Sun's main sequence life is about 10 billion years.

All main-sequence stars are fusing H to He:

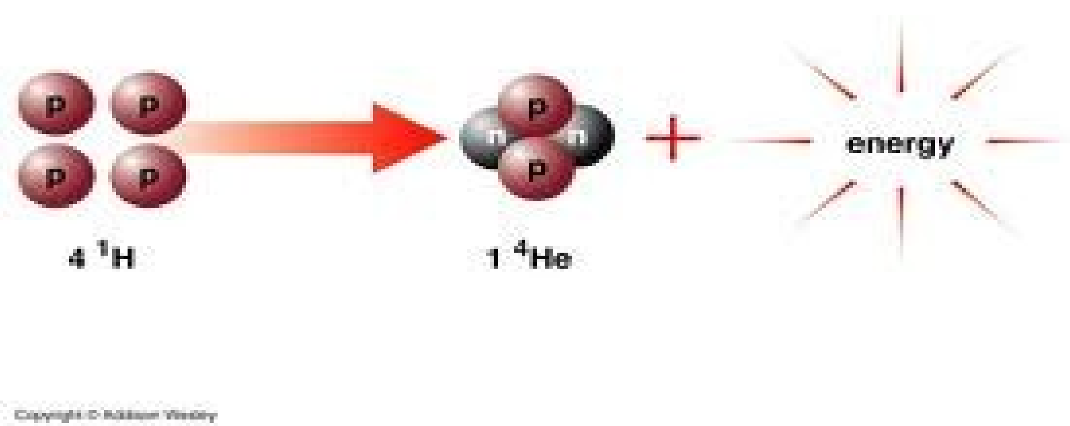
conversion of 4 protons = (2p + 2n) + energy.

(the specific reaction sequence depends on the temperature of the core, that is mass of the star).

The mass of the products is less than the mass of the reactants.
This deficit of mass has been converted to energy.

$\Delta E = \Delta m\, c^2$

Photons take 100,000 years to leak out. (opaque layers).
So it takes that long for the energy produced to leak out of the Sun.

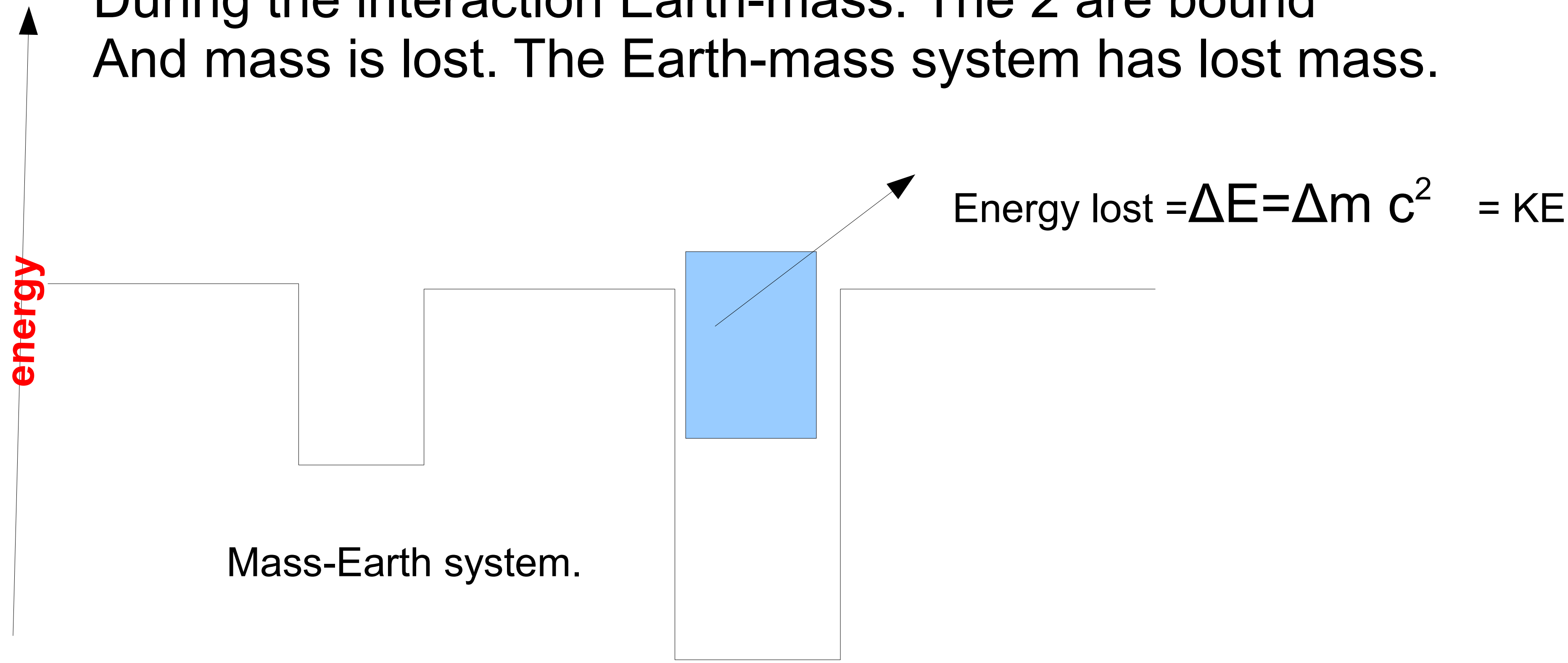


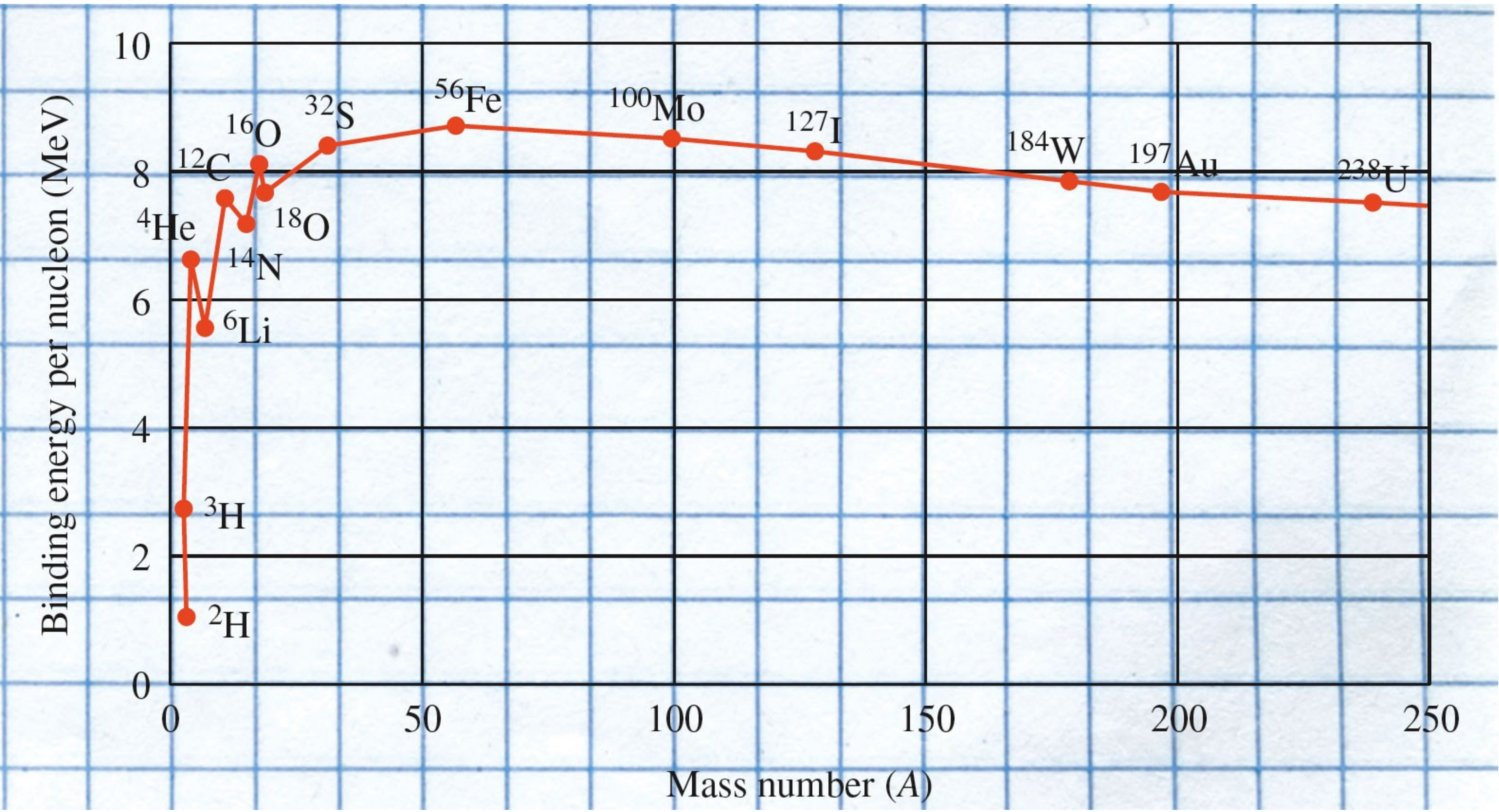
Controlled thermonuclear
Reactor. Not a bomb.
We try to build one on EArth.

