Astronomy 330

This class (Lecture 6):

Why does the Sun shine?

Next Class:

Making C, O, and N

HW2 due Thursday

Music: *Carl Sagan -Glorious Dawn*– Colorpulse
http://www.youtube.com/watch?v=zSgiXGELjbc&feature=fvw

Outline

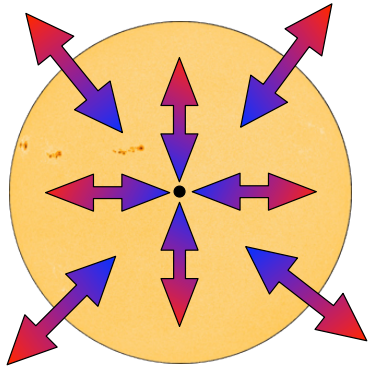
- Why does the Sun shine?
- Sneaky little neutrinos (proof of fusion)
- C and O for the first time (1st gen of stars)
- N for the first time (2nd gen of stars)

The Sun

- We spent the last class discussing hydrostatic equilibrium in the Sun.
- In groups write a 4-5 sentence explanation of hydrostatic equilibrium in the Sun. What would be a great example of this one could do in the classroom?

Life as a Main Sequence Star

- Main sequence stars generate energy by hydrogen fusion
- Long, stable part of a star's life
- Energy generated keeps their interiors hot
- Resulting pressure balances gravity and prevents the star from collapsing



In a main sequence star, gravity and pressure are in balance

The Sun's Energy Output

3.85 x 10^{26} Watts, but how much is that?

A 100W light bulb…

…the Sun could supply 4 x 10^{24} light bulbs!

U.S. electricity production in 2010: 4.1 trillion kWh…

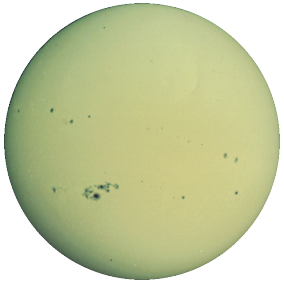
… Sun = 3 x 10^{7} times this *every second*

World's nuclear weapons: 3 x 10^{4} megatons…

… Sun = 4 million times this *every second*

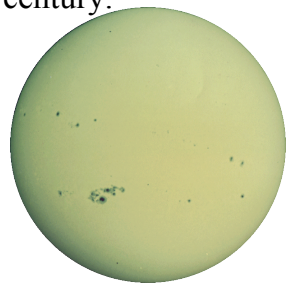
So, What Powers the Sun?

- The Sun does not collapse nor even change it's radius.
- Gravity pushes in, but what pushes out?
  - Okay, heat, but what makes the heat?



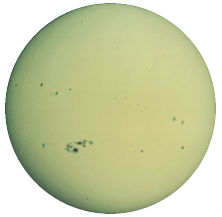
So, What Powers the Sun?

- What is its power source?
- What keeps the Sun hot? It doesn't cool like a hot coffee cup.
- Biggest mystery in Astronomy up until 20th century.



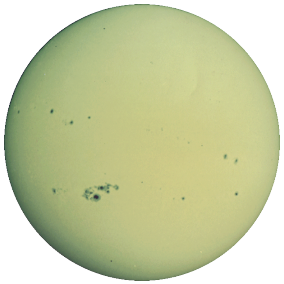
How to Test?

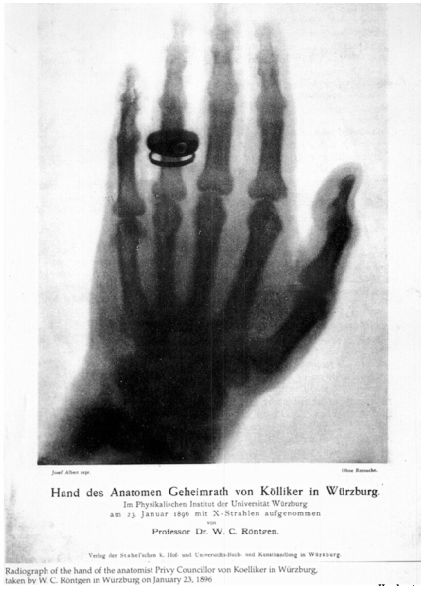
- Without an energy source, the Sun would rapidly cool & contract
  - Darwin: evolution needs Sun & Earth to be > 10^{8} years old
  - Lyell: geological changes also need > 10^{8} years
- Process must be able to power Sun for a long time! At least 4.5 Byrs.



So, What Powers the Sun?

Discuss with neighbors possible heating options. List at least 2 possibilities, even if you know the correct one. List all feasible ideas.



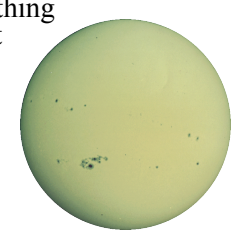


Radiograph of the hand of the anatomist Privy Councillor von Koelliker in Würzburg, taken by W. C. Röntgen in Würzburg on January 23, 1896

Eyes began to turn to the nuclear processes of the Atoms

How to Test?

- Gravity:
  - Seems like a good idea. Remember Jupiter gives off heat.
  - A contracting Sun releases gravitational energy.
  - But only enough for 20 million years
- Chemical:
  - If the Sun was made from TNT, something that burns very well, then it would last for only 20,000 years
- Need something more powerful!



