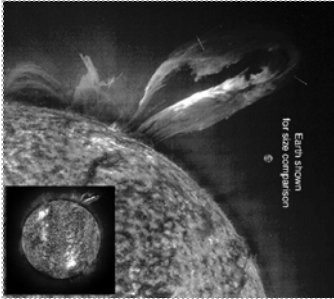


# ASTR 1120: Stars & Galaxies



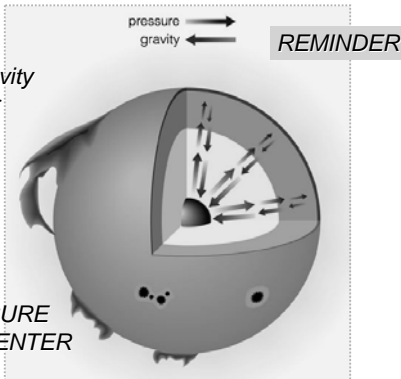
Prof. Juri Toomre TA: Ben Brown  
 Lecture 9 Mon 31 Jan 05  
[zeus.colorado.edu/astr1120-toomre](http://zeus.colorado.edu/astr1120-toomre)

## Topics for Today

- What is the Sun's energy source? What keeps it shining? Fusion of H to He !
- Elusive solar neutrinos from p-p chain
- Next lecture: Different layers of Sun and their roles – and helioseismology
- Graded HW # 1 still available, plus pick up answer sheet (if not already)
- Homework # 3 still available, due Friday
- Finish reading Chap 15, *The Sun*, in detail

Pull of gravity = Push of pressure gradient

SPHERICAL nature of gravity makes a star ROUND



High PRESSURE needed at CENTER

### REMINDER

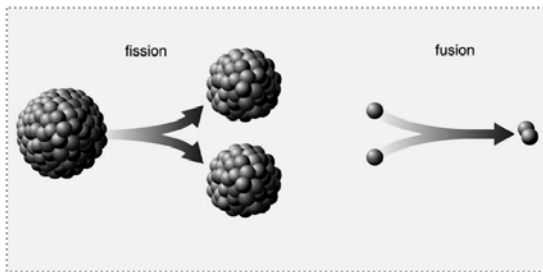
## How to get high central pressure?

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

$$PRESSURE = DENSITY \times TEMPERATURE$$

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?



FUSION is the answer: H converted to He

## 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":

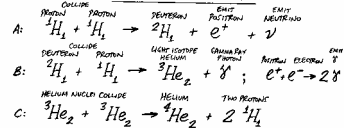
- GRAVITY FORCE PULLING INWARD
- BALANCED BY
- PRESSURE FORCE PUSHING OUTWARD

HIGH ENOUGH CENTRAL PRESSURE NEEDED

HIGH TEMPERATURE:  $T \sim 16$  MILLION K

THERMONUCLEAR FUSION IS THE ENERGY SOURCE:

"PROTON-PROTON CHAIN"



P-P chain

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

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

## How hydrogen is built into helium...

Hydrogen nucleus = 1 proton

Helium = 2 protons + 2 neutrons

Fusion occurs via the Proton-Proton Chain

4 protons (or 4 Hydrogens) → 1 Helium  
PLUS Energy !

## Clicker Q -- nuclei **B.**

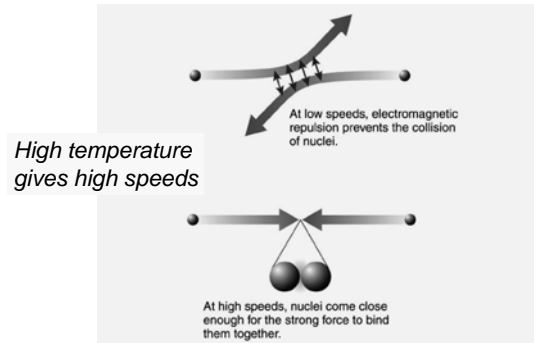
The atomic nucleus PPN (two protons plus a neutron):

- A. Is an isotope of hydrogen
- B. Is an isotope of helium
- C. Is an isotope of lithium

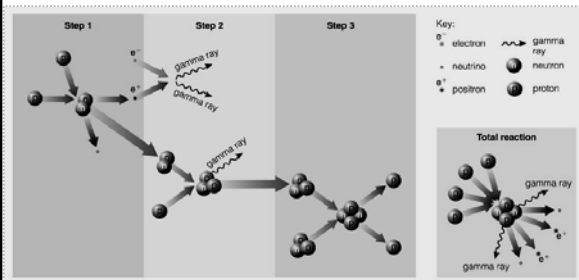
## What is it?

