Astronomy 122

Homework #5 is posted.

This Class (Lecture 11):

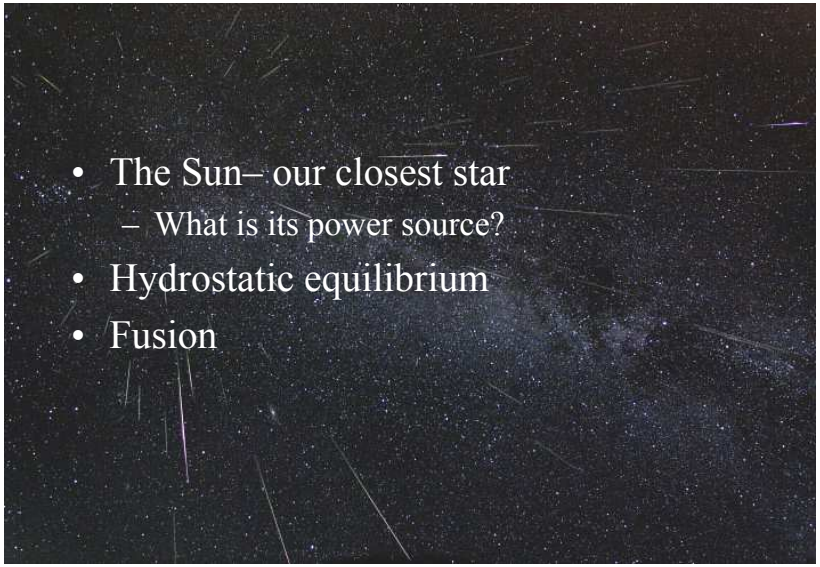
The Sun

Next Class:

Stars

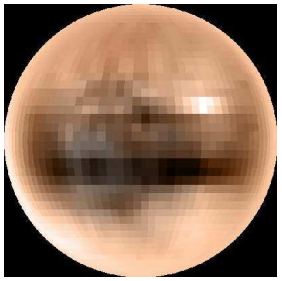
Music: *Sonne* – Rammstein

Outline



The Outer Reaches

- Beyond the orbit of Neptune lie countless bodies of rock & ice
- Pluto is the largest of these bodies
  - Not a rocky planet
  - Not an ice giant



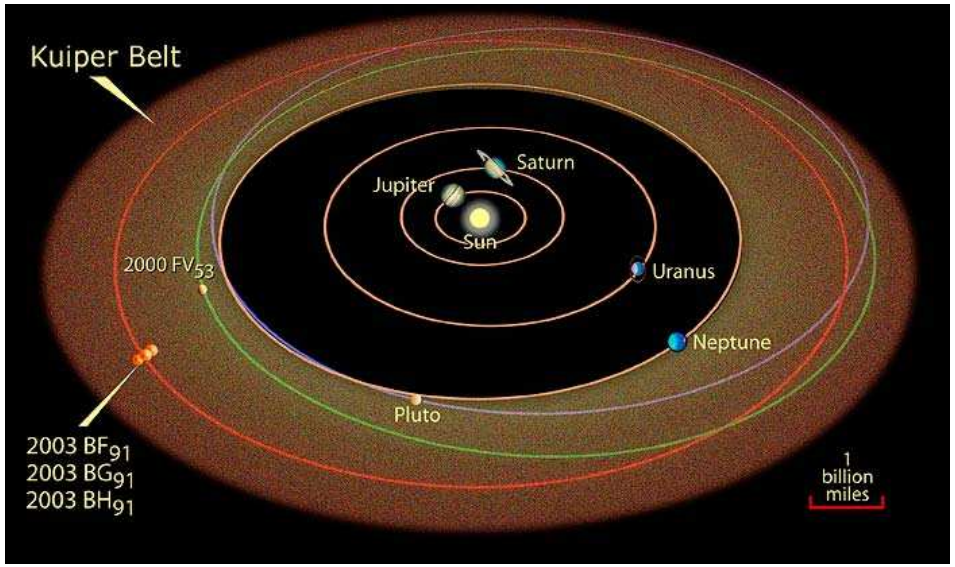
First Pictures of Pluto/Charon

- 1995 – Hubble Space Telescope infrared
- 1996 – Hubble Space Telescope visible

Do we know of all of the Bodies in our Solar System?