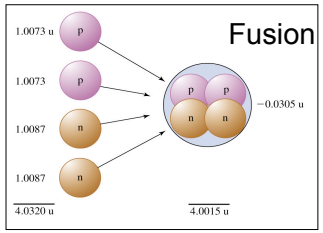
What is Fusion?

$$4\,p \rightarrow {}^{4}\mathrm{He}\ (2p,2n)$$

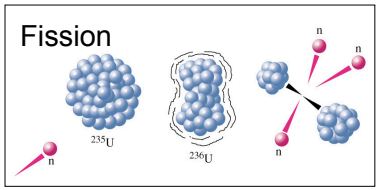
Basic idea is to take 4 protons (ionized hydrogen atoms) and slam them together to make an ionized helium atom.

Fusion vs. Fission

- Light nuclei: fusion
  - Fuse together light atoms to make heavier ones
  - Happens in the Sun
  - H-Bomb

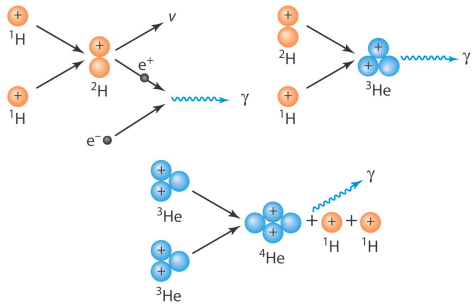


- Heavy nuclei: fission
  - Break apart heavier atoms into lighter ones
  - Used in power plants
  - A-Bomb



Nuclear Fusion in the Sun's Interior

- Proton-Proton Chain
  - 4 hydrogen atoms fuse to make 1 helium atom
  - Requires very high density and temperature (at least 7 million K)

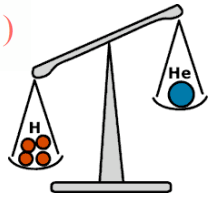


The Proton-Proton (p-p) Chain

Why does fusion release energy?

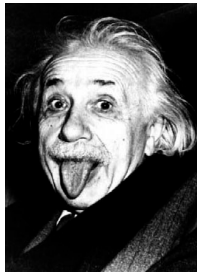
Fusion: $4\ p \rightarrow {}^{4}\mathrm{He}\ \ (2\ p, 2\ n)$

Fact: **4m(*p*) > m(⁴He)** !
mass of whole < mass of parts!



Einstein says ***E* = *mc*²**:
- Mass is a form of energy!
- Each ⁴He liberates energy:

$$E_{\text{fusion}} = m_{\text{lost}}c^2 = 4m(p)c^2 - m(^4\text{He})c^2 > 0!$$

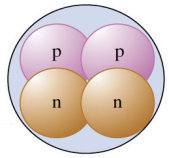


The Nucleus

- Okay, so we know that the nucleus can have numerous protons (+'s) very close.

Helium

- **Something is odd here!**
- **What is it?**
- **Discuss with neighbor.**

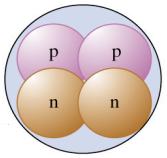


The Nucleus

- **Why doesn't the nucleus of the atom fly apart?**
- **Discuss with neighbor.**

Helium

- **Something is odd here!**
- **What is it?**



4 Fundamental Forces

- Gravity
- Electromagnetic
- **Strong Nuclear**
  - **The strongest of the 4 forces**
  - **The force which holds an atom's nucleus together, in spite of the repulsion between the protons.**
  - **Does not depend on charge**
  - **Not an inverse square law– very short range.**
- Weak Nuclear

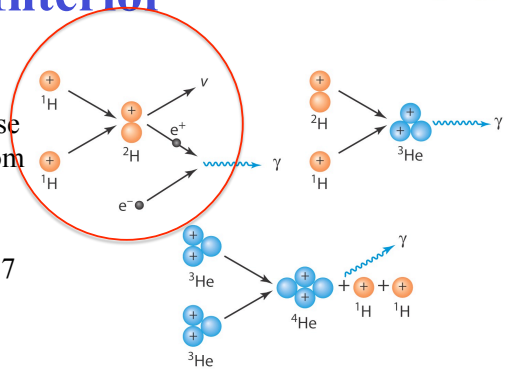
Question

Why does the Sun shine?

a) Nuclear burning.
b) Nuclear burning of helium to carbon.
c) Nuclear burning of dreams to pure energy.
d) Nuclear burning of hydrogen to helium.
e) Nuclear burning of carbon to helium.

Nuclear Fusion in the Sun's Interior

- Proton-Proton Chain
  - 4 hydrogen atoms fuse to make 1 helium atom
  - Requires very high density and temperature (at least 7 million K)



The Proton-Proton (p-p) Chain

http://www.youtube.com/watch?v=Czbh_sdqX84

Nuclear Fusion in the Sun's Interior

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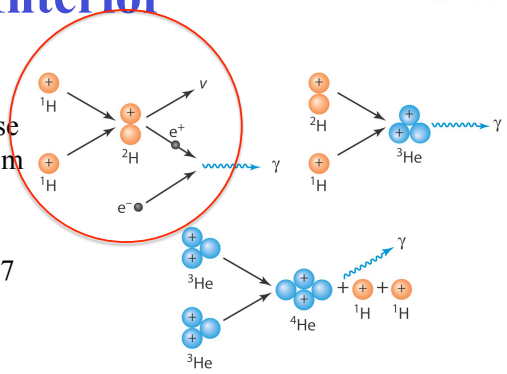

The Proton-Proton (p-p) Chain

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Nuclear Reactions in the Sun

- Chain: 4 protons ⇒ helium
- First step in chain (2 protons combine):

$$p + p \rightarrow [np] + e^+ + \nu$$

- Start with 2 particles (protons)
- End up with 4 particles (two of which are glued together)
- Each product is very interesting in its own right....

