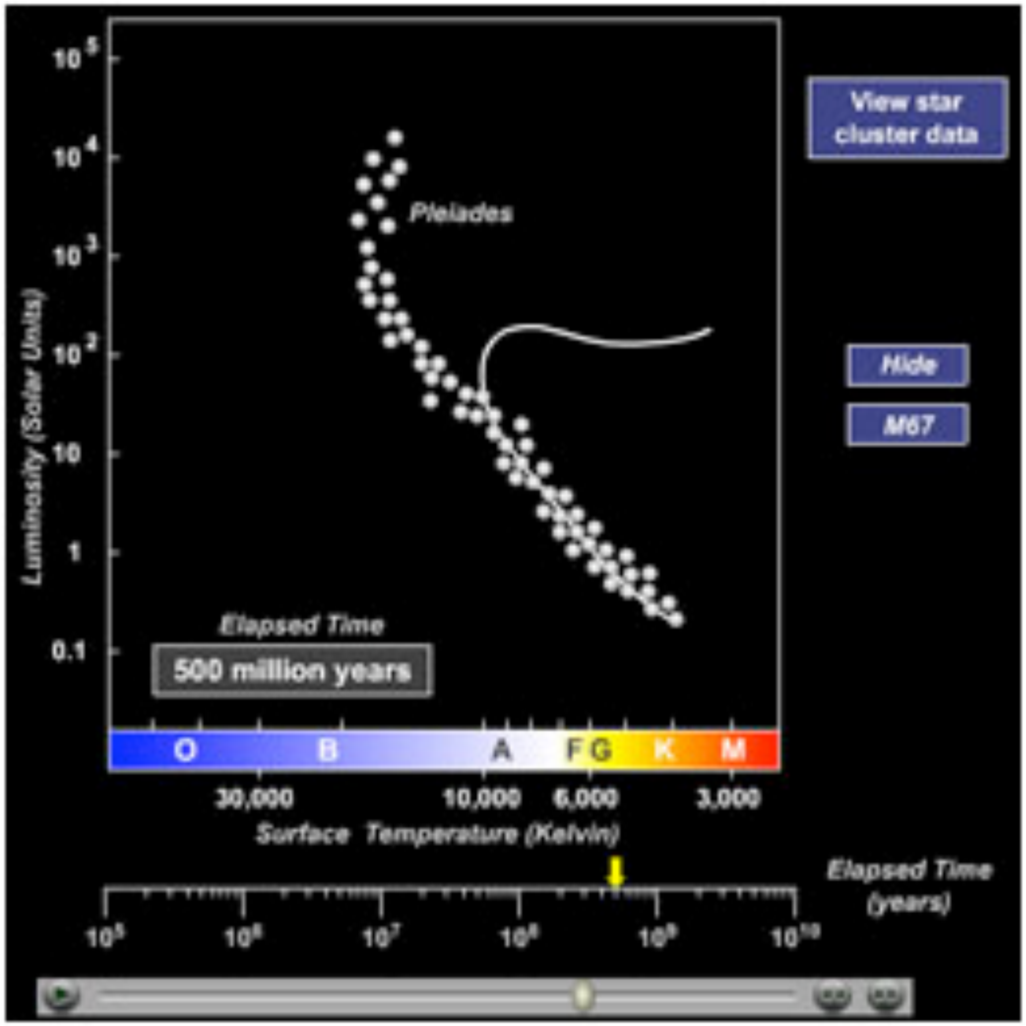
Evidence for helium capture:

