Astronomy 330

<u>This class (Lecture 7):</u>

Why does the Sun shine?

<u>Next Class:</u>

Making C,O, and N

HW 2 due Thursday.

Music: *Sonne*– Rammstein

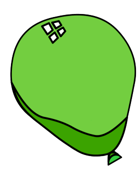
Outline

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

Pressure

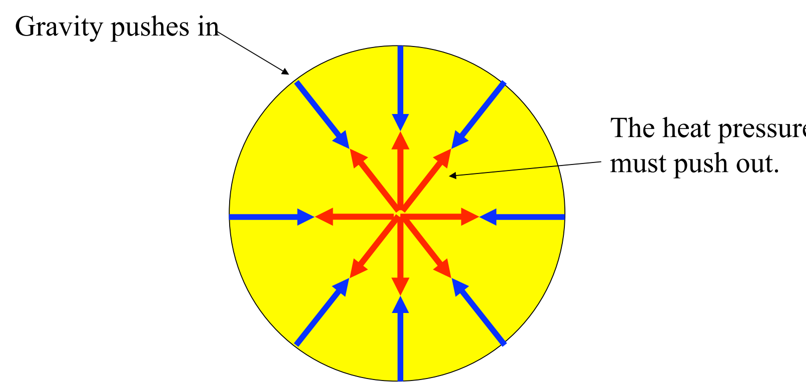
- What is pressure?
  - Pressure $= \dfrac{Force}{Area}$
- Explain blowing up a balloon?

Pressure of Earth's atmosphere is 14.7 pounds per square inch



- http://www.phys.hawaii.edu/~teb/java/ntnujava/idealGas/idealGas.html

The Battle between Gravity and Pressure



Hydrostatic equilibrium: Balanced forces

Question

A star is in hydrostatic equilibrium. What does that mean?

a) Keeps the Sun burning H into He.
b) Keeps the Sun from turning into a big cloud in the shape of a bunny.
c) Keeps the Sun a flattened disk.
d) Keeps the Sun a constant size.
e) Keeps the Sun unstable.

The Sun's Energy Output

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

A 100W light bulb…

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

U.S. electricity production in 2009: 4.1 trillion kWh…

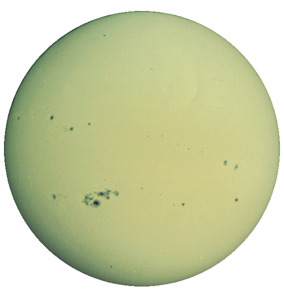
… Sun = 3×10^7 times this *every second*

World's nuclear weapons: 3×10^4 megatons…

… Sun = 4 million times this *every second*

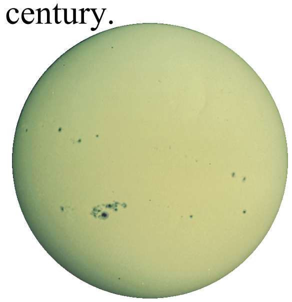
So, What Powers the Sun?

- 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?



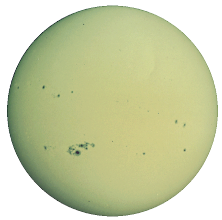
So, What Powers the Sun?

- 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.



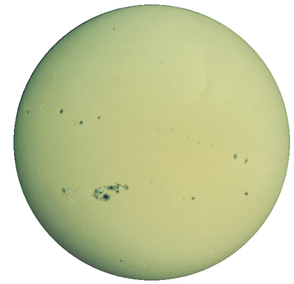
How to Test?

- 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.



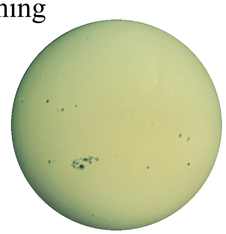
So, What Powers the Sun?

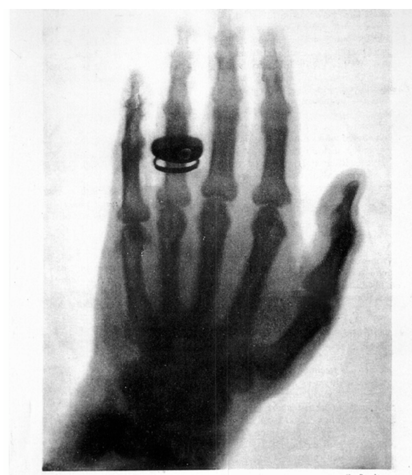
Discuss with neighbors possible heating options. List at least 2 possibilities, even if you know the correct one. List all feasible ideas.



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!





Josef Albert repr. Ohne Retouche.

Hand des Anatomen Geheimrath von Kölliker in Würzburg.
Im Physikalischen Institut der Universität Würzburg
am 23. Januar 1896 mit X-Strahlen aufgenommen
von
Professor Dr. W. C. Röntgen.

Verlag der Stahel'schen k. Hof- und Universitäts-Buch- und Kunsthandlung in Würzburg.

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

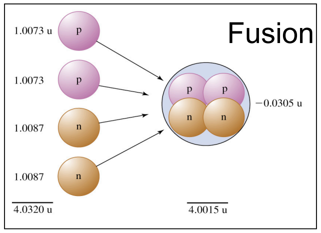
What is Fusion?

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

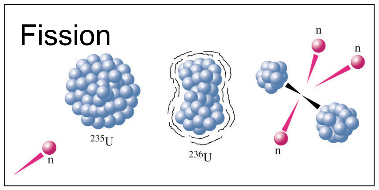
Basic idea is to take 4 protons (ionized hydrogen atoms) and slam them together to make an ionized helium atom.