$\Delta E = \Delta m\, c^2$

Is not just for nuclear reactions. More energy means More mass. A hot cup of coffee weighs more than A cold one.

When a mass falls toward earth, kinetic energy is lost During the interaction Earth-mass. The 2 are bound And mass is lost. The Earth-mass system has lost mass.





FUSION or FISSION are nuclear reactions. Both produce energy to increase The binding energy between the nucleons. The binding energy is negative. The final atoms (after fission or fusion) have less mass then the initial ones. This loss of mass was converted to energy (photons or kinetic energy). Iron is the most stable of the elements, below elements are willing to fuse And above they are willing to split.

Deaths of stars, $0.08M_{sun}<M<8M_{sun}$

• For 10 billions years the Sun lives happily on the **main sequence**.

• During this time the Sun is in **hydrostatic balance** (gravity pulling in is balanced by pressure pushing out).

• Energy is lost from the surface, but nuclear reactions provide energy to prevent contraction.

• But eventually a helium core builds up to $0.1M_{sun}$, and there isn't enough hydrogen left in the core for appreciable burning.

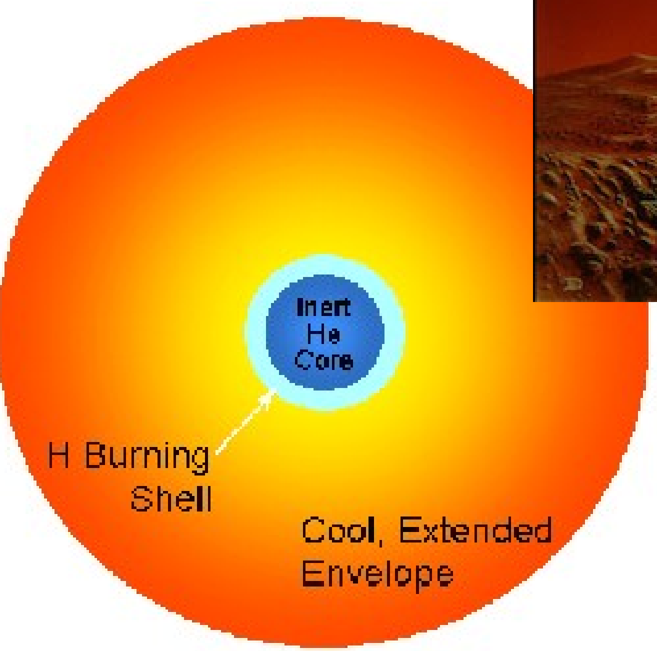
• Contraction begin in core -> heating the star -> hydrogen burning becomes stronger in surface layers.

• Star bloats to a huge size: **RED GIANT!**

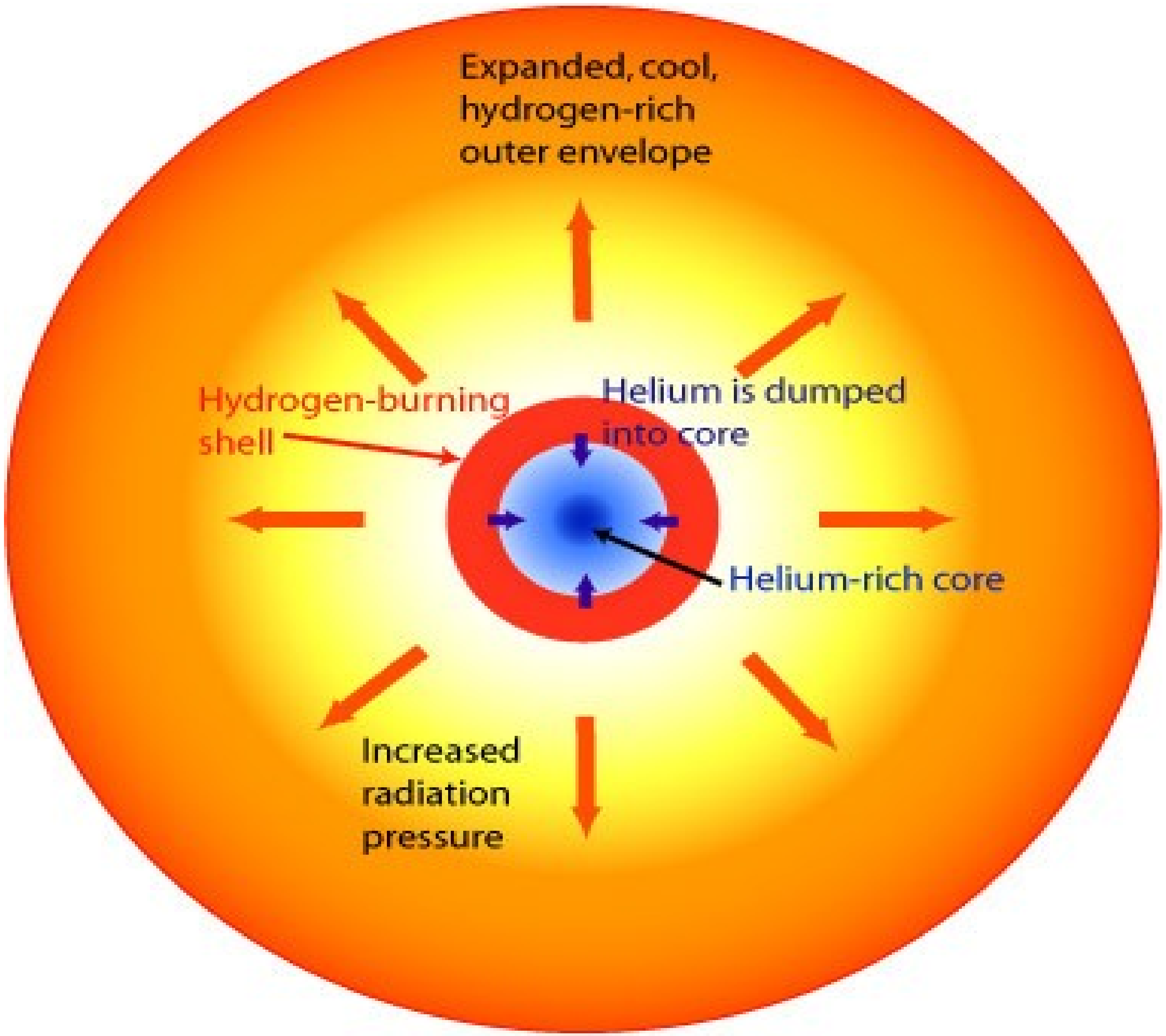
This extra energy produced by the burning shell heat the H envelope . The envelop is heated ->expands → surface cools. (gas expanding cools). The color switches because the temperature decreases .red

Star bloats to a red giant !!

Surface low but huge star, high luminosity T^4, Earth is fried.