Higher abundances of elements with even numbers of protons

Star Clusters and Stellar Lives

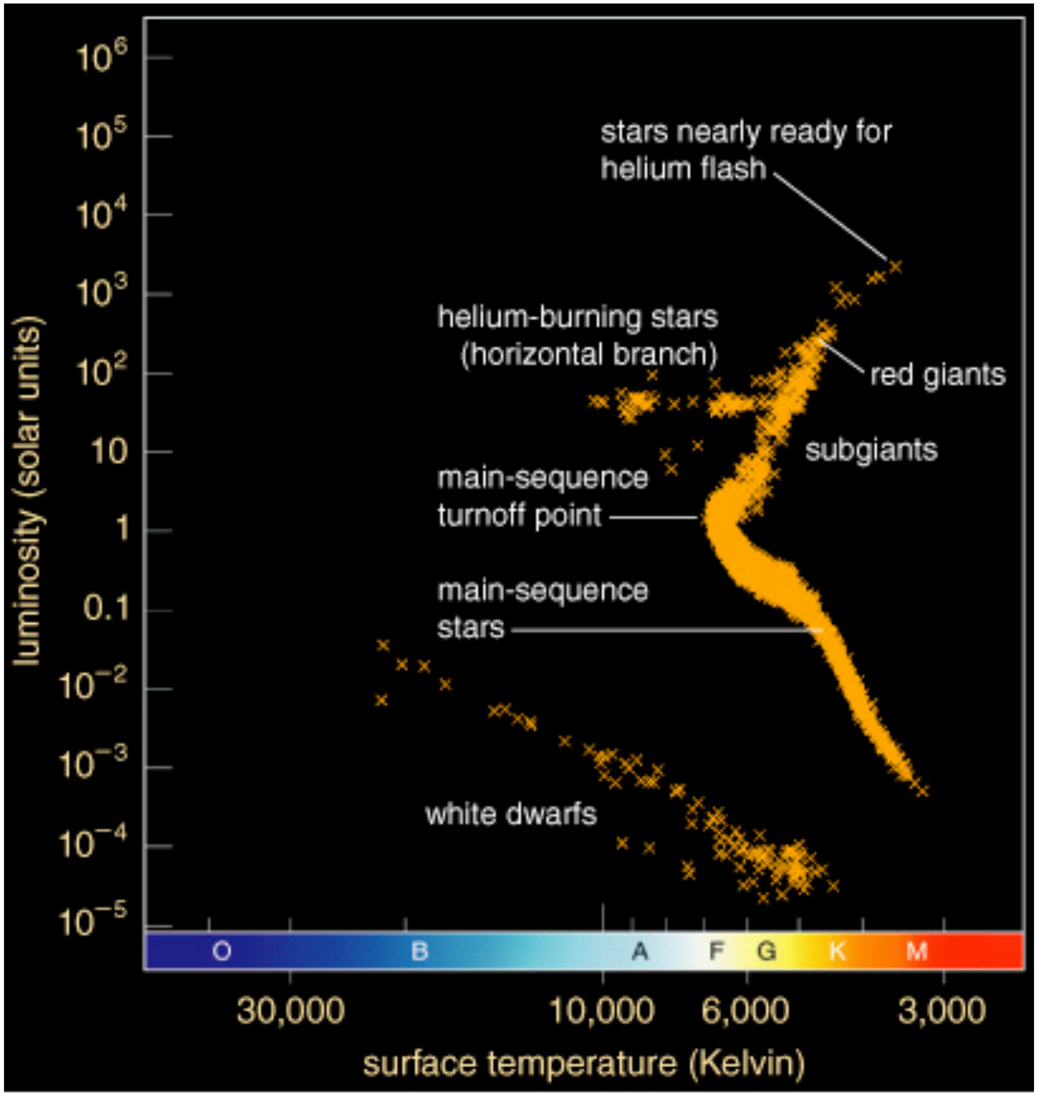
- Our knowledge of the life stories of stars comes from comparing mathematical models of stars with observations

- Star clusters are particularly useful because they contain stars of different mass that were born about the same time



Combining models of stars of similar age but different mass helps us to age-date star clusters