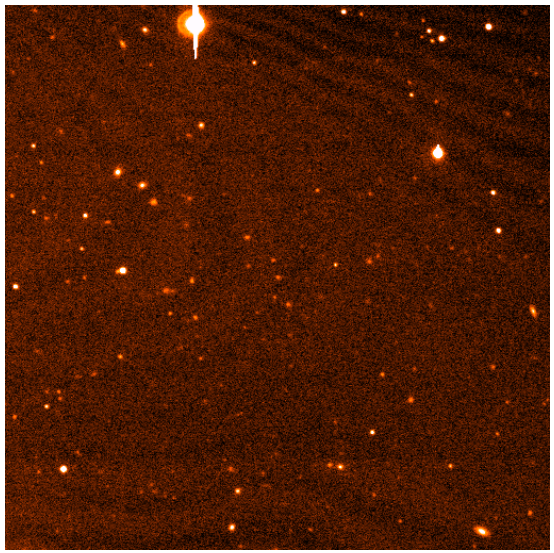
- No. Even at in the 21st century, we are still discovering new comets, or large asteroids, or even large planet-like objects?

The Kuiper Belt



New Planet?

- 2003 UB313
- Kinda called Xena



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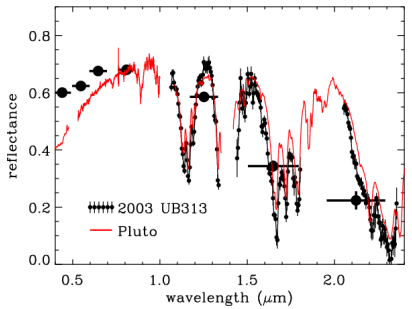
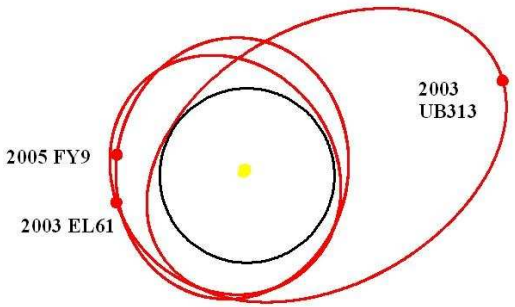
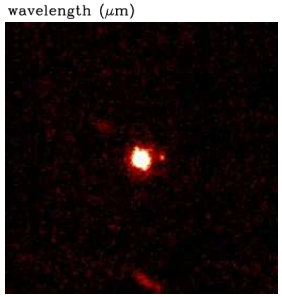
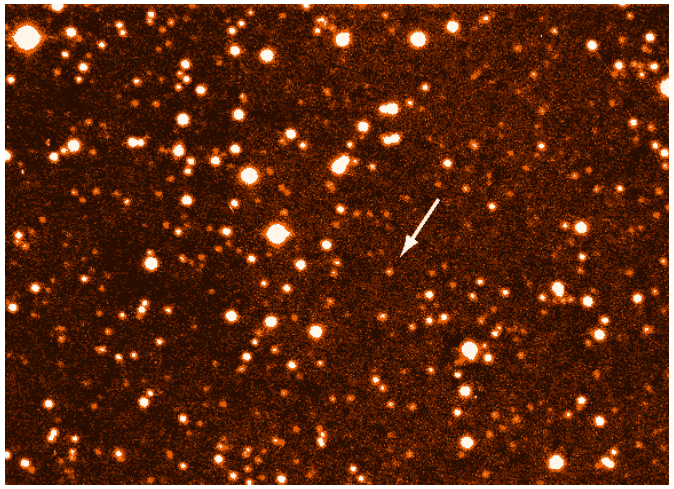