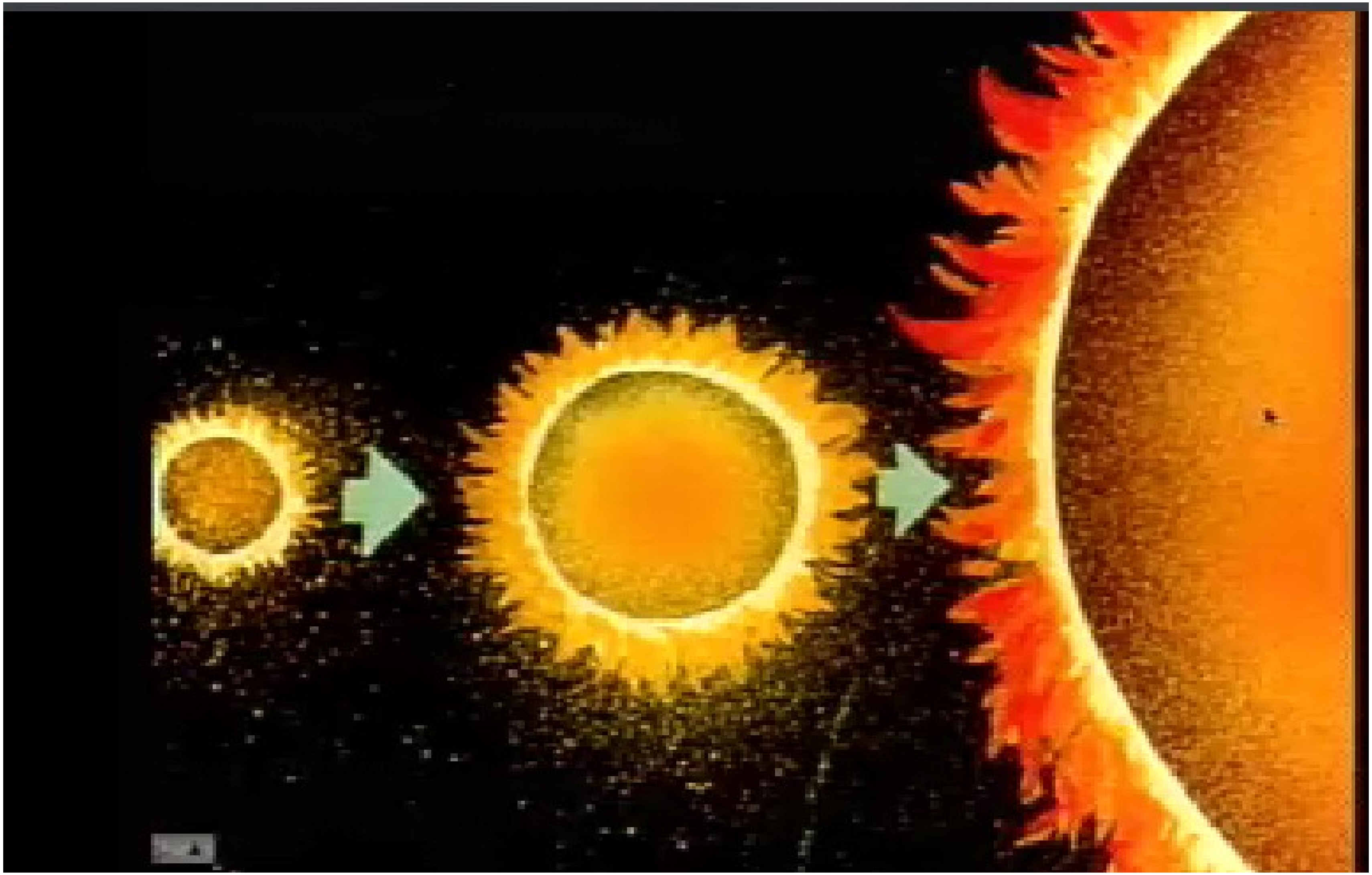
http://www.daviddarling.info/encyclopedia/R/redgiant.html



Hydrogen Shell Burning on the Red Giant Branch

The helium core collapses but the outer shell expands because of the
Extra energy /pressure pressure by increase rate fusion in the hydrogen layer
Around the core. The outer envelop cools so the color shifts to red

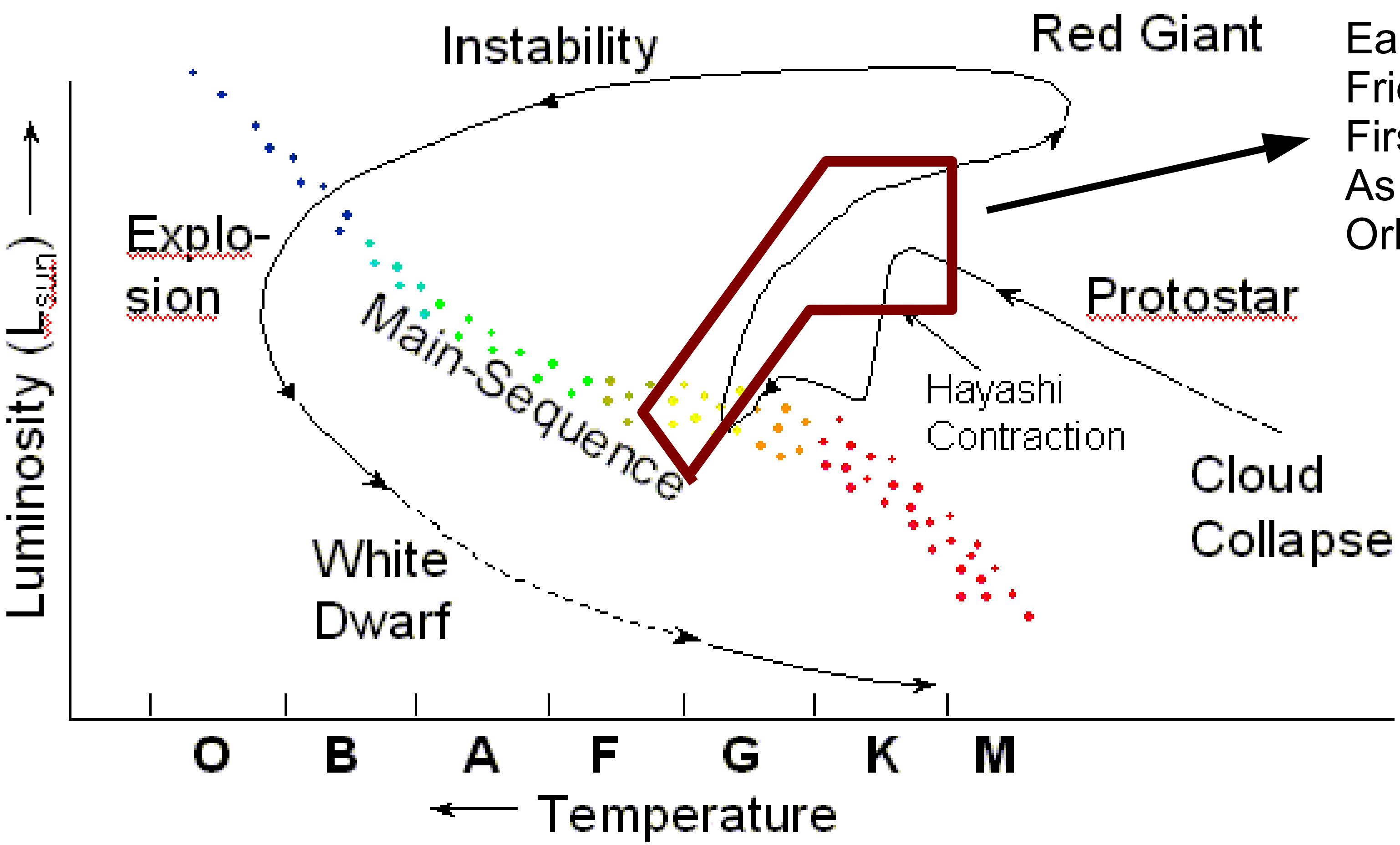
http://outreach.atnf.csiro.au/education/senior/astrophysics/stellarevolution_postmain.html



The helium core collapses but the outer shell expands because of the
Extra energy /pressure pressure by increase rate fusion in the hydrogen layer
Around the core. The outer envelop cools so the color shifts to red

During this process the temperature decreases
So color changes, but the sun is more luminous
Because larger, because more energy is produced.
Before fusion of helium.

Evolution of the Sun



Earth gets
Fried.
First stage=
As big as Mercury
Orbit.

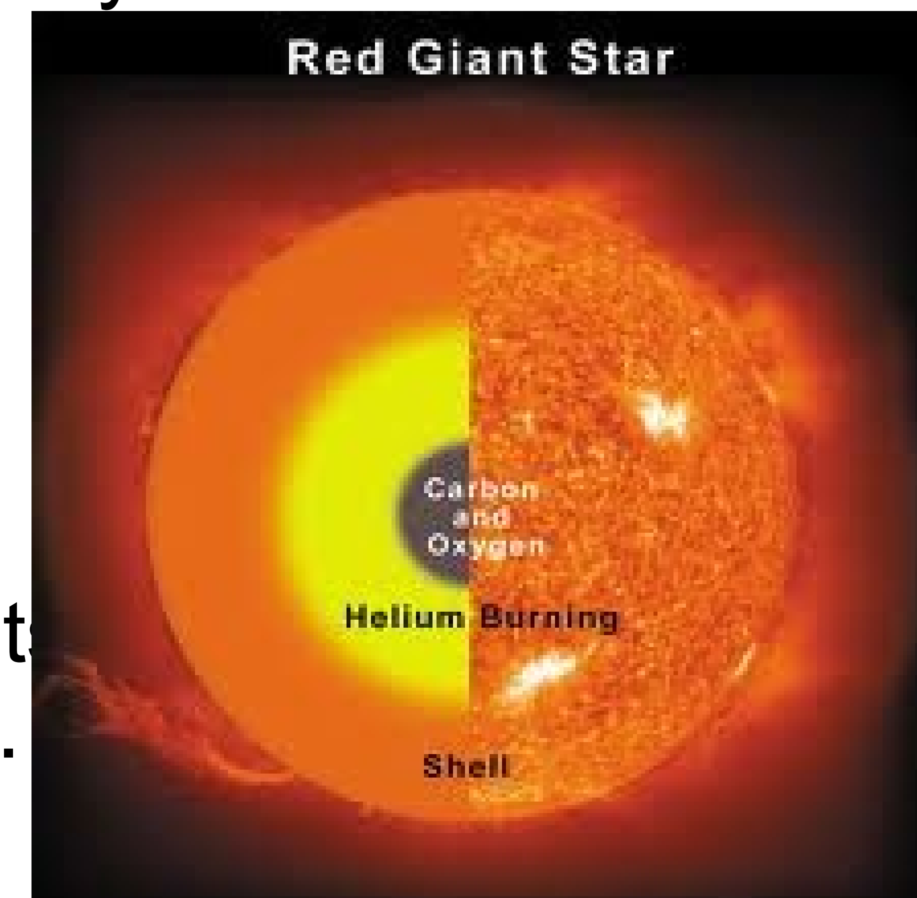
http://www.astro.cornell.edu/academics/courses/astro101/herter/lectures/lec19.htm