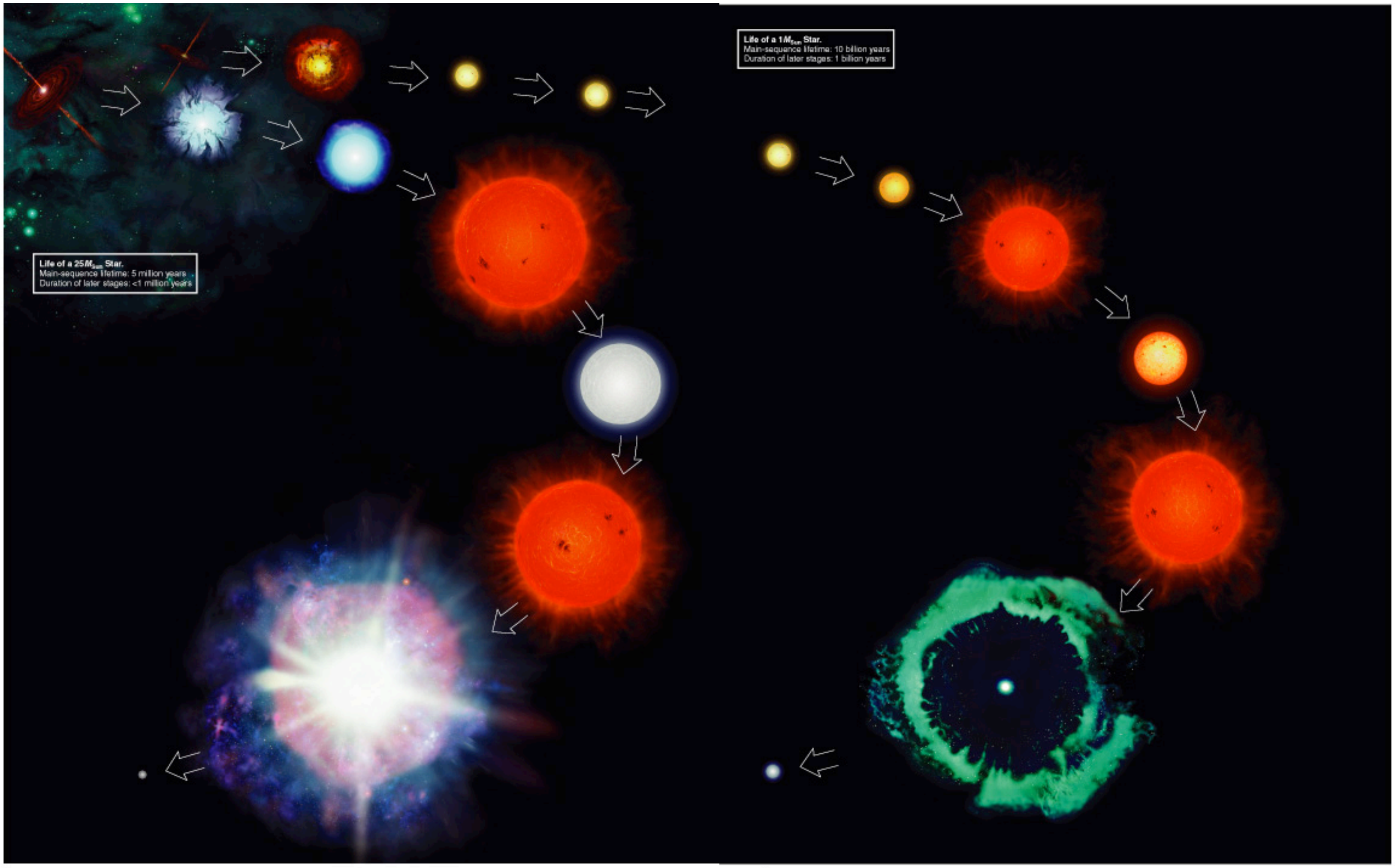
Life Track after Helium Flash



- Observations of star clusters agree with those models

- Helium-burning stars are found in a *horizontal branch* on the H-R diagram

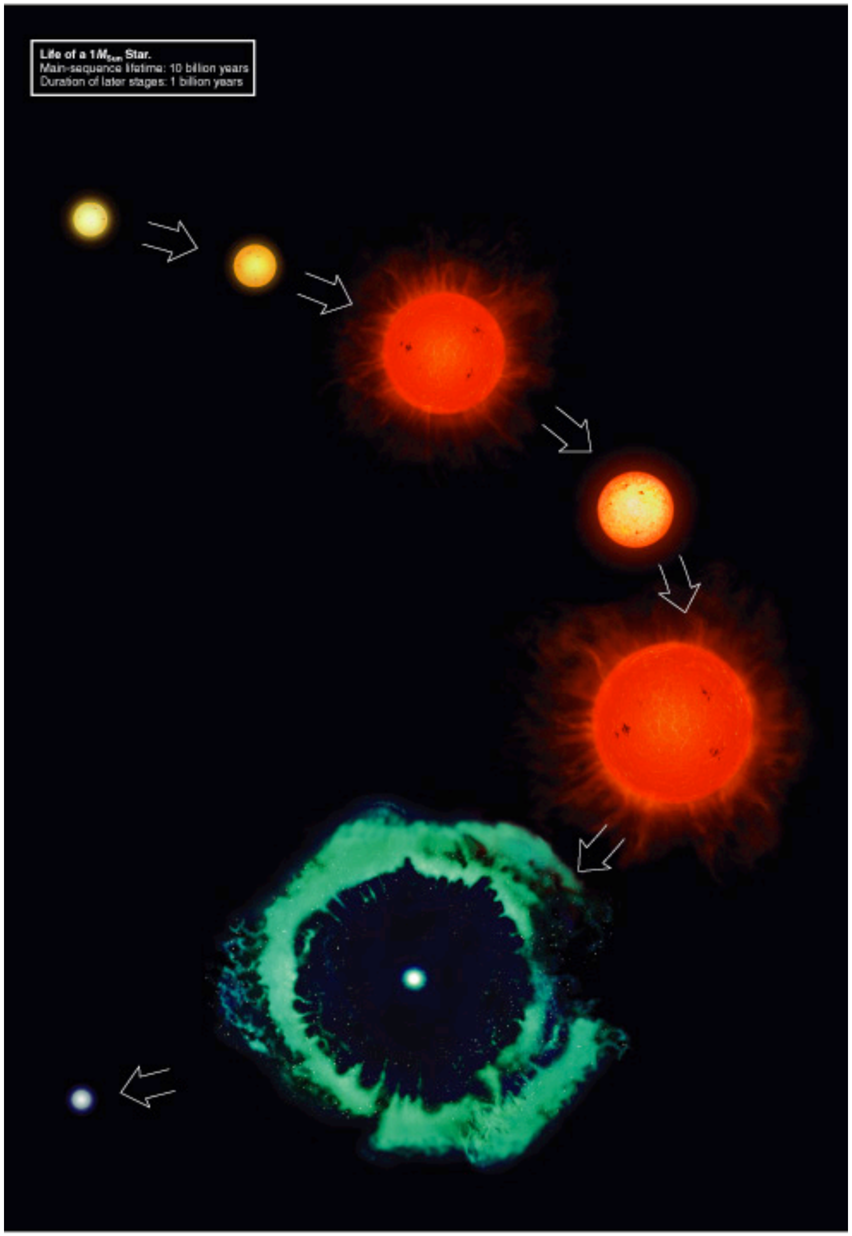
How does a star's mass determine its life story?



Role of Mass

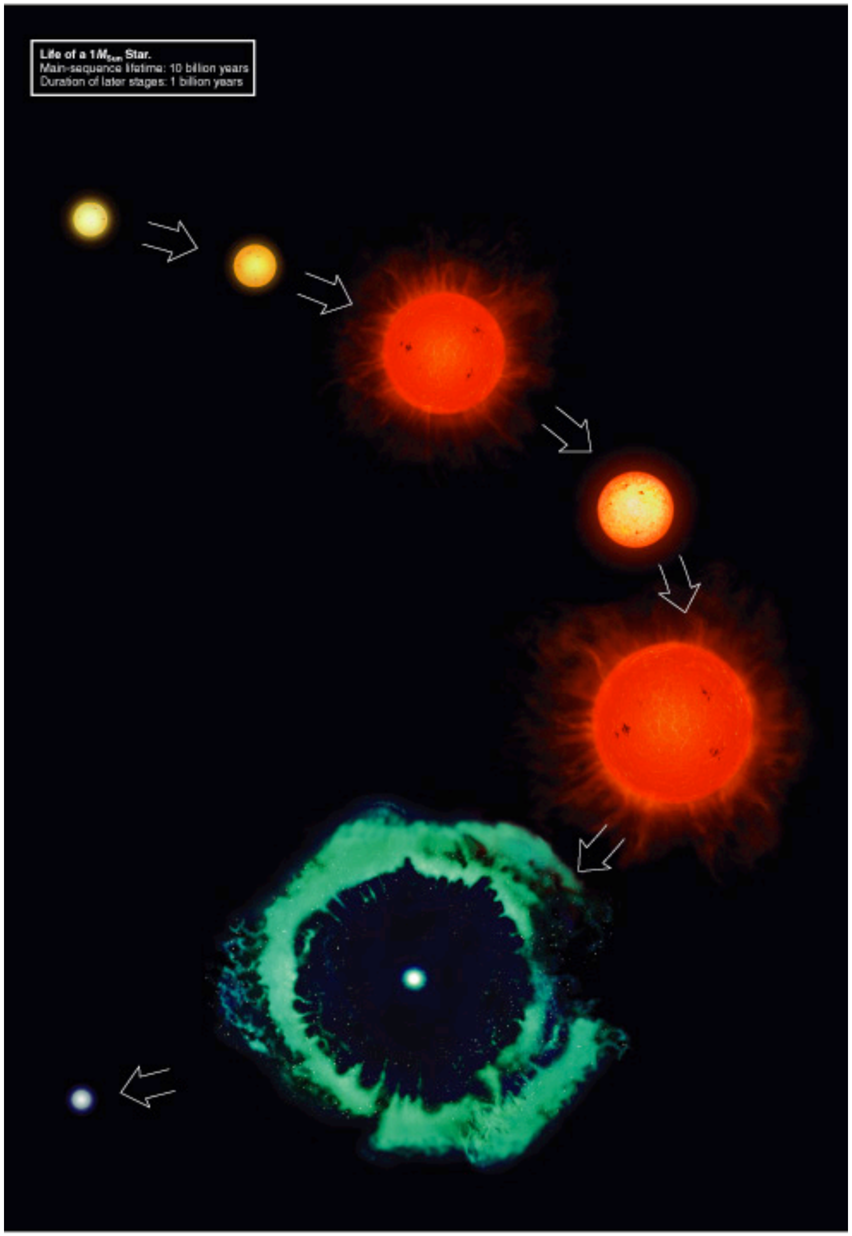
- A star’s mass determines its entire life story because it determines its core temperature
- High-mass stars with $>8M_{\mathrm{Sun}}$ have short lives, eventually becoming hot enough to make iron, and end in supernova explosions
- Low-mass stars with $<2M_{\mathrm{Sun}}$ have long lives, never become 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

