Today

- Stars
  - Stellar Lifetimes
  - Life cycles of low-mass stars

Reminders About Second Exam

- Will be in this room, 9:30-10:45, Thursday
- Format is the same as first exam
- No calculators, no books, no notes, no phones
- Bring your student ID, put on desk
- Bring more than one #2 pencil!
- We will seat you
- Leave times at 10:15, 10:35 onwards
  Hand in to *your* TA at top of stairs

Exam Review Session

- Today, 6-8 PM, PHYS 1410 (the large lecture hall next to ours)
- Completely driven by your questions! The TAs will not prepare summary slides, but can go to the lecture slides if needed.
- When your questions are done, the review is over
- Don’t ask TAs what will be on the exam; they don’t know :)

10^7yr

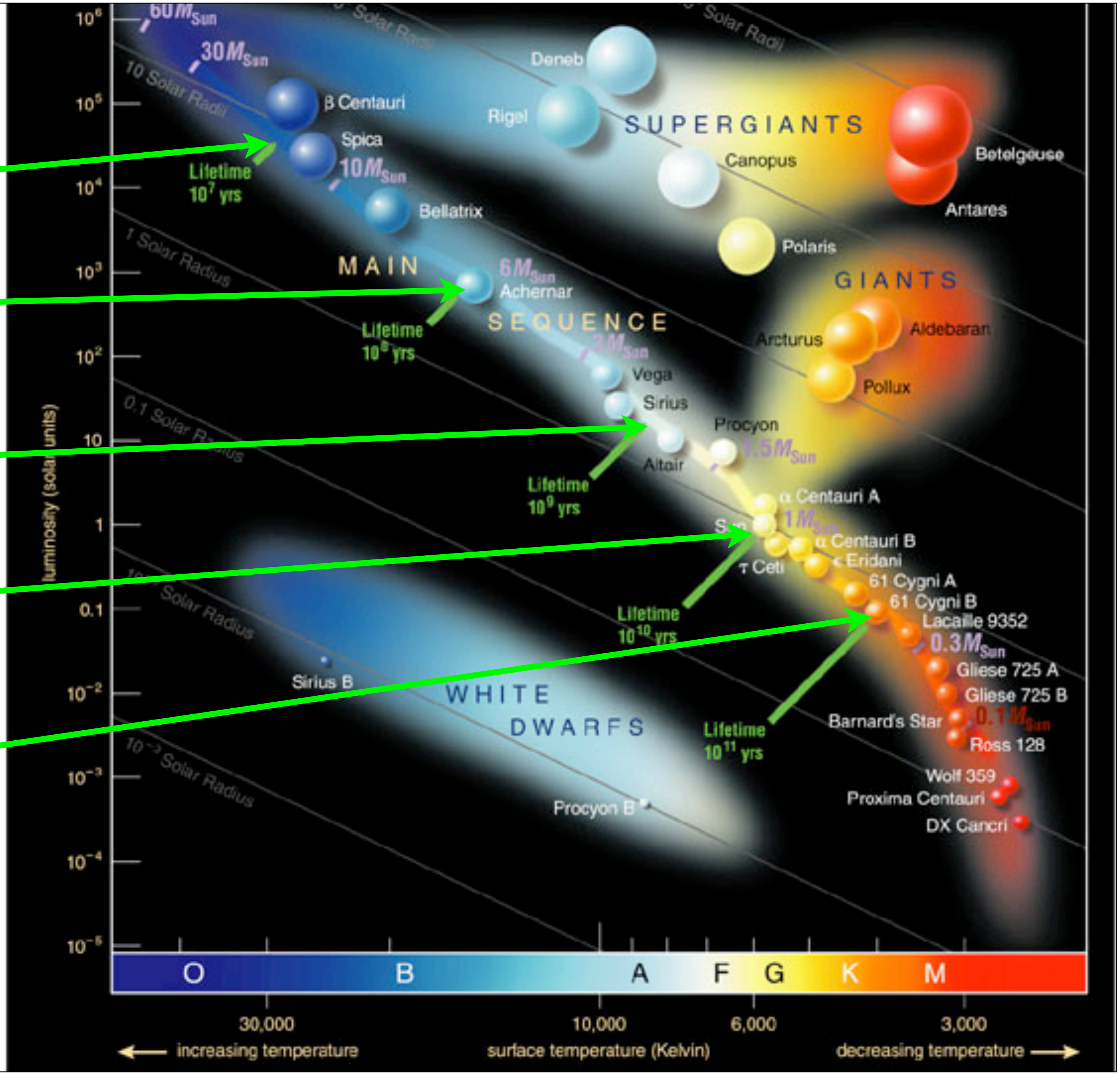
10^8yr

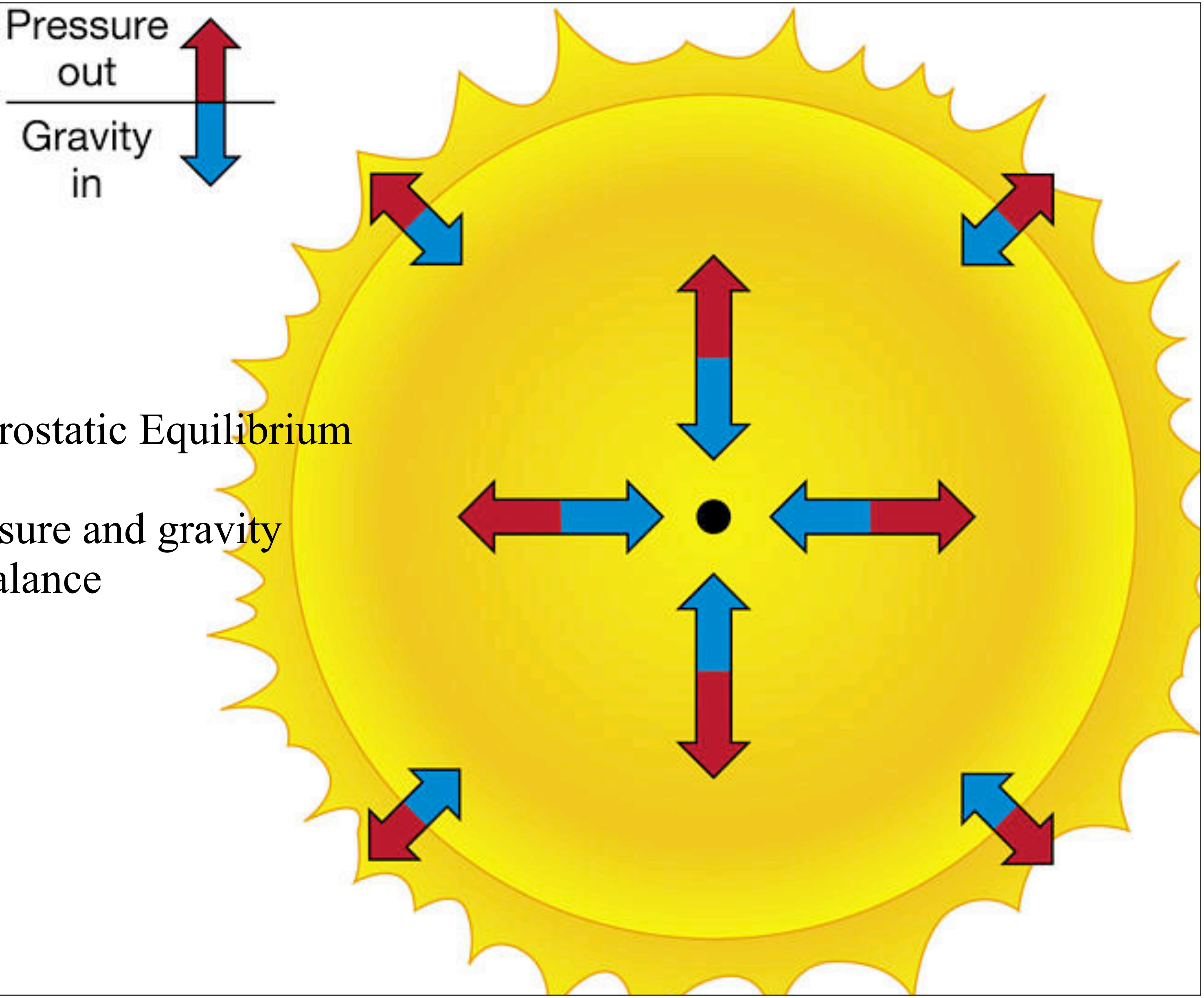
10^9yr

10^{10}yr

10^{11}yr

Life cycle



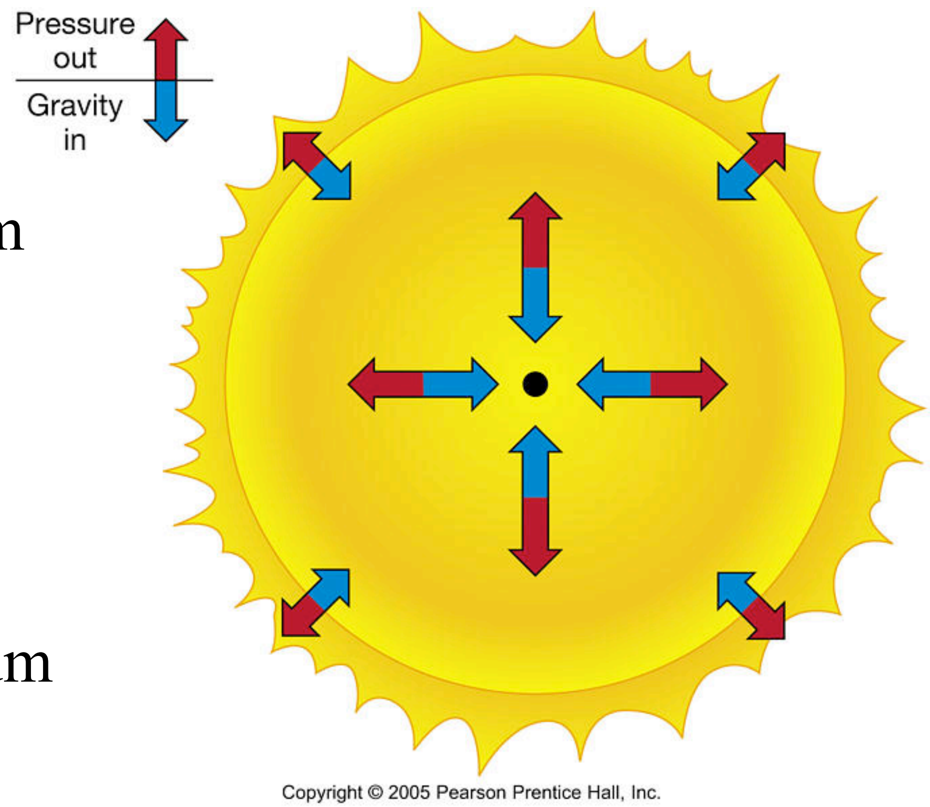


Hydrostatic Equilibrium

Pressure and gravity
in balance

Hydrostatic Equilibrium

Pressure and gravity
in balance



Stars attempt to maintain equilibrium by striking a balance between the gravity of their enormous mass and the pressure produced by the energy of fusion reactions.