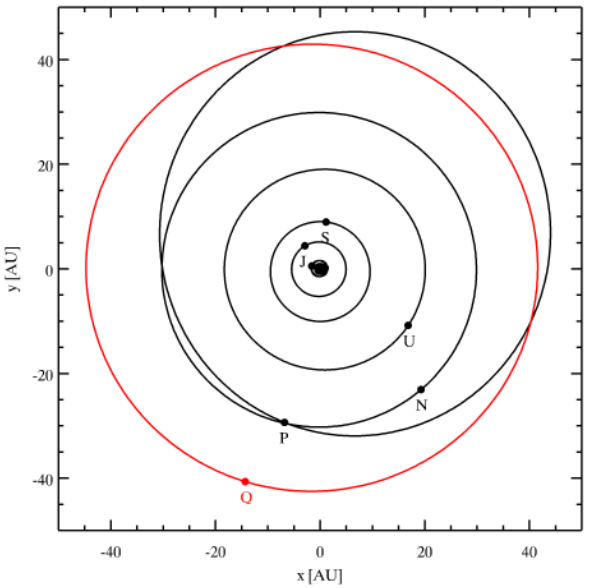
Kuiper Object Quaoar : Found 2002

- **pronounced kwa-whar**
- **diameter of about 800 miles (half of Pluto)**
- **42 AU orbit**



http://antwrp.gsfc.nasa.gov/apod/ap021009.html

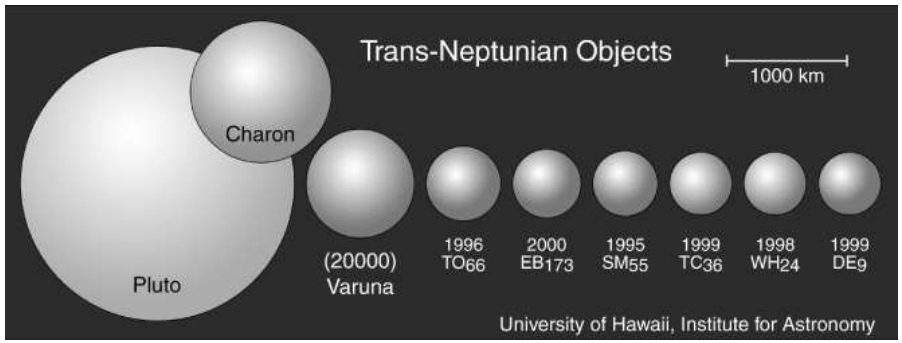
Quaoar Orbit



http://www.gps.caltech.edu/~chad/quaoar/

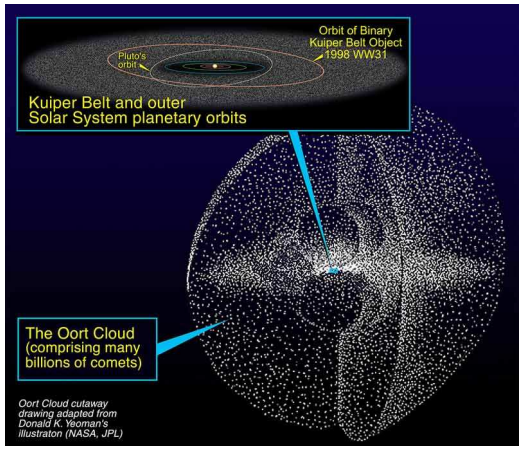
Large KBOs

- Pluto still larger, but not by that much
- Note: plot below doesn't include Quaoar or Xena.



Oort Cloud

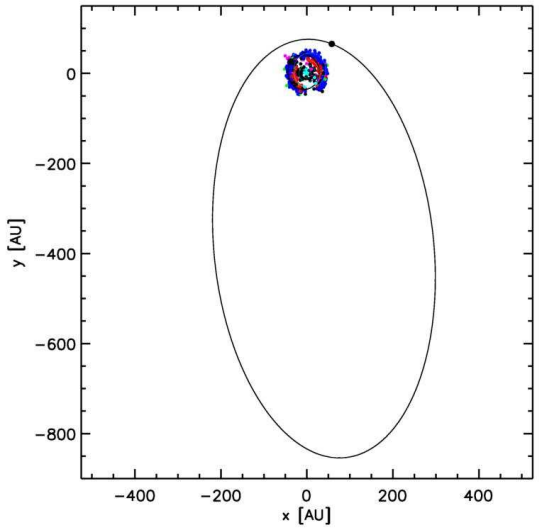
- Billions of icy minor planets – comet nuclei
- Roughly spherical out to 50,000 AU
- Predicted by Jan Oort
- Explains long-period comets
- No observations to date. Or is there?