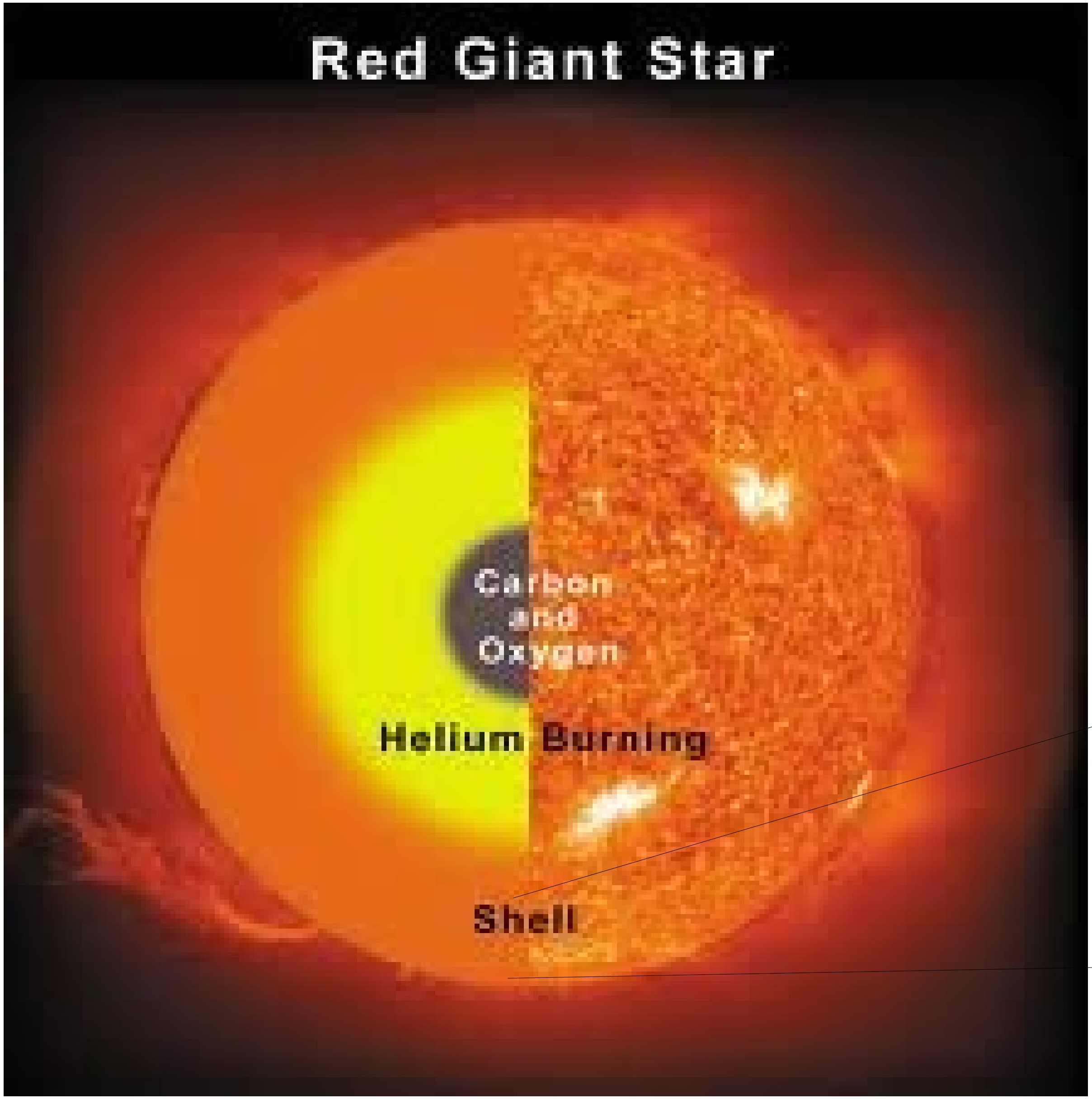
When He contracts enough the temperature and pressure are high enough for fusion to take place. You get carbon and then you get easily oxygen.

100.000.000 K is reached.

This phase lasts about 1 million years.
The sun will make oxygen and carbon during this stage.

3 He → carbon-12 + energy
Carbon-12 + He → oxygen + energy
We can't fuse heavier elements
Temperature not high enough.





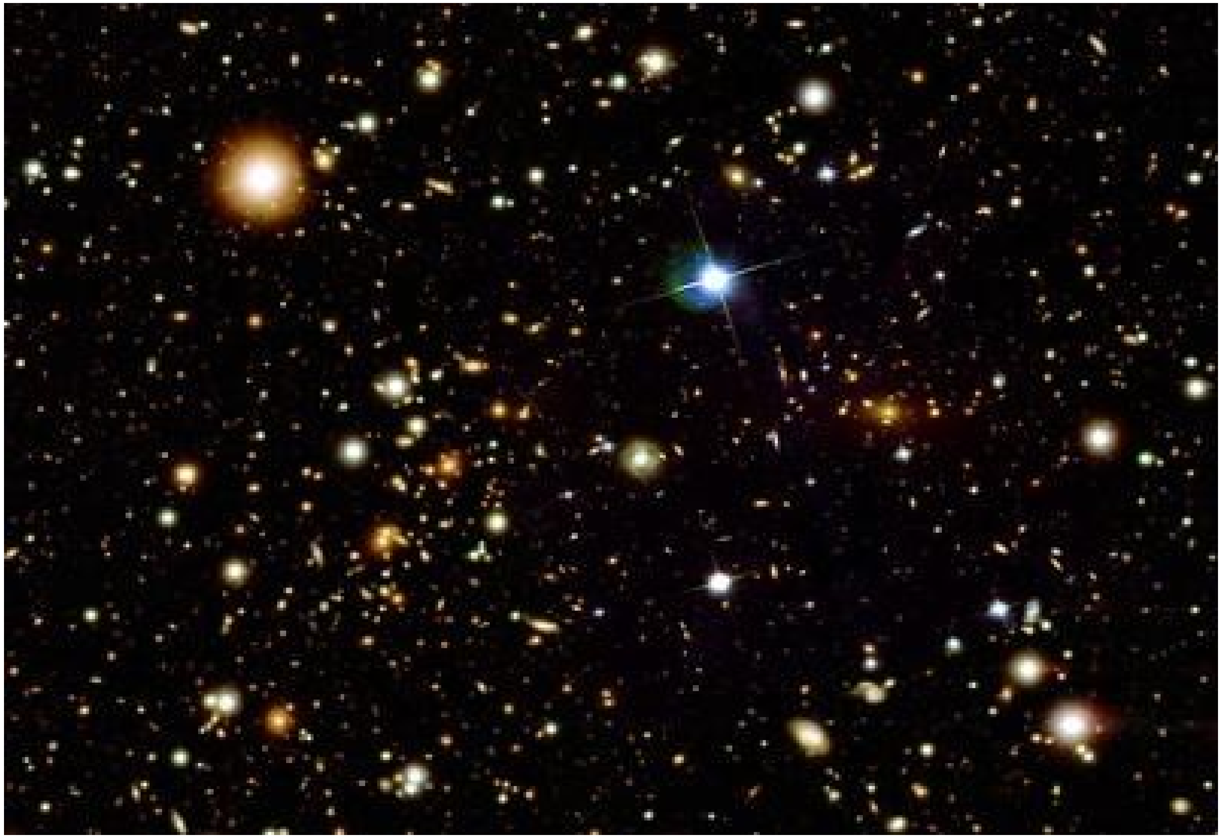
H burning shell

H inert shell

EMERGENCE of the PERIODIC TABLE of ELEMENT as a result Of NUCLEAR FUSION in STARS.