Low Mass Star Summary



Not to scale!

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

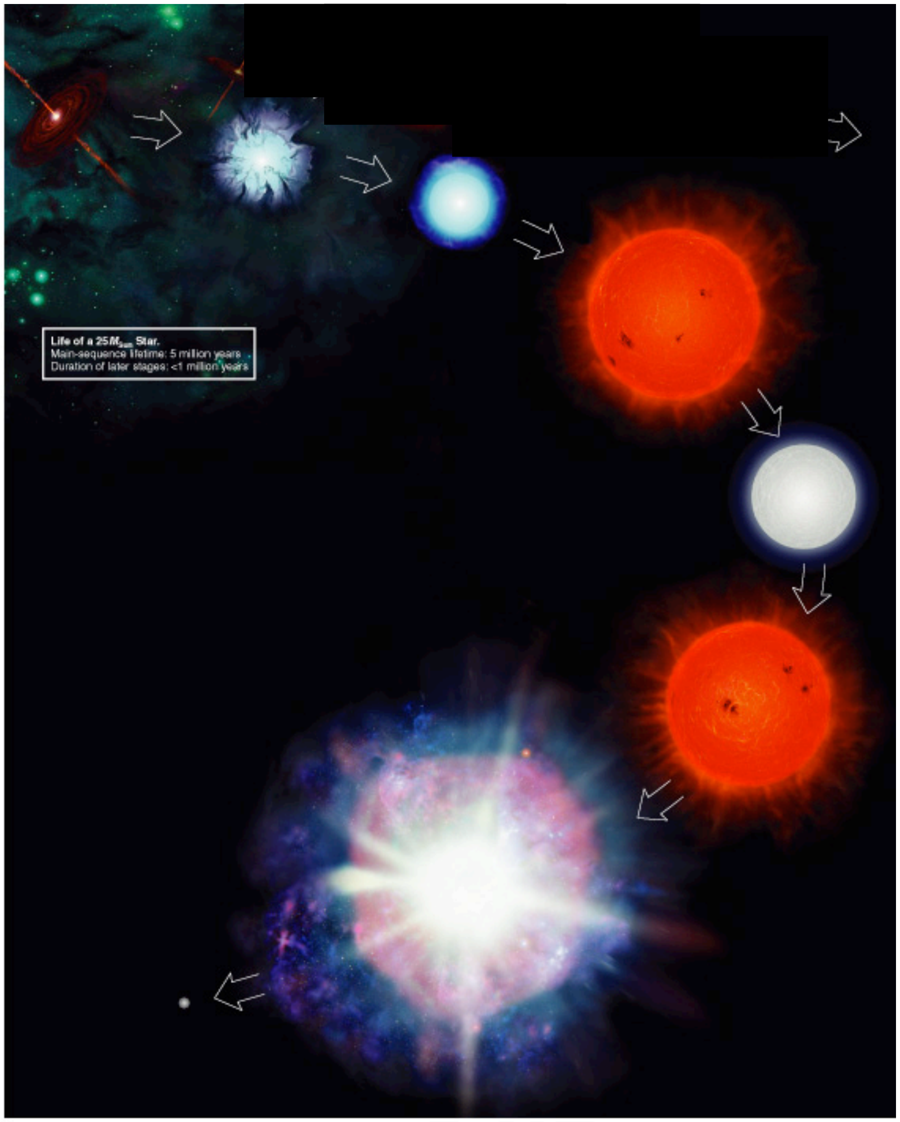


Not to scale!