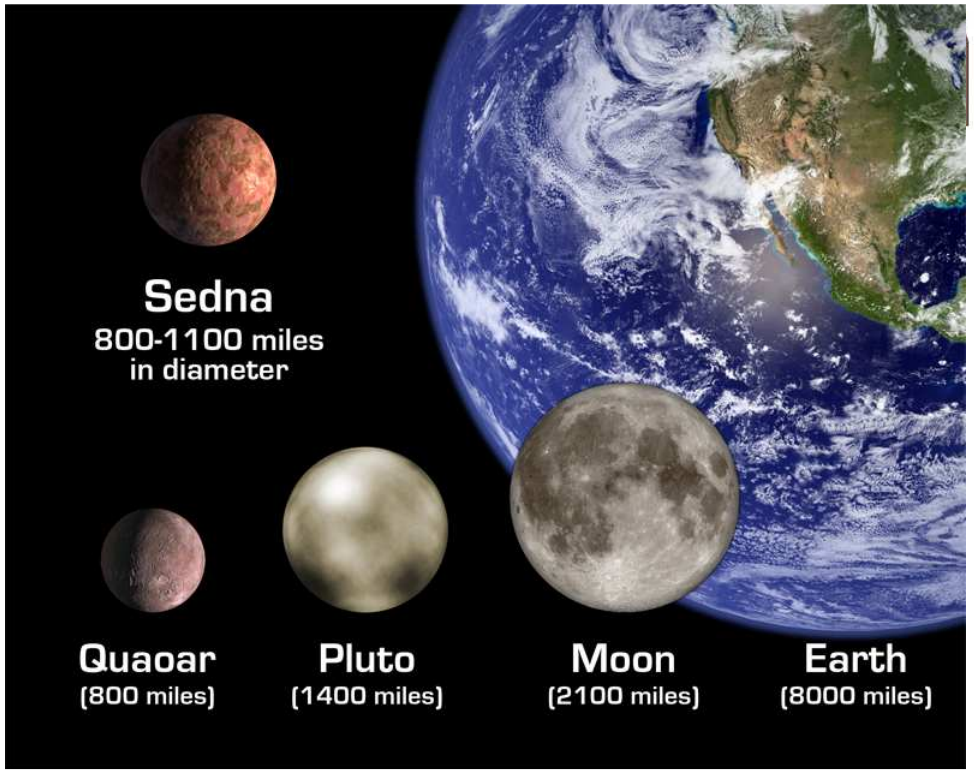


http://www.solarviews.com/browse/comet/kuiper3.jpg

Sedna – the Inner Oort Cloud?

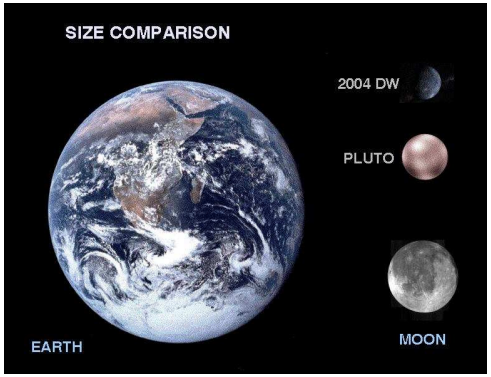
- Orbit 76 – 840 AU
  - outside Kuiper Belt
  - inside Oort Cloud
- Very red color
- Slow rotation





Black Sheep of the Planets

- Pluto is the oddball
  - Size
  - Companion
  - Composition
  - Orbit
- Pluto/Charon as double ice planet?



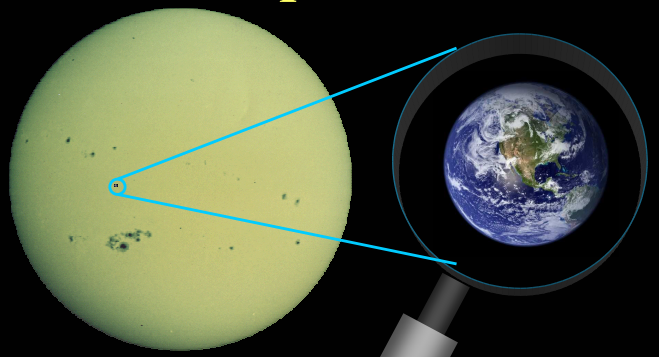
What is Pluto?

- You make the call
  - Singular ice planet
  - Mutant giant double comet
  - King of the Kuiper Belt
  - ???