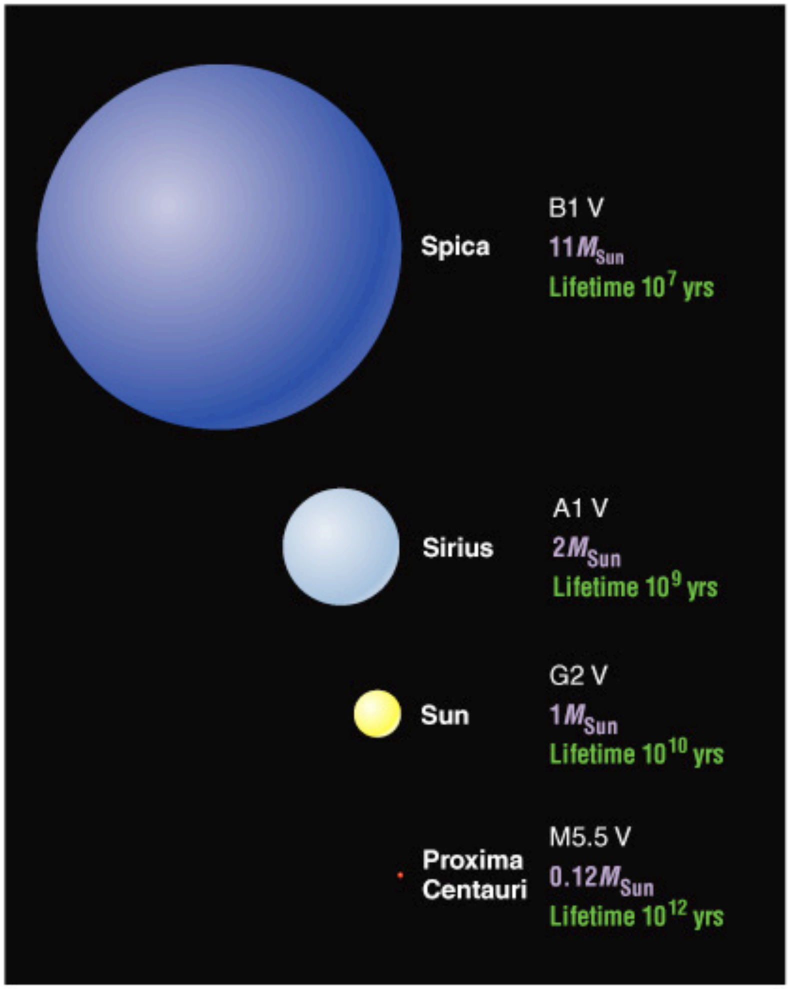
A main sequence star is in equilibrium as Hydrogen burning supports it against gravitational collapse.

What happens as the hydrogen runs out?

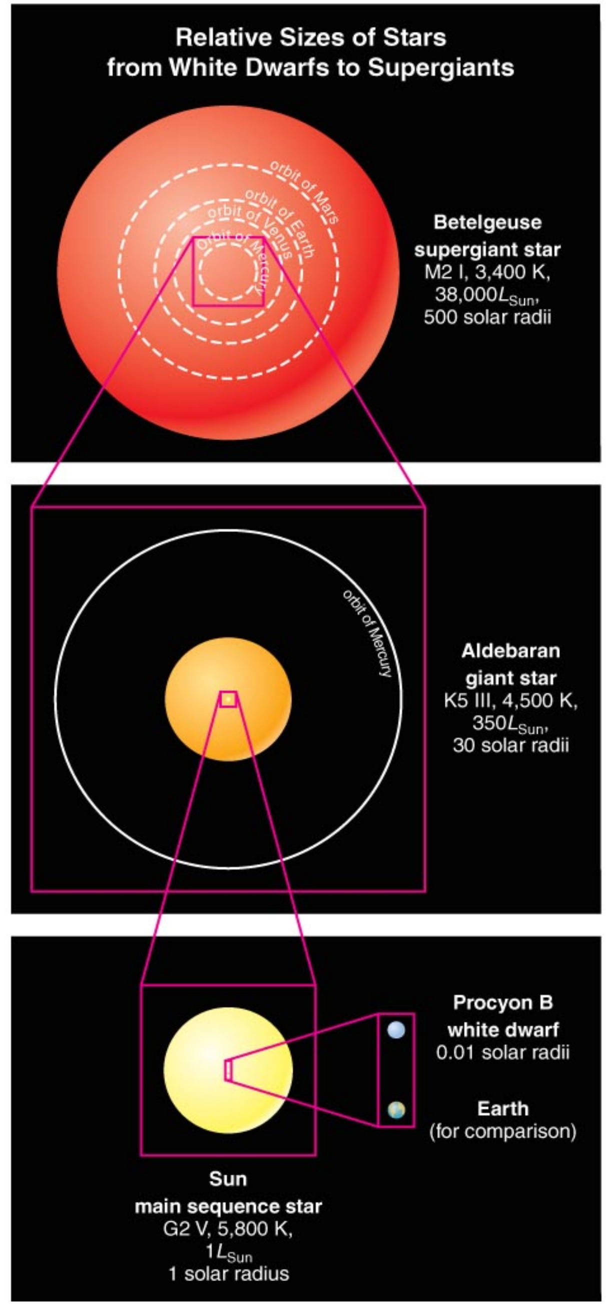
PoC

Off the Main Sequence

- Stellar properties depend on both mass and age: those that have finished fusing H to He in their cores are no longer on the main sequence.
- All stars become larger and redder after exhausting their core hydrogen: **giants** and **supergiants.**
- Most stars end up small and dim after fusion has ceased: **white dwarfs.**

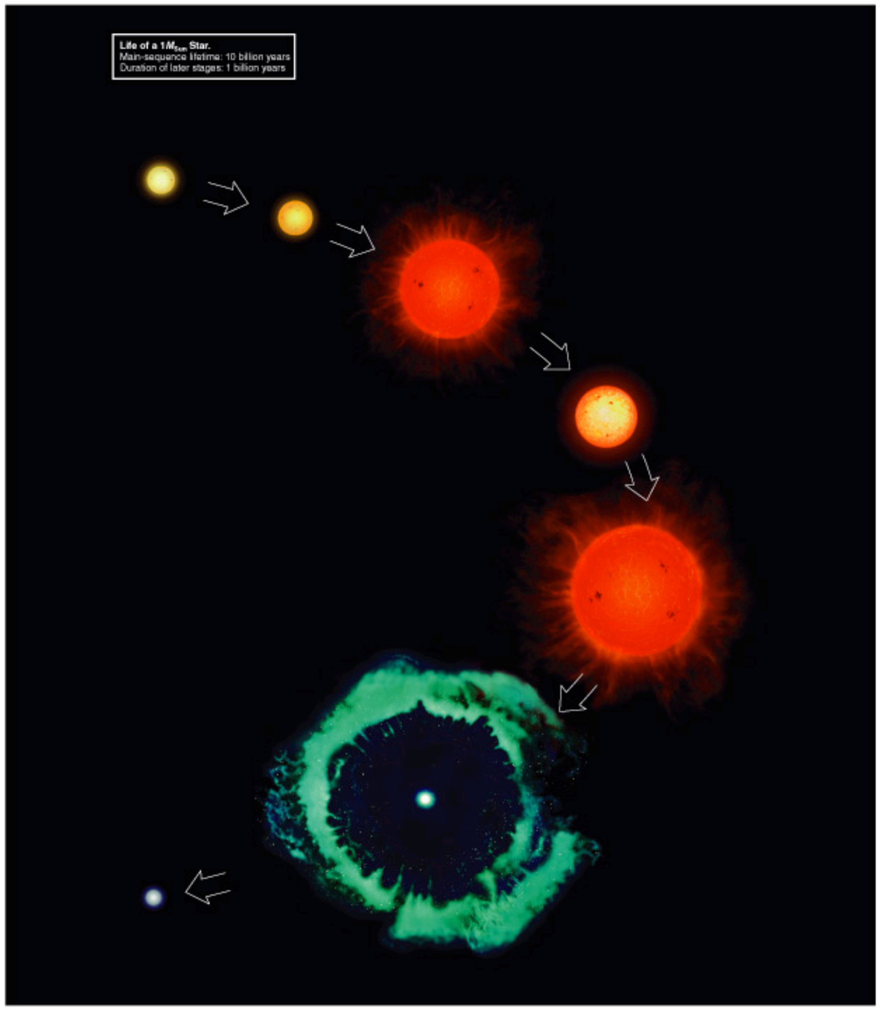


Main-sequence stars (to scale)

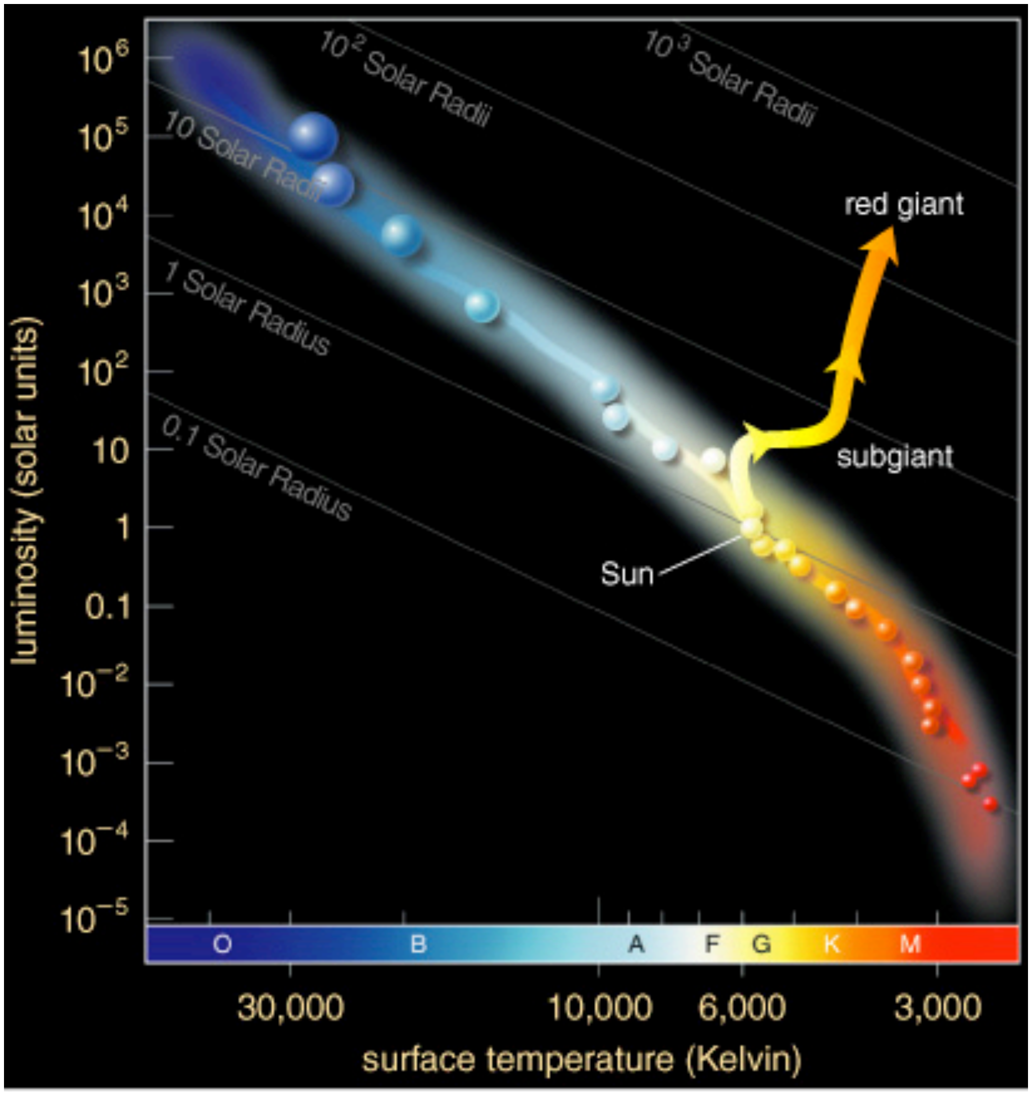


Giants, supergiants, white dwarfs

The life stages of a low-mass star



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.

