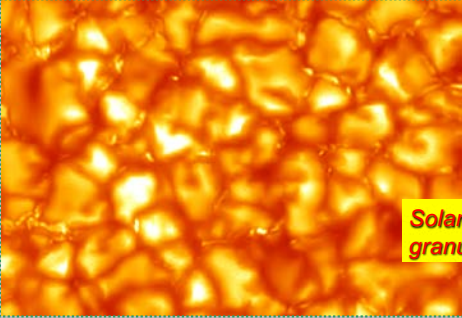


**ASTR 1040: Stars & Galaxies**



**Solar granulation**

Prof. Juri Toomre TAs: Piyush Agrawal, Connor Bice  
Lecture 7 Tues 7 Feb 2017  
[zeus.colorado.edu/astr1040-toomre](http://zeus.colorado.edu/astr1040-toomre)

**Topics for Today and Thur**

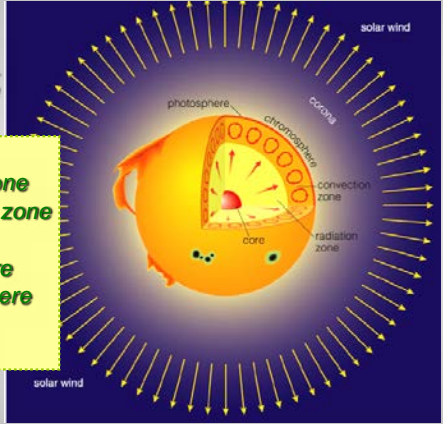
- Consider Sun's energy source (fusion H--He)
- What about the elusive neutrinos ?
- Transport of energy by convection
- Heliogeismology: acoustic waves excited by convection to probe interior

- Finish second read of **Chap 14 (Our Star)**, for magnetism discussion on Thurs
- Re-read **S4.1, S4.2** (quarks, leptons, ..)
- **Observ # 2** this Thur eve; HW #2 returned

**Reading Clicker Q D.**

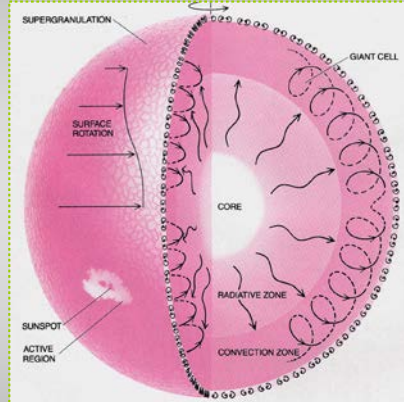
- What is the composition (by mass) of the Sun ?
- **A.** 100% hydrogen (H) and helium (He)
- **B.** 50% H, 25% He, 25% other elements
- **C.** 70% He, 28% H, 2% other
- **D.** 70% H, 28% He, 2% other
- **E.** 98% H, 2% He and other

**Big System View of Sun**



**core**  
**radiative zone**  
**convection zone**  
-----  
**photosphere**  
**chromosphere**  
**corona**  
**solar wind**

**Convection Zone and Radiative Interior**



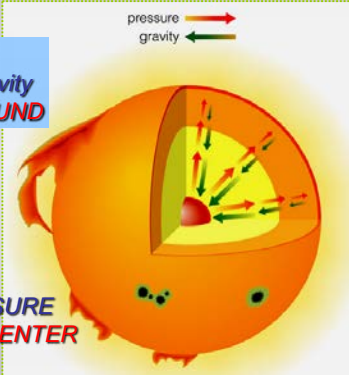
**Just below the photosphere:**

**Deep shell (30%) of very turbulent convection**

**Drives strong differential rotation**

**Pull of gravity = Push of pressure gradient**

**SPHERICAL nature of gravity makes it ROUND**



**High PRESSURE needed at CENTER**

**Gravitational equilibrium**

**PRESSURE vs GRAVITY**

**HOT CENTER**

GRAVITATIONAL (HYDROSTATIC) EQUILIBRIUM (HSTAR)

"HOW A STAR HOLDS ITSELF UP"

NEED VERY HIGH PRESSURE AT CENTER, LOWER PRESSURE OUTSIDE

GAS MOLECULES NEED TO MOVE VERY FAST TO YIELD HIGH PRESSURE = VERY HOT

TO KEEP CENTER HOT: OPERATE A NUCLEAR "FURNACE"!

**How to get high central pressure?**

In gases, plasmas, "equation of state" is roughly

**PRESSURE = DENSITY x TEMPERATURE**

1. Making the **CENTER HOT** yields **high pressure** that keeps star from collapsing
2. If **really hot**, **NUCLEAR BURNING** can supply the energy that **always leaks away** from hot places

**Fusion or fission as star's energy source?**

**Plenty of H for fusion, almost no 'heavy' fuel for fission: H converted to He**

**Need high temperatures to make fusion happen**

**High temperature gives high speeds**

At low speeds, electromagnetic repulsion prevents the collision of nuclei.