Fusion vs. Fission

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

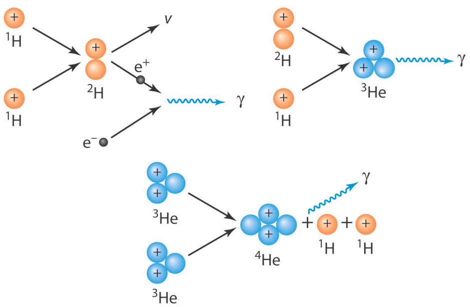


- Heavy nuclei: fission
  - Break apart heavier atoms into lighter ones
  - Used in power plants
  - A-Bomb



Nuclear Fusion in the Sun's Interior

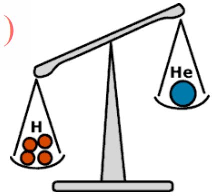
- Proton-Proton Chain
  - 4 hydrogen atoms fuse to make 1 helium atom
  - Requires very high density and temperature (at least 7 million K)



The Proton-Proton (p-p) Chain

Why does fusion release energy?

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

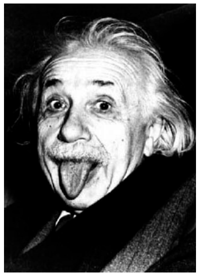


Fact: **4m(*p*) > m(^{4}He)** !
<u>mass of whole < mass of parts</u>!

Einstein says ***E = mc²***:

- Mass is a form of energy!
- Each ^{4}He liberates energy:

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

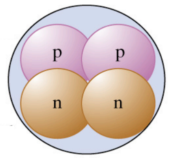


The Nucleus

- 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.**

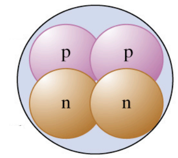


The Nucleus

- **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– <u>very short range</u>.**
- Weak Nuclear

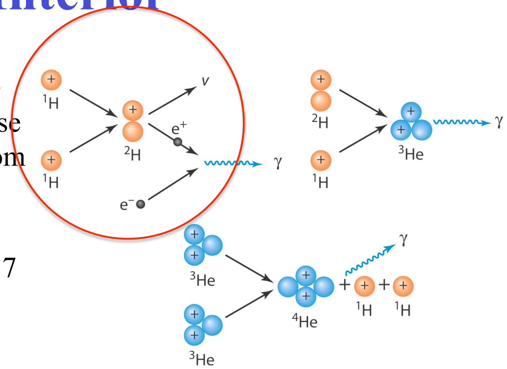
Question

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

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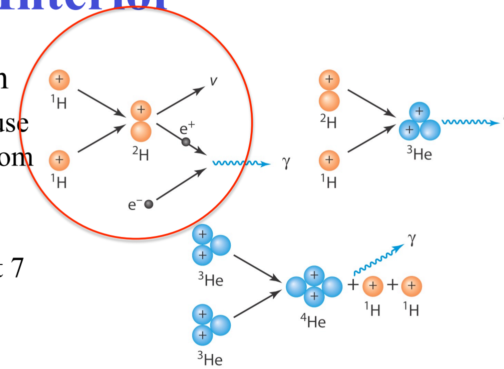


The Proton-Proton (p-p) Chain

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

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

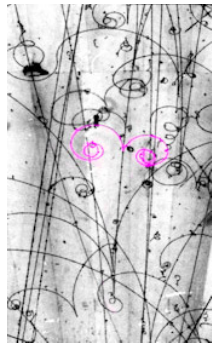
Discovery of D in lab: ***Nobel Prize***
about 0.01% of all H on earth is D
✓ including in your body:
you contain about 10 kilos (20 lbs) of H, and about 2 grams of D
✓ Water (normally H_2O) with D is D_2O : "heavy water"

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

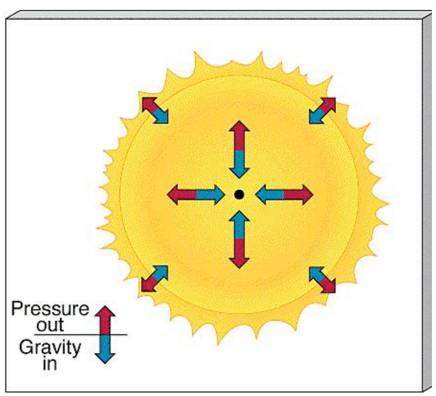
Discovery of neutrino in lab: ***Nobel Prize***

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!



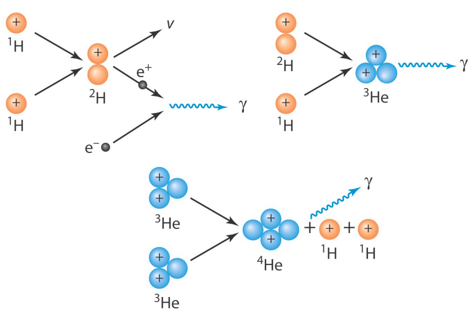
Alf Doesn't Care?