- At the end of their main sequence life time - when hydrogen in the core is exhausted - stars ascend the **red giant branch**.

What happens when the Hydrogen is gone?

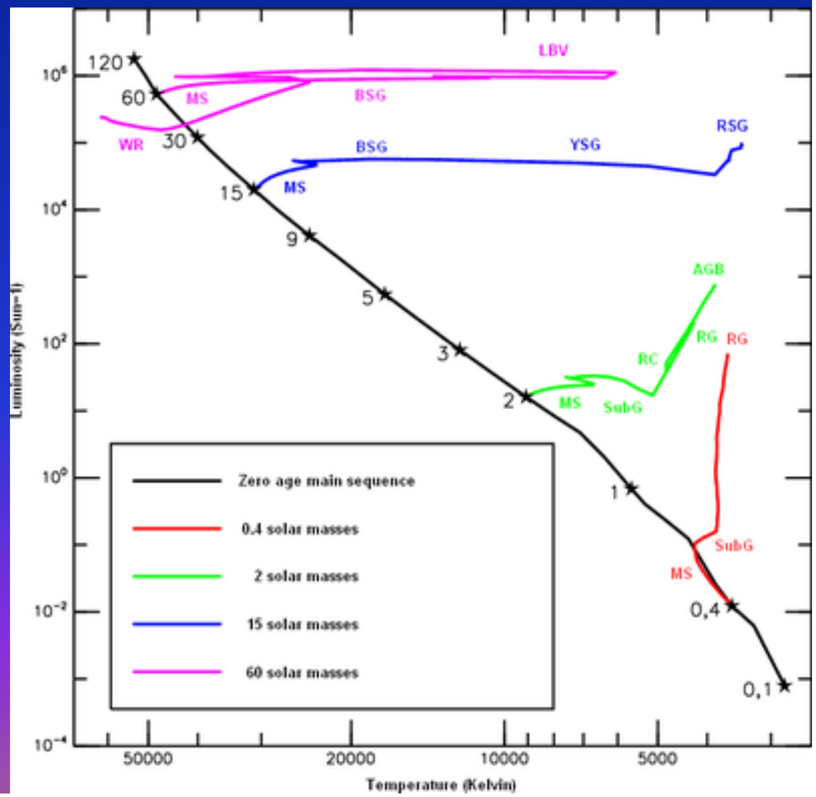
As the hydrogen "burns", the helium "ash" builds up in the core.

This interferes with hydrogen burning. The star's core contracts to become hotter and denser to continue the "burning".

The outer layers of the star expand and become cooler as the core contracts and becomes hotter.

So the star appears to become cooler in the HR diagram.

The details depend on the mass of the star….



The Final Years of a 1 Solar Mass Star

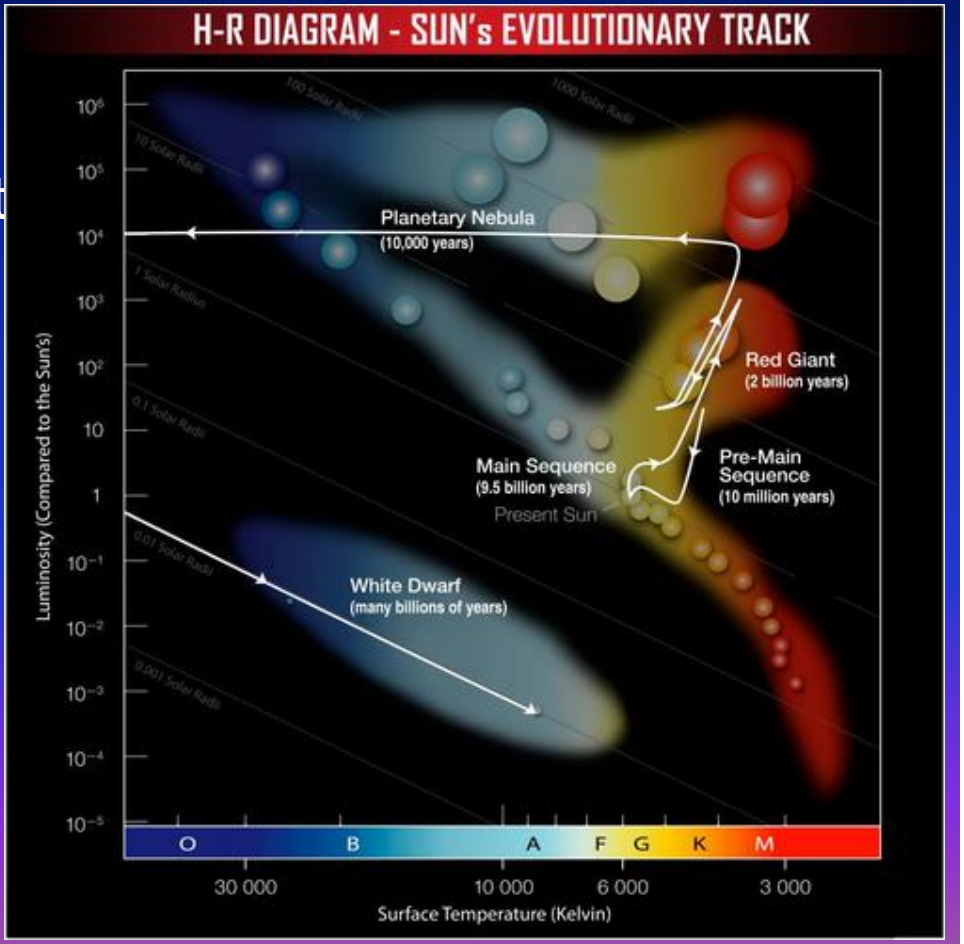
Let's look at the evolution of a star like our Sun.

Fundamental principle:

The star is in a battle against gravity trying to crush it. The star's weapon in the war is nuclear "burning" to create energy.

It will try everything it can.

The changes in the core are mirrored in its physical appearance to us.

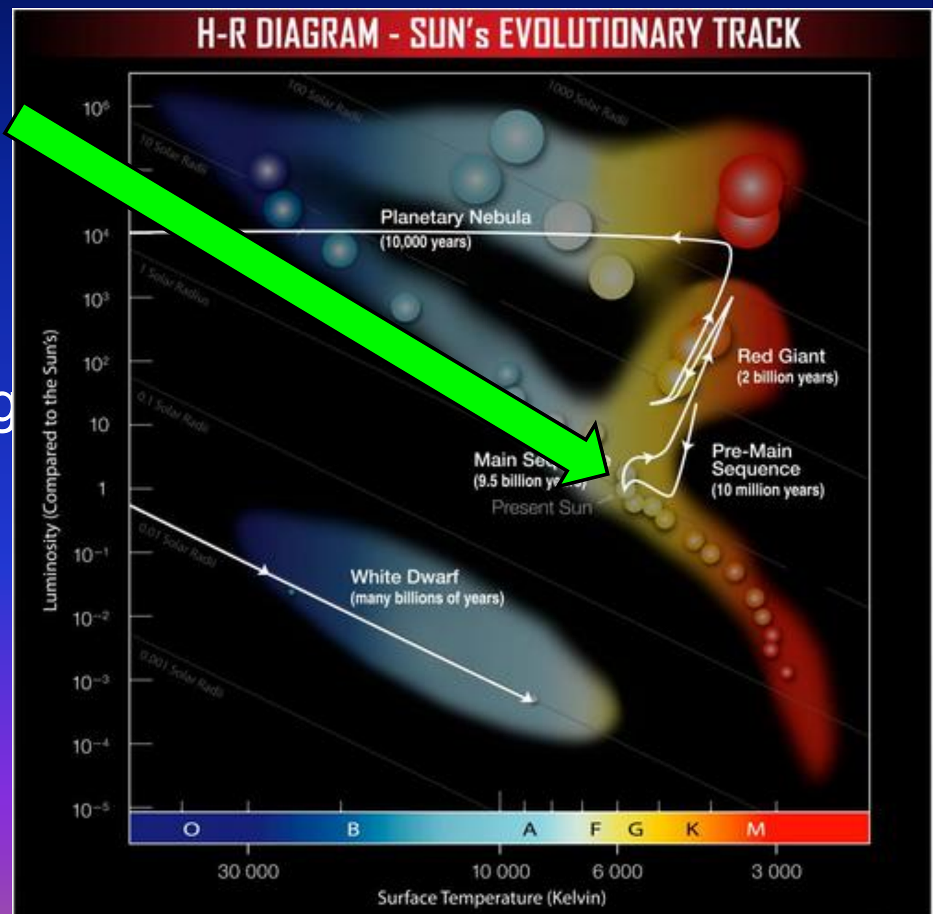


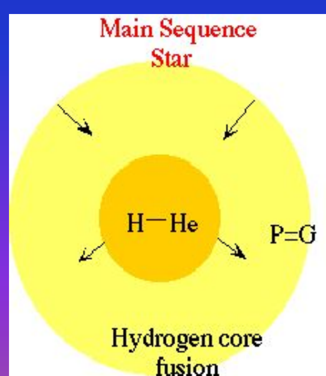
The Final Years of a 1 Solar Mass Star

Let's look at the evolution of a star like our Sun.

1. H "burning" in the core on the main sequence for 10 billion years.

   As it reaches the end of this the core is contracting and the outer layers expanding.



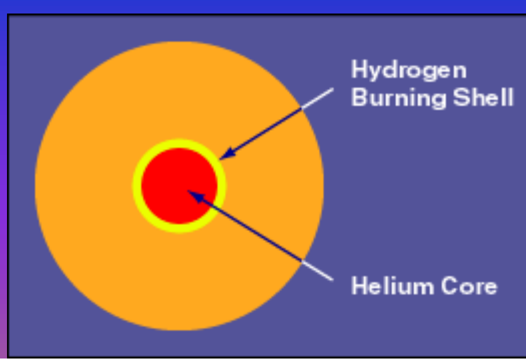


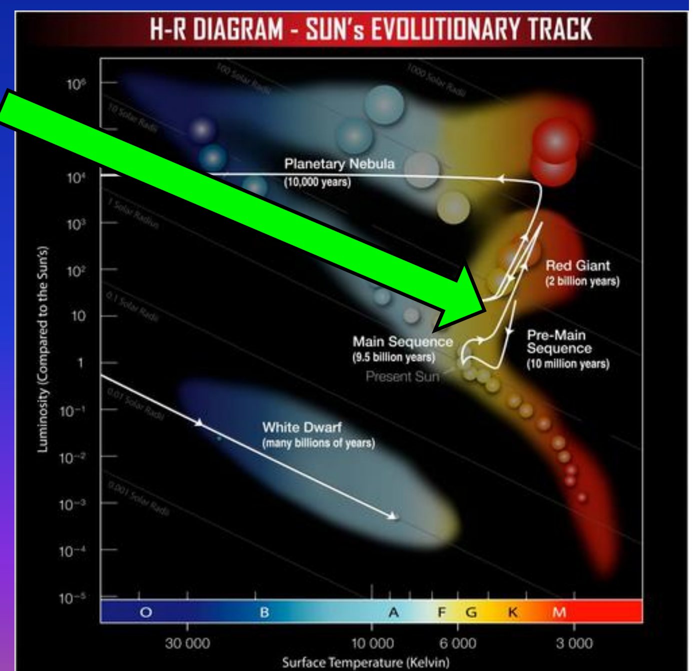
The final years of a 1 solar mass star

2. The core becomes so filled with helium that fusion stops in the core.

The core contracts and becomes hot and dense enough in layers beyond the core star undergoing nuclear reactions: a new phase: Hydrogen Shell Burning.