At high speeds, nuclei come close enough for the strong force to bind them together.

**SUN as a SPHERE**

**NUCLEAR BURNING near center**

WHY IS THE SUN A SPHERE? THE INSIDE STORY

GASEOUS SPHERE IS IN "HYDROSTATIC BALANCE OR EQUILIBRIUM":

- GRAVITY FORCE PULLING INWARD
- BALANCED BY
- PRESSURE FORCE PUSHING OUTWARD

HIGH ENOUGH CENTRAL PRESSURE NEEDS HIGH TEMPERATURE:  $T \sim 16$  MILLION K

THERMONUCLEAR FUSION IS THE ENERGY SOURCE:

"PROTON-PROTON CHAIN"

A:  ${}^1_1\text{H} + {}^1_1\text{H} \rightarrow {}^2_1\text{H} + e^+ + \nu$

B:  ${}^2_1\text{H} + {}^1_1\text{H} \rightarrow {}^3_2\text{He} + \gamma$ ;  $e^+ + e^- \rightarrow 2\gamma$

C:  ${}^3_2\text{He} + {}^3_2\text{He} \rightarrow {}^4_2\text{He} + 2 {}^1_1\text{H}$

**P-P chain**

**Hans Bethe (1937)**

0.7% MASS CONVERTED TO ENERGY  $\Rightarrow$  POWERS SUN ( $E=mc^2$ )

$\sim$  MILLION YEARS FOR ENERGY TO LEAK TO SURFACE!

"PROTON-PROTON CHAIN"

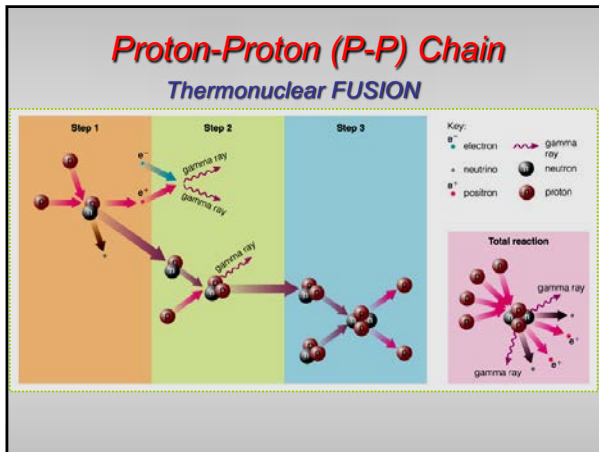
A: COLLIDE PROTON PROTON  $\rightarrow$  DEUTERON + EMIT POSITRON + EMIT NEUTRINO

B: COLLIDE DEUTERON PROTON  $\rightarrow$  LIGHT ISOTOPE HELIUM + GAMMA RAY + EMIT NEUTRINO + EMIT ELECTRON

C: HELIUM NUCLEI COLLIDE  $\rightarrow$  HELIUM + TWO PROTONS

0.7% MASS CONVERTED TO ENERGY  $\Rightarrow$  POWERS SUN ( $E=mc^2$ )

$\sim$  MILLION YEARS FOR ENERGY TO LEAK TO SURFACE!



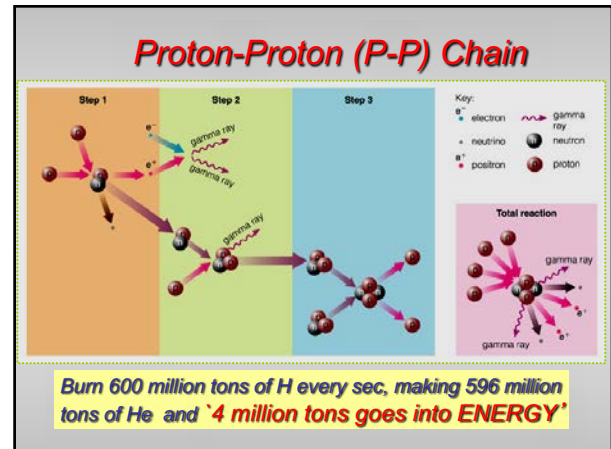
### Clicker Question

The Sun is made up of (mostly) hydrogen. Yet the P-P chain starts with two protons. Why are they not with their electrons?

- The core is very hot so the electrons are all ionized.
- The electrons have all moved to the outer layers of the Sun.
- The Sun is electrically positive, so all that exists are hydrogen ions.
- Neutral hydrogen only consists of one proton and one neutron in the first place.