- 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

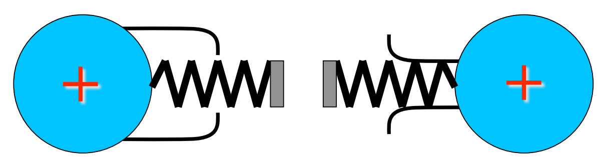
But even when it's out of sight
The Sun shines night and day
We need its heat, we need its light
The Sun light that we seek
The Sun light comes from our own sun's atomic energy

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

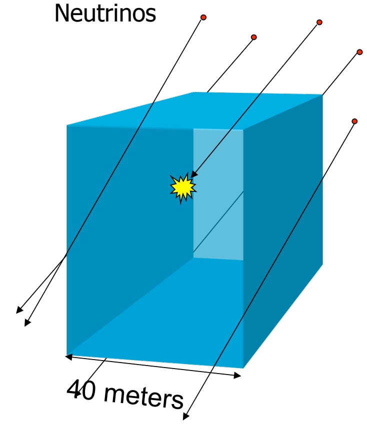
- Fusion requires:
  - High enough temperature (> 5 million K)
  - High enough density
  - Enough time

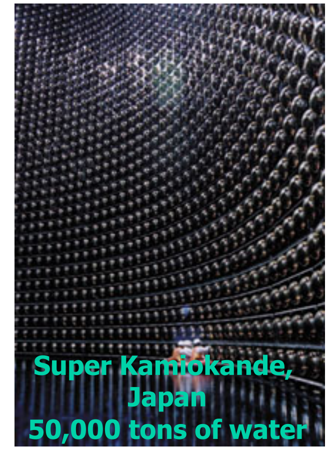


Sneaky Little Neutrinos

- 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!

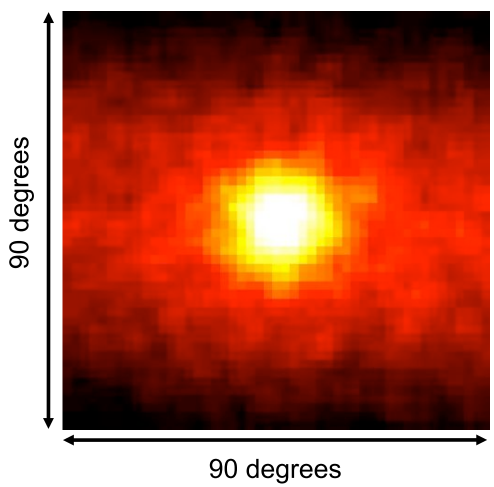
Detecting Neutrinos





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!



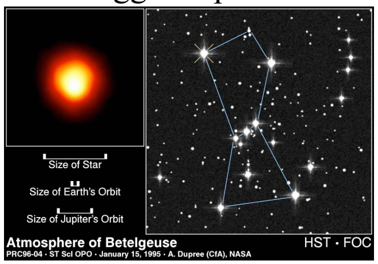
Cosmic Gall

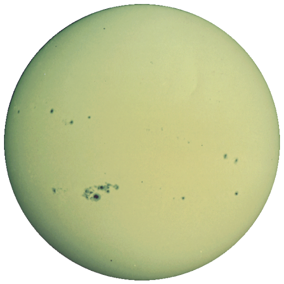
NEUTRINOS, they are very small. very little
They have no charge and have no mass
And do not interact at all. hardly
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the 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.

- *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?

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?

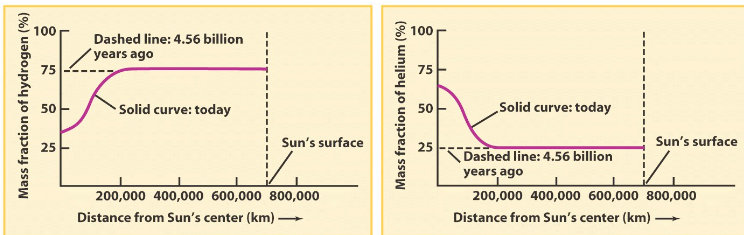
How much Gas do we have left?

- 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

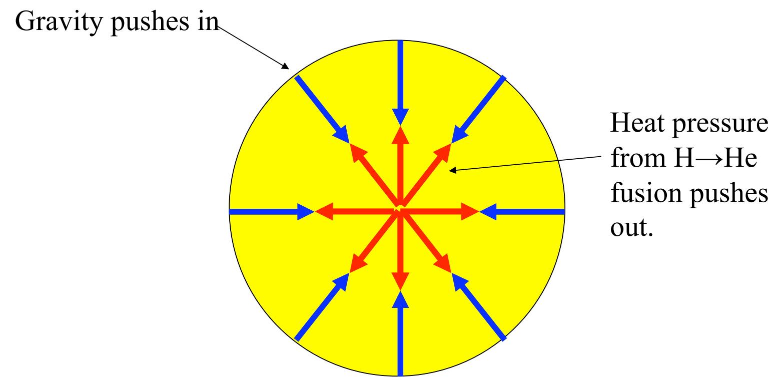
Hungry, Hungry Sun

- On the main sequence for ~11 billion years.
- The core is where fusion occurs- H ⇒ He
- Eventually, runs out of hydrogen in the core.
  - Rest of Sun is mostly hydrogen, but not in the core.
- And it's not hot enough to fuse helium!.....yet