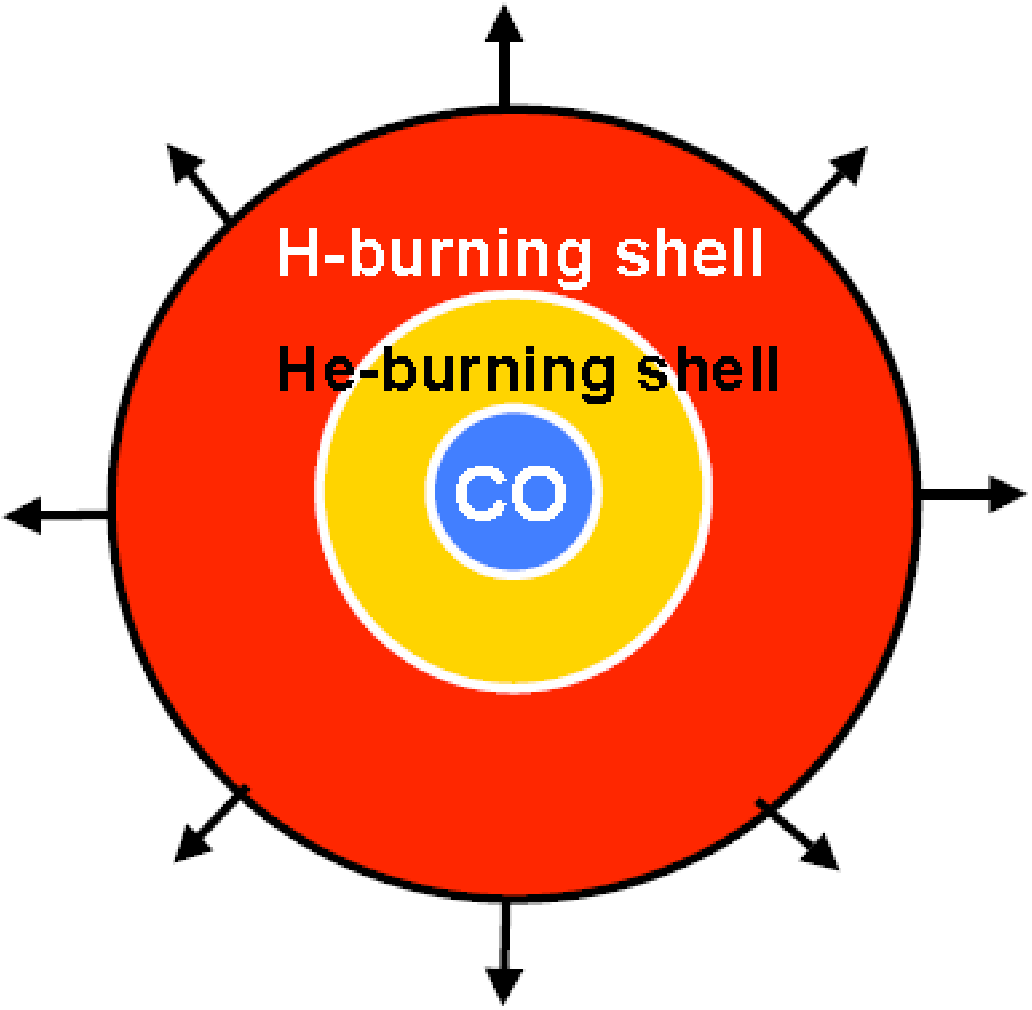
THIS IS CALLED NUCLEOSYNTHESIS

“ WE ARE ALL STARSTUFF “ Carl Sagan



BIGGER RED GIANTS!

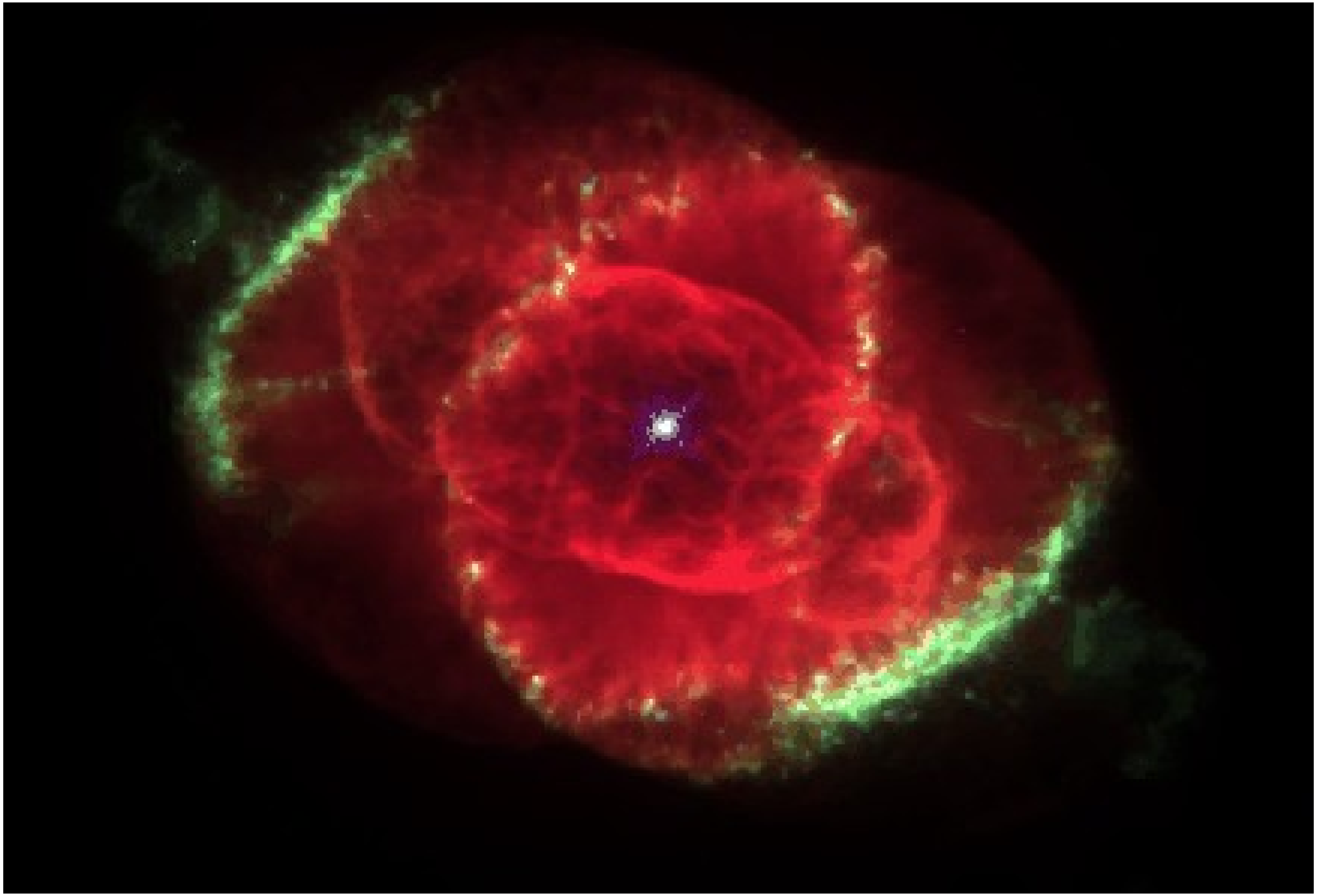
- Once again, T is too low for C/O core fusion, so the core contracts.
- Off-center burning expands envelope again, creating an even larger Red Giant.
- Depending on the mass of the star, this process can repeat, creating heavier elements.



- For stars like our Sun, it becomes unstable and begins ejecting the outer layers: **planetary nebula.**