The star's outer layers expand and become redder.

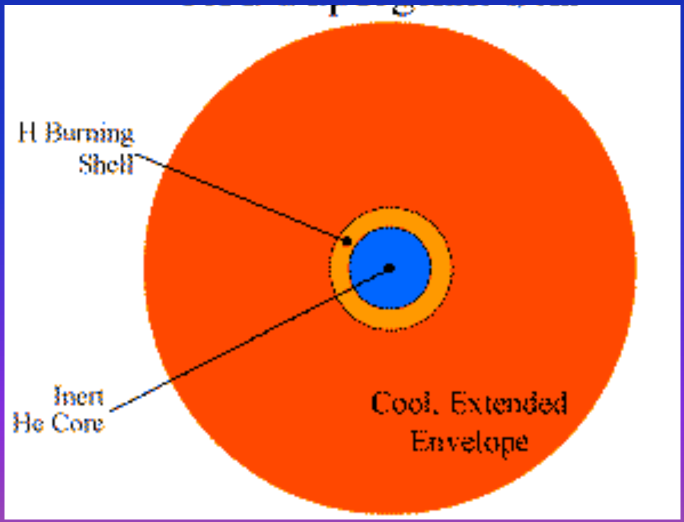


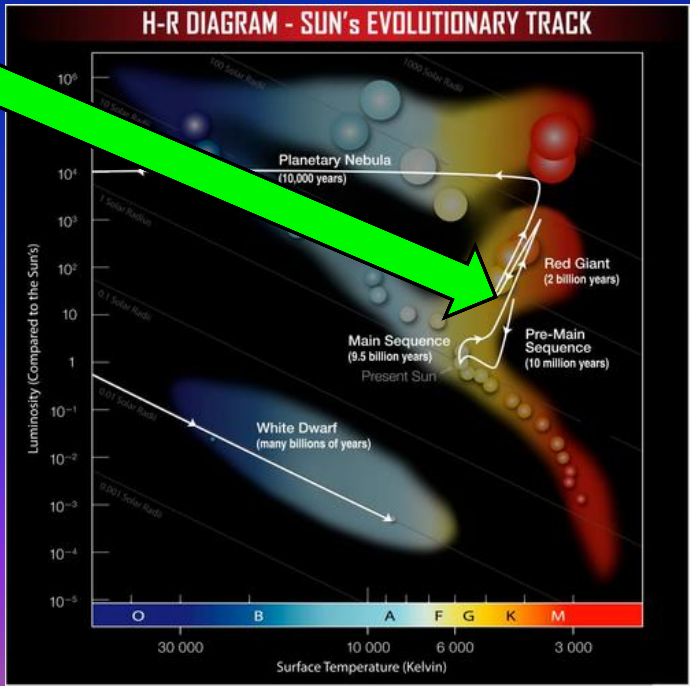


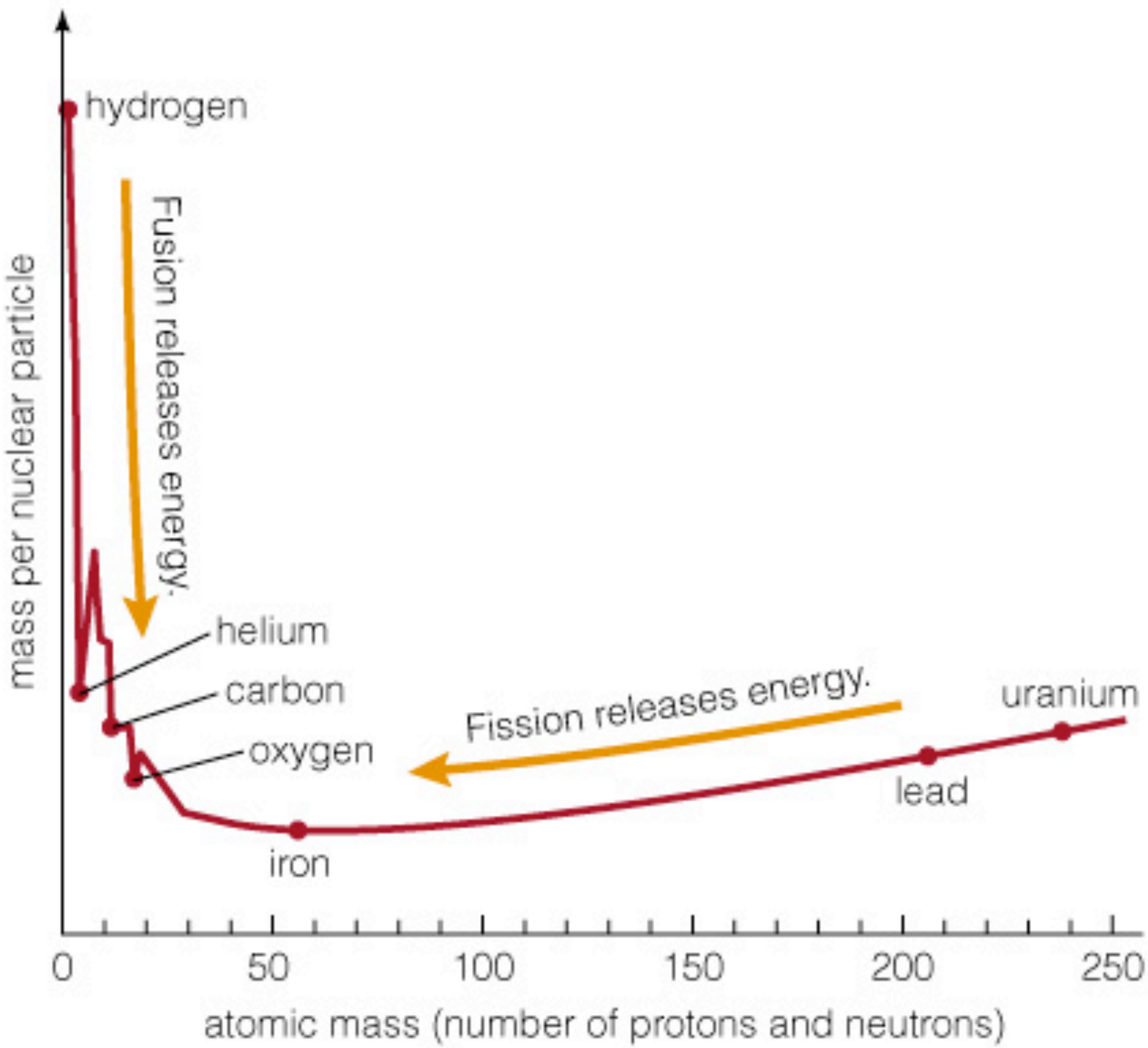
The final years of a 1 solar mass star

2. Hydrogen shell burning continues and the shell moves outward creating a hotter and denser helium filled core.

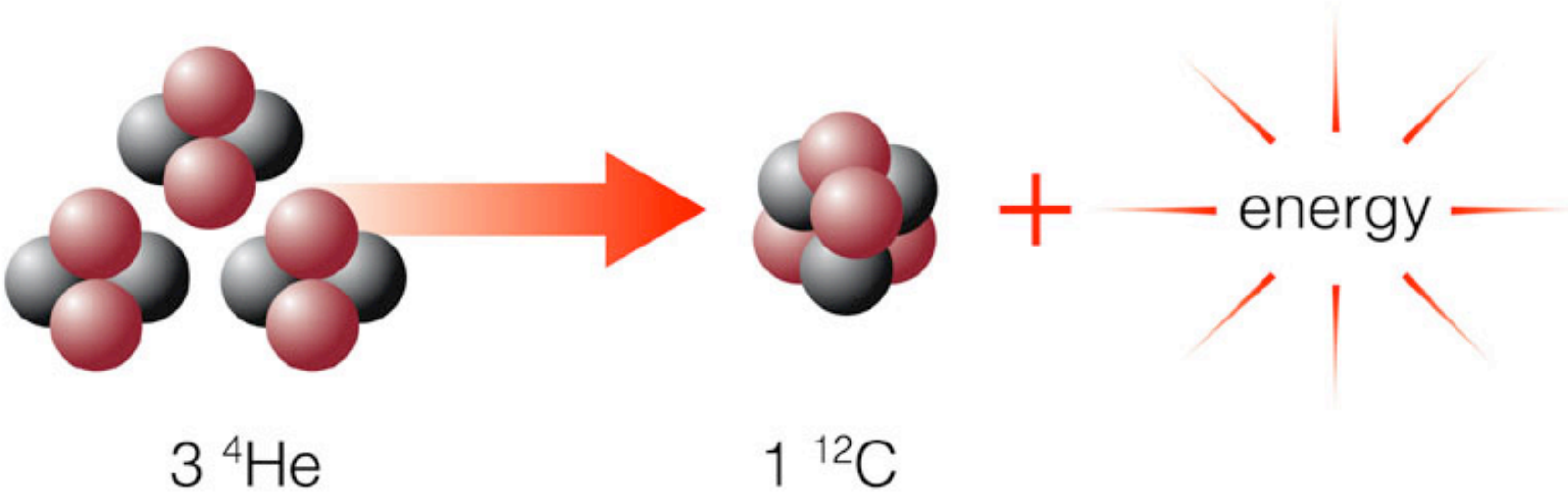
The helium cores builds and becomes denser and hotter.







Helium is *more* stable than the next few nuclei. Can only release energy by going to carbon.



Helium fusion is tough—larger charge leads to greater repulsion. Worse, the fusion of two helium nuclei doesn't work; ^{4}He is more stable than Beryllium (^{8}Be).
Need three ^{4}He nuclei to make carbon (^{12}C).
Only works because of resonant state of carbon predicted by Fred Hoyle.

3alpha

Helium Fusion

How do you expect the duration of helium fusion to compare to the duration of hydrogen fusion?

A. There is not enough information to say

B. Helium fusion lasts a shorter time

C. They last the same time

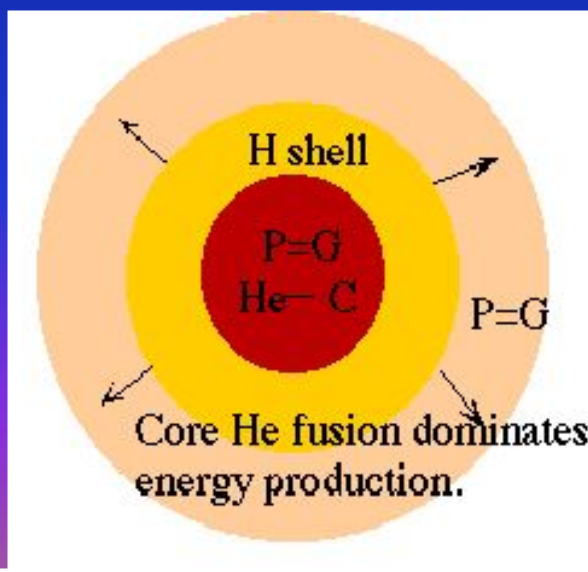
D. Helium fusion lasts a longer time

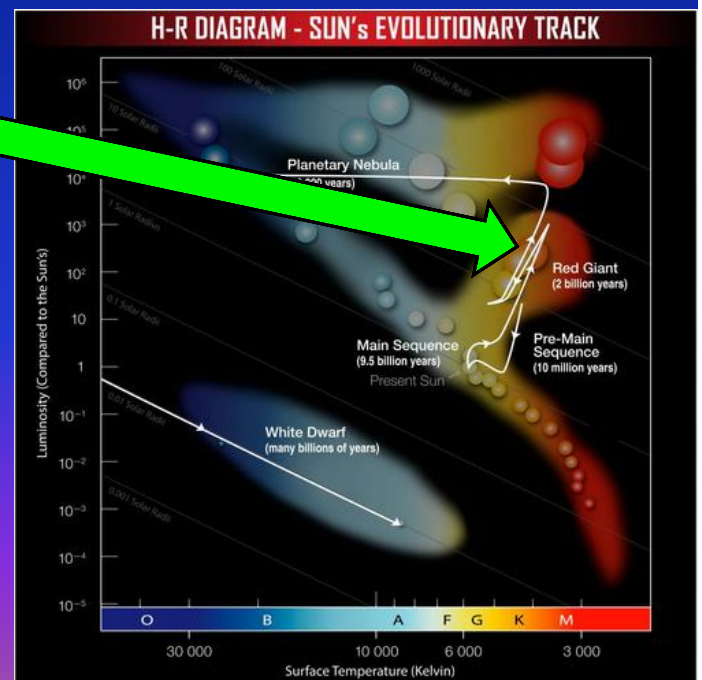
E. I don't know

The final years of a 1 solar mass star

3. The helium core become hot enough to allow the triple alpha reaction. Helium starts “burning” into carbon in the core. A new short-lived source of energy for the star!