IAU Official Position

- IAU defines Pluto to be a planet
- IAU cannot define "planet"
  - Upper limit: not massive enough to produce any form of fusion at its core
  - Deuterium fusion occurs for objects about 15 times Jupiter's mass
  - No lower limit specified
- Reasonable lower limit?
  - Massive enough for gravity to make it spherical
  - At least 14 planets
  - No reasonable definition produces 9 planets

Earth-Sun Comparison



Visual radius	109 Earth
Mass	3.3×10^5 Earth
Luminosity	3.9×10^{26} W
Surface temperature	5800 K
Central temperature	1.5×10^7 K
Rotation period	25 days

Question of Stability

- The Sun's size is constant.
- No weatherman says it will be especially hot tomorrow as the Sun's size will be increasing.
- Not expanding or collapsing. The Sun is stable! Why?
- Not trivial, could have gone the other way

"I just don't feel stable."

- Think: Sun is made of gas, yet not like cloud, for example, which is made of gas but size, shape changes all of the time
- Not a coincidence: really good reason

 http://www.londonstimes.us/toons/index_medical.html

Why is the Sun Stable?

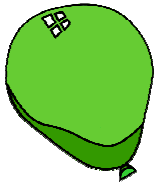
- What keeps gravity from collapsing it?
- What keeps Sun from exploding?

Pressure Stable

- What is pressure?
  - Pressure $= \frac{Force}{Area}$

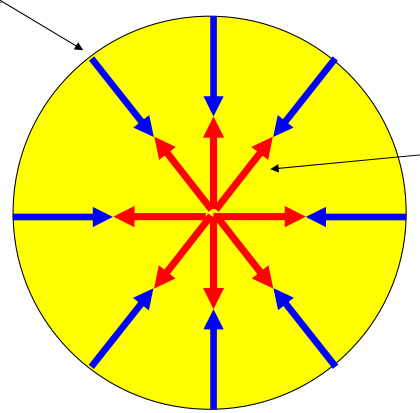
Pressure of Earth's atmosphere is 14.7 pounds per square inch

- Explain blowing up a balloon?



- http://www.phy.ntnu.edu.tw/java/idealGas/idealGas.html

The Battle between Gravity and Pressure



Hydrostatic equilibrium: Balanced forces

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 2000: 3.8 trillion kWh…

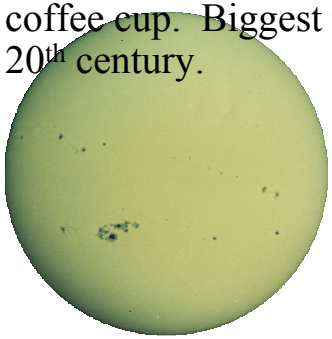
… Sun = 3 x 10^{7} times this *every second*

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

… Sun = 4 million times this *every second*

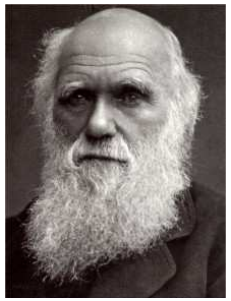
What Keeps the Sun from shrinking?

- The Sun does collapse or even change it's radius.
- Gravity pushes in, but what pushes out?
- What is its power source?
- What keeps the Sun hot? It doesn't cool like a hot coffee cup. Biggest mystery in Astronomy until 20th century.

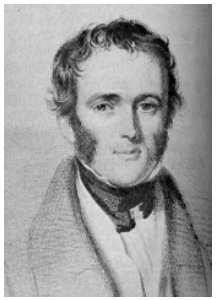


What Holds Up the Sun?

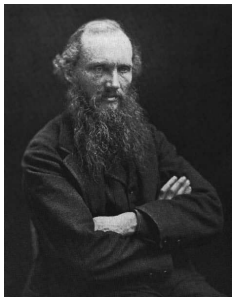
- Without an energy source, the Sun would rapidly cool & contract
- Mid-1800s:
  - Darwin: evolution needs Sun & Earth to be > 10^8 years old
  - Lyell: geological changes also needs > 10^8 years
  - Kelvin: gravitational heating gives only a few million years!
- No physical process then known would work!



