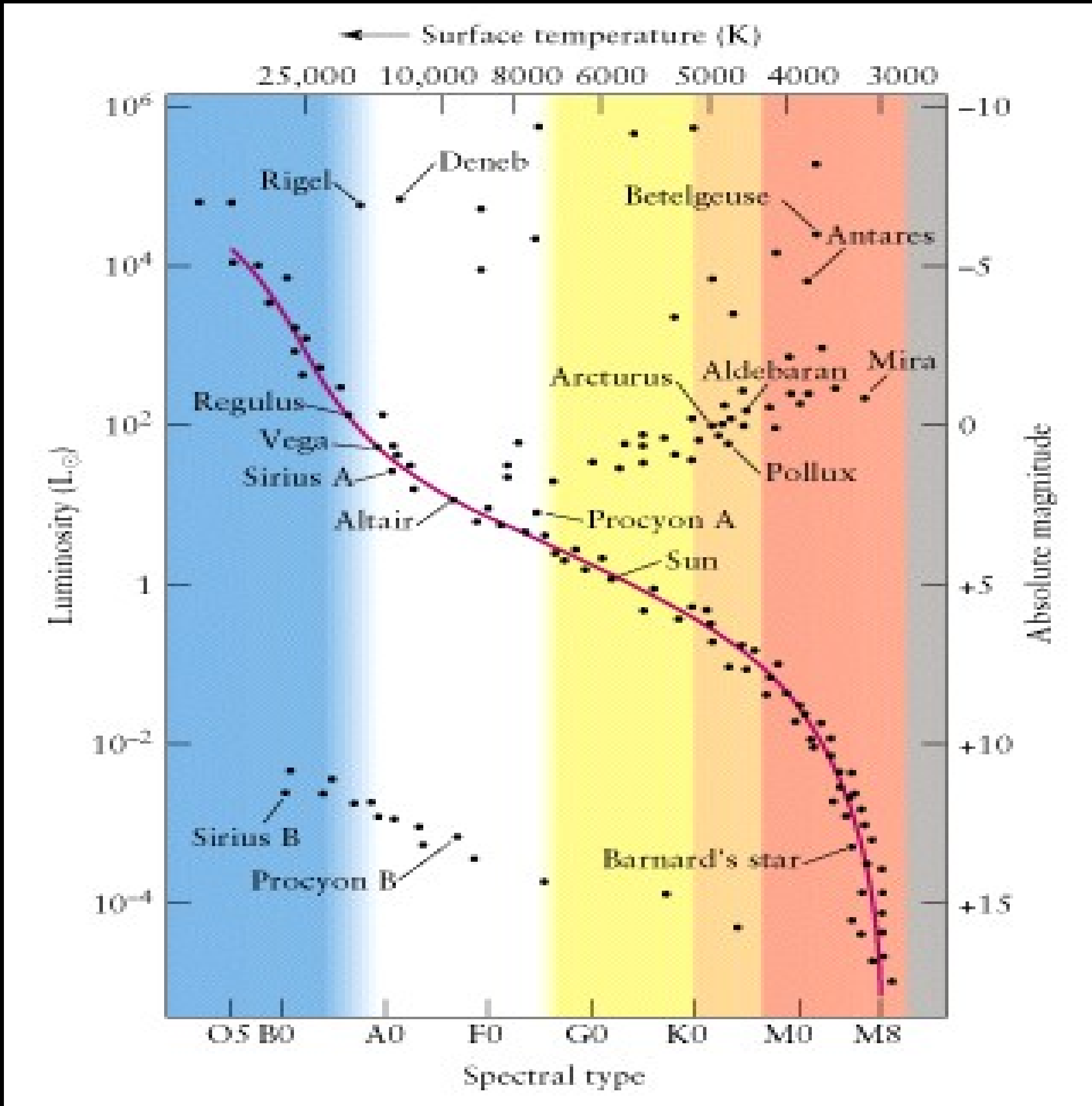
Relativistic Universe

Star evolution

The H-R Diagram

If a star's absolute luminosity and temperature are both known, they can be plotted against each other. This is called the Hertzprung-Russel (H-R) diagram.

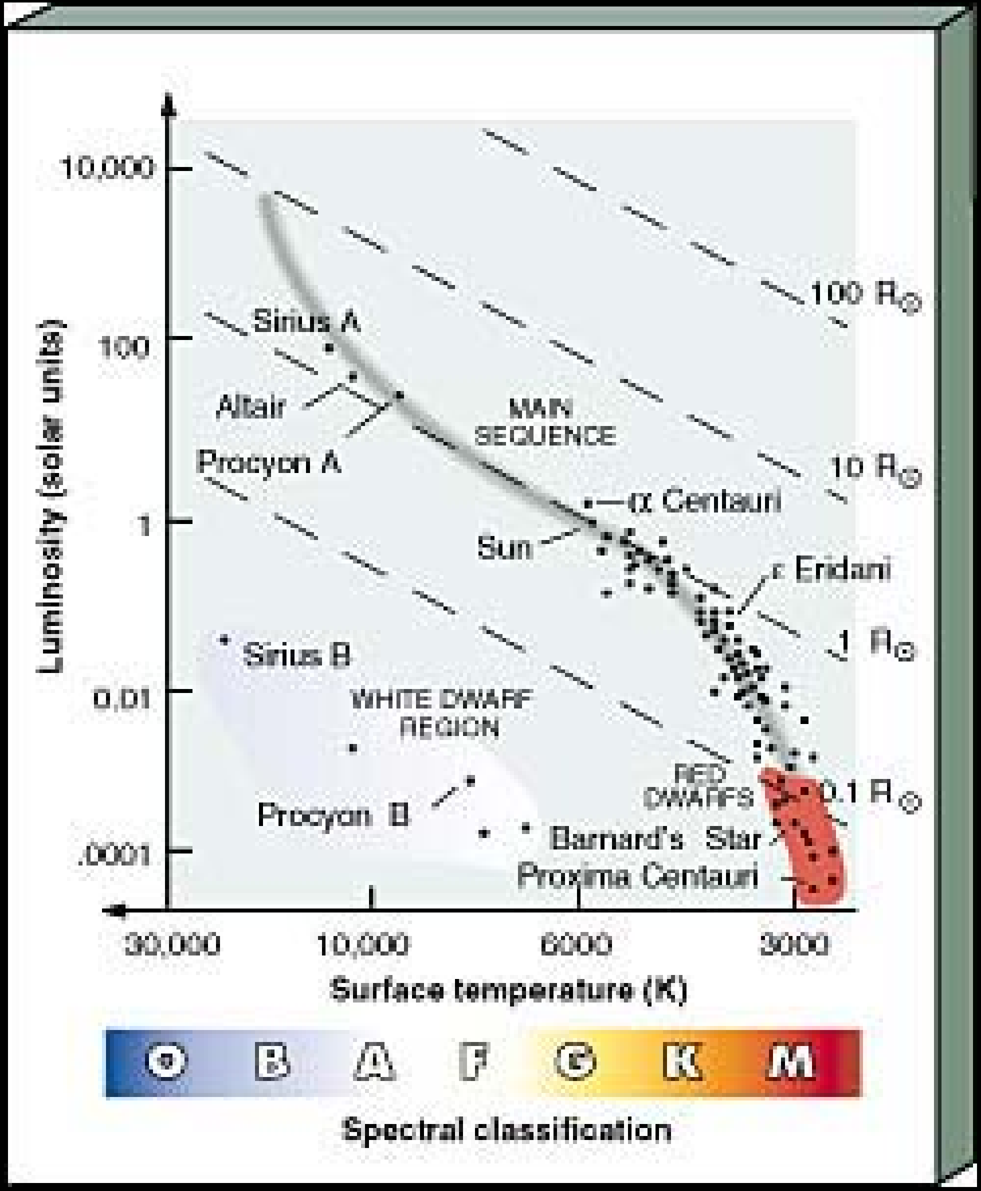
(As usual, the diagram is plotted somewhat backwards. Hot stars are plotted on the left, and cool stars on the right.)



The Sizes of Stars

The relationship between luminosity, radius, and temperature is

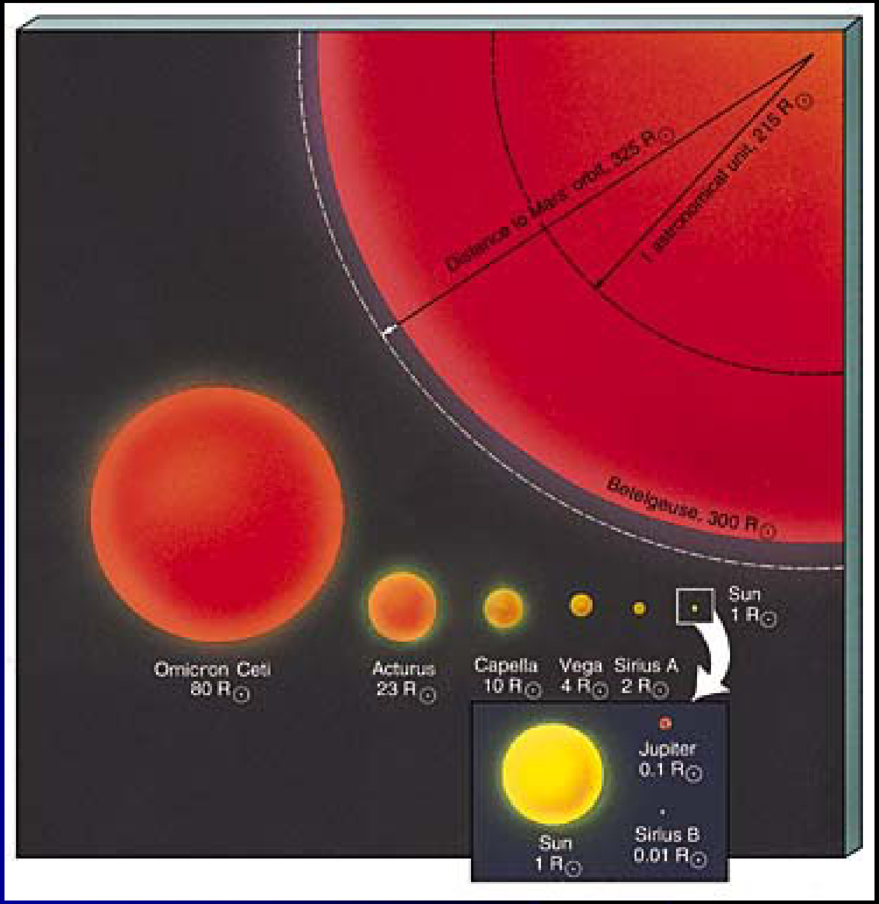
$$L = 4 \pi R^2 \sigma T^4$$

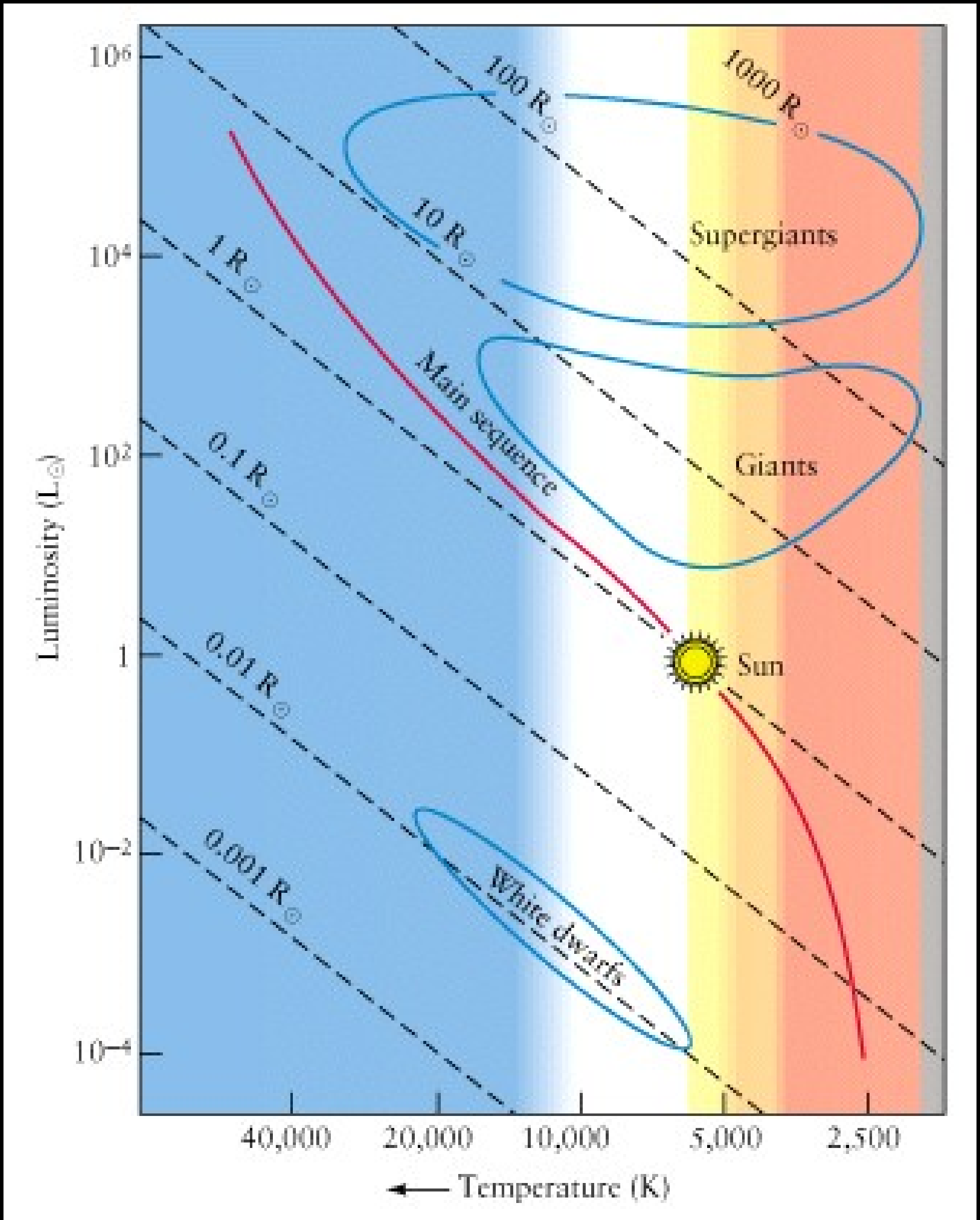


(π and σ are just numbers to make the units come out right)