The star expands further to become a Red Giant.

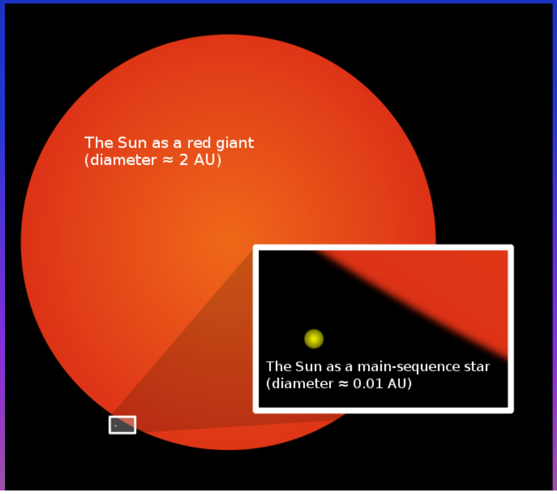


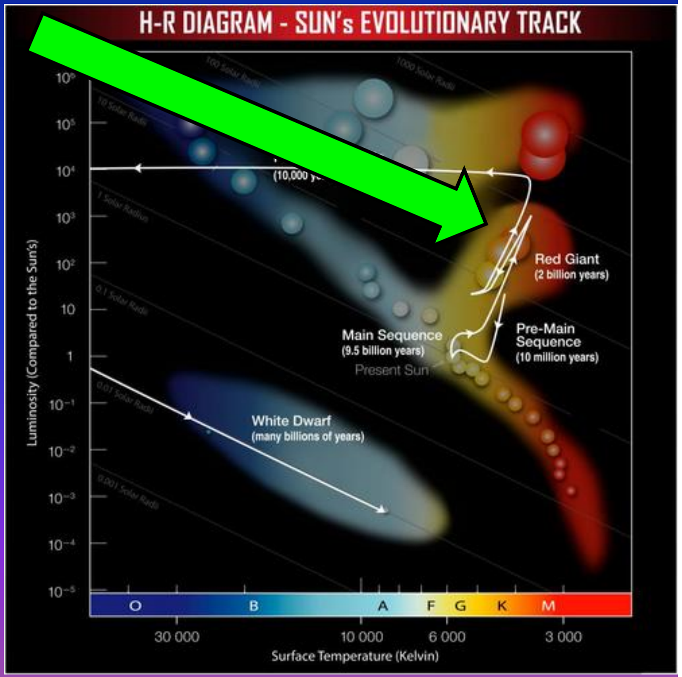


The final years of a 1 solar mass star

A red giant is a K or M type star. It
is characterized by its increased size – 100 times or more the size of our current Sun – due to H-shell burning and helium core burning.

What drives this size increase? The hotter core is like turning up the flame on a boiling pot of spaghetti: The pot boils more furiously and the froth expands.

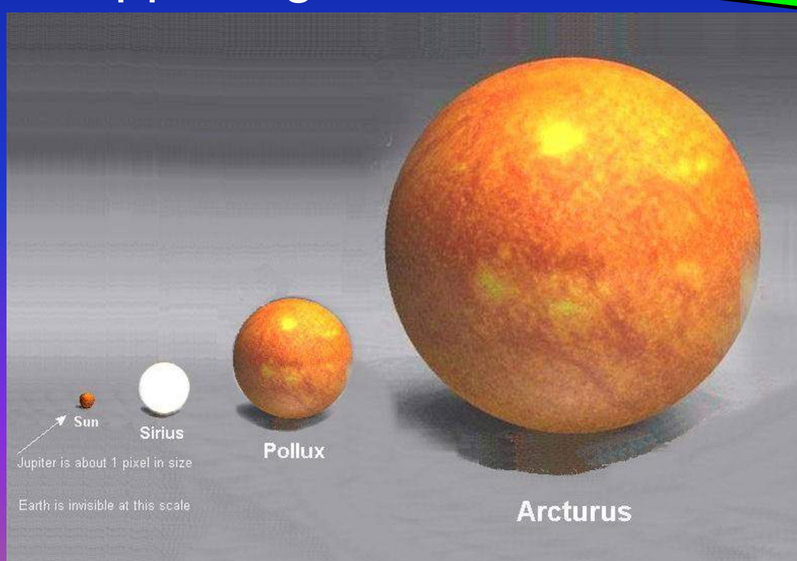


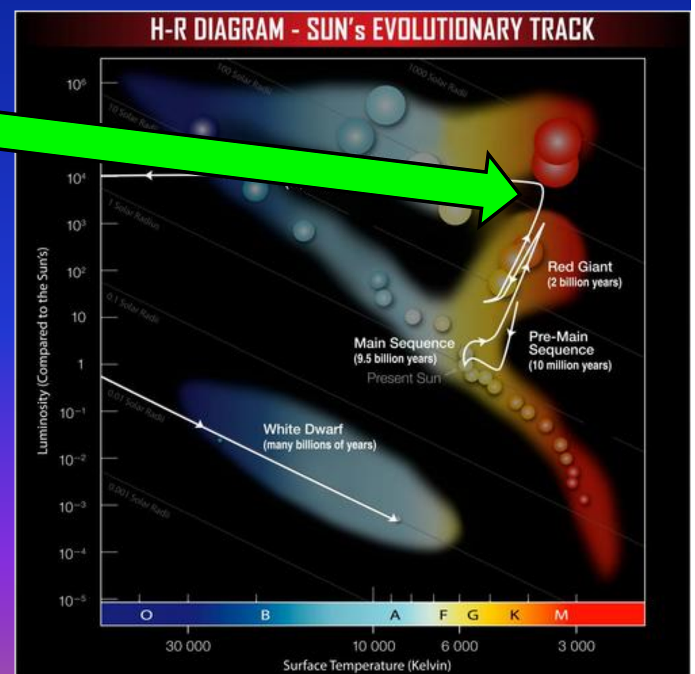


The final years of a 1 solar mass star

4. For a star like our Sun…. this is the end of the line for nuclear reactions. The core become hotter and denser as it converts helium into carbon, and some oxygen, but it can not get hot enough to drive further reactions….

However, something else is happening in the surface.



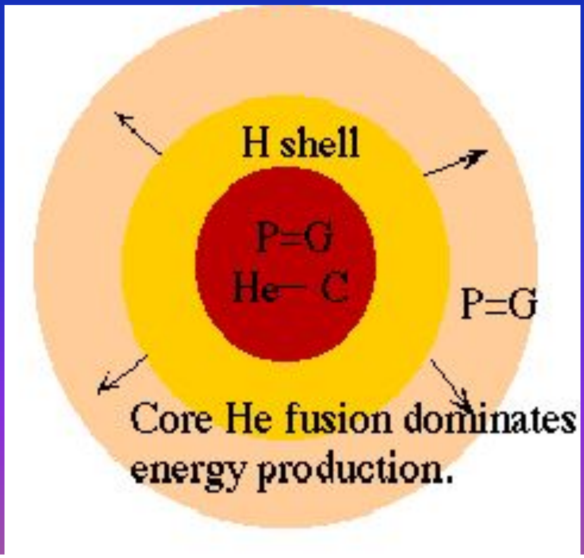


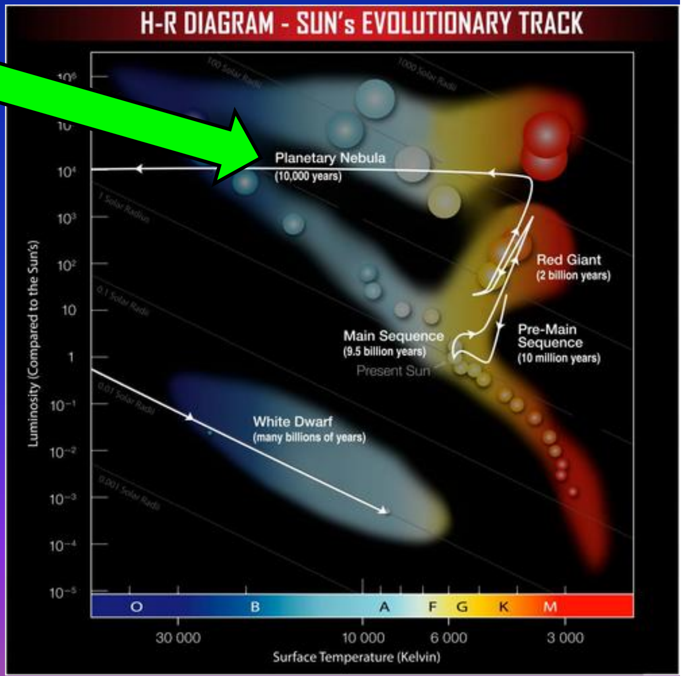
The final years of a 1 solar mass star

4. The surface is boiling off – being pushed out into space.

As more and more is pushed out, the hotter layers underneath are revealed and the star becomes bluer in appearance.

Quickly, for a star… it loses ½ or more of its mass to space.

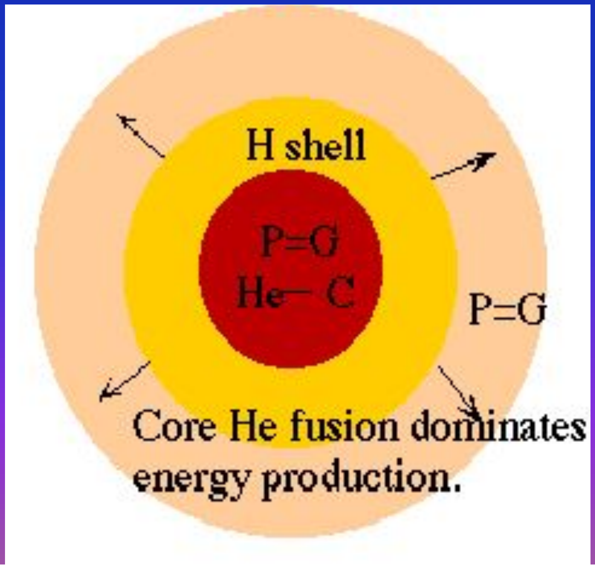


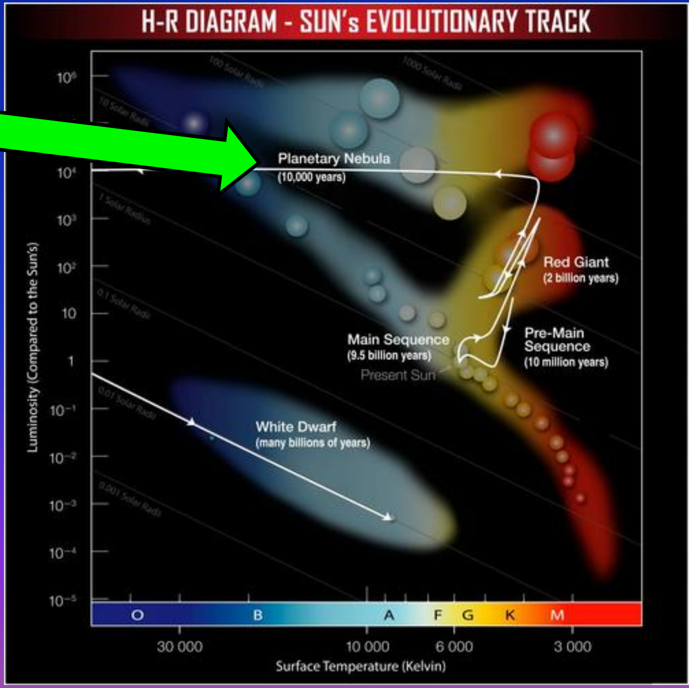


The final years of a 1 solar mass star

4. As the mass is lost, the weight bearing down on the core decreases so the density and temperature of the core decrease ---- and nuclear fusion shuts down.