Charles Darwin



Charles Lyell

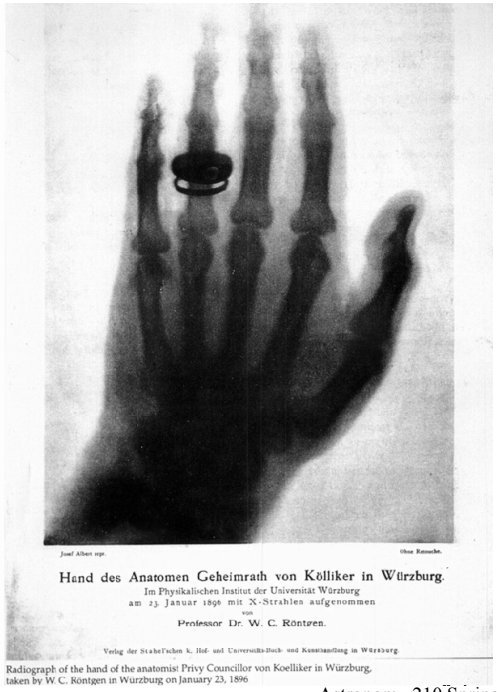


William Thomson, Lord Kelvin

How to Test?

- Process must be able to power Sun for a long time! At least 4.5 Byrs.

- Gravity:
  - Seems like a good idea. Remember Jupiter gives off heat.
  - A contracting Sun releases gravitational energy.
  - But only enough for 17 million years
- Chemical:
  - If the Sun was made from TNT, something that burns very well, then it would last for 20,000 years



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

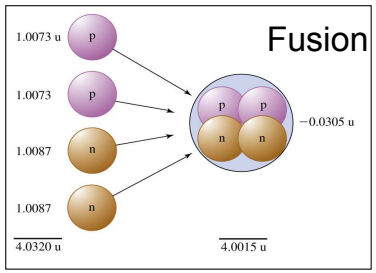
What is Fusion?

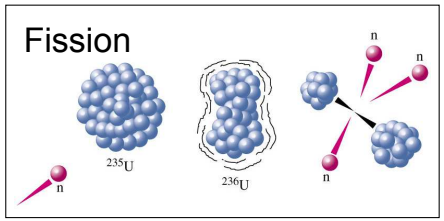
$$4\ p \rightarrow {}^{4}\mathrm{He}\quad (2\ p, 2\ n)$$

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

Fusion vs. Fission

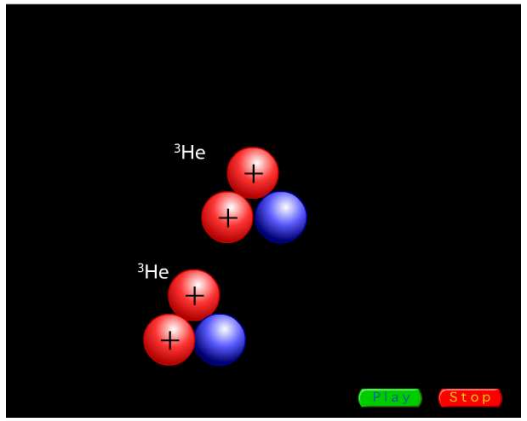
- Light nuclei: fusion
  - Happens in the Sun
  - H-Bomb
- Heavy nuclei: fission
  - Used in power plants
  - A-Bomb





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)



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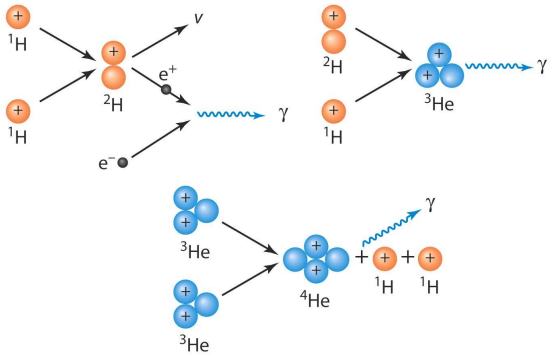
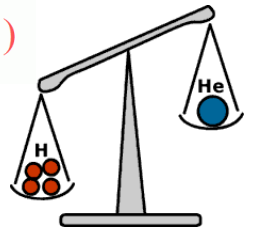


The Proton-Proton (p-p) Chain

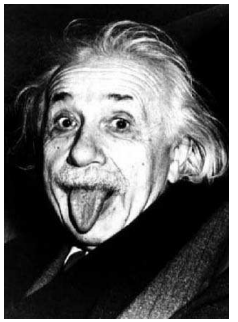
Why does fusion release energy?