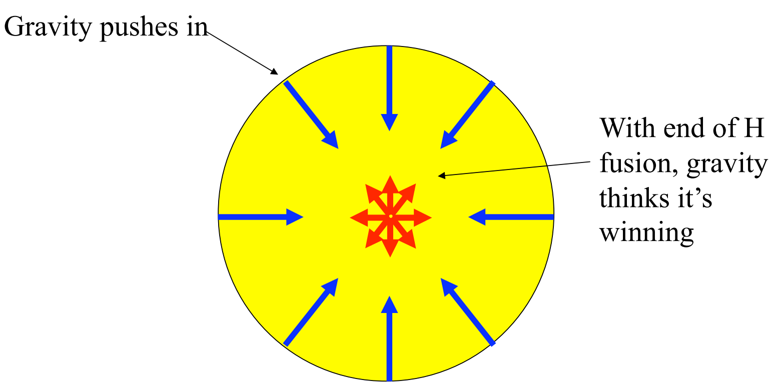
(a) Hydrogen in the Sun's interior (b) Helium in the Sun's interior

The Battle between Gravity and Pressure



Hydrostatic equilibrium: Balanced forces

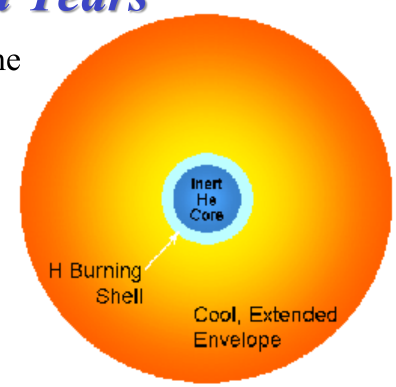
The Battle between Gravity and Pressure



Unbalanced forces

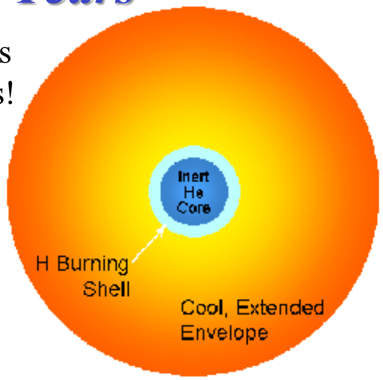
The Red Giant Phase: 6 Billion Years

- 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

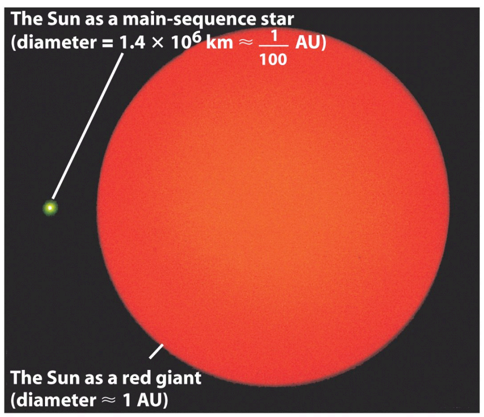
Question

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.

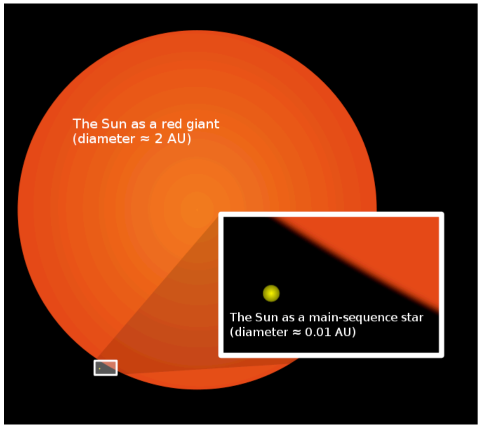


The Sun today and as a red giant

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

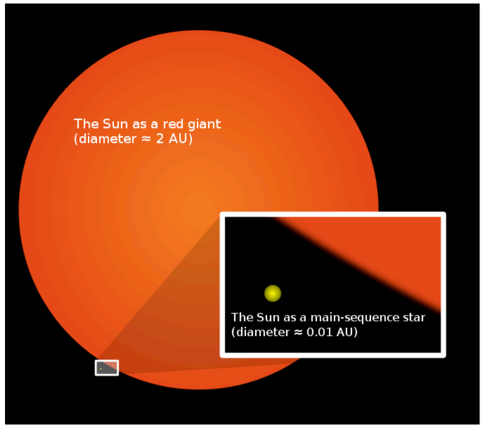
In 6-7 Billion years

- We use to think that the Sun would gobble the Earth.
  - Mercury gone
  - Venus probably gone
  - Earth?
- BUT even if not, with the Earth's oceans and atmosphere gone, crust still melts.
- Not good…



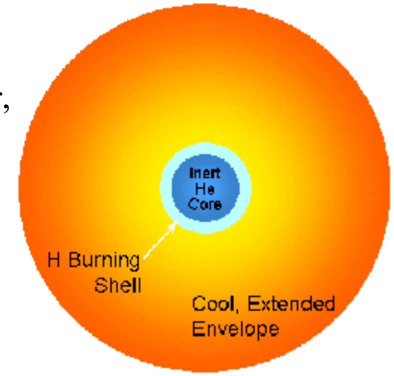
Life in 6-7 Billion years?

- 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.