The Sizes of Stars

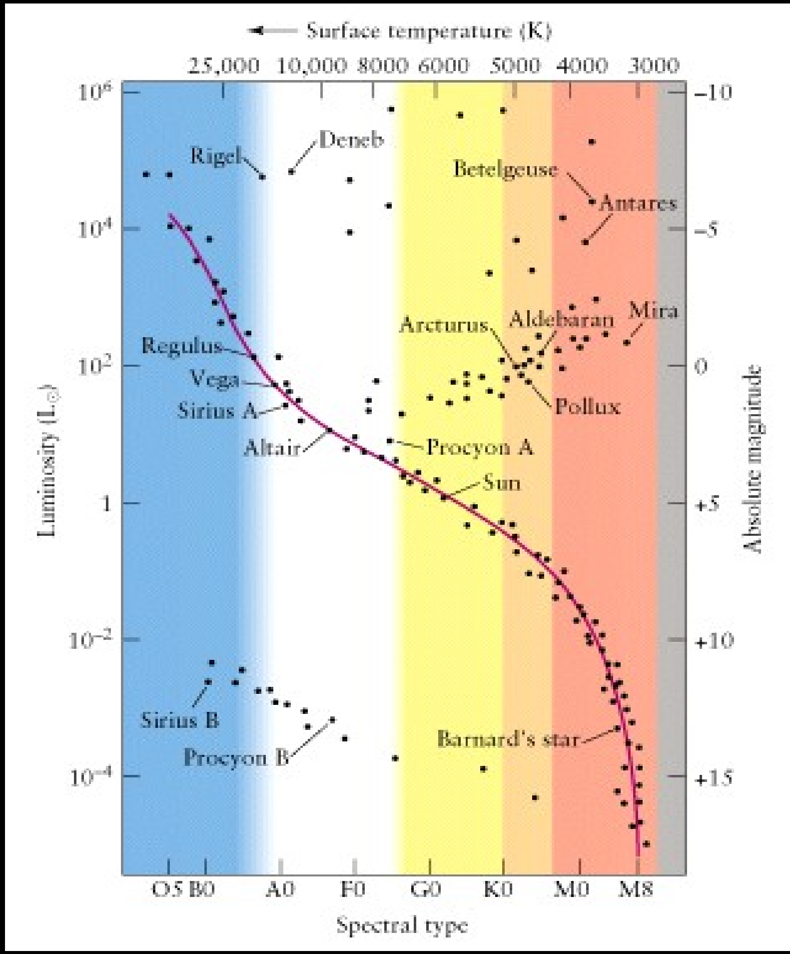
The sizes of stars can be anywhere from 0.01 $R_\odot$ to 1000 $R_\odot$!





Results from Binary Stars Measurements

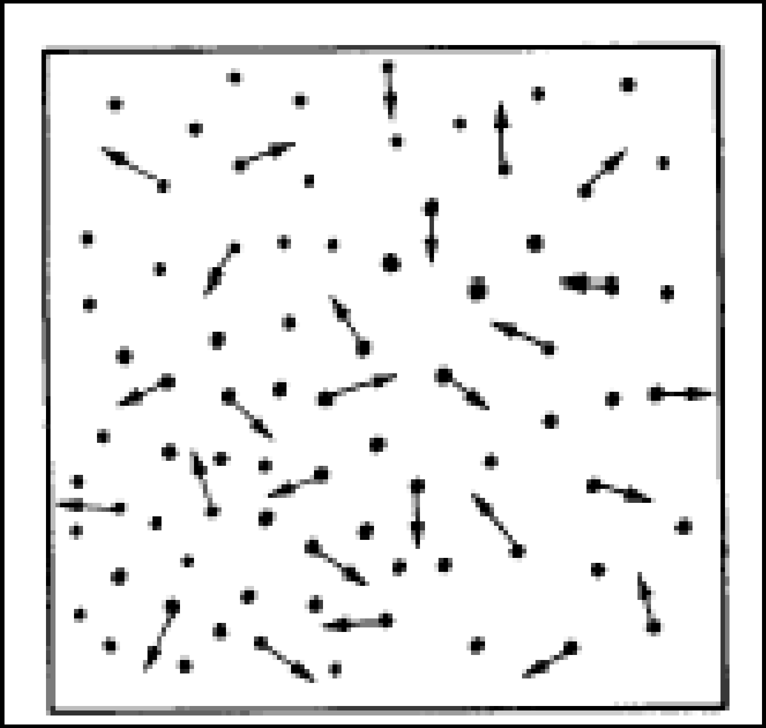
1) All stars have masses between 0.1 $M_\odot$ and 60 $M_\odot$
2) Main sequence stars obey a mass-luminosity relation: the brighter the star, the more massive the star.



3) The white dwarf stars are all less than 1.4 $M_\odot$
4) There is no pattern to the masses of red giants.

Temperature, Pressure, and Energy

- Gas Temperature: a measure of how fast atoms are moving in random directions
- Gas Pressure: the "force" these atoms put on their surroundings via their collisions



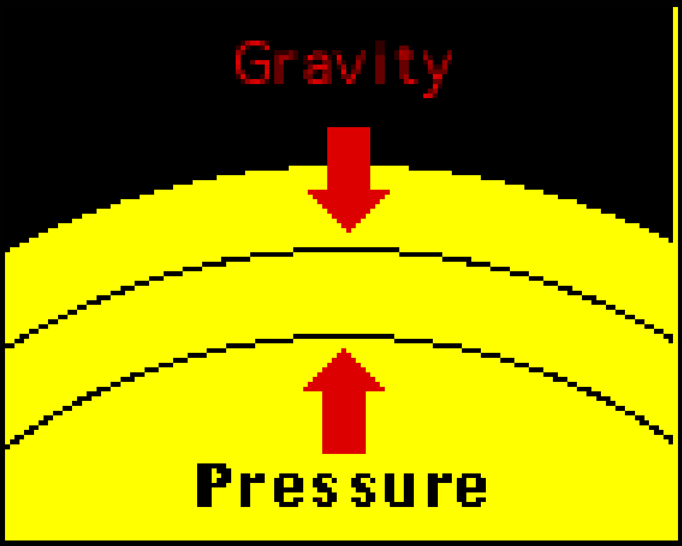
Energy, Temperature, and Pressure are related through the Equation of State: where one goes, the others go!

Energy ↑ ⇔ Temperature ↑ ⇔ Pressure ↑

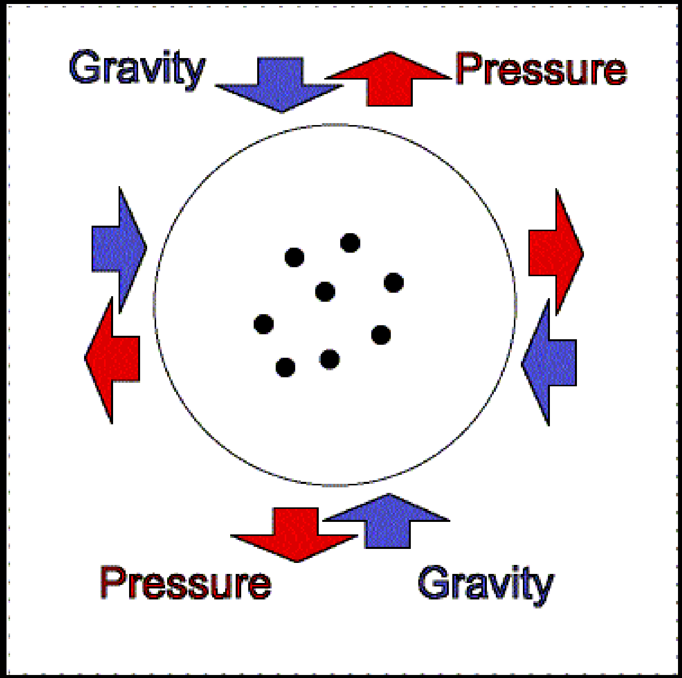
Energy ↓ ⇔ Temperature ↓ ⇔ Pressure ↓

Hydrostatic Equilibrium

- The Sun is *very* massive, so it has a lot of gravity. The center of the Sun is under great pressure!
- In order to keep from collapsing, the gas pressure must balance the pull of gravity. This is called hydrostatic equilibrium.



- High pressure means high temperature: the center of the Sun is very hot: about 14,000,000° !
- High temperature means the Sun produces a lot of energy (through the blackbody law). This heat must flow out!



How Does Heat Get Transported?

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  - Conduction: fast moving electrons hit slower moving electrons. (This does NOT happen in most stars.)

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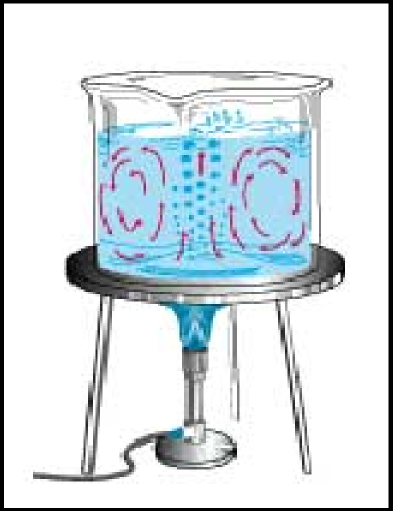

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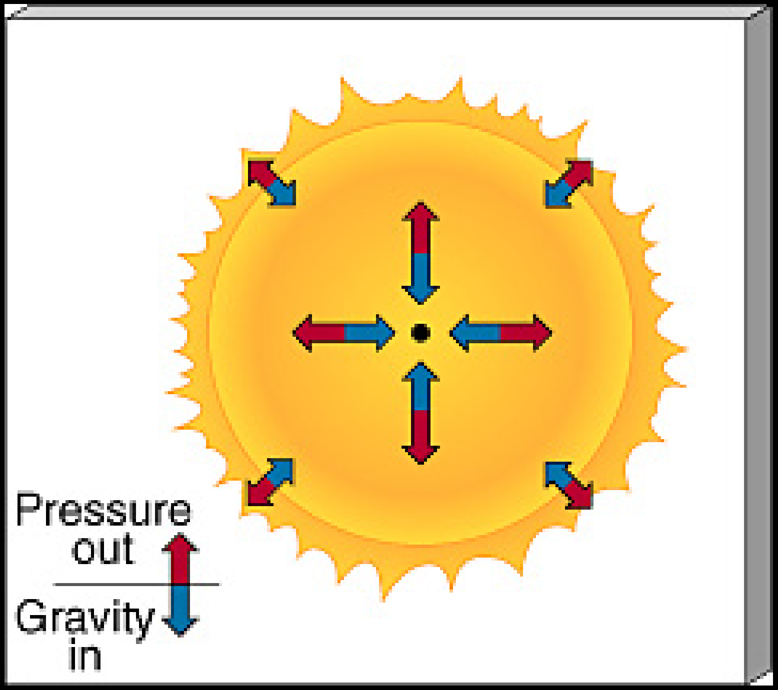
  - Radiation: blackbody law photons are emitted, then absorbed by cooler material

Energy is transported via the random walk of photons. In the Sun, it takes energy over 10,000,000 yr to get to the surface!

How the Sun Does Not Shine

- As the energy leaks out, the central temperature of the Sun drops
- Lower temperature means lower gas pressure
- The lower gas pressure cannot hold up against gravity – the Sun shrinks
- The added compression puts the Sun's center under greater pressure, so the central temperature increases
- The higher temperature produces higher pressure, which fights off gravity
- The high temperature produces blackbody photons which leak out…



Gravitational contraction could keep the Sun shining for 40,000,000 yrs!

About the Proton-Proton Chain

- The net result of the proton-proton chain is to turn 4 hydrogen atoms into 1 helium atom. But there is a mass defect – the 4 hydrogen atoms have 0.7% more mass than the 1 helium atom (plus the other junk). Where did the missing mass go?

