Fusion Powers the Sun—10 Oct

- Big questions
  - What powers the sun?
  - Where does carbon come from?
  - How long does the sun live?
  - What happens to the sun when it dies?
- Lifetime of the sun
  - Chemical reactions
  - Gravitational energy
  - Nuclear fusion
- Fusion
  - $4\text{H} \rightarrow 4\text{He}$

19th Century “Energy Crisis”

- Luminosity $L=4 \times 10^{26}$ Watt
- Mass $m=2 \times 10^{30}$ kg
- How long will the sun last if the energy is produced by burning coal? $\text{C}+\text{O}_2 \rightarrow \text{CO}_2$
  - Life time = $m \times (E/m)/L$
  - $E/m=9\text{MJ/kg}$
  - 1500 years
- Earth is much older than that.

Extract Energy from Gravity

- Luminosity $L=4 \times 10^{26}$ Watt
- Mass $m=2 \times 10^{30}$ kg
- How long will the sun last if the energy is produced by the sun contracting?
- If material falls from $R_{\text{sun}}$ to $0.9R_{\text{sun}}$
  - Energy = $\frac{1}{2} m v^2 = m g h = m \left(\frac{GM_{\text{sun}}R_{\text{sun}}^2}{R_{\text{sun}}^2}\right)(0.1R_{\text{sun}})$
  - Life time = $m \times (E/m)/L$
  - 1.6 Million years
- Kelvin’s calculation includes material falling not just on surface. Got 100 Myr.
  - Kelvin thought earth could be this old, but later in 19th century, age of earth was shown to be much larger.

E=mc$^2$

- Crisis: No solution with physics of 19th century.
- Einstein’s new theory (1906)
  - $E = mc^2$
  - Energy = mass × (speed of light)$^2$.
- Energy can change into mass, and mass can change into energy.
- Changing a little mass produces a lot of energy. Compare kinetic energy $\frac{1}{2} m v^2$ with $m c^2$.
  - Speed of light $c = 300,000 \text{ km/s}$
  - Air in blast furnace moves at 0.2 km/s
- Chemical reaction $\text{C}+\text{O}_2 \rightarrow \text{CO}_2$
  - $E=m c^2/100,000,000,000$. One part in 100 billion of mass disappears and changes into energy.
- Sun contracts by 10%
  - $E=m c^2$. One part in a million of mass disappears and changes into energy.
Nuclear fusion

• In a nuclear reaction, converting a significant fraction of the mass to energy is possible.
• Bethe figured out how.
• $4 \times ^1H \rightarrow ^4He +$ neutrinos +2e+ energy
  – 4 hydrogen nuclei fuse
  – One helium nucleus is produced
• Life time = $m \times (E/m)/L$
  – $m \times (0.007mc^2/m)/L$
  – 100Byr
  – In reality sun uses 10% of fuel. Lifetime is 10Byr


Proton-proton chain

• Watch a proton for an average of 10 Byr before reaction in step 1 occurs.
  – Electrical repulsion; Coulomb repulsion; Coulomb barrier
  • Requires fast speed or high temperature to overcome repulsion.
  – Neutrino indicates a “weak” reaction, which is weak.


Model of the Sun

1. At what radius is the density of the sun that of water (1gm/cm³)? Same for gold (19gm/cm³)
2. 90% of the energy is produced within ____ $R_{sun}$ of the center.

Interior of the sun

• Use physics to construct models
• Energy is generated by nuclear fusion, which depends on temperature and composition.
• Energy moves from center, where fusion occurs, to outside, where it radiates into space.
• Gas pressure holds the mass of the parts above.
3. Why is there so much helium at the center of the sun?

4. The sun loses 4 million tons of mass every second. How can you capture some of that mass?