The core of the star is no longer hot enough to generate energy from fusion but it is still plenty hot!

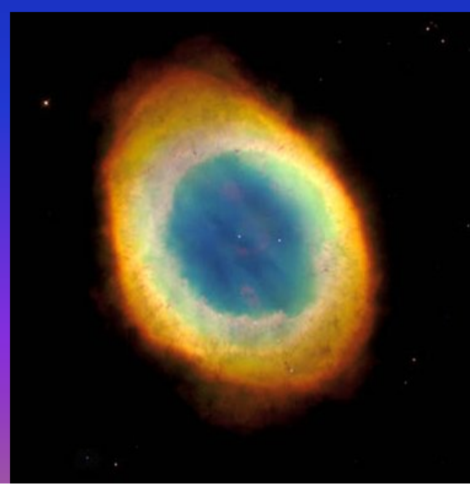


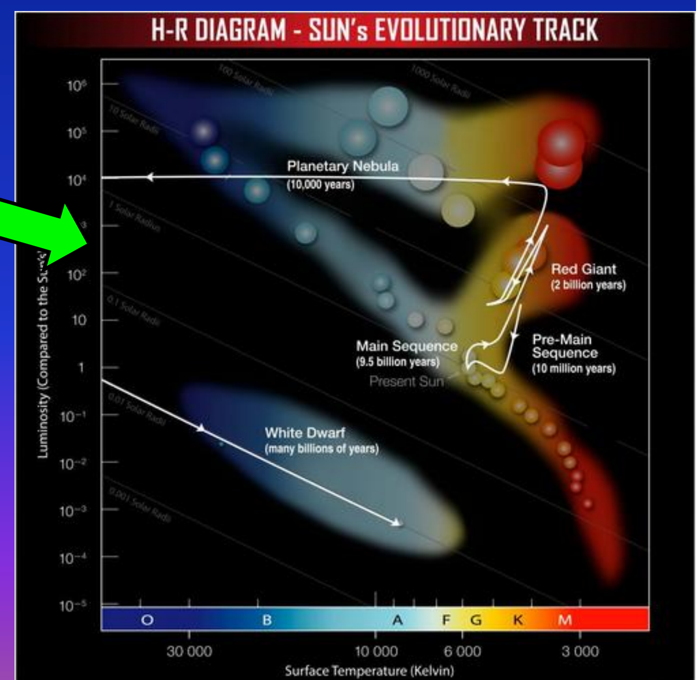


The final years of a 1 solar mass star

5. As the layers are removed, the hot core of the star is revealed. This core is now contracting to the size of the Earth and its surface is 100,000 K. It is a White Dwarf.

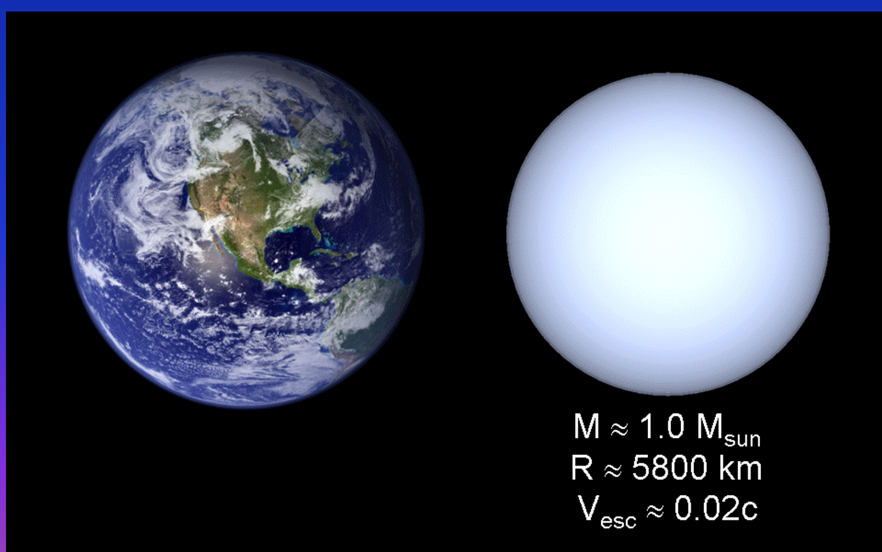
Its very hot surface illuminates the material that was thrown out into space to create a Planetary Nebula.

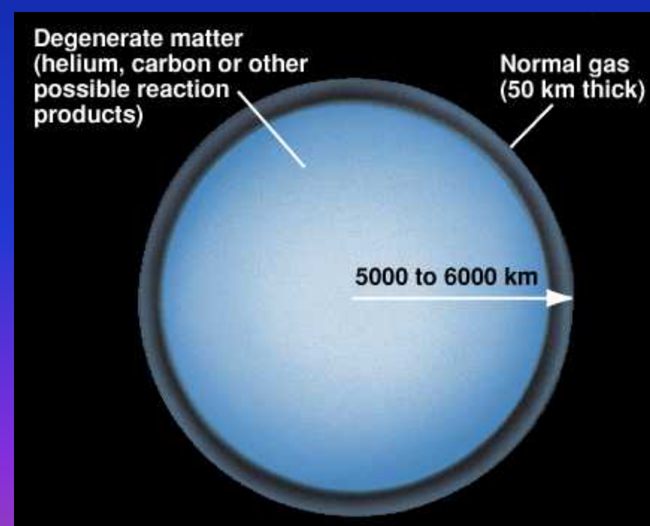




The final years of a 1 solar mass star

White Dwarf: The end state of evolution of a star with mass like our Sun. It is about the size of the Earth but can have a mass from 0.3 to 1.4 times the mass of the Sun. Much of the mass of a white dwarf is carbon, oxygen, and helium – the products of the nuclear reactions during the life of the star.





Extra credit
(2 points)

- Place white dwarfs on the Hertzsprung-Russell diagram
- Be sure to include your name and section number
- You may consult your notes, but do not communicate with anyone else

Why can a White Dwarf cool and not collapse?

A star's life is spent generating energy in the core to create the high temperatures needed to balance against gravity.

Hydrostatic Equilibrium of pressure (high density and temperature) against gravity.

Why doesn't a white dwarf shrink smaller and smaller as it cools from millions of degrees in the core?

Why can a White Dwarf cool and not collapse?

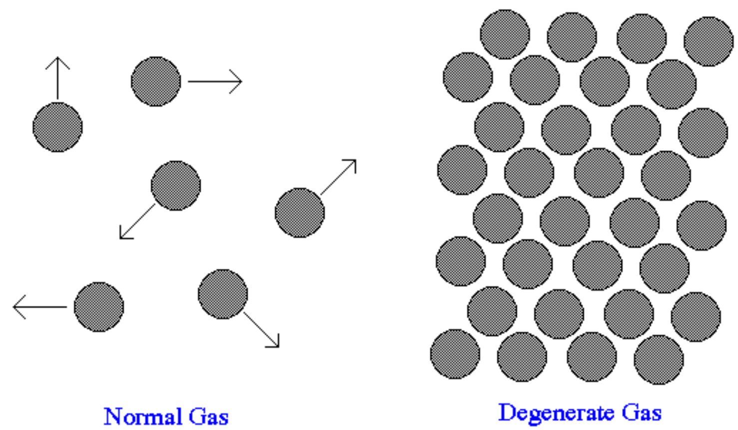
The answer is Degenerate Electron Gas Pressure.

What is that in plain talk?

In normal gas, the atoms are free to move around.

As the gas gets denser, the atoms bounce around more and the electrons in the atoms begin to overlap in their motion.

When a gas becomes extremely high in density, the atoms are not as free to move and they become degenerate.



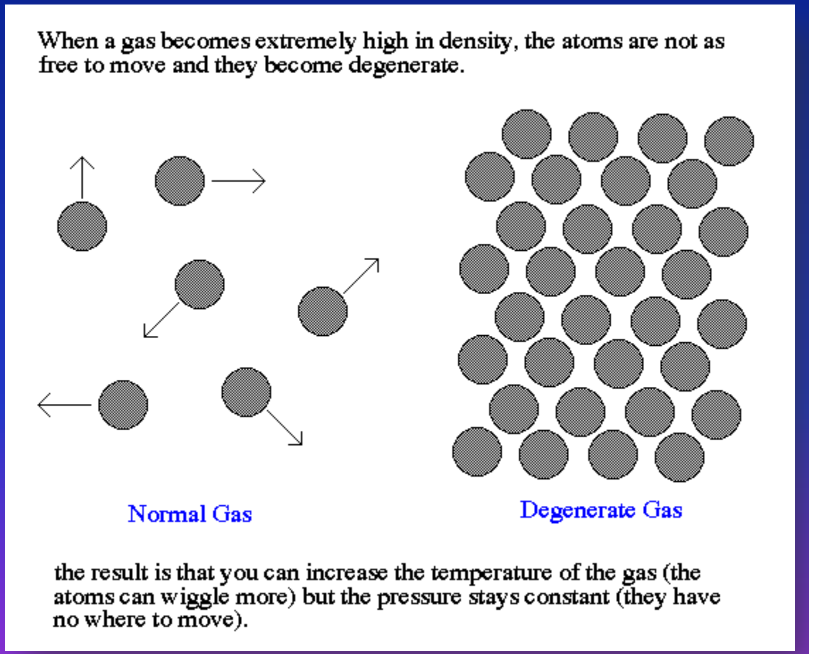
the result is that you can increase the temperature of the gas (the atoms can wiggle more) but the pressure stays constant (they have no where to move).

Why can a White Dwarf cool and not collapse?

Degenerate Electron Gas is when the gas density is high enough that the electrons are freed from the atoms.

The electrons fight being pushed into smaller volumes as the star tries to shrink as it cools – this is the source of pressure.

The pressure does not depend on the temperature.