Nuclear Reactions in the Sun

$$p + p \rightarrow [np] + e^+ + \nu$$

$[np]$ = **deuterium**

- 1 proton + 1 neutron bound together into nucleus of element…
- Hydrogen, but has neutron, so 2 times mass of normal H
  - "Heavy Hydrogen"
- Simplest composite nucleus

Discovery of D in lab: ***Nobel Prize***
about 0.01% of all H on earth is D
✓ including in your body:
you contain about 10 kilos (20 lbs) of H, and about 2 grams of D
✓ Water (normally H_2O) with D is D_2O : "heavy water"

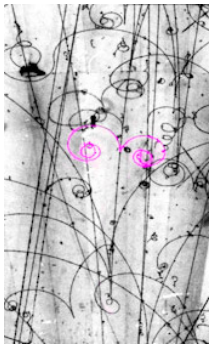
Nuclear Reactions in the Sun

$$p + p \rightarrow [np] + e^+ + \nu$$

e^+ = **positron**

- Exactly the same as electron but charge **+1**
- **Antimatter**
- Combines with normal e^-
  - Both are gone, release of energy
  - ***Annihilation***

Discovery of positron in lab: ***Nobel Prize***
Because of this reaction
➢ The Sun contains a small amount of antimatter!



Nuclear Reactions in the Sun

$$p + p \rightarrow [np] + e^{+} + \nu$$

ν (Greek letter "nu") = **neutrino**

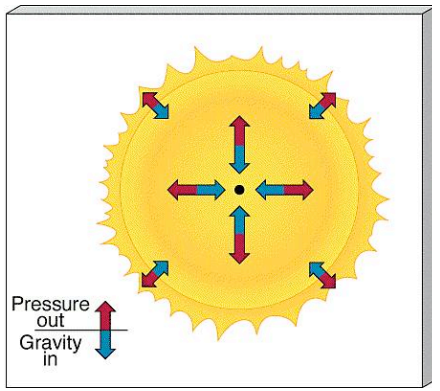
- Particle produced in nuclear reactions ***only***
- Tiny mass: $m(\nu) < 10^{-6} m(e)$!
- Moves at nearly the speed of light
- ***Very*** weakly interacting

Discovery of neutrino in lab: ***Nobel Prize***

10 billion from Sun go through hand every sec
- Reach out!
- Go through your body, Earth, but almost never interact

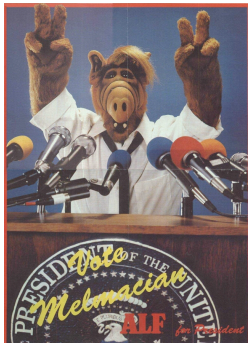
Why Doesn't The Sun Shrink?

- Sun is currently stable
- Pressure from the radiation created by fusion balances the force of gravity.
- Gravity is balanced by pressure from fusion!



Alf Doesn't Care?

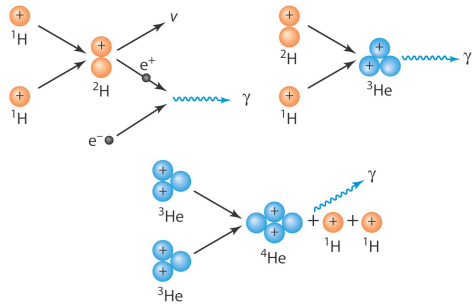
- A star in hydrostatic equilibrium will not shrink or swell.
- It will maintain constant size, density, and temperature for more than a million years!
- At this point, the star is called a main sequence star.
  - MS is when a star burns H into He
- If stars were not constant, what effect would that have on life on orbiting planets. Ultraviolet light variations?



http://alf.disim.com/photos/photoposter.htm

Nuclear Fusion in the Sun's Interior

- Proton-proton in stars like the Sun
  - Hydrogen fused to make helium
  - 0.7% of mass converted to energy



The Proton-Proton Cycle

They Might Be Giants
Why Does The Sun Shine

The Sun is a mass of incandescent gas
A gigantic nuclear furnace
Where hydrogen is built into helium
At a temperature of millions of degrees

The Sun is hot, the Sun is not
A place where we could live
But here on Earth there'd be no life
Without the light it gives

We need its light
We need its heat
The Sun light that we seek
The Sun light comes from our own Sun's atomic energy

The Sun is a mass of incandescent gas
A gigantic nuclear furnace
Where hydrogen is built into helium
At a temperature of millions of degrees

The Sun is hot

The Sun is so hot that everything on it is a gas: Aluminum, Copper, Iron, and many others

The Sun is large... If the sun were hollow, a million Earth's would fit inside
And yet, it is only a middle-sized star

The Sun is far away... About 93,000,000 miles away
And that's why it looks so small