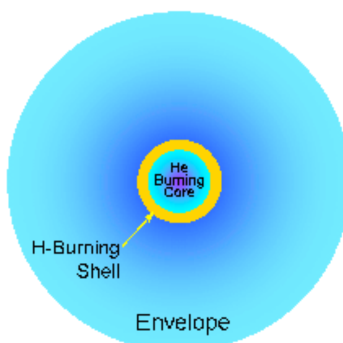
Contraction Junction

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



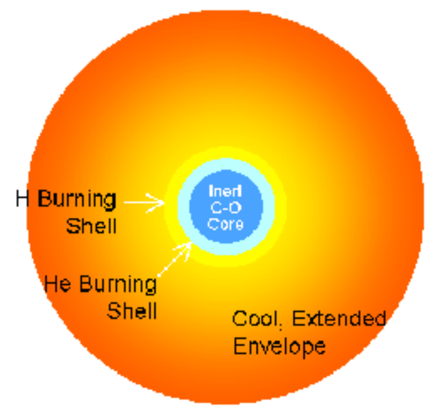
The Horizontal Branch

- 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

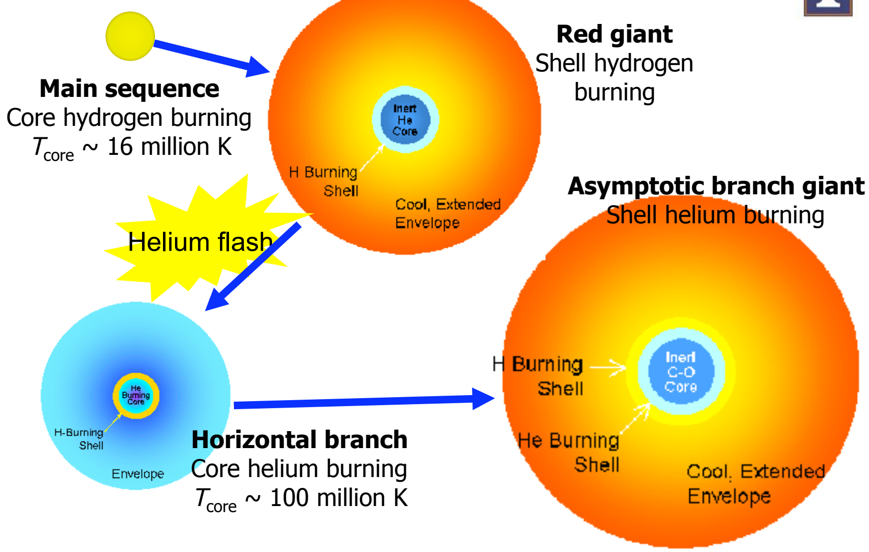


When Helium Runs Out… 7.8 Billion Years

- 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



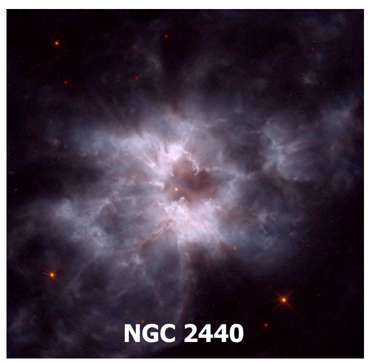
Question

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.

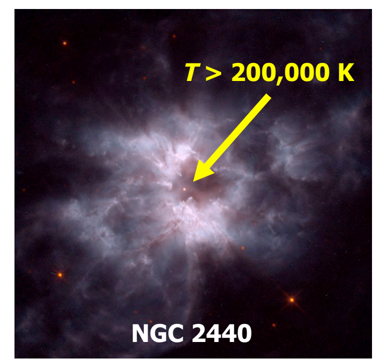
End Game

- 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

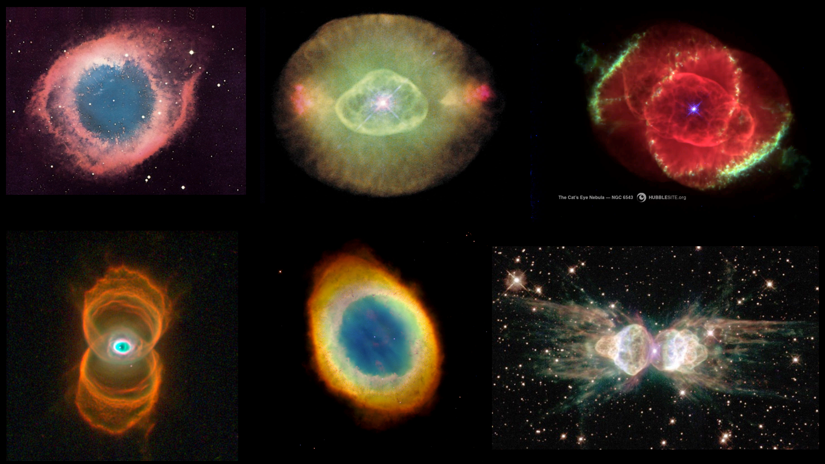


End Game

- "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.*



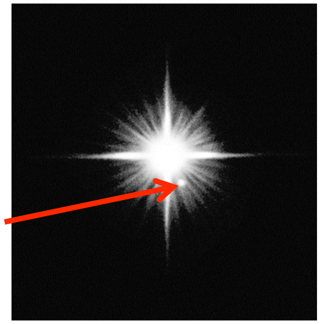
Planetary Nebulae



What About the Core?

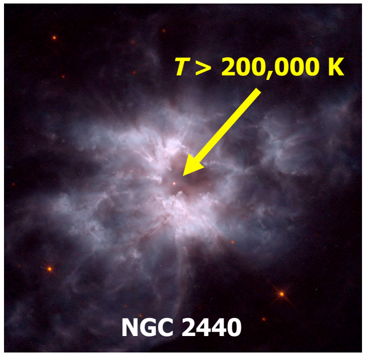
- Final fate - **White dwarf**
  - Slowly cools off over billions of years
  - Just a hot body
  - No fusion
  - Not really a star in some ways
  - Size of the Earth

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.



