Today +

- Neutrino puzzle -- test of deep interior
- Probing inside of sun with sound: helioseismology
- Interior structure – what is run of temperature and density with radius

- New HM # 4 given out, HW # 3 due today
- Next discussion response (for Tues Feb 9): What are effects of solar activity on our technological society?

Proton-Proton (P-P) Chain

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

Nuclear vs chemical burning

- Nuclear p-p burning:
  1 kg of H becomes 0.993 kg He
- 7 grams releases: 6.3 x 10^{14} joules

- Same energy released by chemically burning ~20,000 tons of coal!! (2 unit trains)
- Sun’s luminosity: (vs 40 W lightbulb)
  \( L \approx 3.8 \times 10^{26} \text{ joules/sec (watts)} \)

Proton-proton chain: summary

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

DO WE SEE THE GAMMA-RAYS, NEUTRINOS?
Elementary Particles

If the Sun’s core went out of balance and shrank a little, what would happen there?

A. Density would decrease and fusion would slow down, releasing less energy
B. Density and temperature would increase and fusion would speed up, releasing more energy
C. The whole Sun would eventually shrink and thus core would come back into balance
D. Not much would really change, so nothing to worry about

Solar Thermostat

Why doesn’t the Sun go into a runaway reaction?
Fusion rate is very sensitive to temperature, → tight feedback loop
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

However, if energy generation drops:
1. Core pressure drops
2. Solar core starts to shrink
3. Temperature rises
4. Fusion rates go up again

Sun is remarkably stable, only small (30%?) increase in fusion rate over billions of years

Reading Clicker Q

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

Meanderings of outbound photons

P-P chain makes gamma-ray photons, which “random walk” outwards (getting absorbed, re-emitted), gradually cooling

Takes light about one million years from creation to get out
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!

Discussion

• How do we really know what is happening deep within the Sun?
• What is the interplay between theory and observation?

Temperature and density with radius

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: Catching Solar Neutrinos

• 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

Proton-Proton (P-P) Chain

Thermonuclear FUSION

Two “electron” neutrinos produced
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!

Sudbury Neutrino Observatory (SNO)

- Uses “heavy water” -- some H in H\(_2\)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"

Convection Zone and Radiative Interior

- Deep shell (30%) of very turbulent convection
- Drives strong differential rotation
- But how do we know this?

Helioseismology: *Millions of sound waves available to probe solar interior*

- Some waves noodle just below the surface
- Others almost make it to the center
- All excited by turbulent granulation visible in photosphere

BONGO DRUMS and SOLAR TONES

- **HOW THE LENGTH OF DRUM CONTROLS THE TONE (FREQUENCY)**