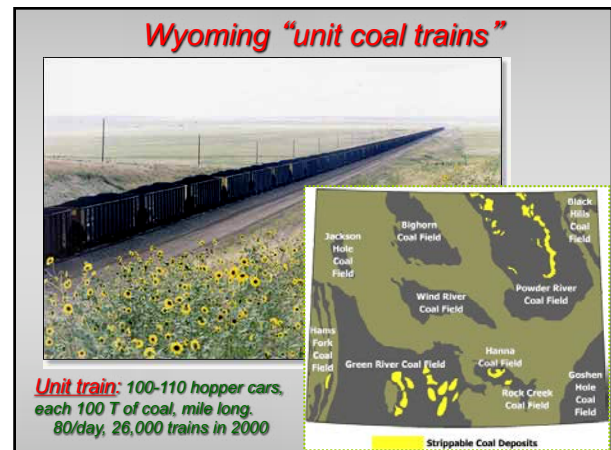
### Sun's energy budget (simply put)

- Helium has atomic mass 3.97 times that of hydrogen, NOT exactly 4 times
- Tiny amount of the protons' mass is lost to energy
- $E = mc^2$  (a little mass makes a lot of energy)
- Rates are fast enough that 4 million tons of mass are converted into energy each second!



### Nuclear vs chemical burning

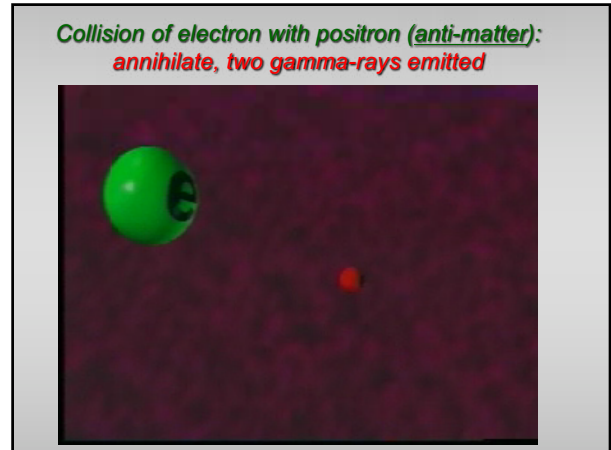
- Nuclear p-p burning :  
1 kg of H becomes 0.993 kg He
- 7 grams releases :  $6.3 \times 10^{14}$  joules
- Same energy released by chemically burning ~20,000 tons of coal !! (2 unit trains)
- Sun's luminosity : (vs 40 W lightbulb)  
 $L \sim 3.8 \times 10^{26}$  joules/sec (watts)





**How much is 7 grams compared to 1000 grams (1 kg) ?**

7 paper clips!

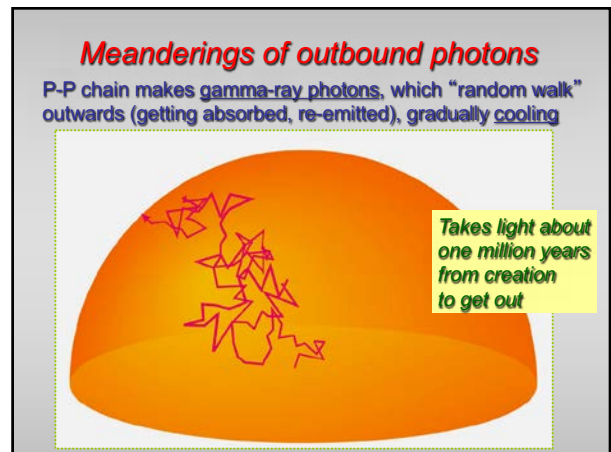
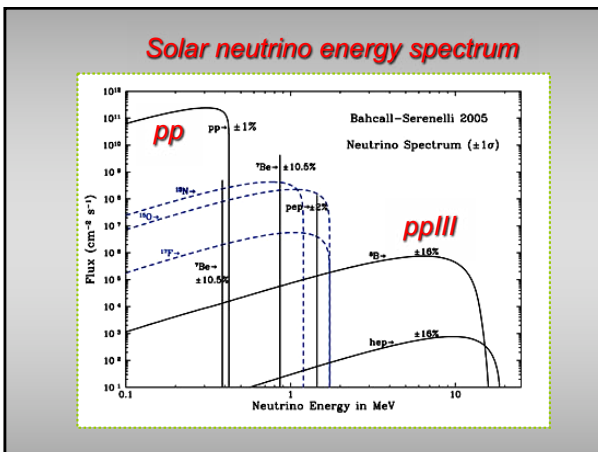
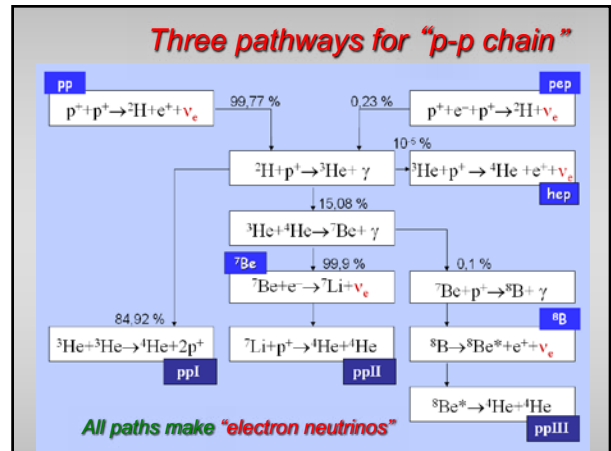