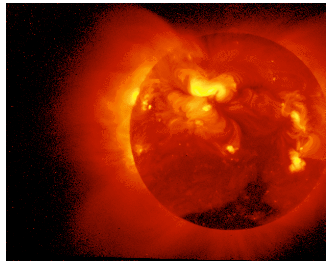
Question

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.

Nuclear Fusion in the First Stars

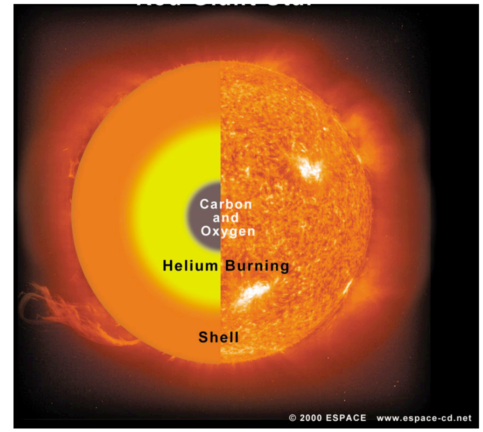
- Core T > 10 million K
  - Violent collisions
  - e^- stripped from atoms (ionized)
  - Nuclei collide, react
    - They get close enough that the nuclear strong force takes over.



- Thru series (chain) of reactions
- 4 protons ⇒ helium (2p,2n) nucleus + energy
- **Fusion:** light nuclei combine ⇒ heavier nuclei

The First Stars

- In the cores of the first stars, it gets hot enough for nuclear fusion.
- In the internal furnace of these first stars is where carbon and oxygen are created for the first time in the Universe.
- Higher density and temperature of the red giant phase allows for the creation of sulfur, phosphorous, silicon, and finally iron.



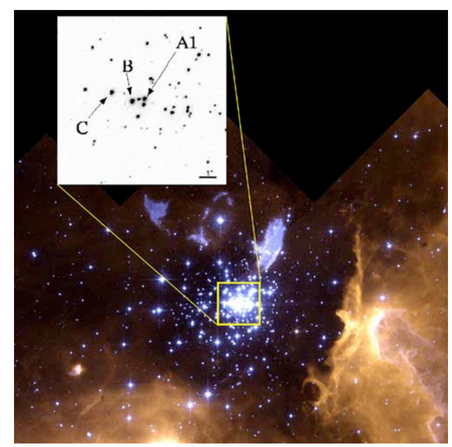
Question

The rocky planets that formed around the first stars would have been?

a) A perfect place to raise a family.
b) Devoid of the molecules necessary for life .
c) Too close to the massive star to have life.
d) Inhabited by truly alien creatures.
e) Trick question. There would not have been any rocky planets.

For High Mass Stars

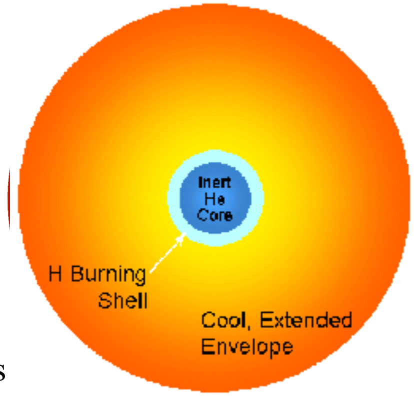
- For stars with an initial mass of more than 10 solar masses
- The final state will no longer be a white dwarf.
- Let's follow more carefully the life path of a high mass star– it's short sweet and ends with a bang!



A1: A 150 solar mass star!

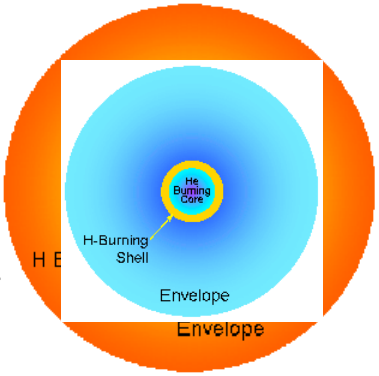
When the Hydrogen Runs out?

- Similar to lower-mass stars in the first few stages, just quicker.
- When the hydrogen supply runs out the core starts to contract
- Hydrogen shell burning (around the helium core) starts
- The outer envelope expands quickly becoming a **red supergiant**



The Supergiant Phase

- Outer envelope of the star grows larger and cooler
  - Up to 5 AU in size!
  - Unlike a low mass star, brightness does not increase dramatically
- Star contracts and heats up
- Now a **blue supergiant**



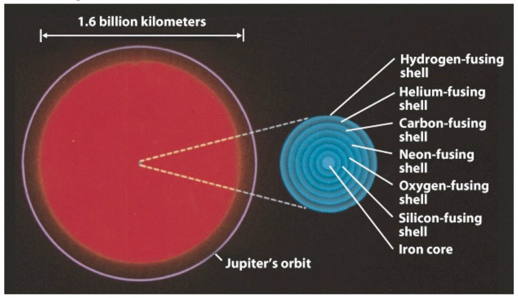
Question

What causes a high-mass star to leave the main sequence?

a) Just gets tired of the main-stream media and lifestyle.
b) Runs out of hydrogen in the core.
c) Runs out of helium in the core.
d) A shell around the core begins to burn helium.
e) A shell around the core begins to burn hydrogen.