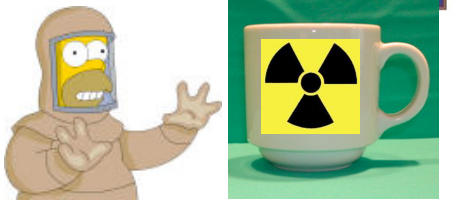
But even when it's out of sight
The Sun shines night and day
We need its heat, we need its light
The Sun light that we seek
The Sun light comes from our own sun's atomic energy

Scientists have found that the Sun is a huge atom smashing machine
The heat and light of the sun are caused by nuclear reactions between Hydrogen, Nitrogen, Carbon, and Helium

The Sun is a mass of incandescent gas
A gigantic nuclear furnace
Where Hydrogen is built into Helium
At a temperature of millions of degrees

Why Nuclear Fusion Doesn't Occur in Your Coffee

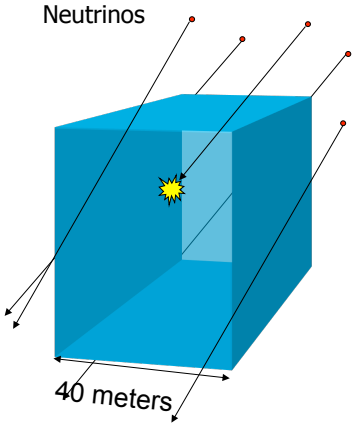
- Fusion requires:
  - High enough temperature (> 5 million K)
  - High enough density
  - Enough time

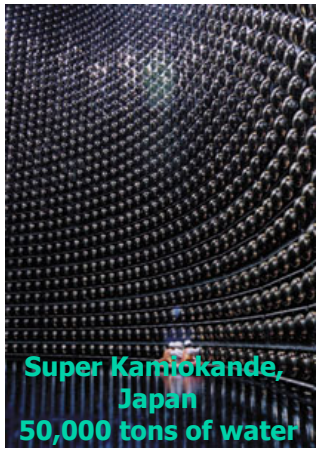


Sneaky Little Neutrinos

- The Sun's nuclear fusion produces a particle called a *neutrino*
- Matter is almost transparent to neutrinos
- On average, it would take a block of lead over a quarter of a light-year long to stop one
- Roughly 1 billion pass through every square centimeter of you every second!

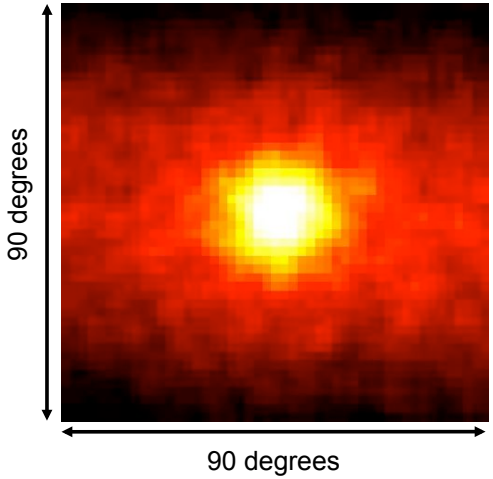
Detecting Neutrinos





The Sun in Neutrinos

- **Confirmation** that nuclear fusion is happening in the Sun's core
- 500 days of data
- As they can only be produced by nuclear processes, our energy source concept must be fundamental
- Proves nuclear burning!



Cosmic Gall

NEUTRINOS, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold shoulder steel and sounding brass,
Insult the stallion in his stall,
And scorning barriers of class,
Infiltrate you and me! Like tall
and painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
and pierce the lover and his lass
From underneath the bed-you call
It wonderful; I call it crass.

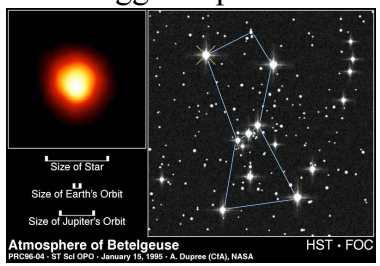
very little

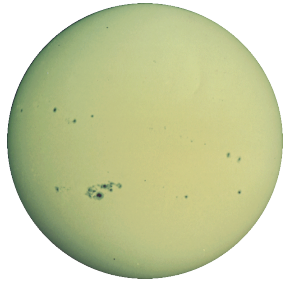
hardly

- *Telephone Poles and Other Poems*, John Updike, Knopf, 1960

Stars as Suns

- The Sun is a nuclear reactor, but I'm saying much more than that: Sun is a typical star
- So all stars are run by thermonuclear fusion
- Night sky, Universe lit up ultimately by dense nuclear furnaces scattered everywhere with life snuggled up close



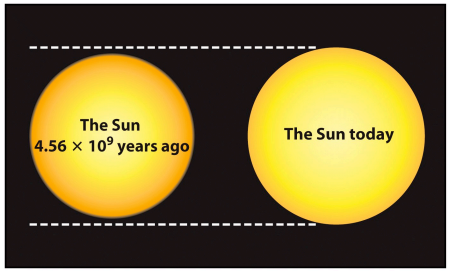


Think-Pair-Share

If we could sustain fusion in the lab we could meet humankind's energy needs nearly forever! Why is it so difficult to achieve this, when stars do it every day?