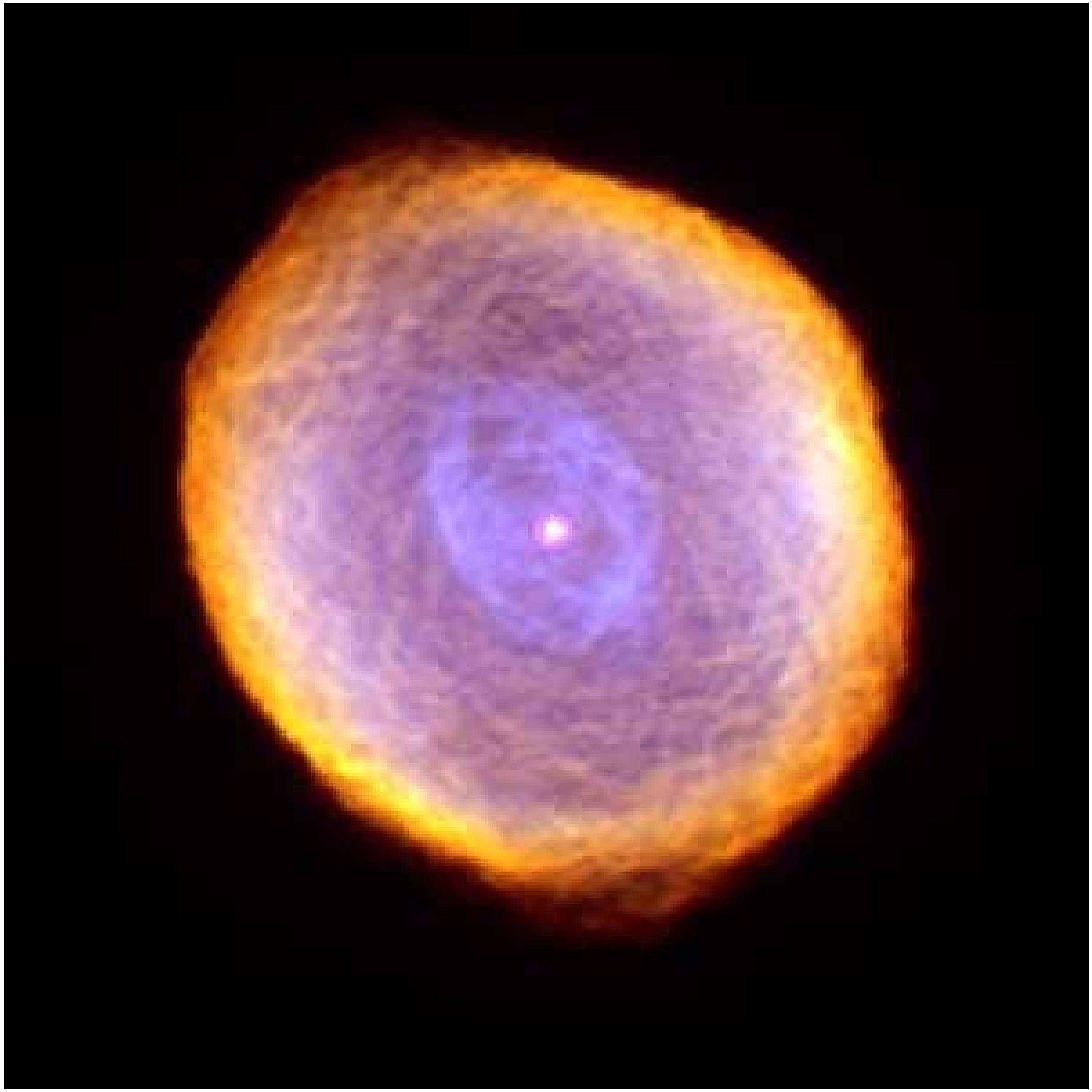
PLANETARY NEBULA

Different gentle ejections produce the nebula.



The inner part is hot and ionize the gas in the nebula that glows.
The denuded hot core is surrounded by gentle ejection of material which is ionized
And caused to glow by the UV photons emitted by the core.
The photons are absorbed by the outer layer gas electrons. When the electrons
Cascade down, they emit optical light. Glowing expanding ejected gas.

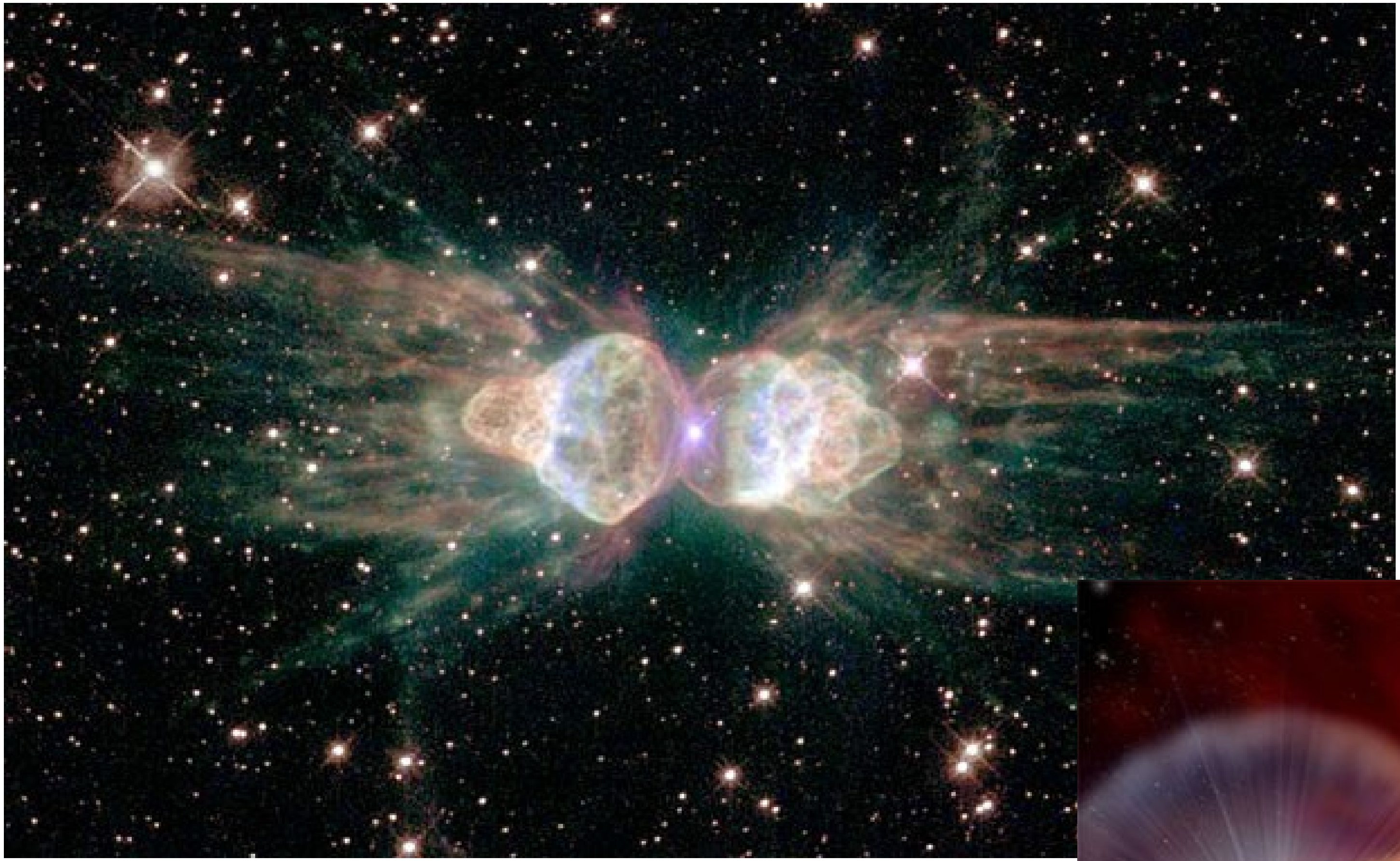
Ring nebula in the constellation Lyra. 1 dying star + another one happens to be there.



Spirograph nebula

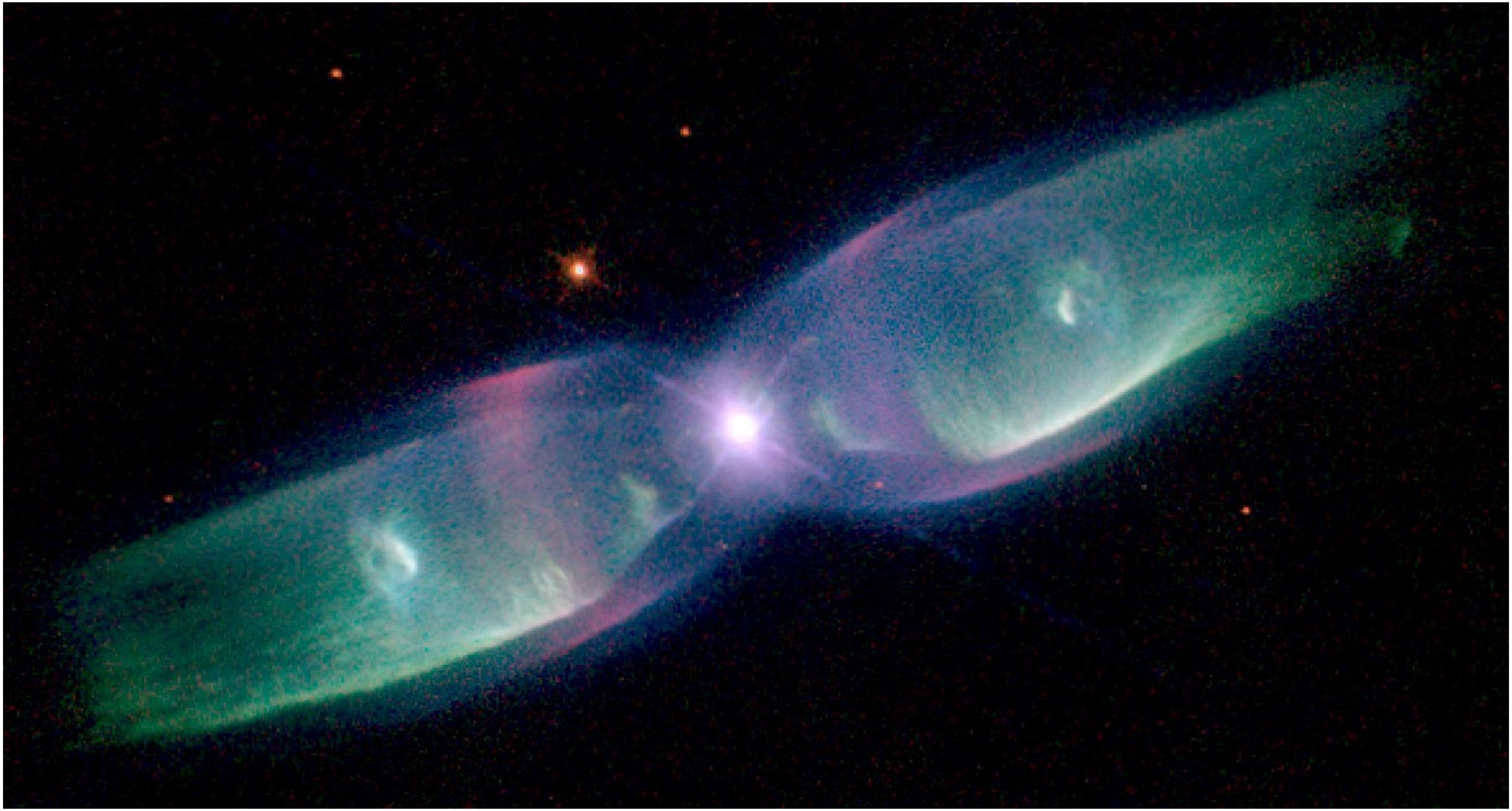
Hourglass nebula

THE ANT NEBULA
Bipolar nebula when 2 stars died (binary system). 1 star died before the other And its material is cannibalized by its companion. Then both of them combine into a red giant and the explosion of material is bipolar



See 42:11

M2-9 is a striking example of a "butterfly" or a bipolar planetary nebula.