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

High Mass Star Summary



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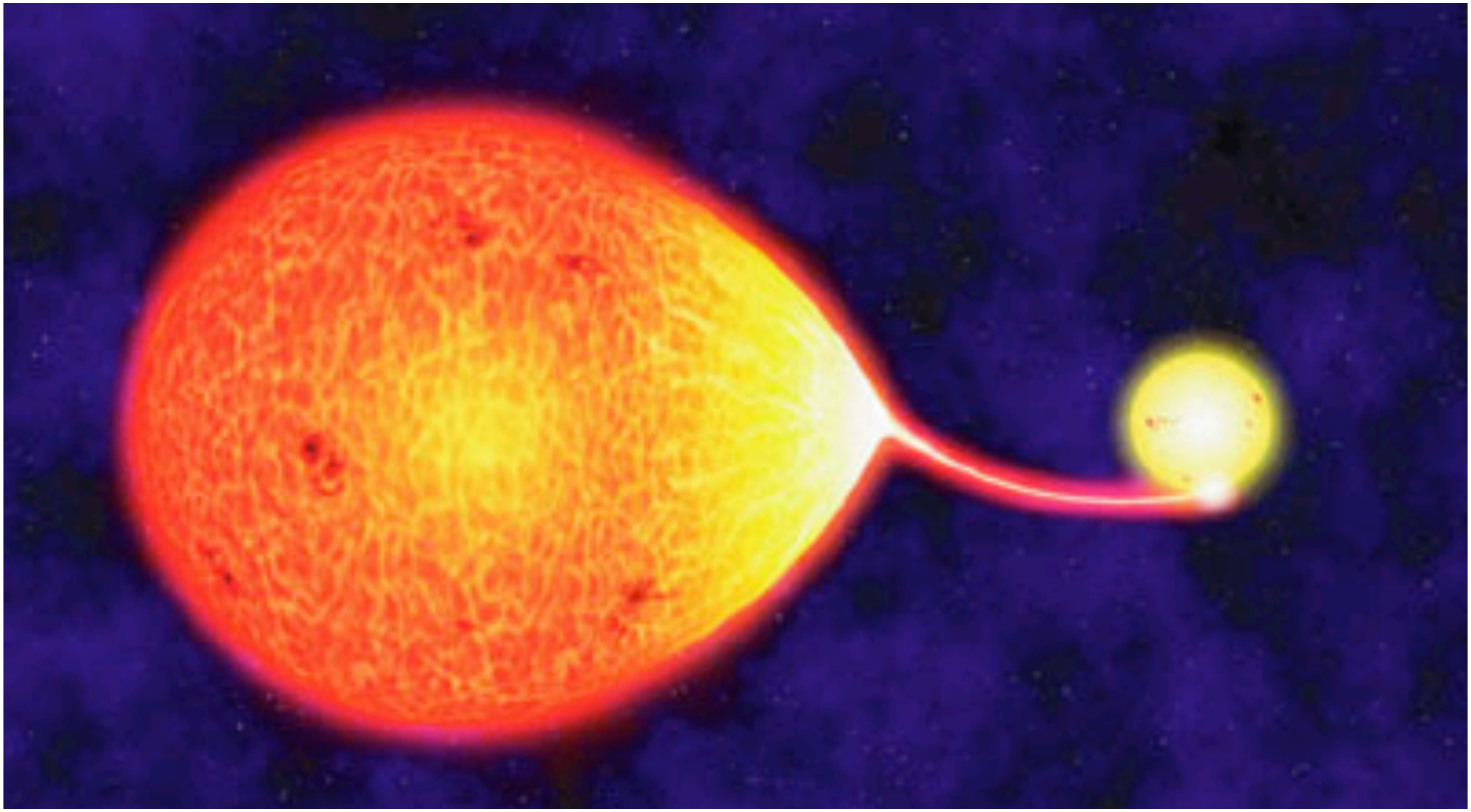
Not to scale!

