Today

- How does the Sun shine? Examine p-p chain energy source (fusion of H to He)
- Workings of solar thermostat to maintain stable energy production in core

- Read S.4.1–4.2 Building blocks of universe: fermions, bosons, quarks, leptons … discuss in recitation on Monday
- Respond to next discussion by Tues on the solar interior

Big Qs about the Sun (and any star)

- Why is a star ROUND?
- What keeps a star from collapsing inward?
- What keeps it shining?
- Why does it rotate and have varying magnetic fields?

Reading Clicker Q

A.

- 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

Big System View of Sun

EUV from SOHO
**Sun is a big ball of “plasma”**

- Hydrogen and helium are ionized by the high temperature throughout most of the star.
- Such electrically-conducting gas is called a plasma.
- Movement of plasma has currents flowing, builds magnetic fields and electric fields.

**How to get high central pressure?**

In gases, plasmas, “equation of state” is roughly

\[
\text{PRESSURE} = \text{DENSITY} \times \text{TEMPERATURE}
\]

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

SUN as a SPHERE

NUCLEAR BURNING near center

Proton-Proton (P-P) Chain

Thermonuclear FUSION

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!

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

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)
  $$L \sim 3.8 \times 10^{26} \text{ joules/sec (watts)}$$

Wyoming “unit coal trains”

Unit train: 100-110 hopper cars, each 100 T of coal, mile long, 80/day, 26,000 trains in 2000

Clicker Q -- nuclei

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

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**

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**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?**