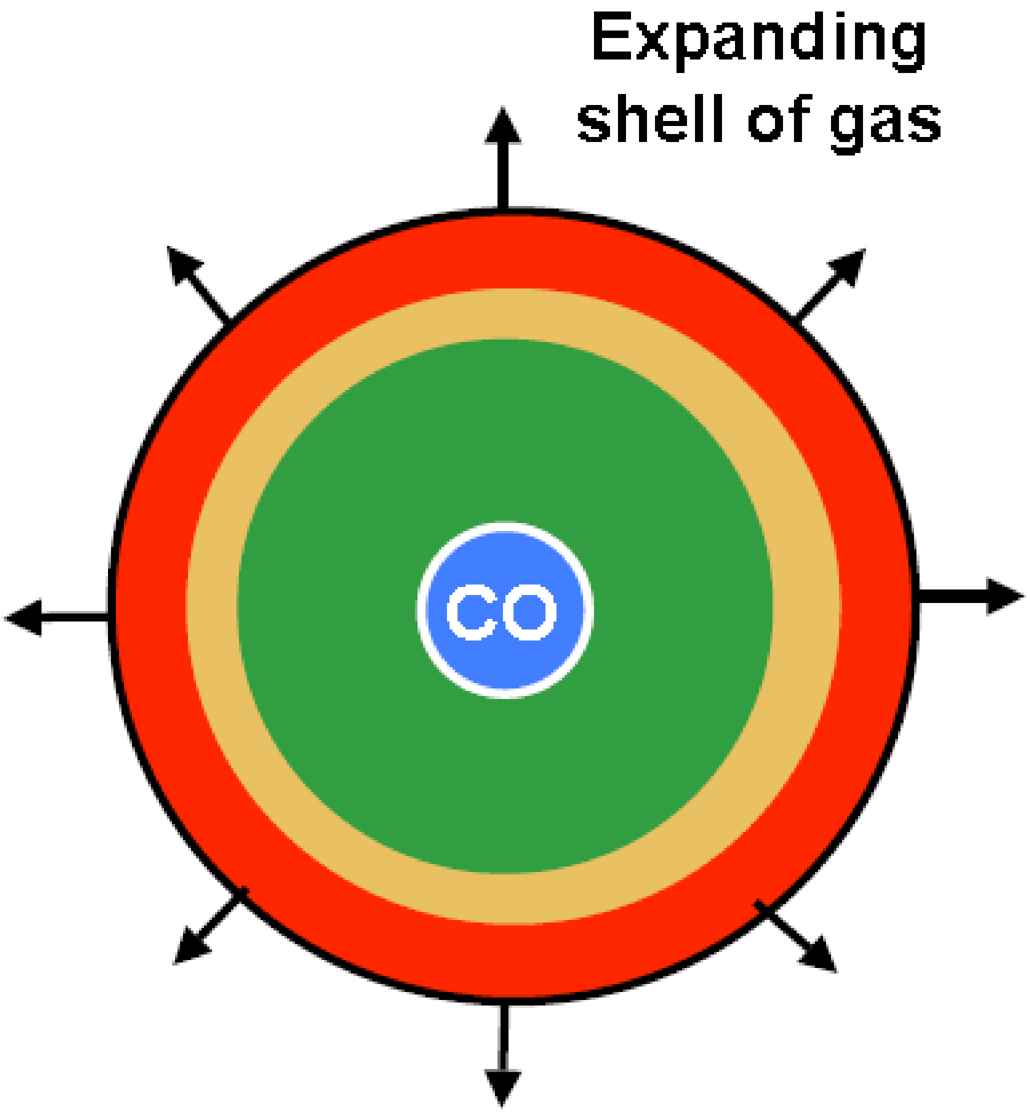


Planetary Nebula NGC 2818

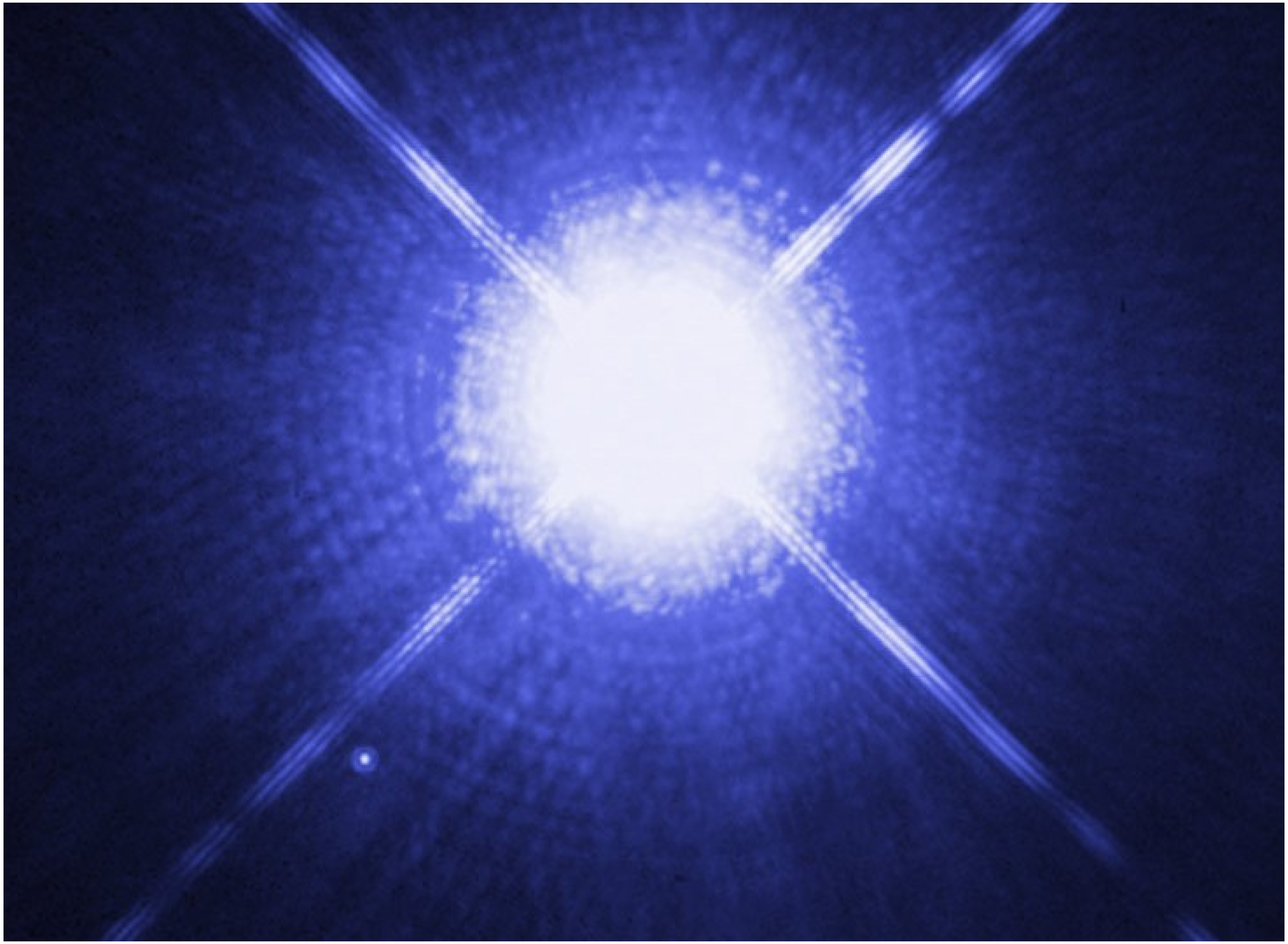
ESKIMO nebula. Can you see the eskimo head?
2 ejections. 1 recently and one long ago in time

Planetary Nebula

- Winds from the star create a planetary nebula.
- The star is mostly carbon and oxygen inside, with a helium layer. Most of the hydrogen is being expelled.
- An inner core of carbon and oxygen (0.6-0.9M_{sun}) is left over, held up by "degeneracy pressure."
- This is left over as a **WHITE DWARF** star.