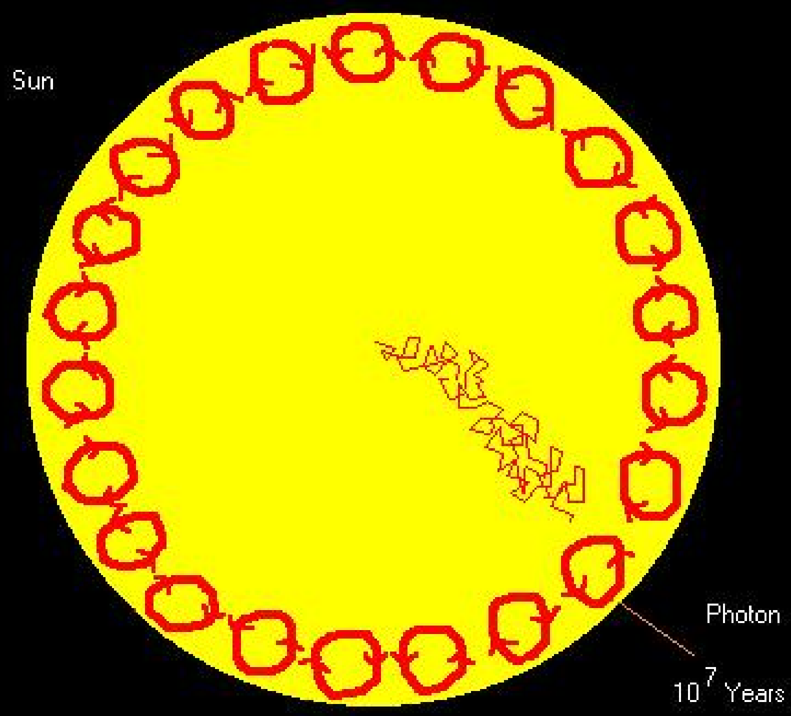
  $E = mc^2$ *Energy!!!*

- If the Sun had more mass, it would have more gravity, and its center would be under greater pressure. The greater the pressure, the greater the temperature, and the more violent the nuclear collisions. More fusion would occur, and more energy would be produced. *This explains the main sequence*!
- Fusion only occurs in the core, where the temperature and density are greatest. The rest of the star just sits there.

The Sun Won't Shine Forever

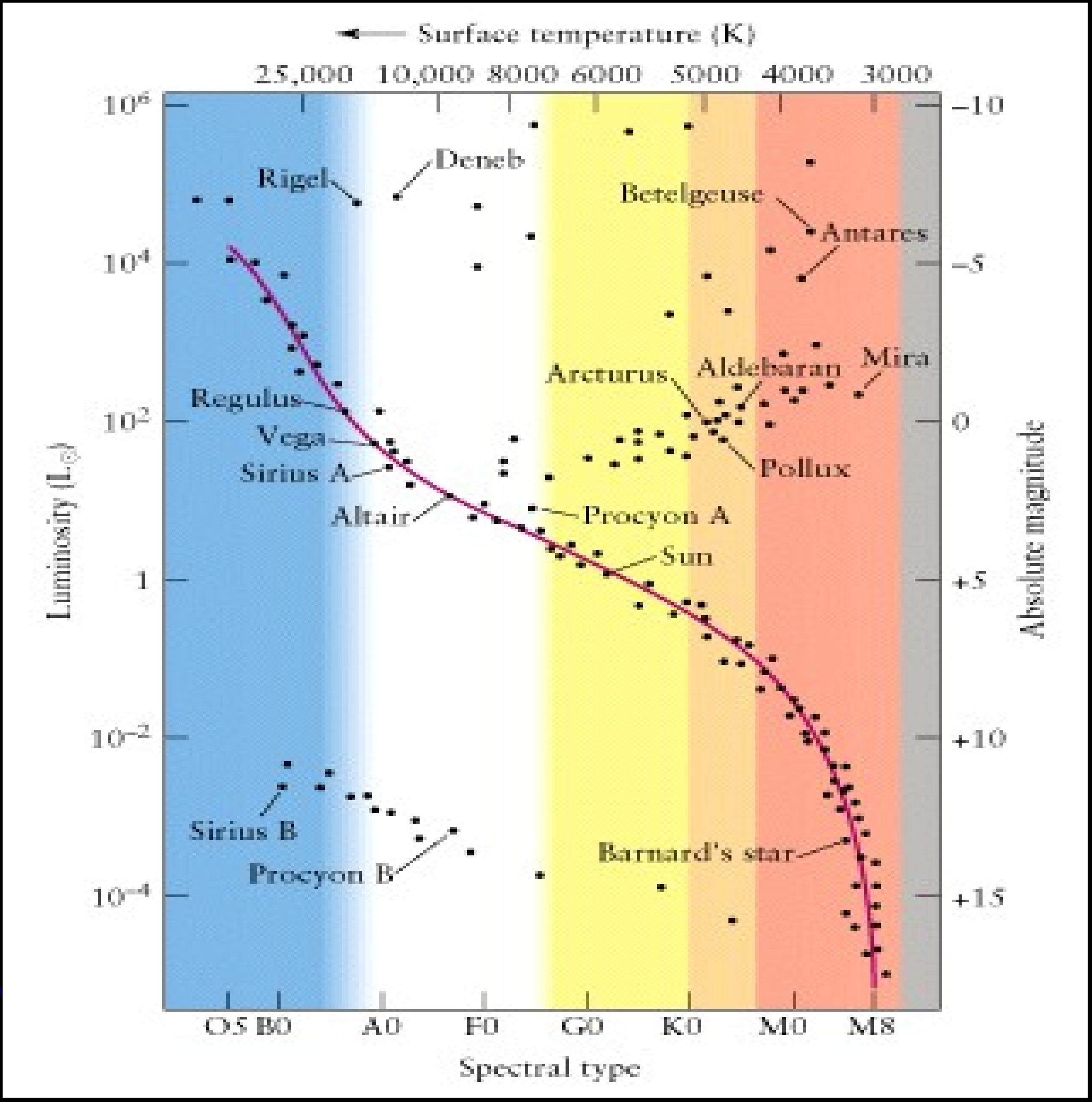
- Stars spend over 90% of their life on the main sequence, fusing hydrogen to helium. The Sun has already lived 4.5 billion years. It will live about 5 billion more years.

Stars transport energy via radiation, not convection. So hydrogen from the outside of the star does not get mixed into the core. When the core's hydrogen runs out, bad things begin to happen.

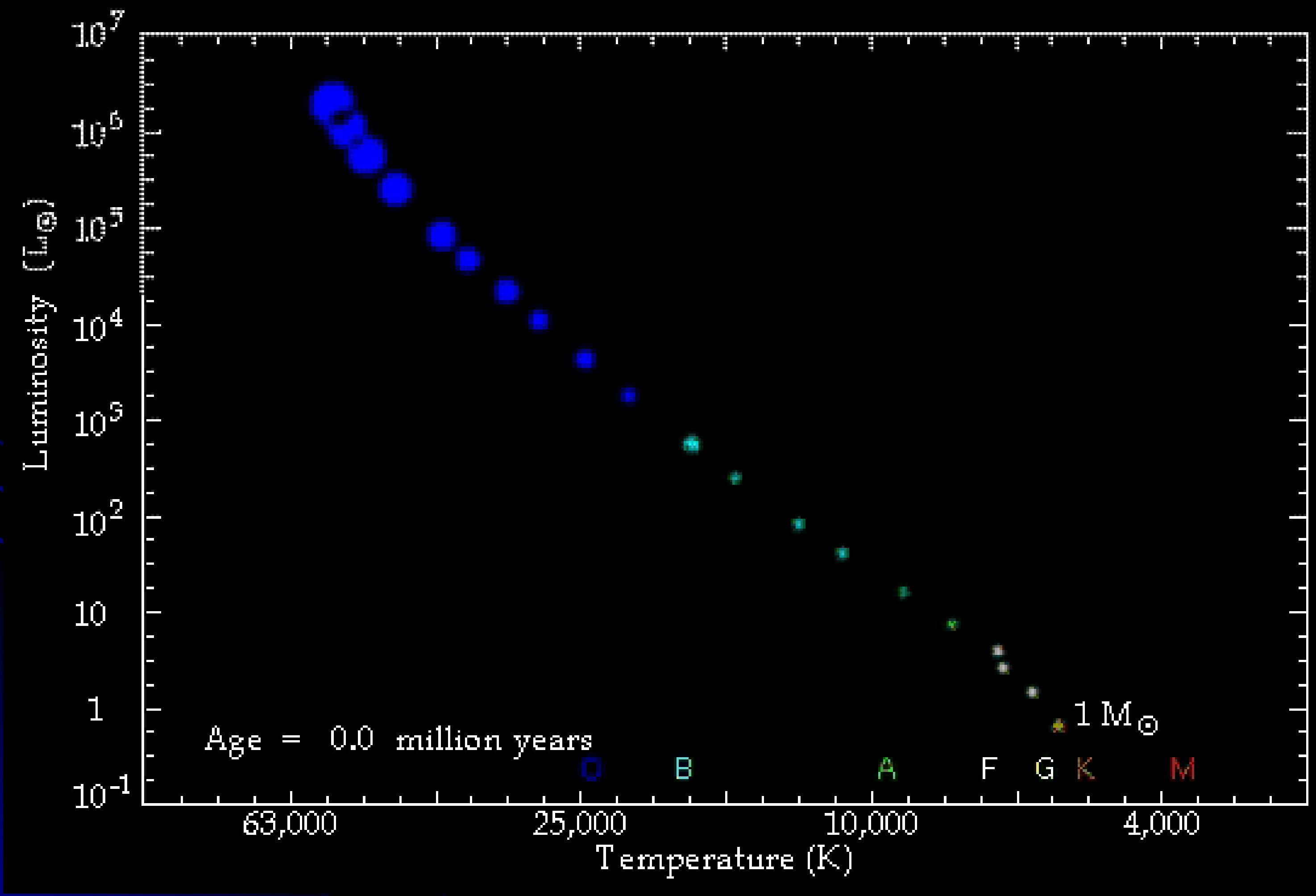


Warning

Stars spend over 95% of their life on the main sequence fusing hydrogen to helium. Although a lot of time will be spent on their subsequent evolution, post main-sequence evolution happens very fast.

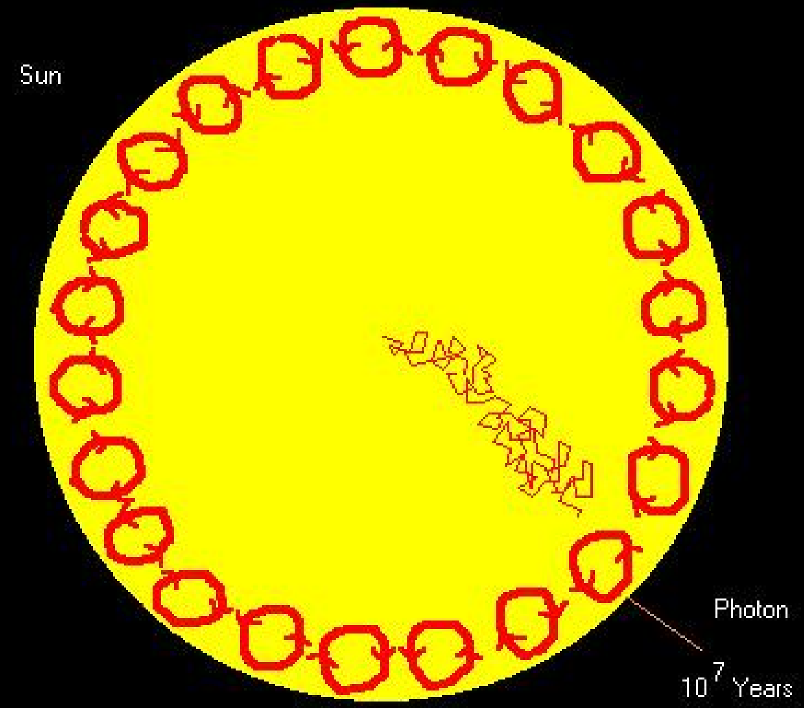


Star evolution movie



Warning

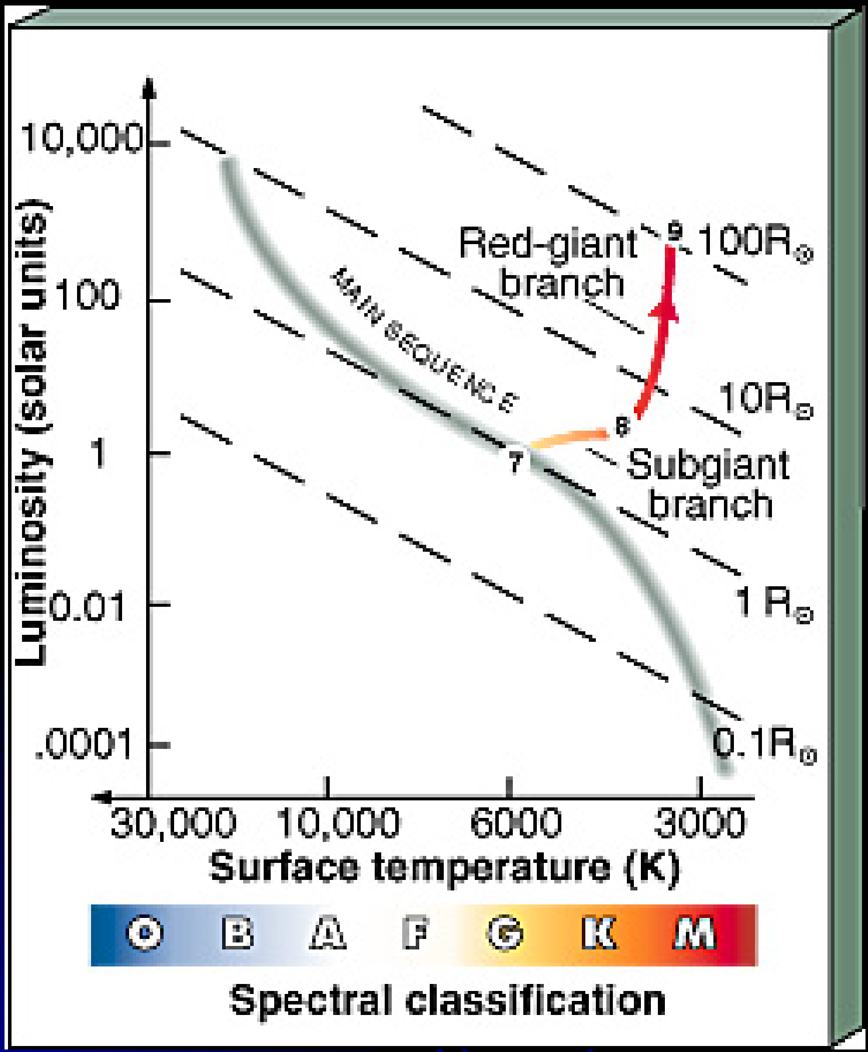
Stars do not convect – all the evolution occurs in their core. The envelope and atmosphere of the star just sit there. We do not directly see the results of the core's nuclear fusion.