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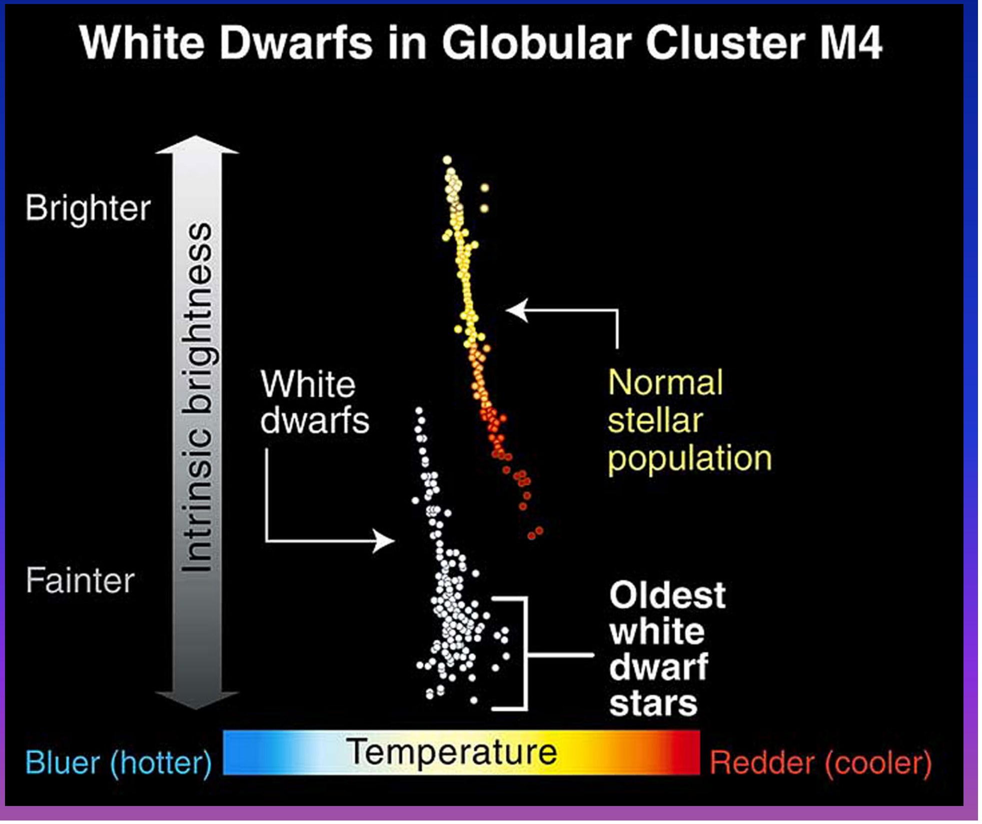
Why can a White Dwarf cool and not collapse?

So White Dwarfs can live forever slowly cooling.

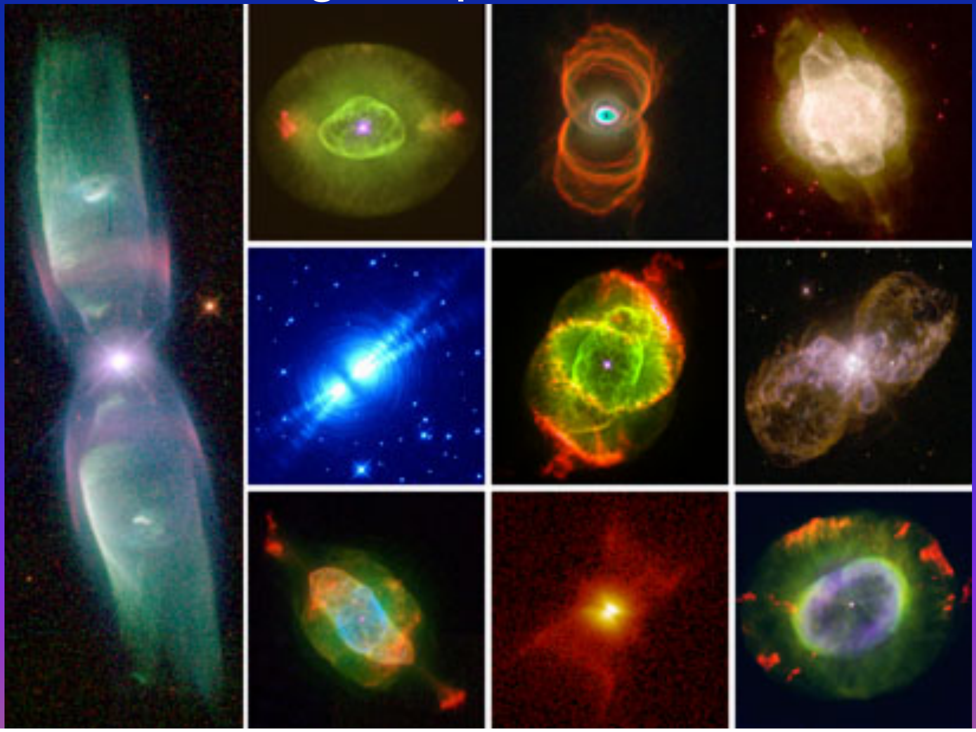
And that is exactly what White Dwarfs do that are not in close binary systems.

So, stars that are 1 to 8 solar masses go through life and throw off their envelopes of H, and keep locked in their white dwarf core most of the He, C, and O that they produced.



The final years of a 1 solar mass star

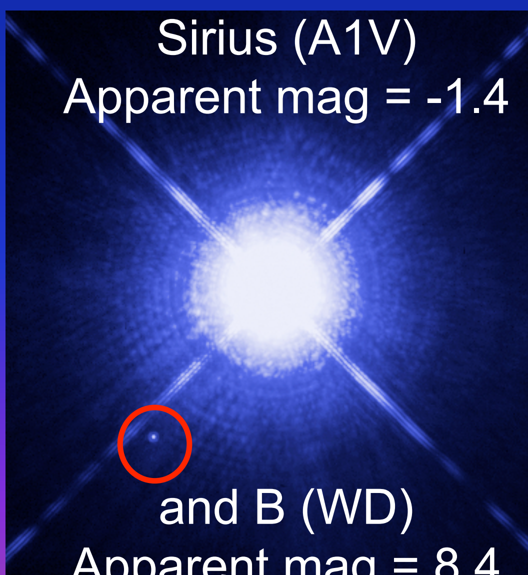
Planetary Nebula: the gaseous nebula illuminated by the bright blue light from the white dwarf. The gases are the envelope of the star thrown out into space during the red supergiant phase. The high energy photons from the hot surface ionized the gases to create the great pictures.



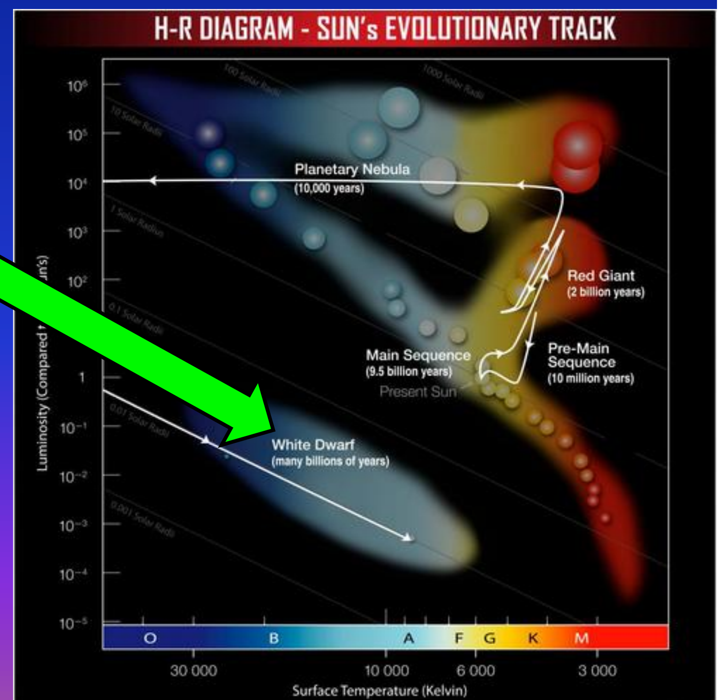
The final years of a 1 solar mass star

6. Over time, the white dwarf cools. The gases of the planetary nebula disperse into space…. And all that is left is a cooling white dwarf that cannot generate new energy.

It is faint so it cools slowly.. Over billions of years.



Sirius B is
Actually 2.5 times
Hotter than Sirius A

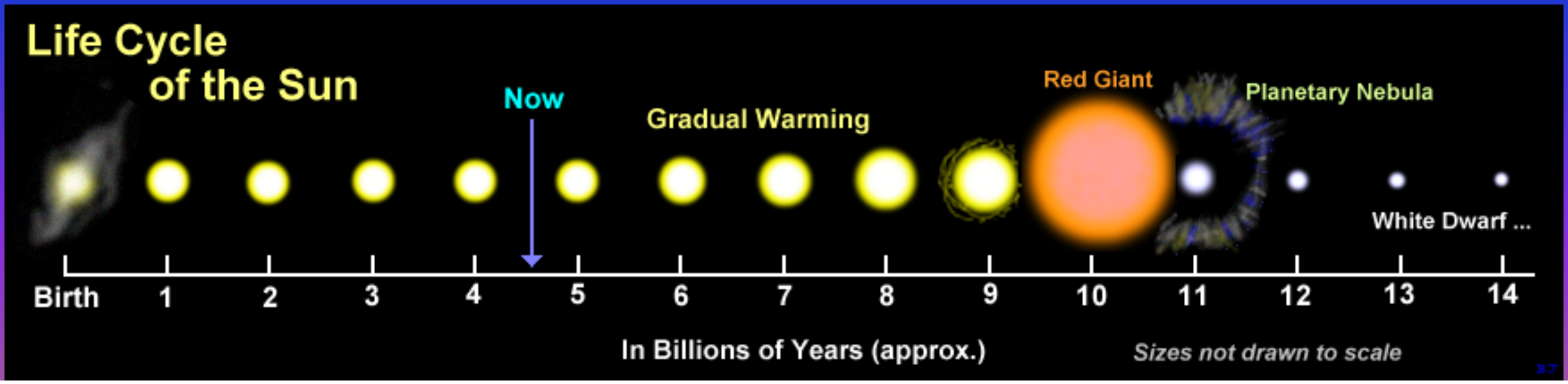


What happens to Earth in all of this?

The Sun will gradually become bright and redder over the next 5 Billion years. And the Earth warmer.

At the end of the 5 Billion years… the Sun will expand to about the orbit of Earth. The Earth may barely escape consumption!

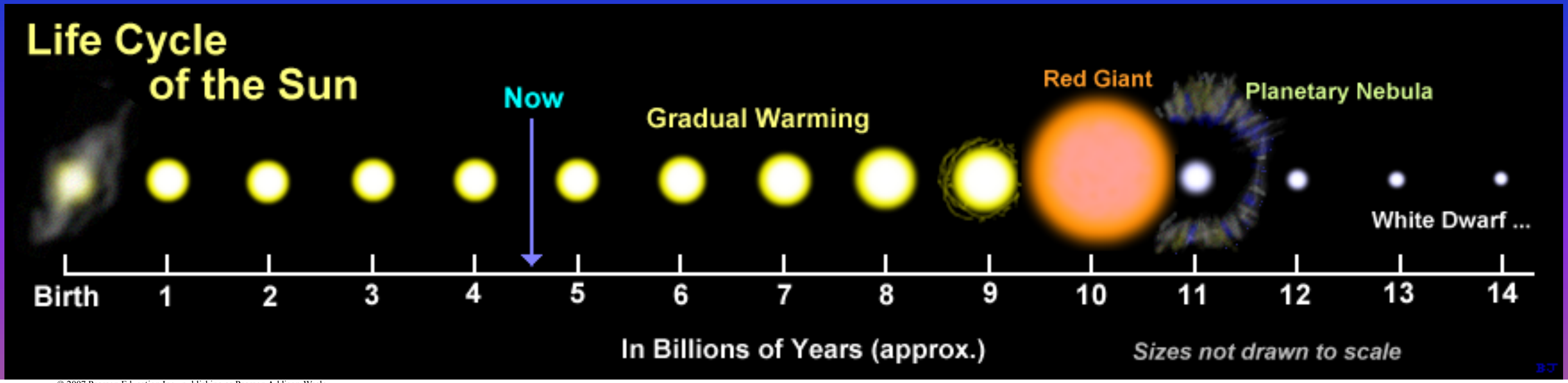
The moons of Jupiter could be great places to live IF you can keep their atmospheres after they warm up.