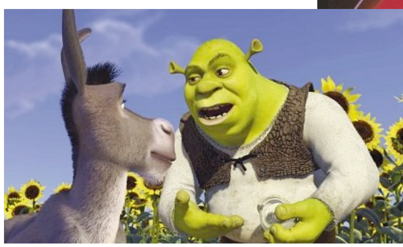
Massive Stars: Cycles of Fusion

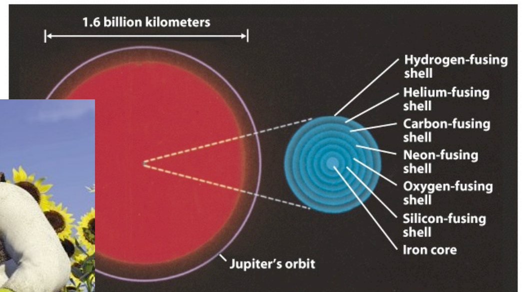
- Helium fusion is not the end for massive stars
- Cycles of core contraction, heating, ignition
- Ash of one cycle becomes fuel for the next
  - hydrogen ⇨ helium
  - helium ⇨ carbon & oxygen
  - carbon ⇨ neon, sodium, & magnesium
  - neon ⇨ oxygen & magnesium
  - oxygen ⇨ silicon & sulfur
  - silicon ⇨ iron



Massive Stars: Cycles of Fusion

- Onion-skin like structure develops in the core
- Has layers…. like an Ogre..





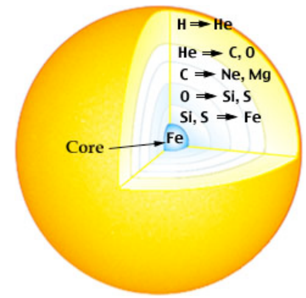
http://servantsthoughts.blogspot.com/2007/08/onion-theory.html

Iron – The End of the Road

- Supergiants "burn" heavier and heavier atoms in the fusion process
- Each stage faster than the last
- After iron - no fuel left!
  - It requires energy to produce heavier atoms

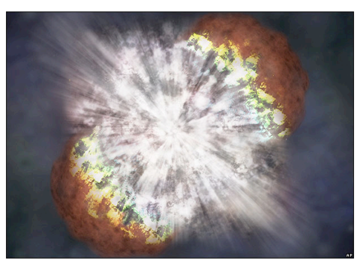
Stage	Temperature	Duration
H fusion	40 million K	7 million yr
He fusion	200 million K	500,000 yr
C fusion	600 million K	600 yr
Ne fusion	1.2 billion K	1 yr
O fusion	1.5 billion K	6 mo
Si fusion	2.7 billion K	1 day

Values for a 25M_{Sun} star



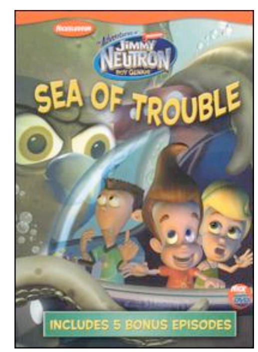
Core Collapse

- Completely out of gas!
- Hydrostatic equilibrium is <u>gone</u>.
- Eventually, gravity wins…



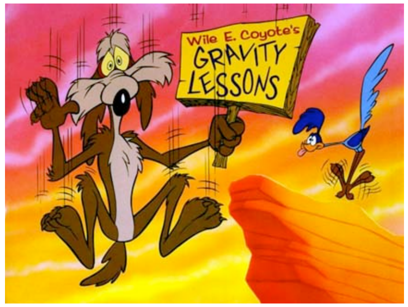
Core Collapse

- From 1,000 km across to 50 km in *1/10th of a second*
- ***Nearly 10% speed of light!***
- The core is transformed into a sea of neutrons
  - Electrons are squeezed into protons, neutrinos released
  - High energy gamma rays produced
  - The core has nuclear density!
  - It Earth has same density, it would be 1000 feet in diameter



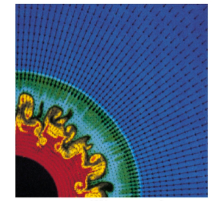
Core Collapse

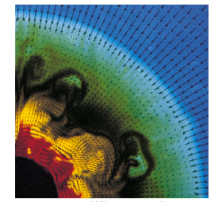
- Core suddenly collapsed
- Envelope has nothing left to stand on
- Envelope falls at significant fraction of the speed of light, slamming into compressed core



Supernova!

- Hitting the compressed core is like hitting a brick wall and the envelope gas reverses direction– blow-back.
  - But, by itself not enough to destroy star.
  - Material is so dense, that it is slightly opaque to the neutrinos produced
  - And 10^{58} neutrinos!
  - Neutrinos give the shock a "kick"
  - Rips the outer layers of the star apart
- Star explodes in a **supernova**


10 milliseconds


20 milliseconds

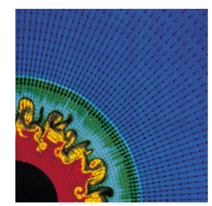
http://www.spacetelescope.org/images/screen/heic0609c.jpg

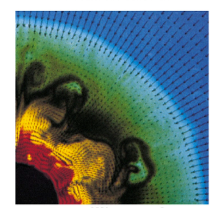
Supernova!

- The lifetime battle against gravity is lost.
- The core collapses under its own weight.
- Much of the mass of the outer region of the star, bounces back into space.