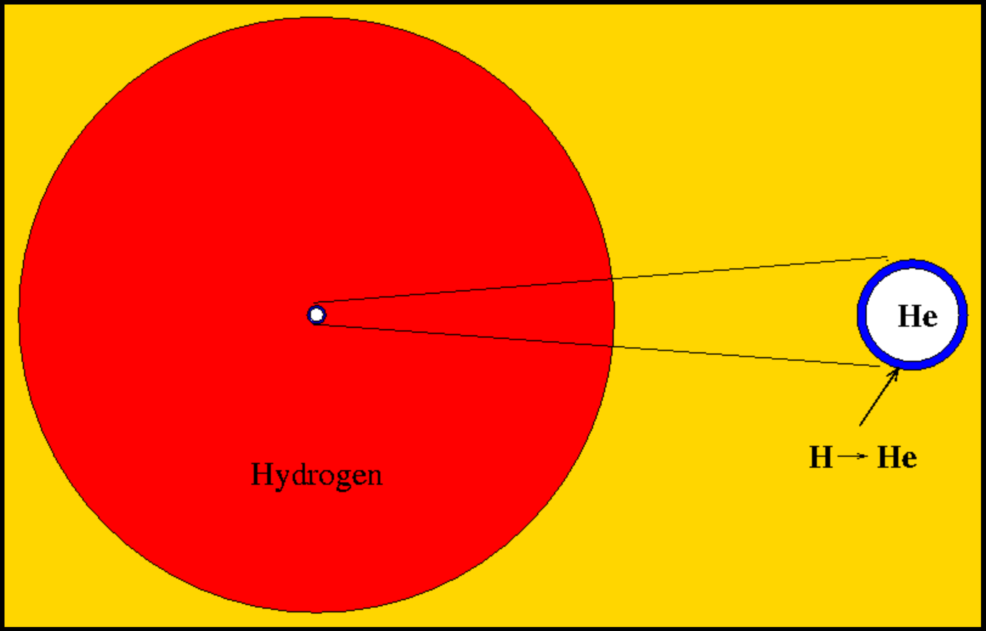


Turning off the Main Sequence

- When all the hydrogen in a stellar core is changed to helium, there is no more energy to hold it up. Gravity takes over and the core contracts. This produces energy.
- In the area right surrounding the core, there is plenty of hydrogen. The pressure in this area increases (since contraction increases the gravity), and hydrogen begin to fuse. This shell burning also produces energy. Since the star now has two sources of energy, it becomes extremely bright.
- The energy from this fusion (the radiation pressure) literally blows up (expands) the outer parts of the star many, many times. The surface of the star is moved far, far away from where the fusion is occurring, and so becomes cool. The star is now a Red Giant.

Red Giant Stars





All stars will eventually become red giants

Why Doesn't Helium Fuse?

In the center of a red giant, helium nuclei collide all the time. But

- There is more electrostatic repulsion (2 protons in each atom)
- When two helium do fuse, they create

$$^{4}He + {}^{4}He \rightarrow {}^{8}Be$$

But beryllium-8 is unstable and decays almost immediately into

$$^{8}Be \rightarrow {}^{4}He + {}^{4}He$$

The result – NOTHING HAPPENS!

The Triple-Alpha Process

Finally, the red giant core becomes so dense and so hot that 3 helium nuclei (sometimes called α-particles) can collide at once.

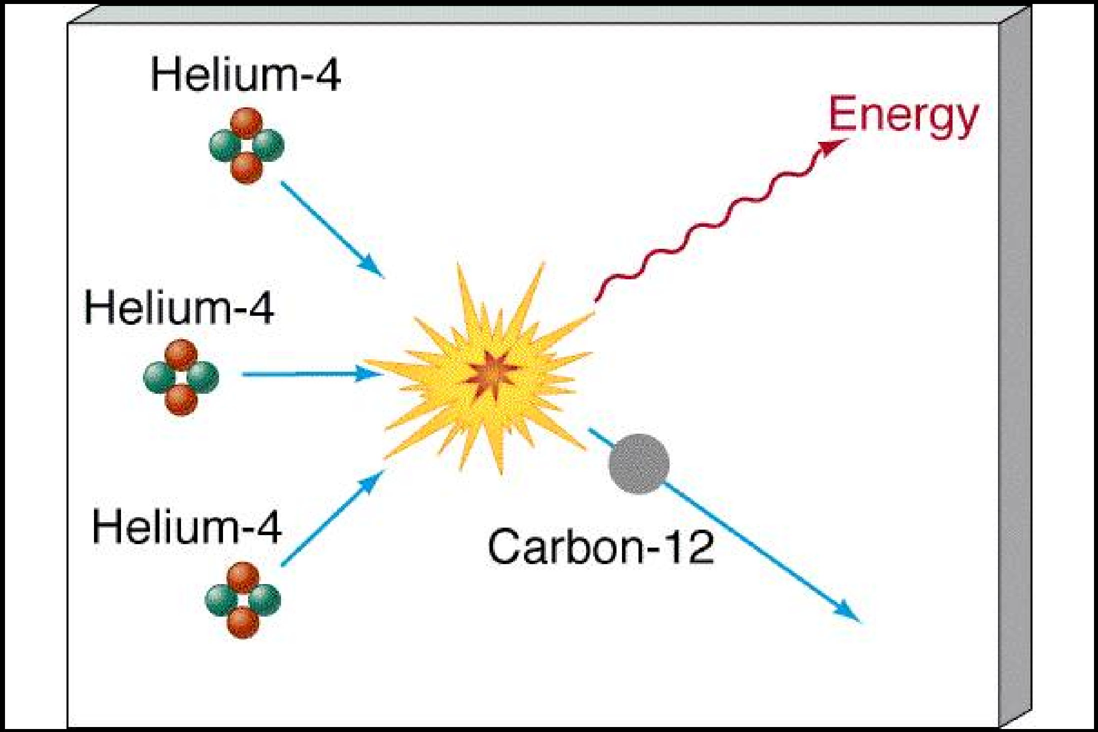
$$3\ {}^{4}He \rightarrow {}^{12}C$$

then

$$^{12}C + {}^{4}He \rightarrow {}^{16}O$$

Note: ^{12}C weighs less than three ^{4}He

($E = m c^2$)

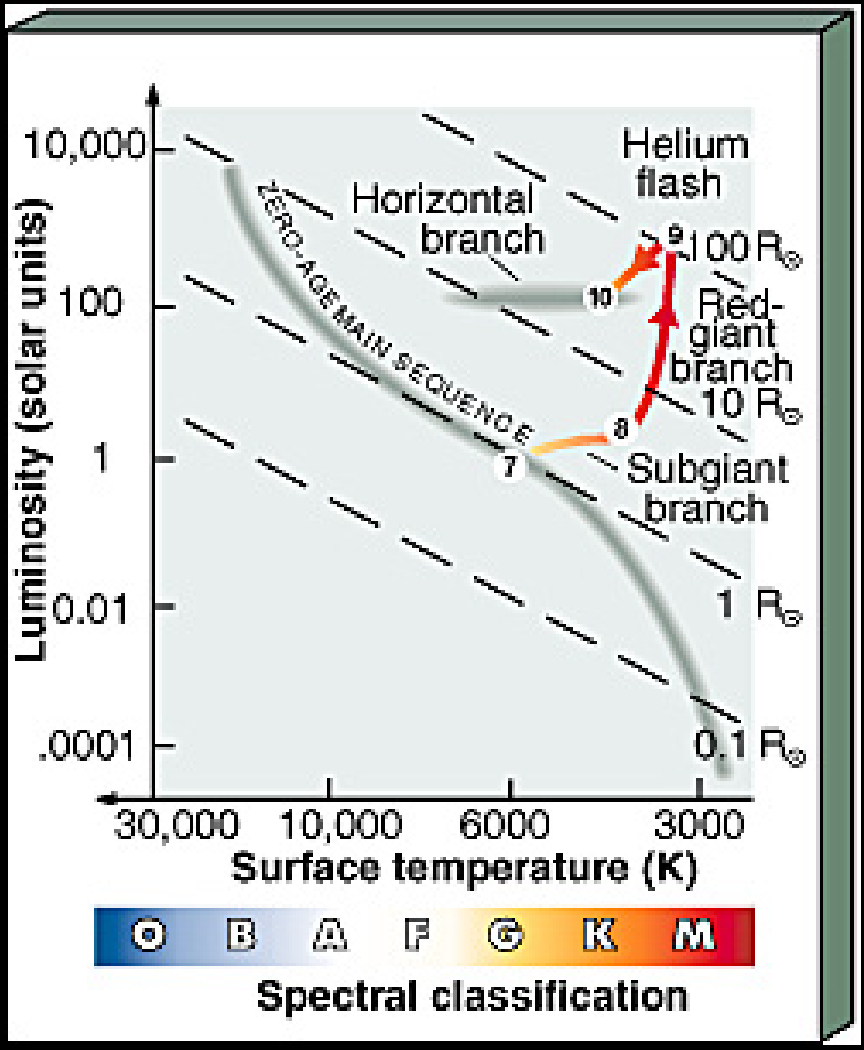


When this happens, energy is released in the core. The energy heats the nuclei and creates more fusion. Within seconds, the entire core is fusing helium. This is called the Helium Flash.

After the Helium Flash

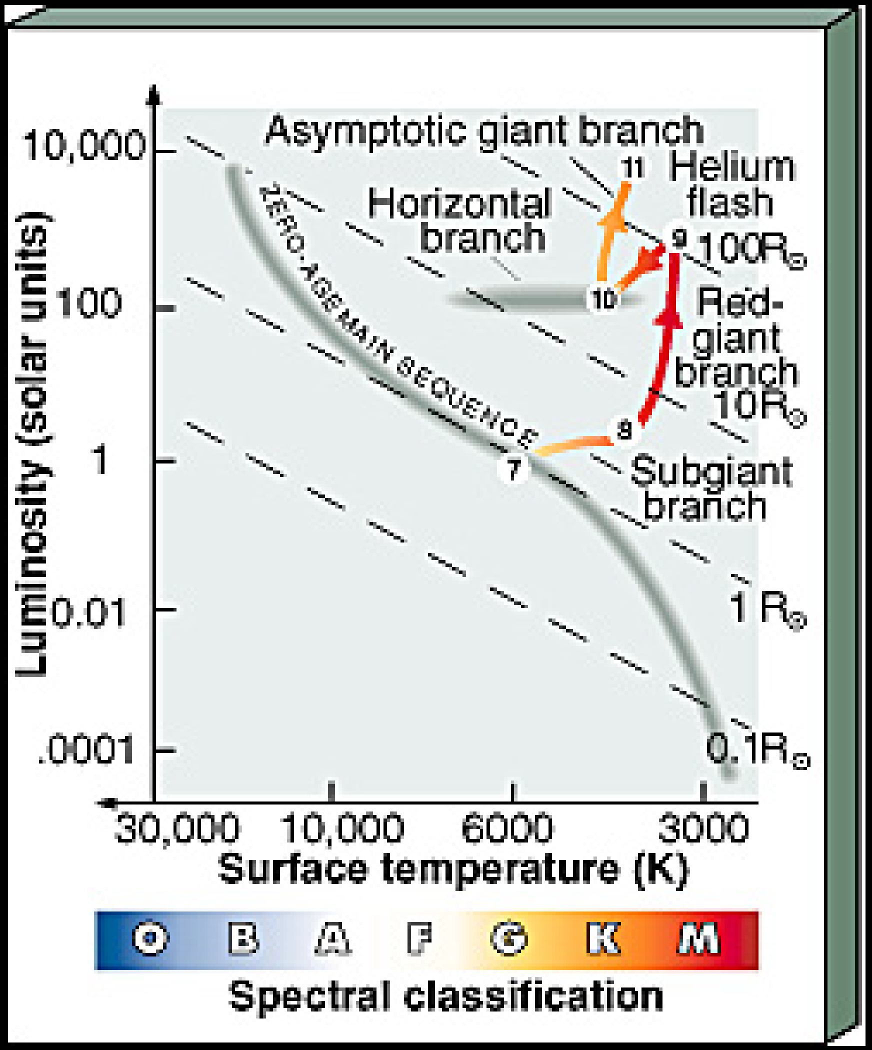
When the helium flash occurs, energy is released in the core. The gas pressure increases, the core expands, the pressure in the shell decreases, and shell-burning stops. The star gets dimmer, and contracts!

Since the surface is now a bit closer to the fusion, the star's surface gets hotter.