Life of a Low Mass (Sun-like) Star

- Most of its life is spent in the happy pursuit of burning H ⇒ He
- With time, luminosity and temperature evolve gradually in response
  - Stays on the Main Sequence, but still evolves..
- The Sun is now 40% brighter and 6% bigger than zero age MS.



http://wings.avkids.com/Book/Myth/Images/ocean_sun.gif

Life of Our Sun

- Increased temperature means that the lighter elements, like water molecules in the air, will have enough speed to escape Earth completely.
- The water of Earth begins to pack up and leave!
- In 1.1 billion years, the continents will be deserts and the oceans are beginning to evaporate.

http://www.esquire.com/cm/esquire/images/Gd/desert-1108-lg.jpg

Life of Our Sun

- As the Sun, uses up the hydrogen in the core, the Sun increases by 40% in brightness in 3.5 billion years.
- By that time, all of the oceans are gone!
- The baking sediments at the bottom of the oceans, release CO2
- Earth will become Venus-like!
- Then the heat makes even those heavier molecules leave the Earth.
- The Earth will be a barren rock in about 4 billion years!

http://wings.avkids.com/Book/Myth/Images/ocean_sun.gif

Important Questions

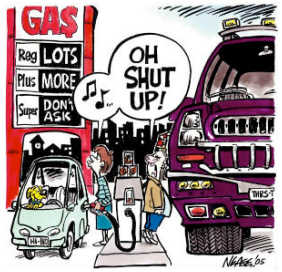
The Sun remains stable and on the main sequence as long as it has hydrogen to fuse in the core… it will evolve and will kill all life on Earth after all the fuel is gone.

How long will the fuel last? What happens when the fuel runs out?

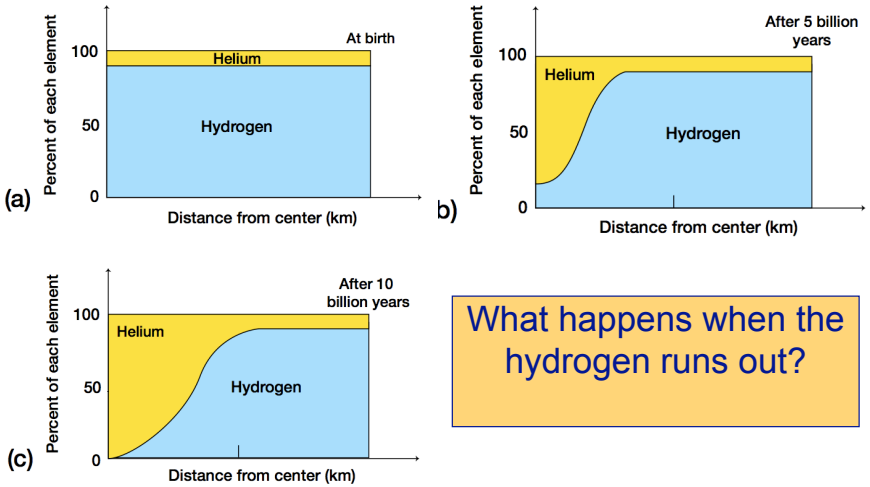
How much Gas do we have left?

- Total energy available is easily calculated by mass of hydrogen in Sun and energy released by each hydrogen conversion.
- We only have about 6 billion years left!!!!!

http://skeptically.org/sitebuildercontent/sitebuilderpictures/_pond/suv-econ-gas-pump.jpg.w300h294.jpg

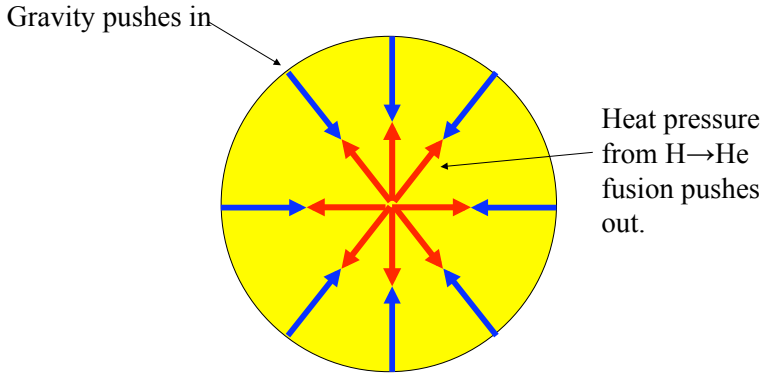


The Sun has used up about half its initial hydrogen supply



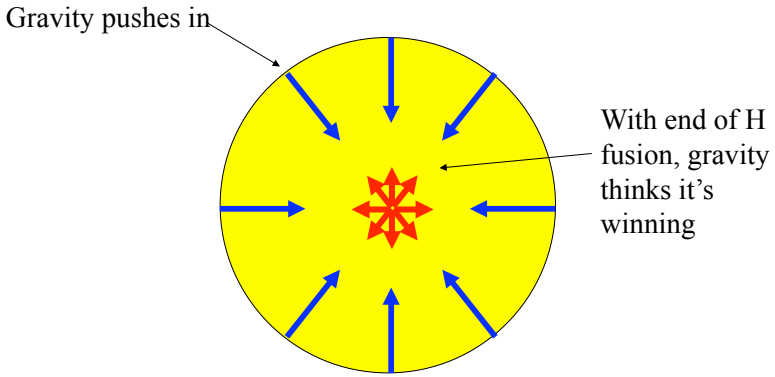
What happens when the hydrogen runs out?

