How does the Sun shine? Examine the energy source? (Fusion of H to He)
The neutrino puzzle — test of deep interior
Interior structure — what is run of temperature and density with radius
Read $S.4$ Building blocks of universe: fermions, bosons, quarks, leptons … discuss in recitation

Discussion this week: How do we know what happens deep within the Sun?
Observatory Night 2 tonight 7pm+

Pros and cons: Lunar Observatory

- No atmosphere, all radiation gets through
- No light/radio pollution
- Moon is solid ground
- No environmentalists!
- Pre-existing crater as (almost) radio dish
- If on far-side, away from Earth noise (but Sun?)

Could it be cost-effective?

What are the solar “layers”, in going from deep inside to outside?

- A. core, radiation zone, convection zone, photosphere, chromosphere, corona
- B. core, radiation zone, convection zone, corona, chromosphere, photosphere
- C. core, corona, radiation zone, convection zone, photosphere, chromosphere

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
Pull of gravity = Push of pressure gradient

SPHERICAL nature of gravity makes it ROUND

High PRESSURE needed at CENTER

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

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

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

SUN as a SPHERE

NUCLEAR BURNING near center

PP chain

Hans Bethe
Proton-Proton (P-P) Chain

Thermonuclear FUSION

Collision of electron with positron (anti-matter): annihilate, two gamma-rays emitted

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
  Releases: \( 6.3 \times 10^{14} \) joules
- Same energy released by chemically burning \( \sim 20,000 \) tons of coal !!
- Sun’s luminosity: (vs 40 W lightbulb)
  \[ L \sim 3.8 \times 10^{26} \text{ joules/sec (watts)} \]

Solar Thermostat

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

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 \rightarrow 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*

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**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?*

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**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*

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**Temperature and density with radius**

*from "stellar structure" theory, helioseismology*

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**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

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**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
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!

Sudbury Neutrino Observatory (SNO)

- Uses “heavy water” -- some H in H₂O 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)

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!