Back to the Giant Branch

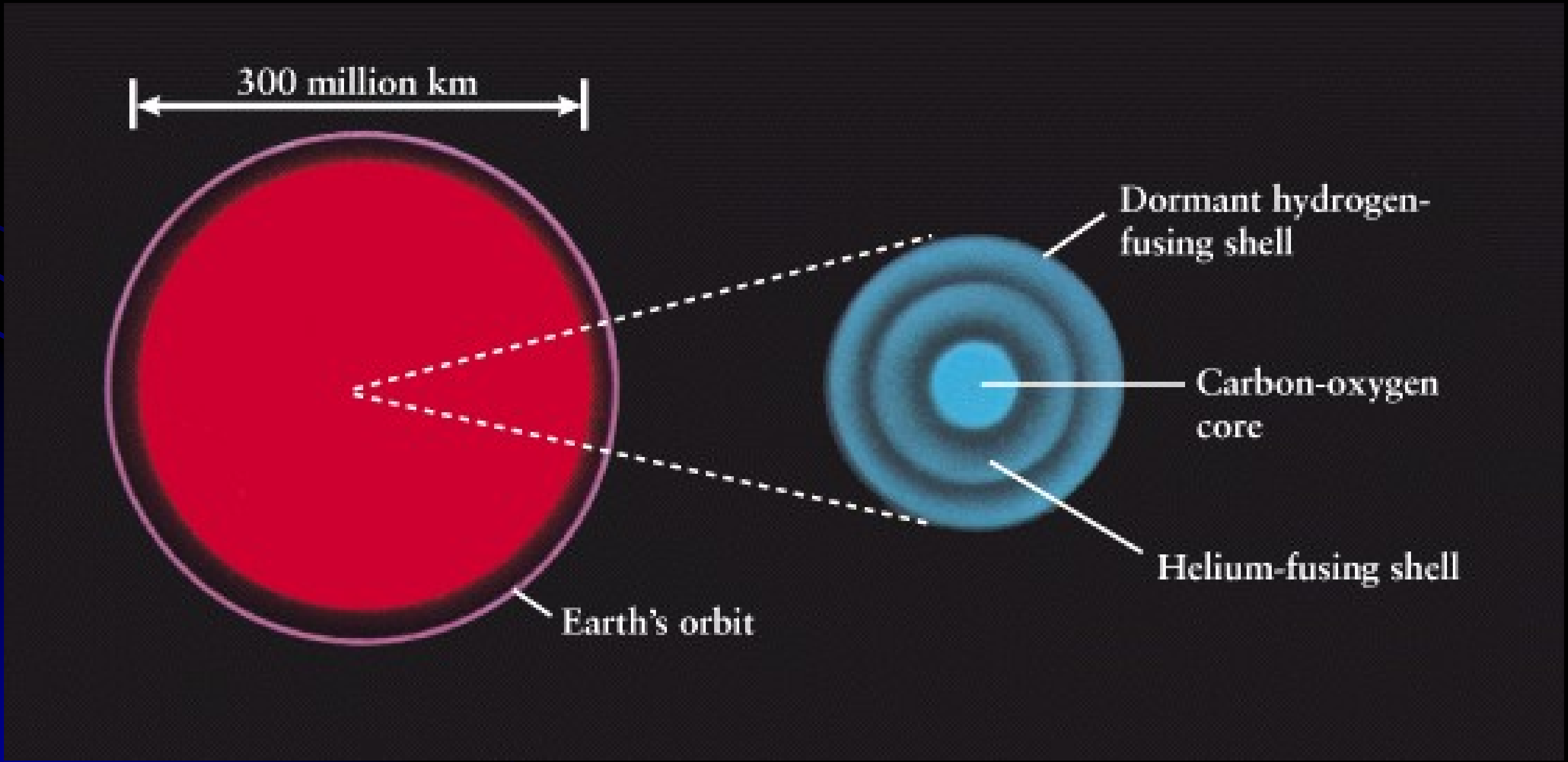
Helium fusion produces energy, but not nearly as much as hydrogen fusion. Very quickly, the helium in the core is exhausted. Once again, there is no source of energy in the core, so it contracts, and forms a helium fusing shell. Just like before, the star moves back to the giant branch, only this time, it's even brighter!



The 2nd Giant Branch

Stars that have returned to the giant branch have

- A small, gravitationally contracting carbon-oxygen core
- A thin shell around the core fusing helium to carbon/oxygen
- A thin shell around the He shell fusing hydrogen to helium
- A **huge** surrounding envelope



Stellar Mass Loss

The gravity at the surface of a red giant star is extremely weak. Any excess motion in the stellar atmosphere can cause the star to lose its mass into space. During this phase, stars can lose a lot of mass.

The Creation of Dust

The atmosphere of a red giant star is less than 3,000°. At those temperatures, carbon and silicon bond to each other (and other atoms) to make soot and sand. When the atmosphere is lost, this stuff becomes interstellar dust.

The Death of a Low Mass Star

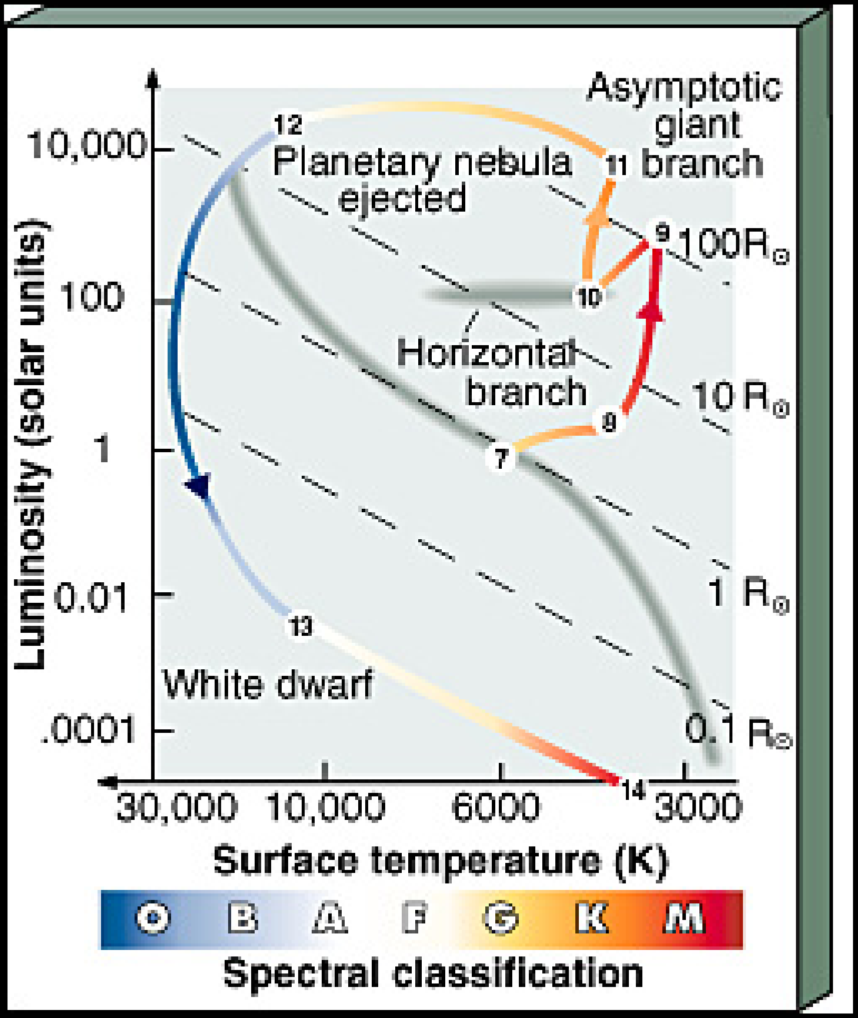
- After mass loss, stars that with initial masses less than about 8 $M_{\odot}$ have final masses less than 1.4 $M_{\odot}$. The electrostatic repulsion of carbon (6 protons) and oxygen (8 protons) is so great that these objects cannot fuse carbon and oxygen.
- When on the 2nd Giant Branch, these stars continue to lose mass from their surface and fuse hydrogen to helium to carbon/oxygen in their shells, until nothing is left. Eventually, all that is left is a very hot core of carbon/oxygen and a very, very, thin envelope.

The Planetary Nebula Stage

Near the end of its life, the envelope of a low-mass star is so thin that it cannot absorb all the high-energy photons emitted by the *very, very, hot* core.

These photons escape and ionize the mass that was recently lost from the star. You see a planetary nebula.

(Note: this is a stupid name for the object – planetary nebulae have nothing to do with planets.)



Planetary Nebulae

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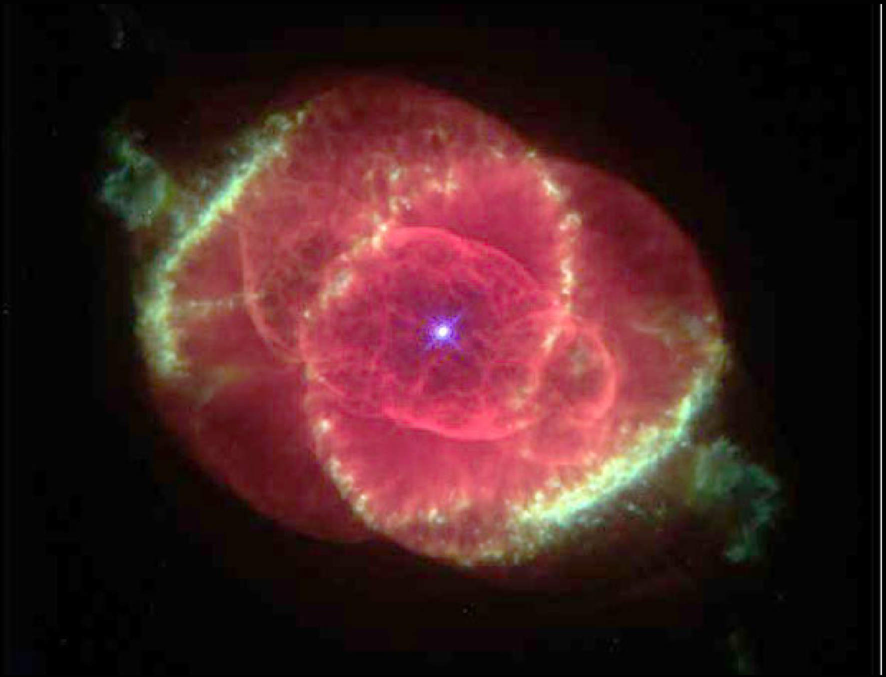
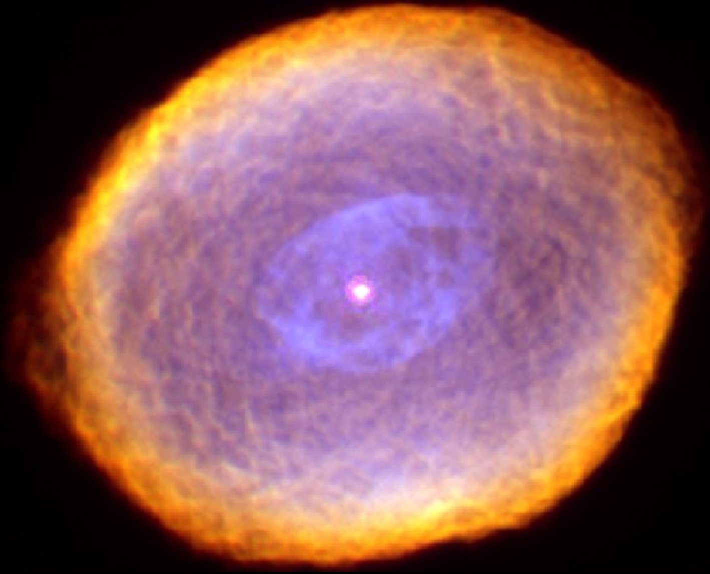
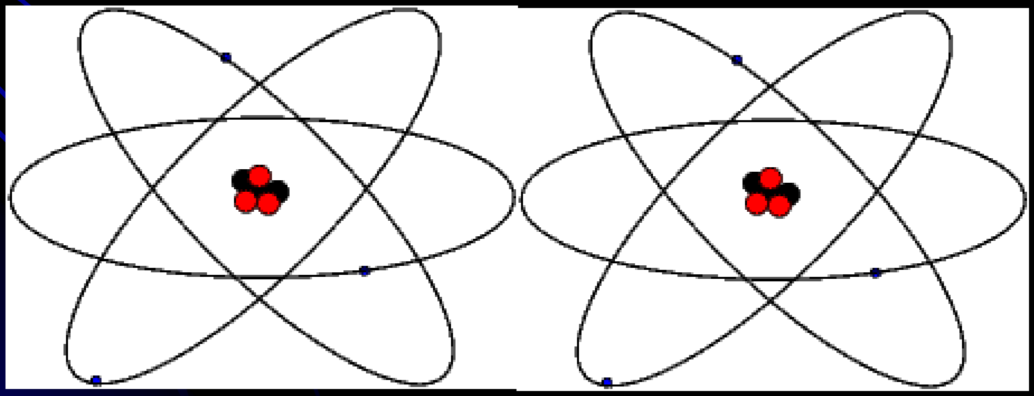




The Endpoint – A White Dwarf

- After the planetary nebula stage, all that's left of the star is the hot carbon-oxygen core.
- Since the core is cooling, the gas pressure becomes less and less, so gravity continues to contract the star.
- Finally, the electrons in the atoms will be squeezed no further. (Remember, they're not allowed to get any closer to the nucleus than their first orbital.) The star becomes supported by electron degeneracy, and will just sit there and slowly cool for the rest of eternity. It is a white dwarf.