The Battle between Gravity and Pressure



Hydrostatic equilibrium: Balanced forces

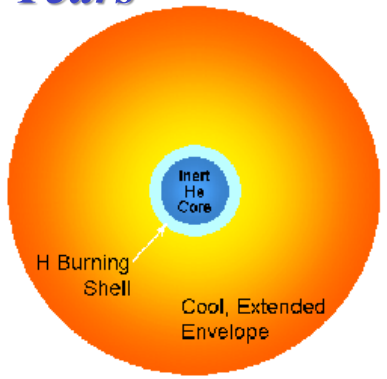
The Battle between Gravity and Pressure



Unbalanced forces

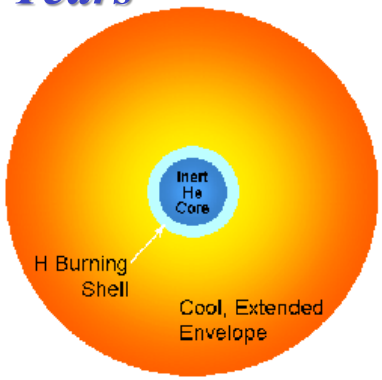
The Red Giant Phase: 6 Billion Years

- When the hydrogen is gone in the core, fusion stops
- Equilibrium is shot.
- Core starts to contract under its own gravity
- This contracting heats the core, and hydrogen fusion starts in a shell around the core



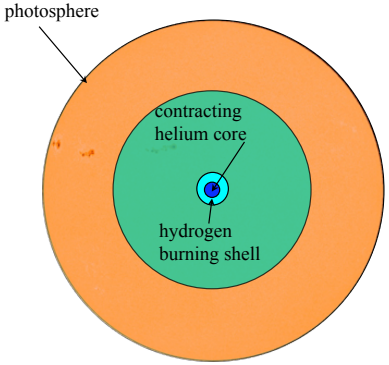
The Red Giant Phase: 6 Billion Years

- Energy is released, expands envelope ⇒ Lum increases!
- As the envelope expands, it cools – so it becomes a **red giant.**
- This process takes 50-100 million years.



http://www.youtube.com/watch?v=fOM7DMxOiAk&feature=related

When the hydrogen runs out...



Star expanding into red giant

Extra energy pushes the outer layers of the star very far outwards

Suppose you represented a typical giant star as the size of a baseball stadium. Its helium core would be only about the size of a baseball. Yet, it would contain about 10 percent of the star's mass.

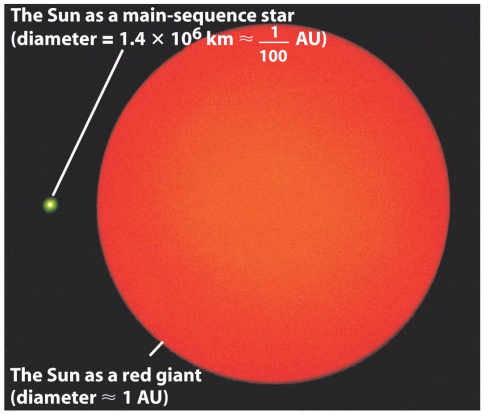
Question

As the Sun moves off the main sequence what happens in the core?

a) Hydrogen burning stops
b) Helium burning stops
c) TNT burning stops
d) We don't know, but it makes the Sun red.

In 6-7 Billion years

- The Sun will expand to 100-250 times bigger than it is now!
- The same mass but now it's bigger.

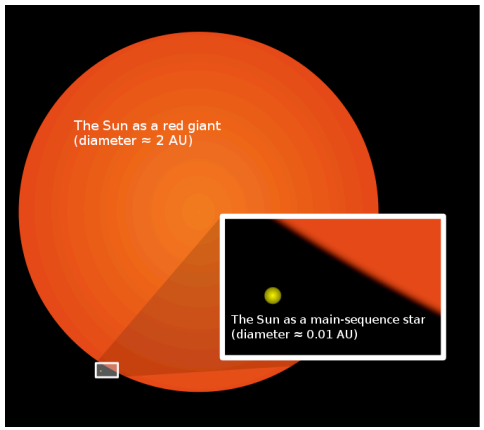


The Sun today and as a red giant

http://www.youtube.com/watch?v=3rH4bMylBKg

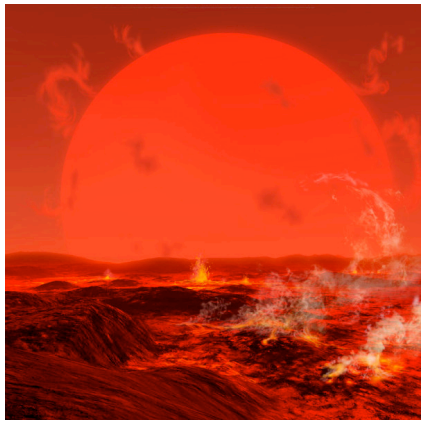
In 6-7 Billion years

- We use to think that the Sun would gobble the Earth.
  - Mercury gone
  - Venus probably gone
  - Earth?