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:



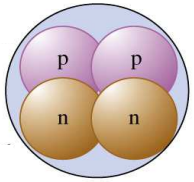
$$E_{\text{fusion}} = m_{\text{lost}}c^2 = 4m(p)c^2 - m(^4\mathrm{He})c^2 > 0!$$

The Nucleus

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

Helium

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

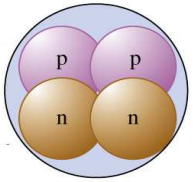


The Nucleus

- **Why doesn't the nucleus of the atom fly apart?**

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

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 of products 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**

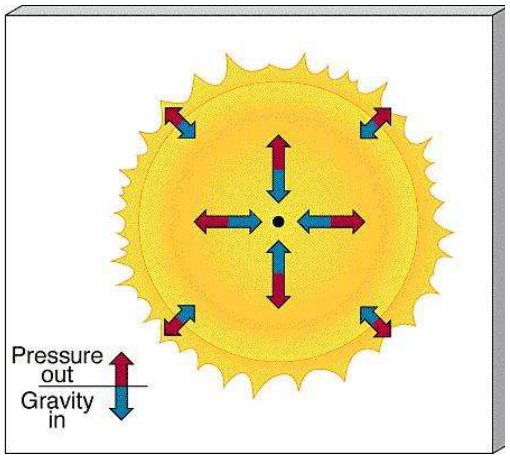
- Particle produced in nuclear reactions ***only***
- Tiny mass: $m(\nu) < 10^{-6} m(e)$!
- Moves at nearly the speed of light
- ***Very*** weakly interacting

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

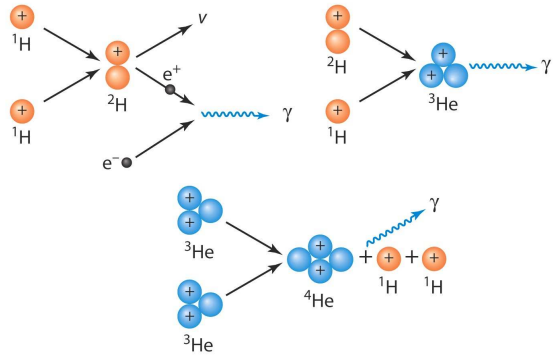
Why Doesn't The Sun Shrink?

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



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

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

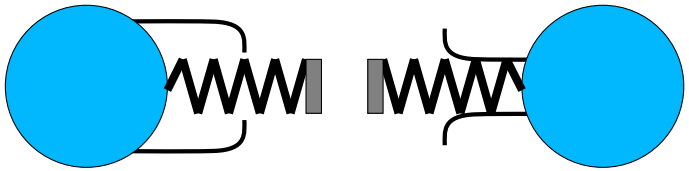
But even when it's out of sight
The Sun shines night and day
We need its heat, we need its light
The Sun light that we seek
The Sun light comes from our own sun's atomic energy

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



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 5 billion years left!

Back to Neutrinos

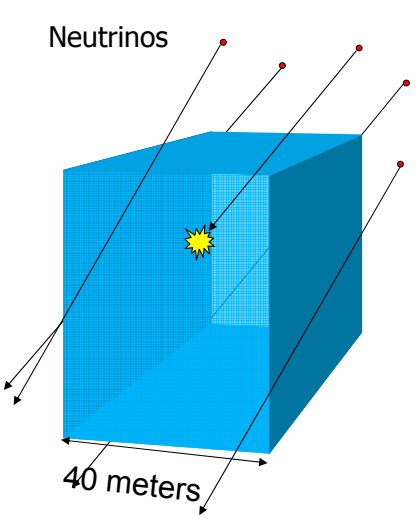
- The Sun's nuclear fusion produces a particle called a *neutrino*
- Matter is almost transparent to neutrinos
- On average, it would take a block of lead over a quarter of a light-year long to stop one
- Roughly 1 billion pass through every square centimeter of you every second!
- They escape the Sun immediately, not in hundreds of thousands of years

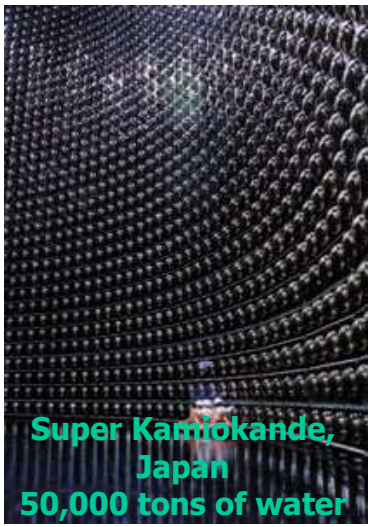
Cosmic Gall

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.