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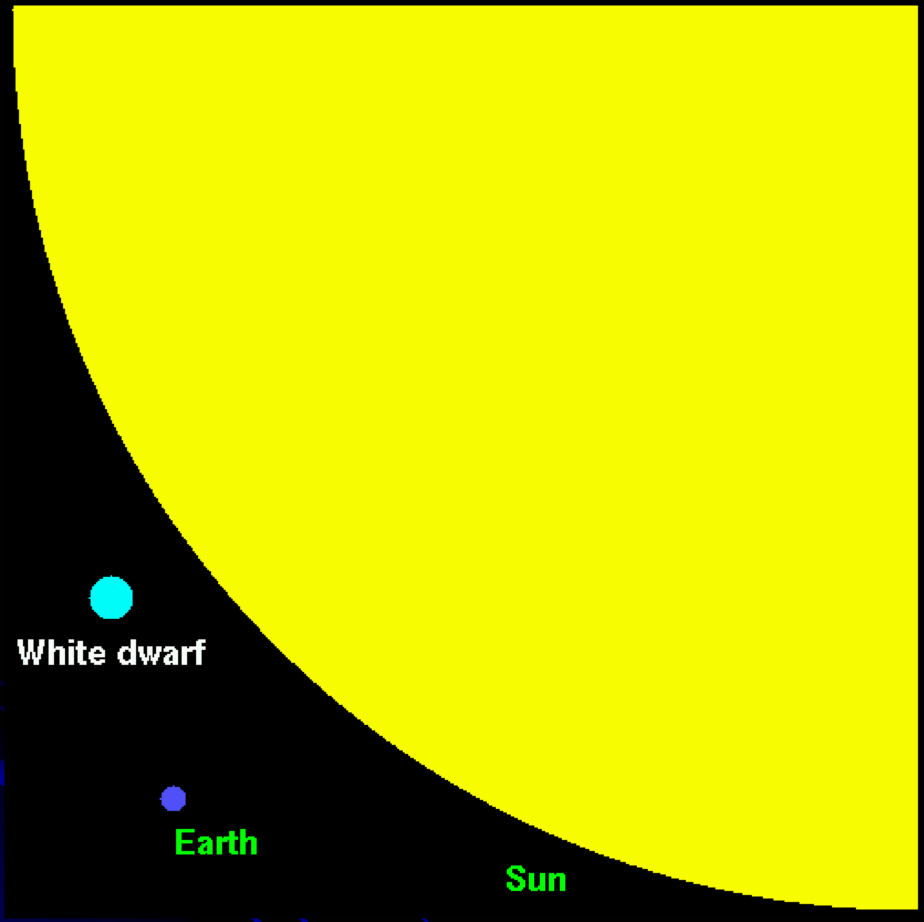
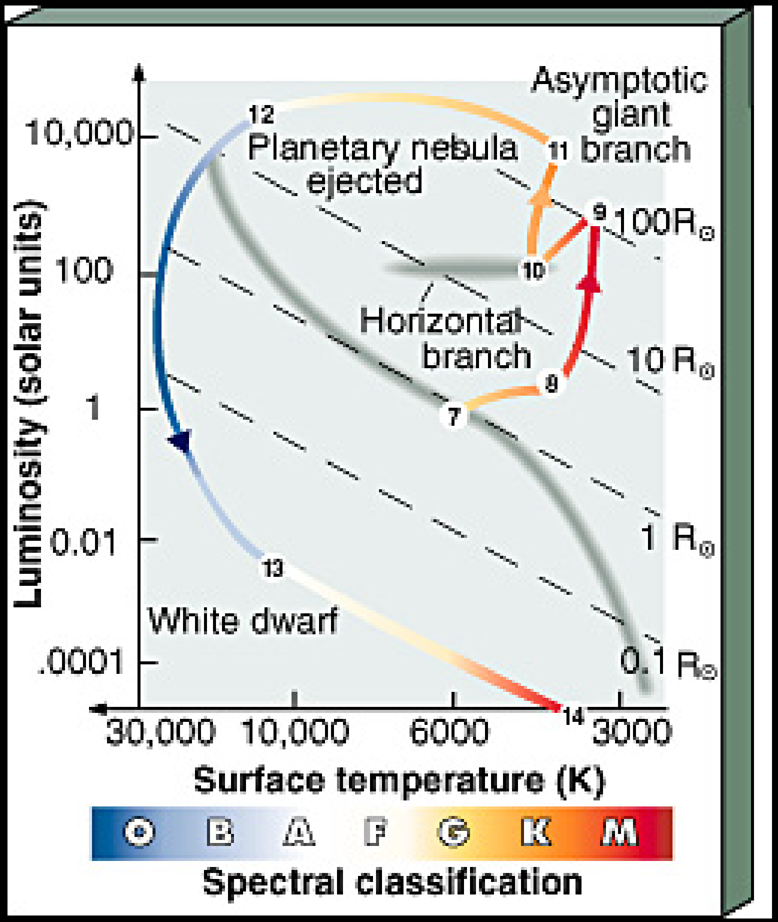
- As the star slowly cools, it will begin to crystallize. It's nice to think that the eventually the Sun will become a very, very, very big ……………………………

Twinkle, twinkle little star…

The Endpoint – A White Dwarf





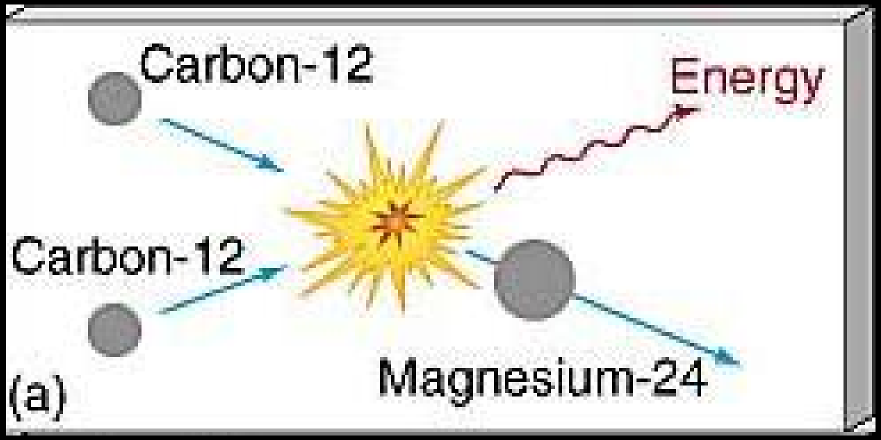
Note: Electron Degeneracy only works if the star is less than 1.4 $M_{\odot}$. This is the Chandrasekhar Limit. If the star is more massive than 1.4 $M_{\odot}$, something else must happen.

Low Mass ($M < 8\ M_{\odot}$) Stellar Evolution

- Main Sequence (core hydrogen fusion)
- Red Giant Star (core contraction, shell hydrogen fusion)
- Helium Burner (helium fusion in core)
- 2nd Giant Branch (core contraction, shell hydrogen and helium fusion, mass loss)
- Planetary Nebula (ionization of mass lost as a giant star)
- White Dwarf star (inert carbon/oxygen core)

The Death of a High Mass Star

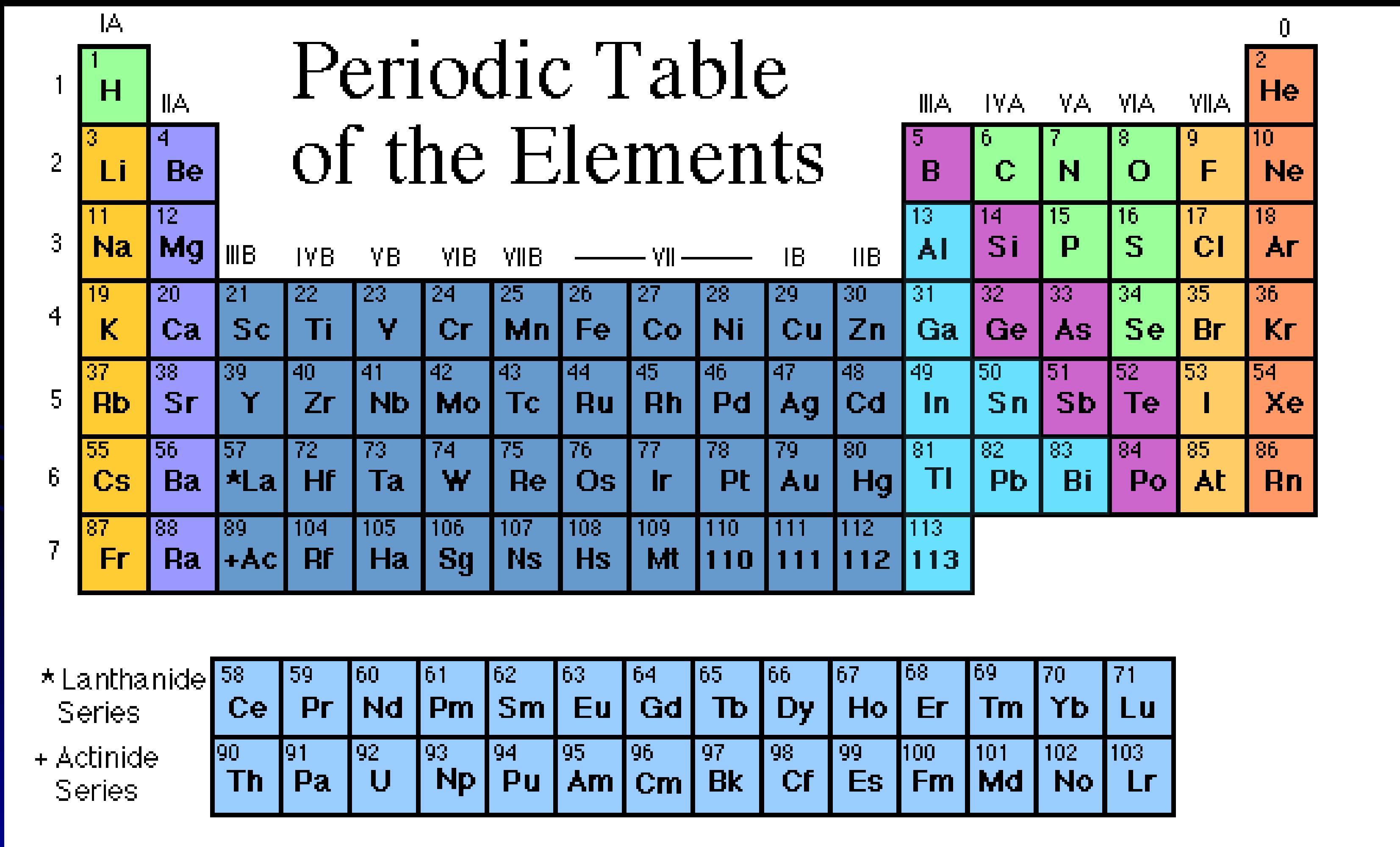
In stars with final masses over the Chandrasekhar limit, the gravity becomes so great that even carbon and oxygen can fuse. The result is a host of products, including neon, sodium, magnesium.



Since ^{24}Mg weighs less than two ^{12}C atoms, the result is energy!

The Death of a High Mass Star

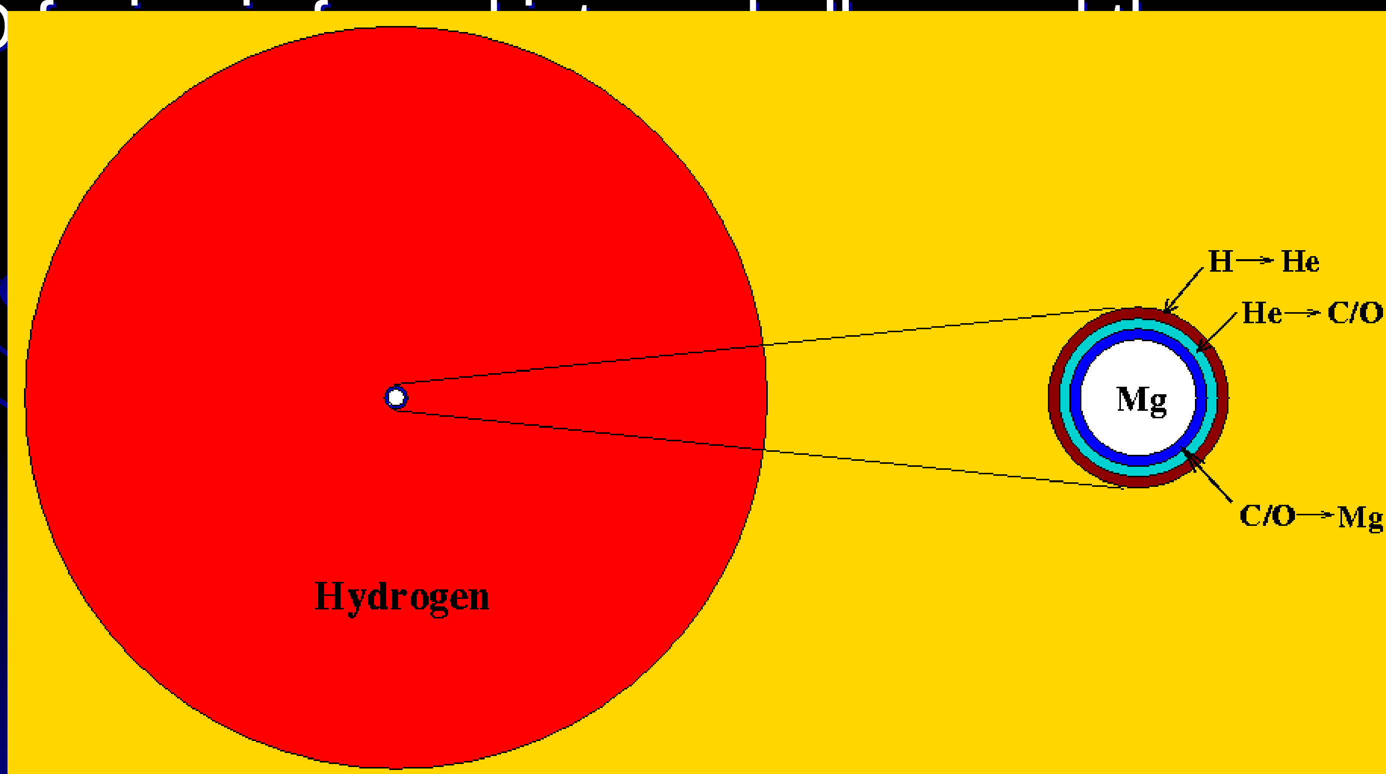
The products of fusion are getting heavier!