- B. An isotope of helium
- Helium is the element with TWO protons, no more, no less
- Helium usually has 2 neutrons (PPNN), but with a single neutron is "Helium-3" = PPN

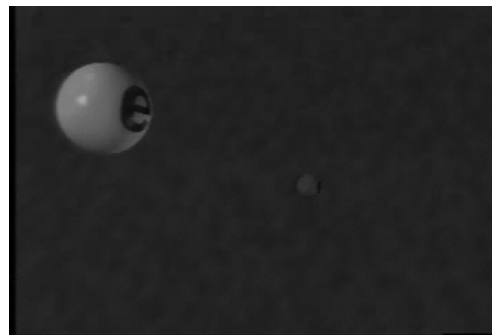
## Need high temperatures to make fusion happen



## Proton-Proton (P-P) Chain Thermonuclear FUSION



## Collision of electron with positron



### Proton-proton chain: summary

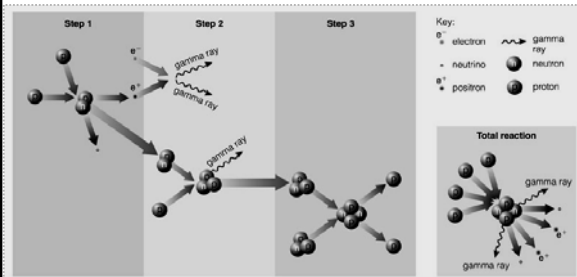
- **Input:** 6 protons
  - **Output:** 1 helium  
2 protons  
2 positrons → gamma rays  
2 neutrinos  
+ more gamma rays
- 4 hydrogens → 1 helium + 2 neutrinos + gamma rays (energy)

### Sun's energy budget

- 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!

### Proton-Proton (P-P) Chain

Thermonuclear FUSION



Burn 600 million tons of H every sec, making 596 million tons of He and 4 million tons goes into ENERGY'

### Solar Thermostat

- Why doesn't the Sun go into a runaway reaction?

Fusion rate is VERY sensitive to temperature,  
→ tight feedback loop

**CRUCIAL**

- A. If energy generation (fusion rate) speeds up:
1. Pressure in core will increase, lifting the gas against gravity (core expands)
  2. Gravitational energy is created from thermal energy → the gas cools
  3. Energy generation (fusion rate) slows down

### More on solar thermostat

B. However, if energy generation drops:

1. Core pressure drops
  2. Solar core starts to collapse
  3. Temperature rises
  4. Fusion rates go up again
- Sun is remarkably stable, only small (30%?) increase in fusion rate over billions of years

### 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,  $10^{15}$  coming through YOU each sec!
- But we can still catch some, using massive underground "detectors": **BIG PUZZLE**

## Big Puzzle: First Neutrino Detector

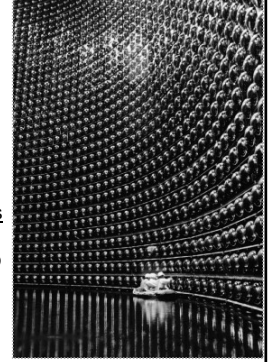
- Located deep underground, rock blocking other particles
- Huge underground vat of dry-cleaning fluid
- Chlorine captures neutrino, becomes radioactive argon
- Only collects 1 neutrino about every 3 days -- even with 100,000 gallons
- Solar theory predicted THREE TIMES more!
- Big hunt started, called **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)
- *Neutrino Oscillations* require neutrinos to have some mass!



Kamiokande Nickel Mine, Japan