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

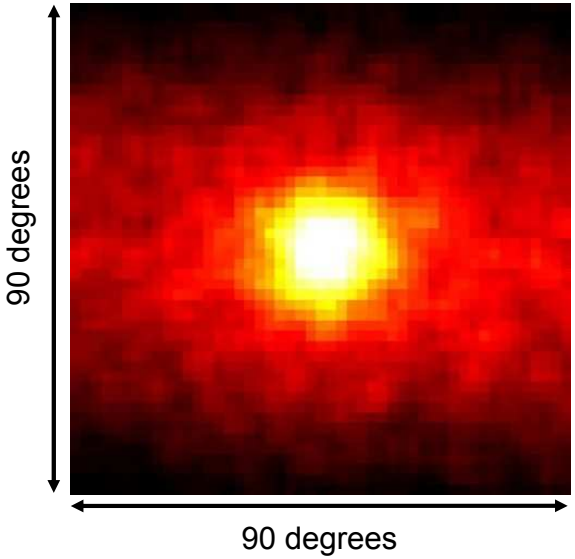
Detecting Neutrinos





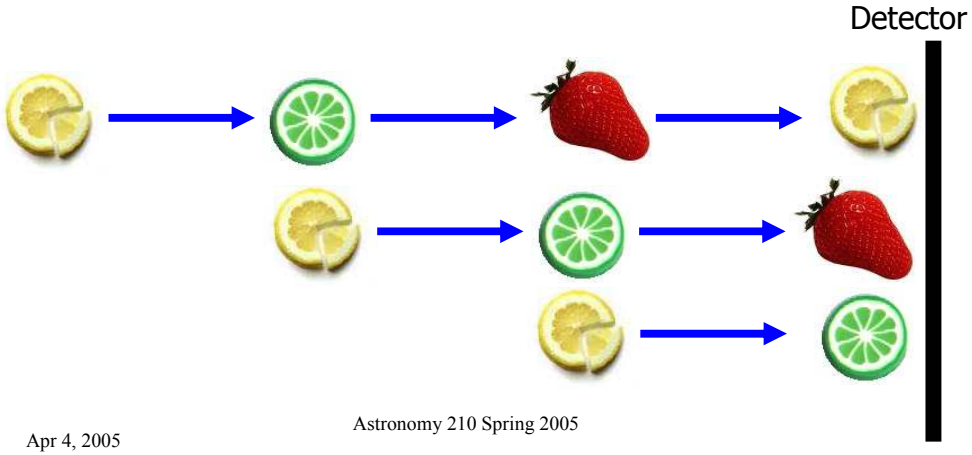
The Sun in Neutrinos

- The **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



The Solar Neutrino Problem

- Only 1/3 the predicted number of neutrinos is seen!
- It turns out, neutrinos come in three types
  - Neutrinos can change type
  - Experiments only looked for one type



Cosmic Gall

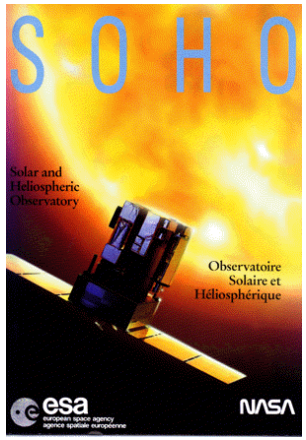
NEUTRINOS, they are very small.
They have no charge and have ~~no~~ very little mass
And do ~~not~~ hardly interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,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

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

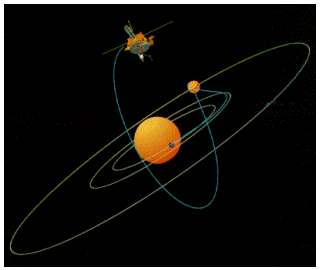
Think-Pair-Share

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

Spacecraft Observing the Sun



SOHO



Ulysses

TRACE

RHESSI