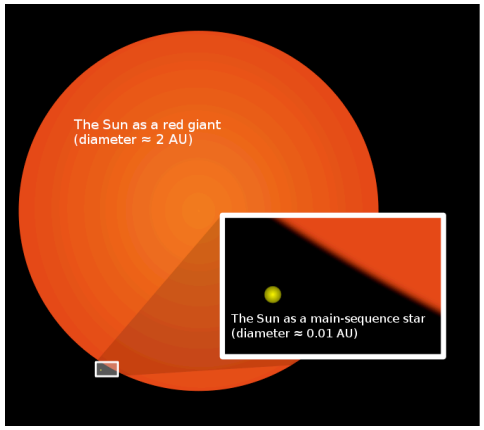
Its the end of the world as we know it, and I feel fine!

- The Sun's growing luminosity will:
  - Evaporate Earth's oceans
  - Drive away its atmosphere
- Leaving Earth as a desiccated, dead planet with a surface of molten rock


Sunrise on Earth
5 billion years from now?

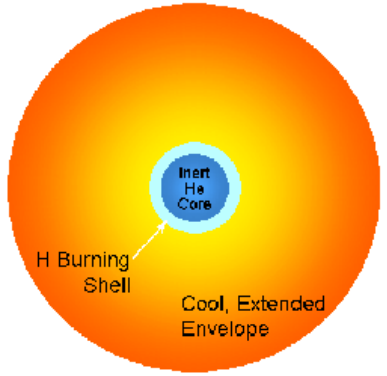
Life in 6-7 Billion years?

- Mars?
  - For sure too hot.
- Jupiter's Moons?
  - Still too hot
  - Europa's water vaporizes
- Even the moons of Uranus and Neptune may be too hot.



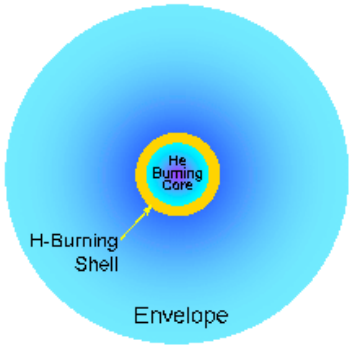
Contraction Junction

- Core gets hotter, and hotter, and hotter until…
- 100 million degrees F
- Core heats ⇒ He fusion ignites
- He ⇒ C & O



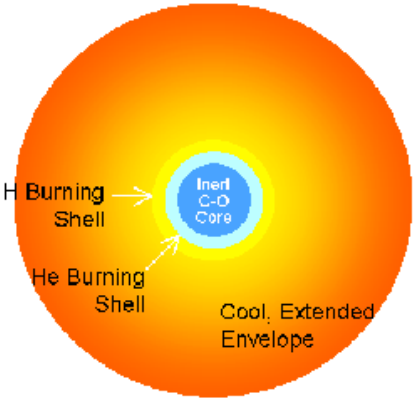
The Horizontal Branch

- Helium burning stabilizes the core
- The outer envelope shrinks, heats up, and dims slightly
- But helium doesn't last very long as a fuel
  - Horizontal branch lifetime is only about 10% that of a star's main sequence lifetime
  - Our Sun will burn helium for about a billion years
  - Also He burning is unstable

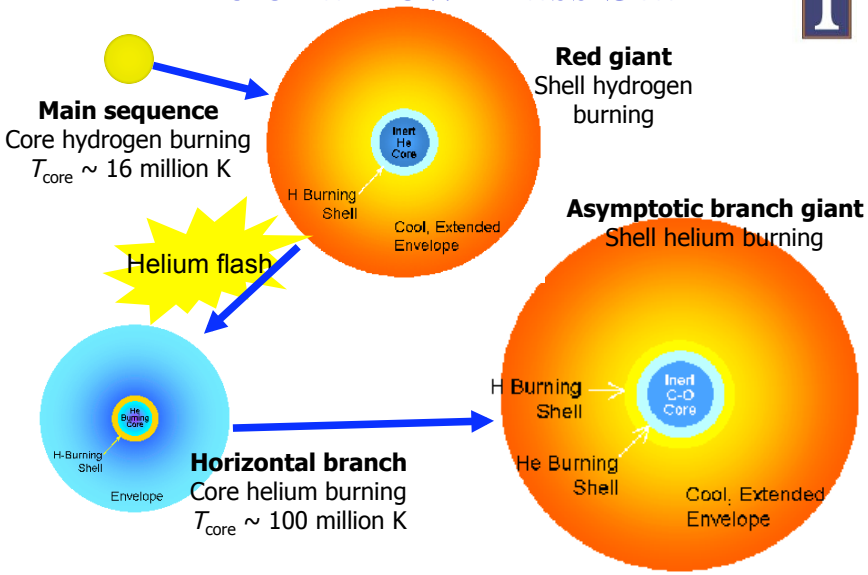


When Helium Runs Out… 7.8 Billion Years

- Fusion in the core stops – the helium has been converted to carbon and oxygen
- Stellar core collapses under its own gravity
- Shell starts fusing helium
- Star starts to grow and cool again
- Called an ***asymptotic giant branch*** star



Life of a Low Mass Star



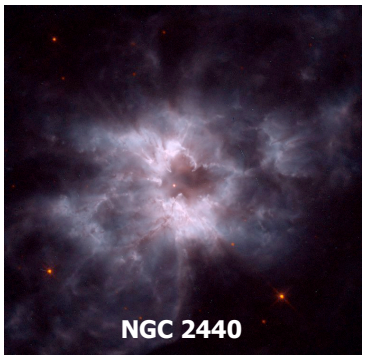
Question

As the Sun becomes an asymptotic giant branch star, what is happening in the central core of the Sun?

a) Hydrogen burning.
b) Helium burning.
c) TNT burning.
d) Nothing is burning, fusion has stopped.
e) We don't know, but it makes the Sun red.