The mass of a dwarf can be half million the mass of the earth but the same volume.
The density is huge. Several tons per tea spoon



The companion of Sirius is a white dwarf

White dwarfs

- Roughly the size of the Earth with the mass of the Sun!
- If you try to pack electrons into the same place they must be at different energy levels (like the energy levels of an atom). Each electron must be at a higher energy than the one before it.
- All these energetic electrons in one place give rise to a pressure: **ELECTRON DEGENERACY PRESSURE**
- This is weird stuff: one teaspoon of white dwarf weighs 3 tons! If a white dwarf is **more massive**, it actually has a **smaller radius**.
- **No nuclear reactions** are taking place, the white dwarf just radiates its heat and continues to cool over time.
- White dwarfs are sometimes used as **age indicators** in globular clusters.

WHITE DWARFS

The degenerate electrons in a white dwarf are moving very fast, but the laws Of quantum mechanics prevent them losing energy.

Atomic nuclei (positive ions) are not degenerate:
They can lose energy.

White dwarf shines because the nuclei lose energy.

No nuclear reactions

The heavier elements can't be produced (heavier than oxygen).

About the mass of the sun. compressed to the volume of the EArth

White dwarf are retired stars.

More mass, less volume for white dward because of the strange degenerate matter.

Electrons are squeezed but “ dislike” each other.
(that's why atoms have volume).
Electrons can't occupy the same quantum state. (Pauli excusion).

+ you know where the electrons are (they are squeezed) ,
that means the speed is huge (heisenberg uncertainty principle).
They can't lose energy. Because of this motion,
They exert a pressure far more important than the pressure due to temperature. (their natural giggling motion)
They can't drop to a lower energy state because all the states lower are occupy.

So gravity can't not win.

Finally (10^{10} years) nuclei cool down.

Luminosity becomes low. Temperature drops.
They fade from sight.

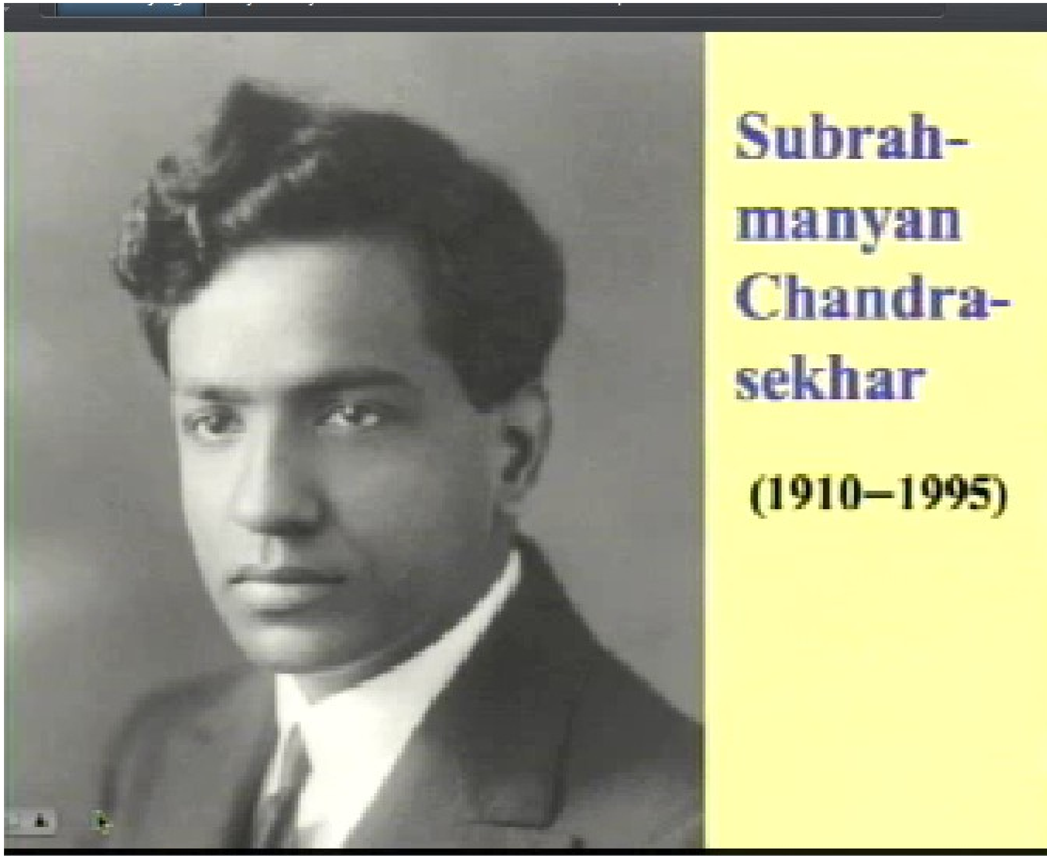
Sometimes they are called black dwarf.
(although they are not black).

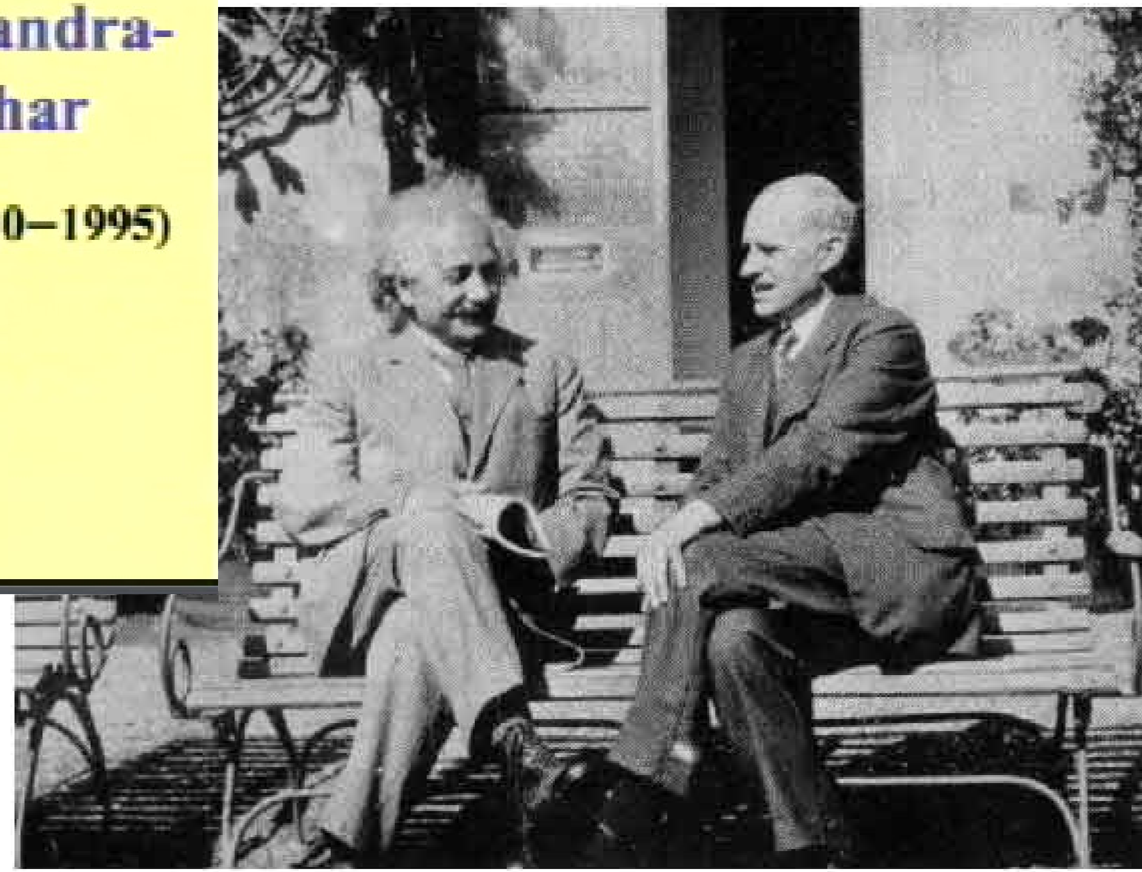
They last for ever.

But they are still supported by electron degeneracy pressure

Types of White Dwarfs

- The Sun will become a carbon/oxygen white dwarf with a mass of $0.6M_{sun}$.
- Stars up to $8M_{sun}$ become carbon/oxygen white dwarfs with masses up to $\sim 1.1M_{sun}$.
- Stars below $0.45M_{sun}$ aren't massive enough to burn helium in their core and become helium white dwarfs.
- Stars with masses from 8-$10M_{sun}$ have an extra stage of burning in their core and make oxygen/neon/magnesium white dwarfs with masses of $\sim 1.2M_{sun}$.
- White dwarfs have a mass limit $1.4M_{sun}$ (the **Chandrasekhar limit**), above which electron degeneracy pressure can't hold up the star.





He figured the limit out, and other things, at age of 20 on his way to England (from India) where he was supposed to be educated. He got the nobel prize 50 years Later. In Cambridge, his advisor Eddington didn't believe him and ridiculed him publicly Always believe your graduate student is the moral.