The Death of a High Mass Star

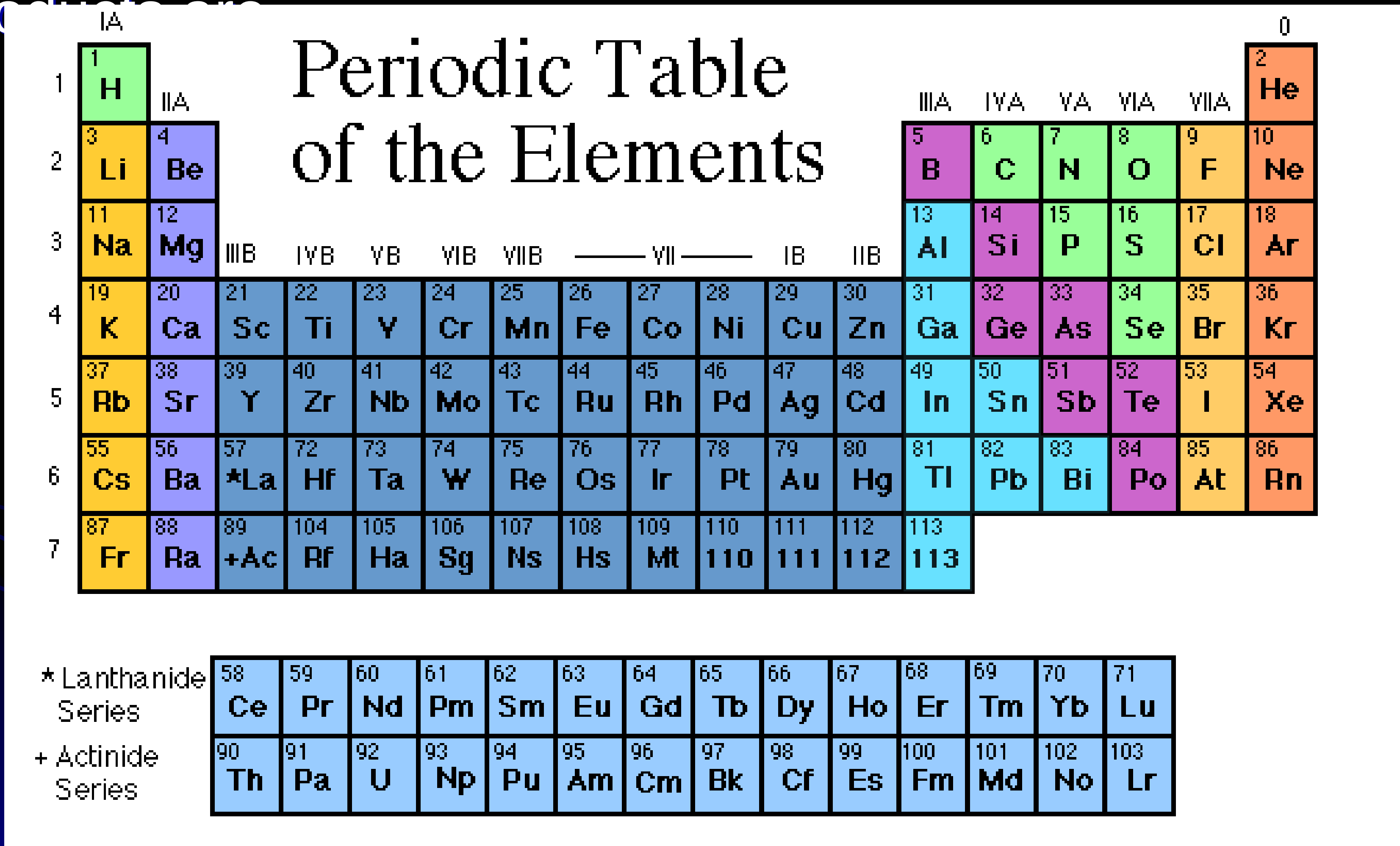
- Carbon-burning (temporarily) supplies energy to core. The core expands, shell-burning stops, and the star contracts.

- It doesn't take long to burn all the carbon/oxygen. When the C/O is gone, the core again contracts, and C/O



The Death of a High Mass Star

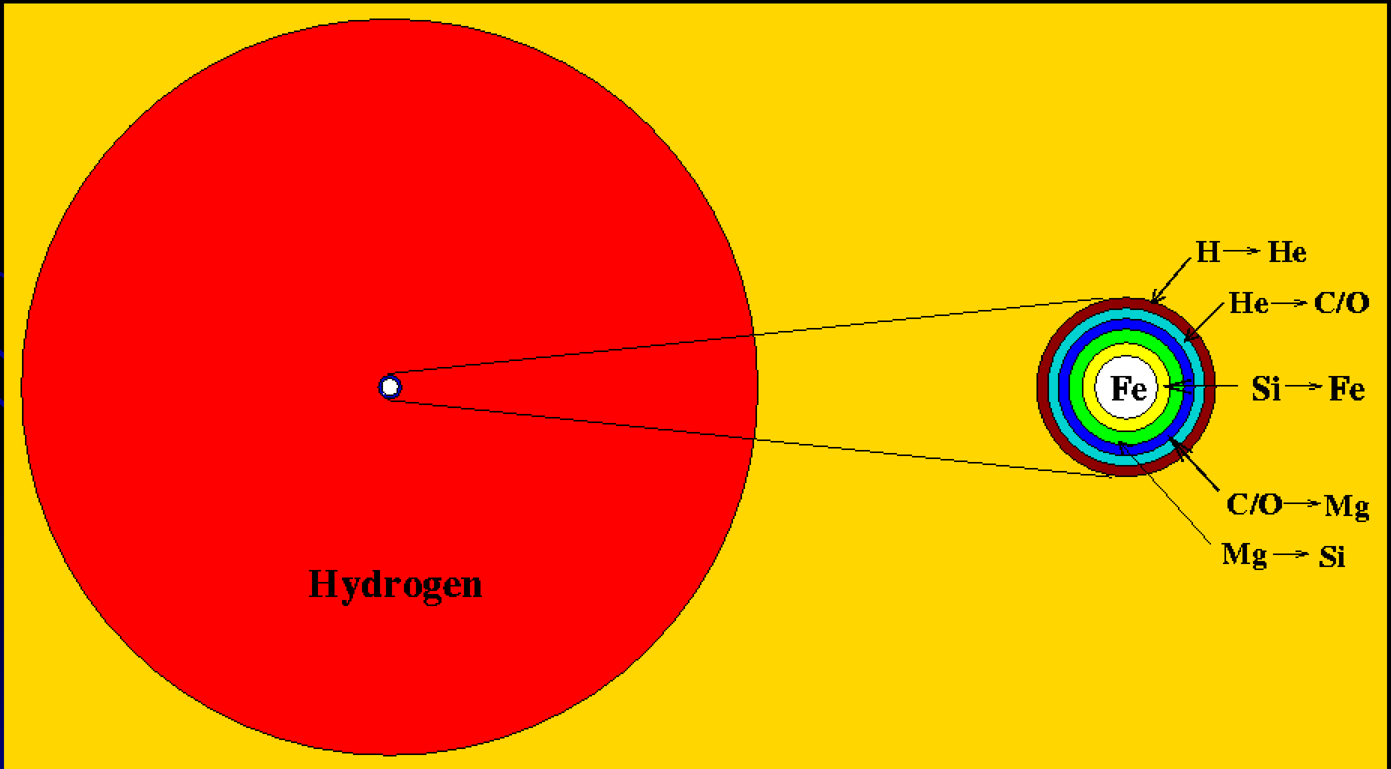
Soon, the core fuses silicon. When it does, the main products are



Iron, Cobalt, Nickel, and Energy!

The Death of a High Mass Star

- This time silicon-burning (temporarily) supplies the energy. The core expands, shell-burning stops, and the star contracts.
- Silicon fuses extremely quickly, and when it's gone, the core again collapses, and shell burning begins.

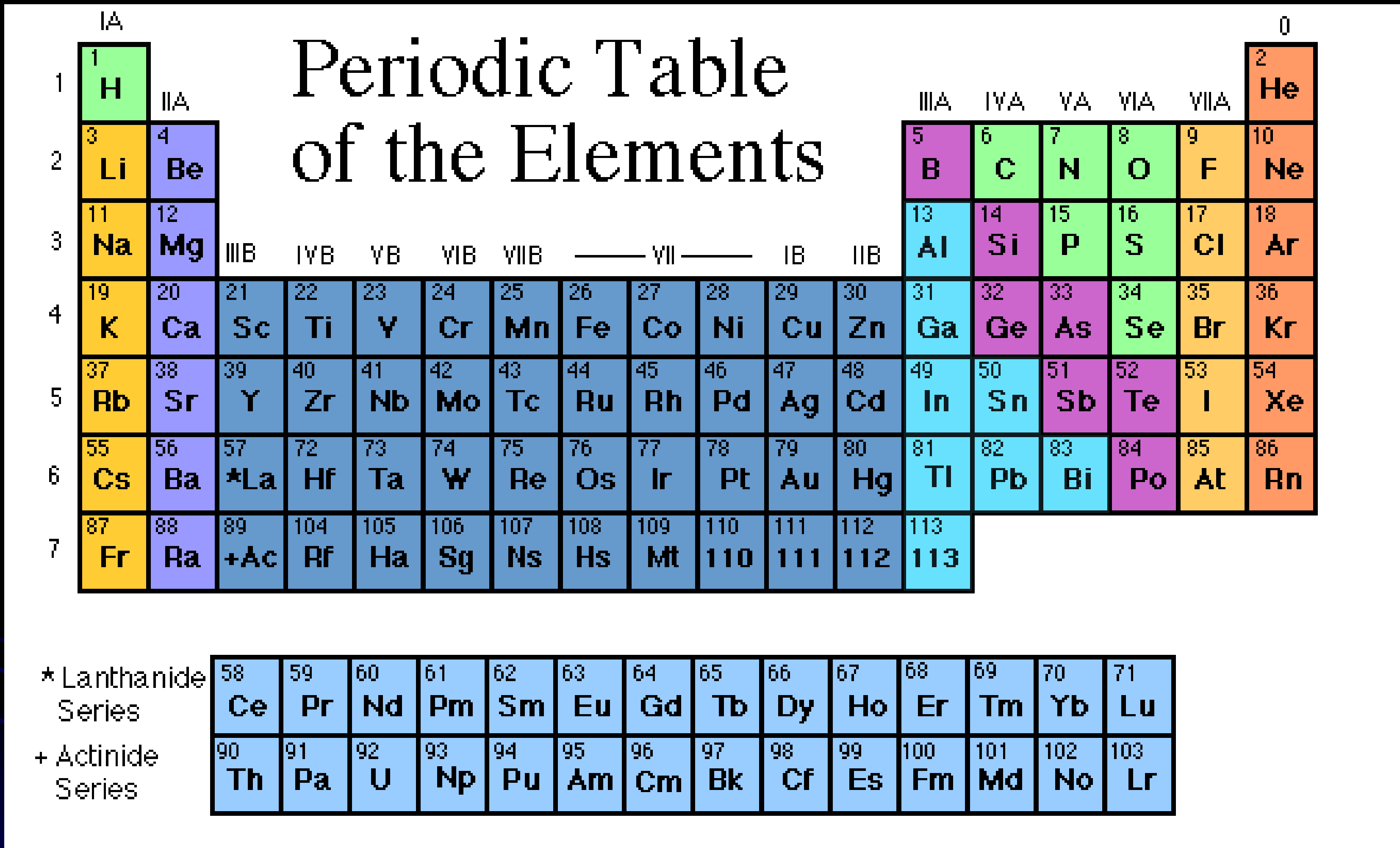


The Death of a High Mass Star

When the star's core turns to iron, it again collapses. The increased pressure and temperature then causes iron to fuse. However…

The products of iron fusion weigh *more* than the initial iron nucleus. According to **$E = m c^2$**, this means that iron fusion does not make energy, it steals energy.