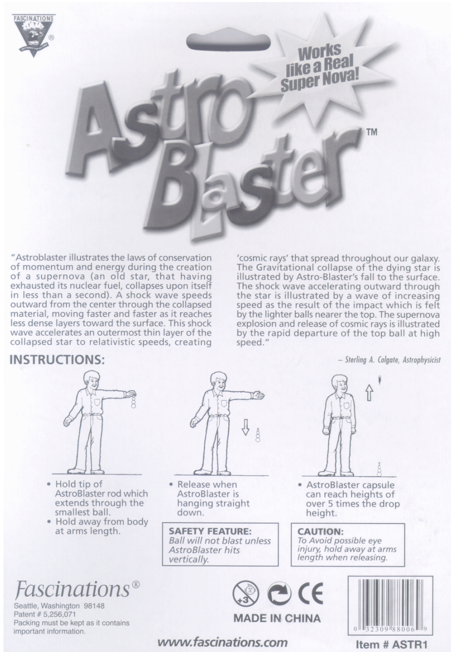
Supernova!

- The energy is enormous! The visible light is around only 1% of the energy output!
  - 99% of the energy in the form of neutrinos
- > 90% of the mass of star is ejected into space!
  - Fast, hot,


10 milliseconds


20 milliseconds

AstroBlaster!



Question

In the astroblaster demo, what did the little red ball represent?

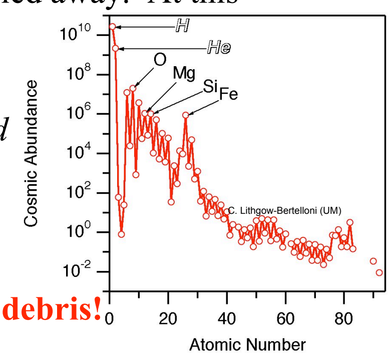
a) The inner core of the massive star
b) The envelope of the massive star
c) A low-mass stellar companion to the high mass star.
d) Iron.

Game Over!

http://www.youtube.com/watch?v=8MHb6_35XJM

Making Heavy Elements

- The star goes **supernova** and explodes. Some of C, O, P, S, Si, and Fe get carried away. At this point, even heavier elements can be made during energy consuming fusion reactions
- These by-products are *blasted* into space (>90% of star)
- Supernovae provide much of the building blocks for planets… and us!
- **We are recycled supernova debris!**
- **We are Star stuff.**



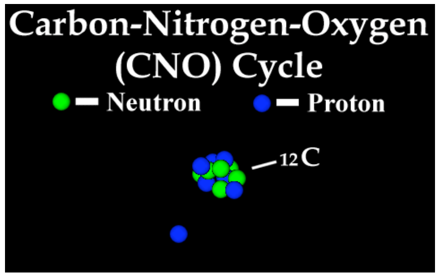
http://www.youtube.com/watch?v=ptwEV0xhTzI&feature=related

2:00 - 3:06

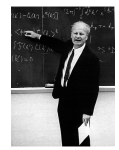
Delenn, B5

CNO-ing

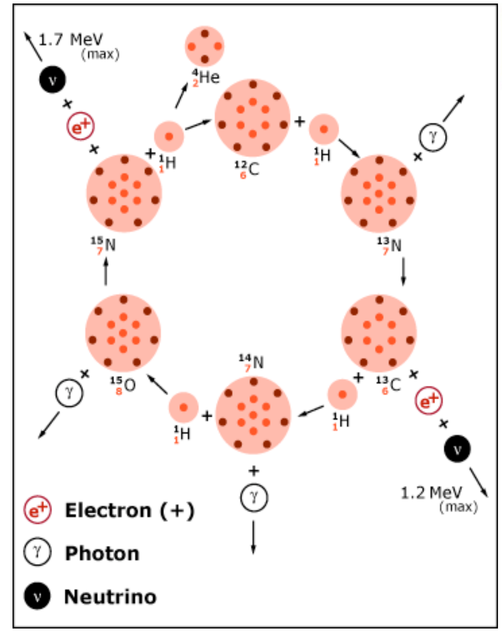
- Now the Universe has some C and O laying around; it can use it.
- In the next generation of stars, the CNO cycle can be used in the fusion process.
- It is more efficient in stars slightly more massive than the Sun.
- Remember the Sun mostly uses proton-proton fusion.



The CNO Cycle



Hans Bethe



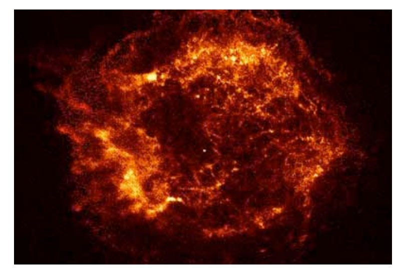
The Second Generation

- The first stars blew up their new elements into the proto-galaxy.
- Now, the second stars form in the ashes of the first.
- With C and N, the 2nd generation can form helium through the CNO cycle, in which most of the Universe's nitrogen is created.
- The 2nd generation also eventually explodes blowing nitrogen and the other elements into the galaxy.

A supernova in a nearby galaxy. A single star exploding can be brighter than millions of stars in the nucleus.

The Next Stars

- The new atomic elements from the 1st and 2nd stars are spread out into the galaxy.
- The Sun must be at least a 3rd generation star as we have **nitrogen** in abundance.
- Indeed, the percentage of heavier elements is larger toward the center of the galaxy, where the first generation of stars probably formed. (Seen in ours and other galaxies.)
- **Again, we are star stuff.**
- Keep in mind that this is all from the nuclear strong force– fusion.



The Chandra x-ray observatory has shown that the CasA supernova has flung calcium, iron, and silicon into space.