**Proton-proton chain: summary**

- **Input:** 6 protons
- **Output:** 1 helium  
2 protons  
2 positrons → **gamma rays**  
2 **neutrinos**  
+ more gamma rays

**4 hydrogens → 1 helium + 2 neutrinos + gamma rays (energy)**

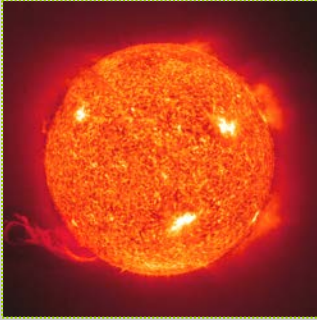
**DO WE SEE THE GAMMA-RAYS, NEUTRINOS ?**



## Heading outward (slow & fast)

**Gamma rays** slowly work their way outwards, cool, and become sunlight (about million years)

**Neutrinos** don't interact with much, zoom right out of Sun and into space, **carry 2% of the Sun's energy** – even travel right through Earth!



## Those Mysterious Neutrinos

### MADE BY P-P BURNING IN CORE

- **Mass-less or with very small masses**, travel close to speed of light
- **Don't interact (almost) with other matter**: requires lead wall 1 light year thick to stop a neutrino!
- **Lots of them**:  $10^{38}$  neutrinos/sec from the Sun, 65 billions/cm<sup>2</sup>/sec coming through YOU!
- But we can still catch some, using massive underground "detectors": **BIG PUZZLE**

## Big Puzzle: Catching Solar Neutrinos

### Visionary: Ray Davis

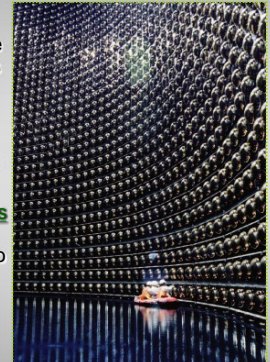
- Located deep underground, rock blocking other particles
- Huge underground vat of dry-cleaning fluid
- Chlorine captures neutrino, becomes radioactive argon
- **Only collects 1 neutrino about every 3 days** -- even with 100,000 gallons
- **Solar theory predicted THREE TIMES more!**
- Big hunt started, called **SOLAR NEUTRINO PROBLEM**



Homestake Gold Mine SD

## Resolving the Solar Neutrino Puzzle

- **Super-Kamiokande** uses massive tank of water to capture neutrinos
- Each rare capture gives flash of light, detected by giant tubes
- **Captures lower energy neutrinos from p-p chain, so more sensitive test of fusion**
- Suggests some **electron neutrinos** may change into **muon and tau neutrinos** during course of flight to us (8 minutes)
- **MSW Neutrino Oscillations** require neutrinos to have some mass!



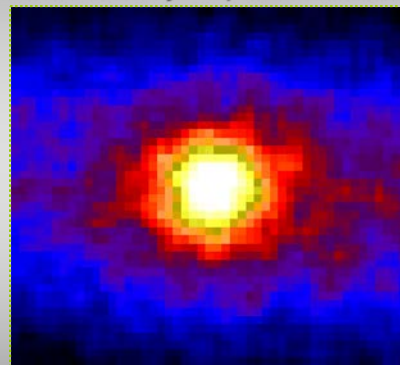
Kamiokande Nickel Mine, Japan

## Sudbury Neutrino Observatory (SNO)

- Uses **"heavy water"** -- one H in H<sub>2</sub>O replaced by its stable isotope deuterium (P+N)
- SNO is capturing **all three types of neutrinos** (electron, muon, tau)
- **"Solar neutrino problem"** leads to big physics advance (2002 Nobel Phys Prize; Davis & Koshiba)



## Sun Viewed by Super-Kamiokande



500 day "exposure"