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

What have we learned?

- What are the life stages of a high-mass star?
  - They are similar to the life stages of a low-mass star
- How do high-mass stars make the elements necessary for life?
  - Higher masses produce higher core temperatures that enable fusion of heavier elements
- How does a high-mass star die?
  - Iron core collapses, leading to a supernova

How are the lives of stars with close companions different?

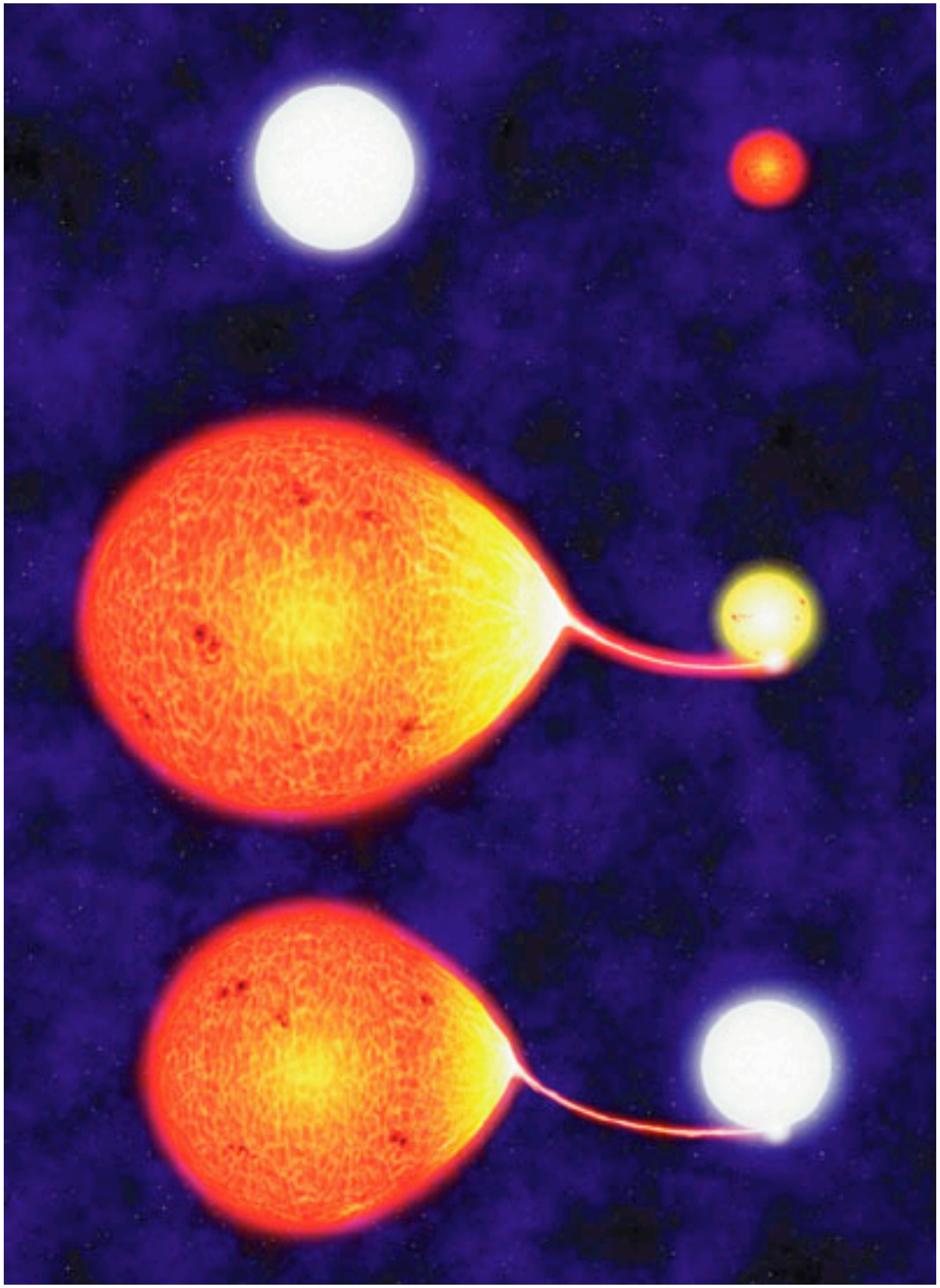


Thought Question

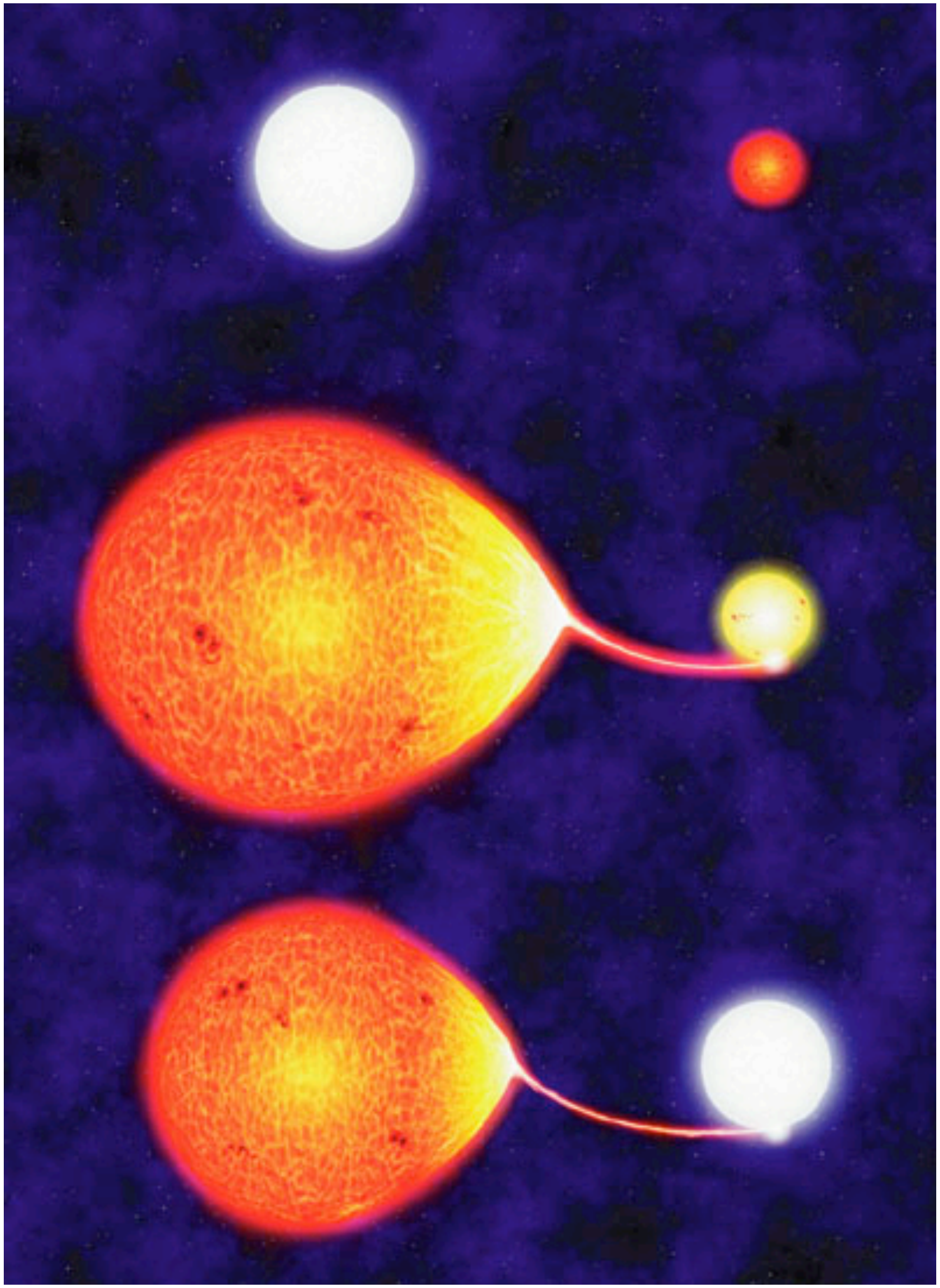
The binary star Algol consists of a 3.7 M_{Sun} main sequence star and a 0.8 M_{Sun} subgiant star.

What's strange about this pairing?

How did it come about?



Stars in Algol 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

What have we learned?

- How does a star’s mass determine its life story?
  - Mass determines how high a star’s core temperature can rise and therefore determines how quickly a star uses its fuel and what kinds of elements it can make
- How are the lives of stars with close companions different?
  - Stars with close companions can exchange mass, altering the usual life stories of stars