Fission and Fusion



Up to iron, the products are lighter than the ingredients: **+ $m c^2$**

After iron, the products are heavier than the ingredients: **- $m c^2$**

The Death of a High Mass Star

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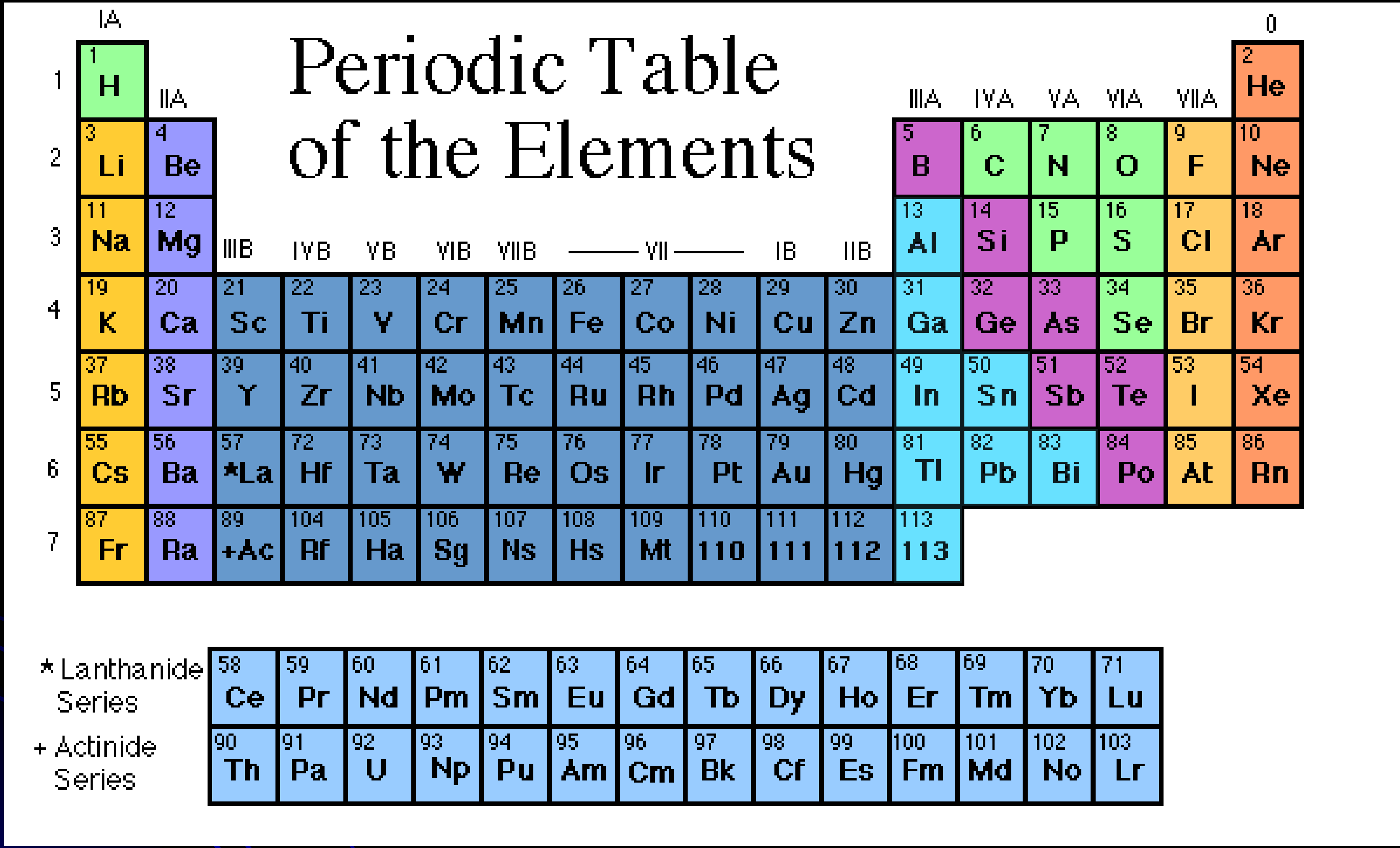
The products of iron fusion weigh *more* than the initial iron nucleus. According to **$E = m c^2$**, this means that iron fusion does not make energy, it steals energy.

The more iron that fuses, the more energy is taken out of the core. The temperature decreases, the gas pressure decreases, the core collapses faster, more iron fuses and …

Supernova

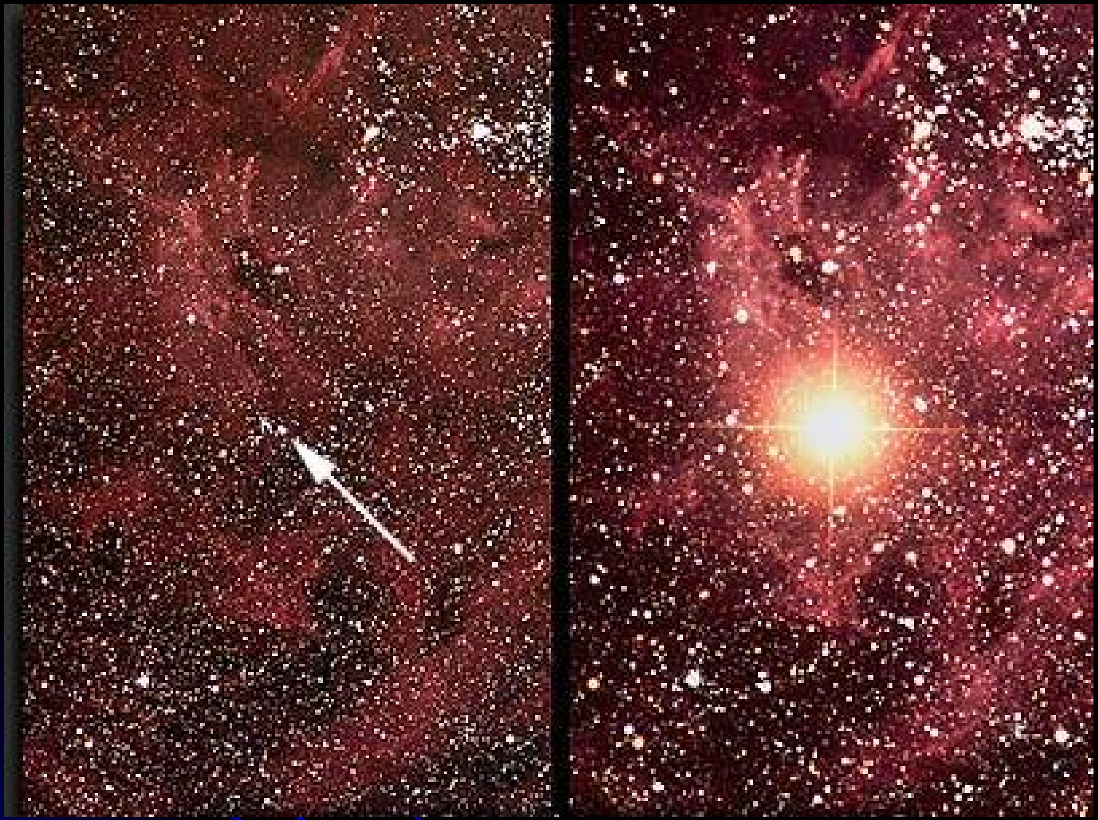
The star explodes! And, in that explosion, every element heavier than iron is created. This is the only way elements such as iron (or silver or gold, etc.) can be created – in a supernova explosion.

The Products of Supernovae



In a supernova, all the elements previously made in a star are thrown out into space. In addition, every element heavier than iron is made and ejected as well.

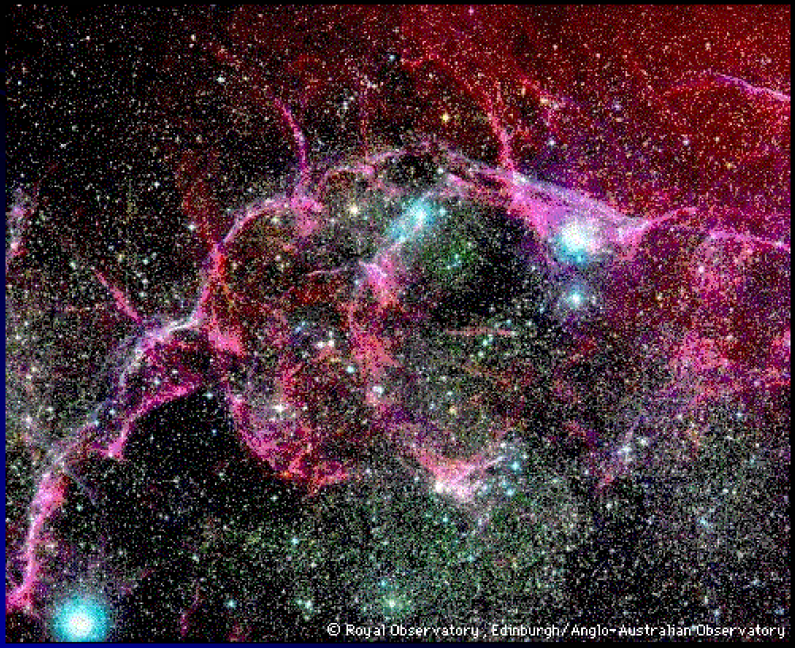
The Supernovae

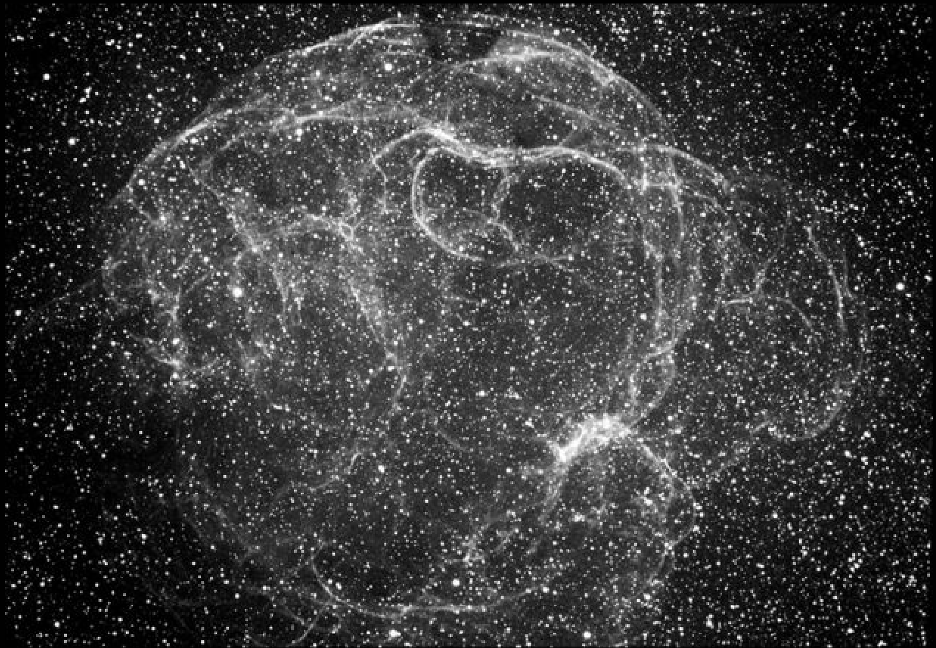


For about a month, a supernova will outshine an entire galaxy of 100,000,000,000 stars!

Many of the elements made in a supernova explosion are radioactive, *i.e.*, they make energy by nuclear fission. This is keeps the star bright for some time.

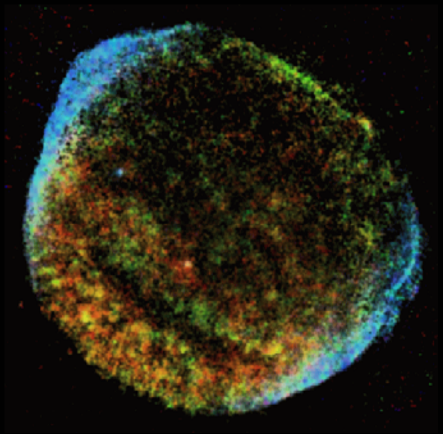
Supernova Remnants





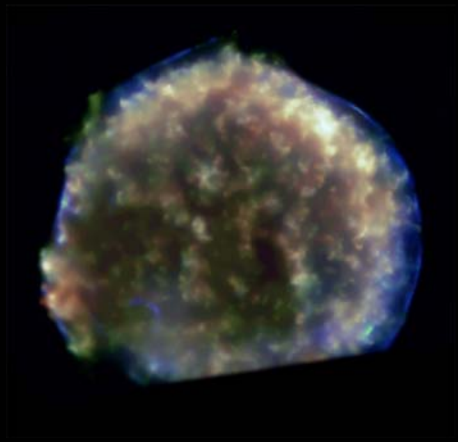
Galactic Supernovae

In a galaxy such as the Milky Way, a supernova occurs once every couple hundred years. The last few were



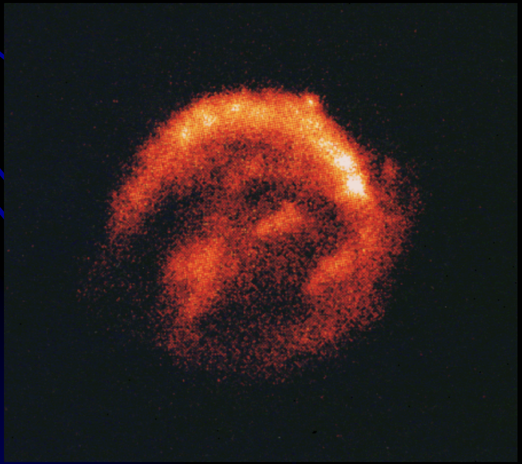
SN 1006
(1006 A.D.)

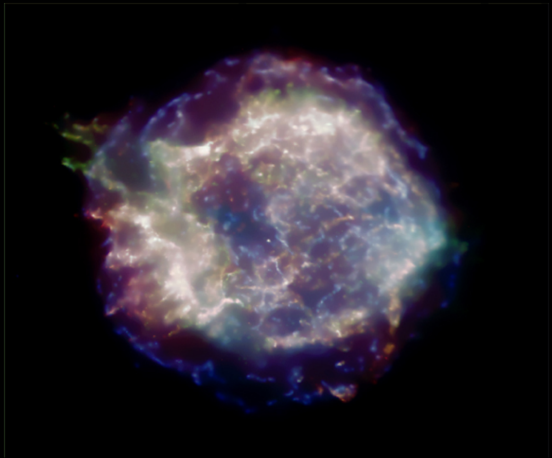
Crab Supernova
(1054 A.D.)



Tycho's Supernova
(1572 A.D.)

Kepler's
Supernova
(1604 A.D.)





Casseopia A
(1680 A.D.?)