ANNOUNCEMENTS

PLEASE CHANGE CLICKER FREQUENCY TO 26
On to Our Nearest Star: the **SUN**
De-Mystifying science
The case of the Sun

• Ancient philosophers/scientists thought that the sun was some kind of fire.

• What things would we want to ask about the Sun in this course?
1. How far is the Sun?
2. What is the Sun made of?
3. How does the Sun produce its energy?
4. Why is the Sun stable?
5. What’s inside the Sun?

6. What will be the end of the Sun?
7. How massive is the Sun?
1. How far is the Sun?

• How can we determine the distance of the Sun?
  1. Find the distance to an inner planet
  2. Find distance to Sun at position of greatest elongation

\[ D_{\text{max}} = 152 \text{ million km} - D_{\text{min}} = 146 \text{ million km} \]
2. What is the Sun made of?

- How can we determine the composition of the Sun?
Use Absorption Line Spectra

70% of Hydrogen; 28% of Helium; 2% of heavier elements
3. How does the Sun produce its energy?
Could it be chemical burning?

1. Energy released by burning oil
   \( \sim 10^7 \text{joules/kg} \)

2. Solar energy output (Luminosity) =
   \( 3 \times 10^{26} \text{joules/sec} \) (mostly in visible light.)

3. Need \( (3 \times 10^{26} \text{joules/sec}) / (10^7 \text{joules/kg}) = 3 \times 10^{19} \text{ kg of burning oil per second} \)

4. How long will the Sun last? \( \Rightarrow M_{\text{Sun}} / (\text{amount burning per second}) \)
   \( = (2 \times 10^{30} \text{ kg}) / 3 \times 10^{19} \text{ kg/s} = 6.6 \times 10^{10} \text{ seconds} = 2,000 \text{ years!!} \)
Maybe it’s gravitational contraction?

- Gravitational contraction (Kelvin-Helmholtz contraction) can give ~10,000 times more energy than chemical burning.

How old can the Sun be if its source of energy is gravitational contraction?

~25,000,000 years.

But geological record showed age > 150,000,000 years!
Energy generated by **FUSION!**

**Hydrogen Fusion by the Proton-Proton Chain**

**Step 1**
Two protons fuse to make a deuterium nucleus (1 proton and 1 neutron). This step occurs twice in the overall reaction.

**Step 2**
The deuterium nucleus and a proton fuse to make a nucleus of helium-3 (2 protons, 1 neutron). This step also occurs twice in the overall reaction.

**Step 3**
Two helium-3 nuclei fuse to form helium-4 (2 protons, 2 neutrons), releasing two excess protons in the process.

**Overall reaction**
- Gamma ray

*Key:*
- **n** neutron
- **p** proton
- **~** gamma ray
- **○** neutrino
- **●** positron

Proton-Proton chain

\[ E=mc^2 \]
**Fission** as energy source:

- Big nucleus splits into smaller pieces
  - (Nuclear power plants)

**Fusion** NOT fission as energy source:

- Small nuclei stick together to make a bigger one
  - (Sun, stars)
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!)

- 600 million tons of H every second is converted to 596 million tons of He...4 million tons of mass are converted into energy each second!
Need high temperatures to make fusion happen

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

High temperature gives high speeds

At high speeds, nuclei come close enough for the strong force to bind them together.
The Sun is made up of (mostly) hydrogen. Yet the P-P chain starts with two protons. Why are they not with their electrons?

A. The material is very hot so the nuclei and electrons are all free.
B. The electrons have all moved to the outer layers of the Sun.
C. The Sun is electrically positive (thus the magnetic fields) so all that exists are hydrogen ions.
D. Neutral hydrogen only consists of one proton and one neutron in the first place.
E. The electrons have been all annihilated with positrons.
The Sun is made up of (mostly) hydrogen. Yet the P-P chain starts with two protons. Why are they not with their electrons?

A. The material is very hot so the nuclei and electrons are all free.
B. The electrons have all moved to the outer layers of the Sun.
C. The Sun is electrically positive (thus the magnetic fields) so all that exists are hydrogen ions.
D. Neutral hydrogen only consists of one proton and one neutron in the first place.
E. The electrons have been all annihilated with positrons.
Do we have direct evidence for fusion in the Sun?

- YES! Neutrinos
Those Mysterious Neutrinos

MADE BY HYDROGEN FUSION IN CORE

• Mass-less or (likely) 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: First Neutrino Detector

- Located deep underground, ground blocked other particles
- Huge underground vat of dry-cleaning fluid (chlorine)
  - 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
Sudbury Neutrino Observatory (SNO)

- Uses “heavy water” -- some H in H\textsubscript{2}O replaced by its stable isotope deuterium (P+N)
- SNO captures all three types of neutrinos (electron, muon, tao)
  - Detects the RIGHT numbers!!
- “Solar neutrino problem” leads to big physics advance (2002 Nobel Prize; Davis & Koshiba)
Could the neutrinos flowing through our bodies be a cause of cancer or other cellular damage?

A. YES, because there are so many and they carry a lot of energy

B. NO, because they don’t interact with anything and just flow through

C. MAYBE, it depends on if they are electron, muon or tau neutrinos.
Could the neutrinos flowing through our bodies be a cause of cancer or other cellular damage?

A. YES, because there are so many and they carry a lot of energy
B. NO, because they don’t interact with anything and just flow through
C. MAYBE, it depends on if they are electron, muon or tau neutrinos.
How does the number of neutrinos passing through your body at night compare with the number passing through during the day?

A. About the same.
B. Much smaller during the night.
C. Much larger during the night.
D. Neutrinos don’t pass through our body.
How does the number of neutrinos passing through your body at night compare with the number passing through during the day?

A. About the same.
B. Much smaller during the night.
C. Much larger during the night.
D. Neutrinos don’t pass through our body.
4. What makes the Sun stable?

- To understand this, we have to look into the forces at work on the Sun.
Hydrostatic Equilibrium

Pull of gravity = Push of pressure

High PRESSURE at CENTER
In gases, we have, roughly:

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

1. A high pressure in the center results in a high temperature.

2. If really hot, NUCLEAR BURNING can supply more energy

- Why don’t we get a runaway reaction?
The Solar Thermostat

Nuclear fusion rate very sensitive to temperature.

... leads to a large decrease in the fusion rate...
... that lowers the core pressure...
... causing the core to contract and heat up...
... thereby restoring the fusion rate to normal.

A slight drop in core temperature...

A slight rise in core temperature...
... thereby restoring the fusion rate to normal.
... leads to a large increase in the fusion rate...
... that raises the core pressure...
... causing the core to expand and cool down...