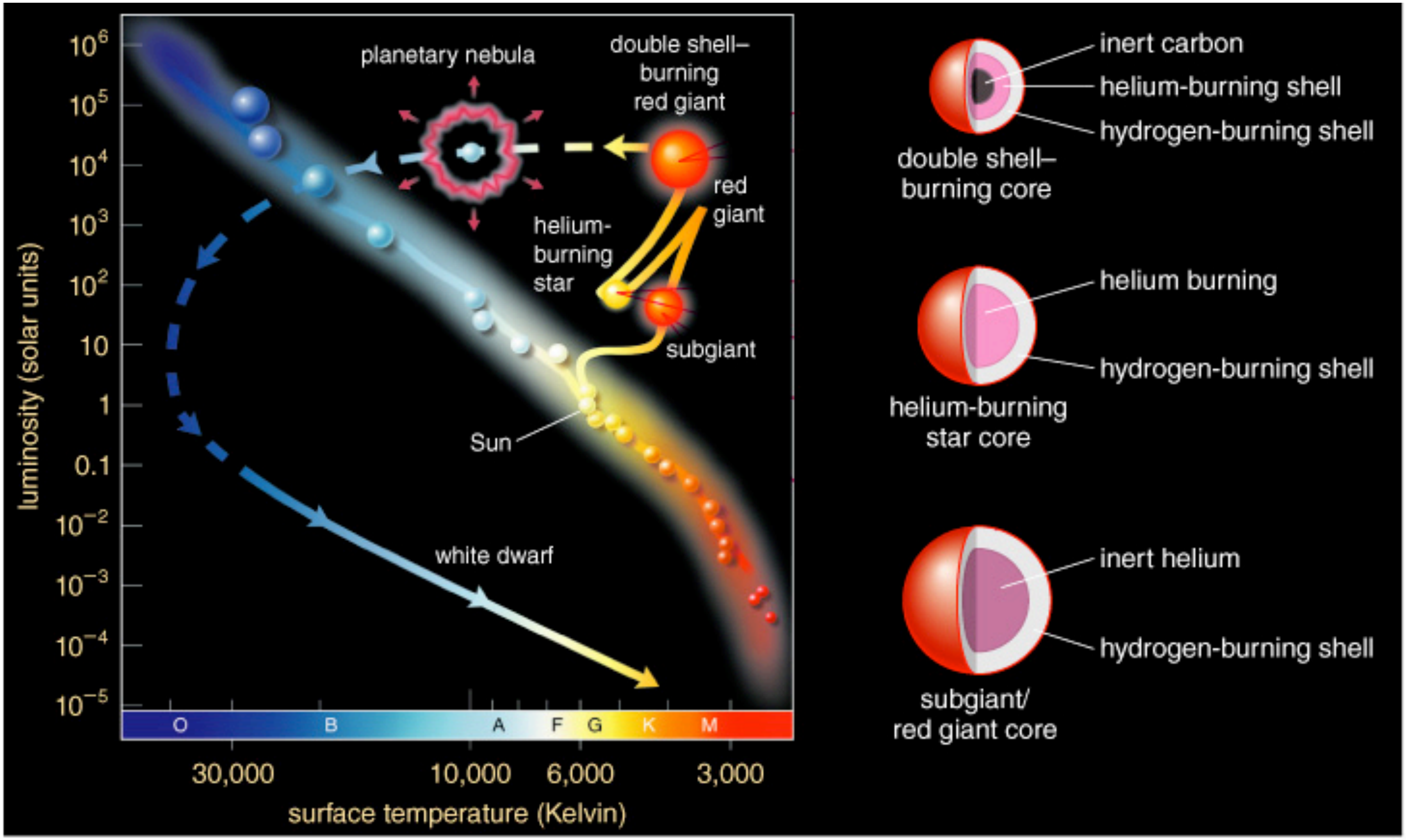
What happens to Earth in all of this?

Then the Sun will become a white dwarf with deadly high energy radiation…

Then it will cool off over the next billion years and the Solar System will be a deep-freeze. The remaining planets will be colder than Pluto.

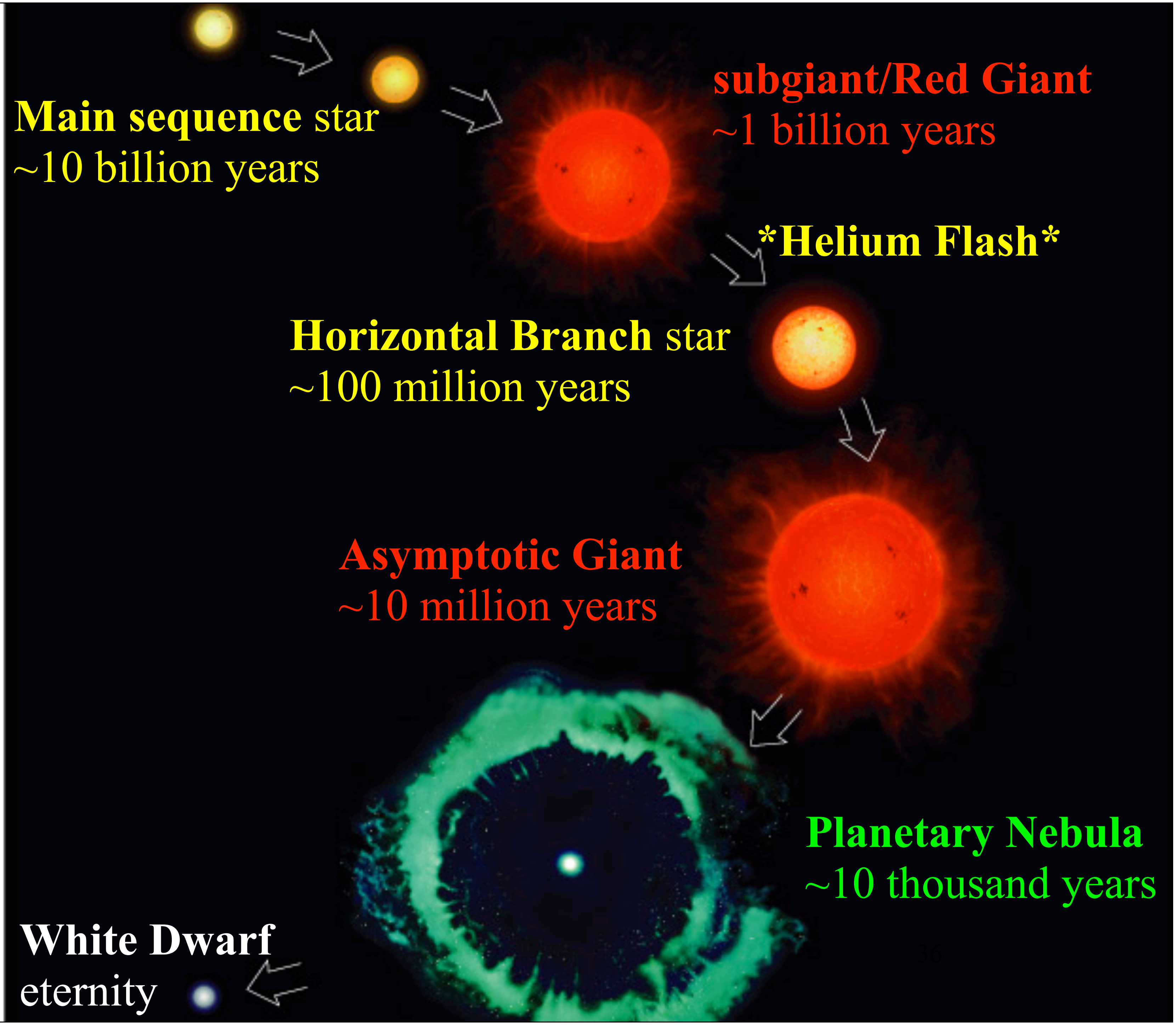


Life Track of a Sun-Like Star

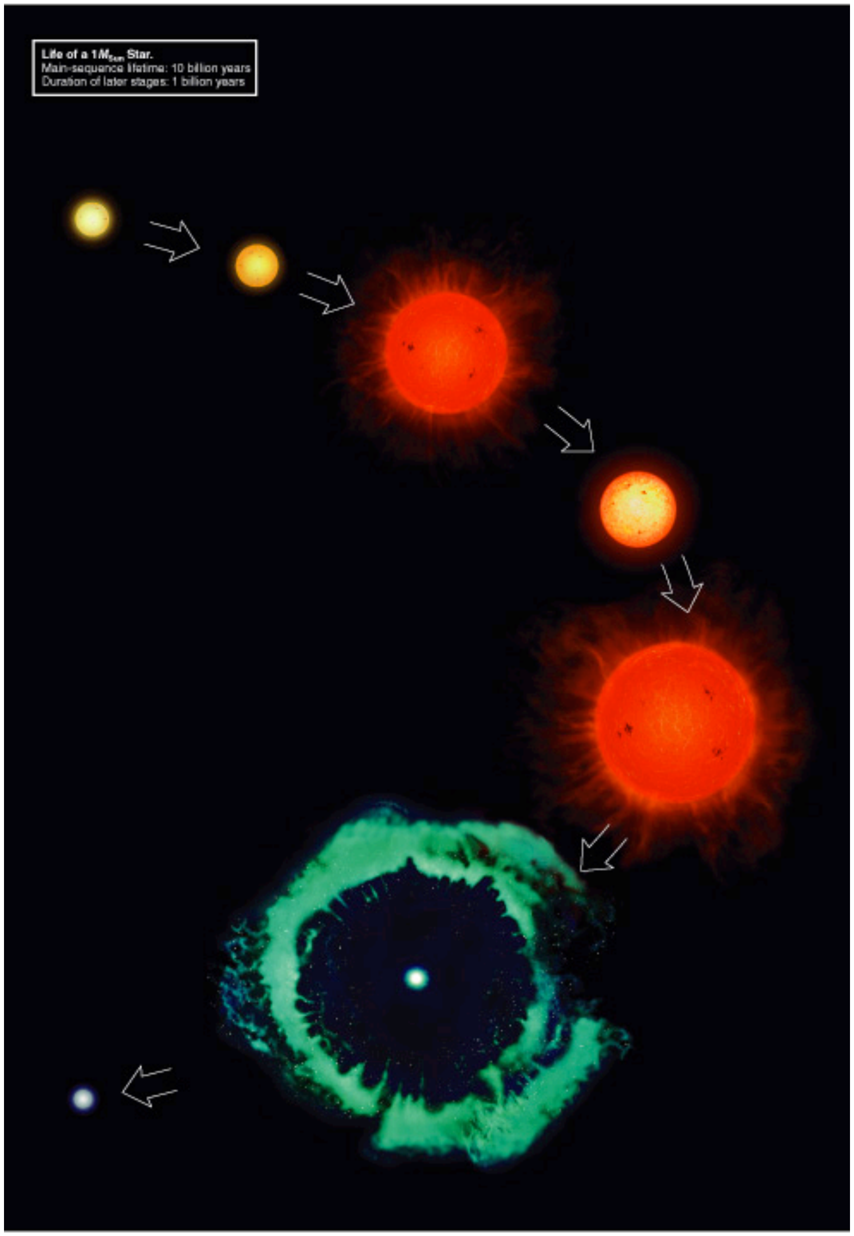


http://janus.astro.umd.edu/astro/stars/SunsLife.html

Life story of a solar mass star



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