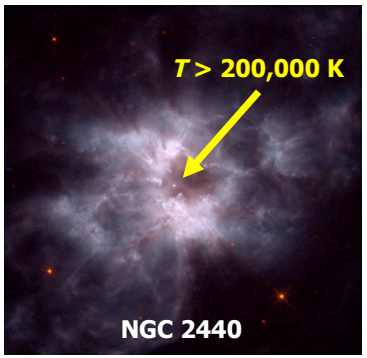
End Game

- At these last stages, the Sun will likely oscillate in size and temperature.
- This is messed up and creates a "Superwind"
- Outer layers of the red giant star are cast off
  - Up to 80% (at least 50%) of the star's original mass

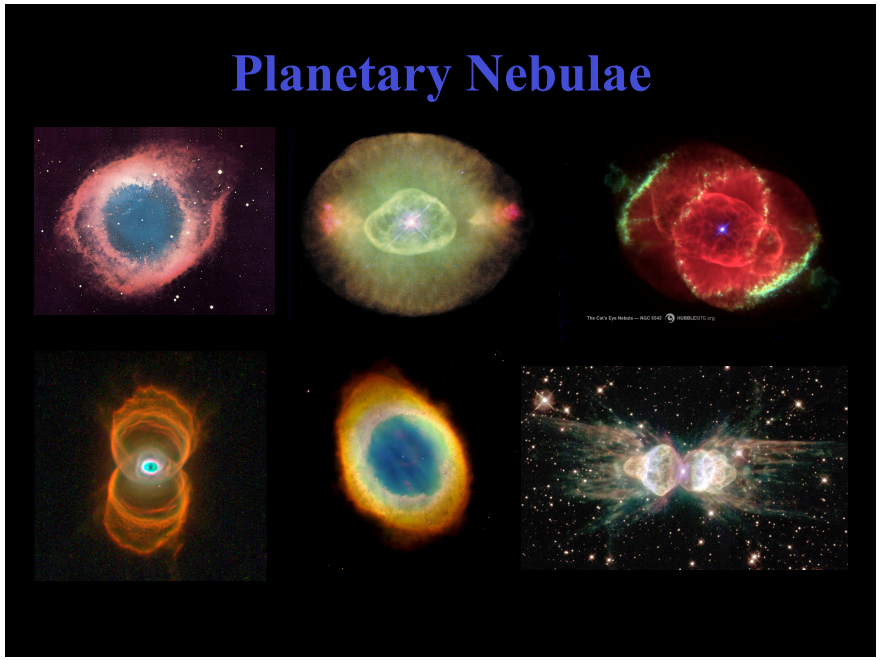


End Game

- "The core remains, made of carbon/oxygen "ash" from helium fusion
  - The core is very hot, above 200,000 K
- Ultraviolet radiation from the core ionizes the cast off outer layers
  - Becomes a *planetary nebula*
  - *Unfortunate name, but some of the most beautiful objects in the sky.*

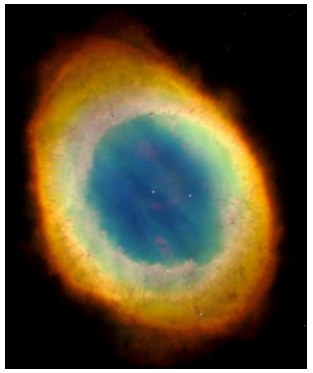


Planetary Nebulae



Planetary Nebula

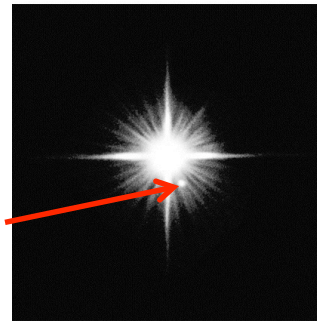
- Ultraviolet radiation from the hot core ionizes the cast off layers
  - A planetary nebula
  - Planetary nebula have nothing to do with planets. Called that because they are round looking like planets.



The Ring Nebula

What About the Core?

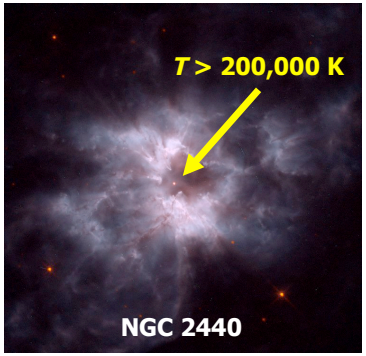
- Final fate - **White dwarf**
  - Slowly cools off over billions of years
  - Just a hot body
  - No fusion
  - Not really a star in some ways
  - Size of the Earth



Sirius B

What Happens to Earth?

- We have detected planets around white dwarfs, but they have presumably had a hard time.
- If you were to visit the wasteland of Earth, the Sun would only be a very bright point of light.
- Not sufficient for life.



Question

This is the way the Sun ends. This is the way the Sun ends, not with a bang but a

a) whimper; it just cools down over time.
b) supernova blasting heavy elements into space.
c) blackhole.
d) planetary nebula and a white dwarf.
e) a helium flash.