Fusion Powers the Sun—6 Oct

- New schedule
  - http://www.pa.msu.edu/courses/AST207/
- Office hours 10/13-10/17
  - Jack Baldwin, 3270 BPS, MWF 12:00-13:00
- Observing (weather permitting)
  - Fri & Sat, 9:00-11:00pm
  - MSU Observatory, Forest & College Rd
- 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
  - $4H \rightarrow {}^4He$

19^{th} Century "Energy Crisis"

- Luminosity of sun $L=4\times10^{26}$Watt
- Mass $m=2\times10^{30}$kg
- How long will the sun last if the energy is produced by burning coal? $C+O_2 \rightarrow CO_2$
  - Life time = m×(E/m)/L
  - E/m=9MJ/kg
  - 1500 years
- Earth is much older than that.

Extract Energy from Gravity

William Thomson
Lord Kelvin
1824-1907
www-history.mcs.st-andrews.ac.uk/history/PictDisplay/Thomson.html /

- Luminosity of sun: $L=4\times10^{26}$Watt
- Mass $m=2\times10^{30}$kg
- How long will the sun last if the energy is produced by the sun contracting?
- If material falls from R_{sun} to $0.9R_{sun}$,
  - Energy = $\frac{1}{2} m v^2 = m g h = m (GM_{sun}/R_{sun}^2)(0.1R_{sun})$
  - Life time = m×(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 19^{th} century, age of earth was shown to be much larger.

$E=mc^2$

- Crisis: No solution with physics of 19^{th} century.
- Einstein's new theory (1906)
  - $E = m c^2$.
  - 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 km/s
  - Air in blast furnace moves at 0.2 km/s
- Chemical reaction $C+O_2 \rightarrow CO_2$
  - $E=m c^2/100{,}000{,}000{,}000$. One part in 100 billion of mass disappears and changes into energy.
- Sun contracts by 10%
  - $E=m c^2/1{,}000{,}000$. One part in a million of mass disappears and changes into energy.

Nuclear fusion

Hans Bethe
1906-2005

- In a nuclear reaction, converting a significant fraction of the mass to energy is possible.
- Hans Bethe figured out the nuclear physics of how this happens.
- 4 ^{1}H $\rightarrow$ ^{4}He + neutrinos +2e$^+$+ energy
  - 4 hydrogen nuclei fuse
  - One helium nucleus is produced

1. Which is heavier? A box of hydrogen and a box of helium, neutrinos, and positrons made from the hydrogen?
   A. H
   B. Products: He, neutrinos, and positrons

Nuclear fusion

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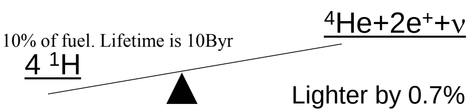
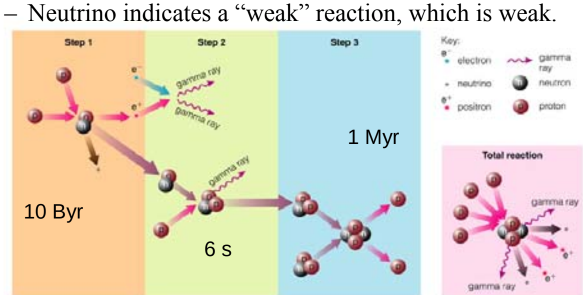
- In a nuclear reaction, converting a significant fraction of the mass to energy is possible.
- 4 ^{1}H $\rightarrow$ ^{4}He + neutrinos +2e$^+$+ energy
  - 4 hydrogen nuclei fuse
  - One helium nucleus is produced
- 4 ^{1}H weighs 0.7% more than ^{4}He + neutrinos +2e$^+$.
  - Part of the mass has been converted into energy.
  - Amount of energy is $E=0.007mc^2$. Most of mass remains.
- Life time = m×(E/m)/L
  - m ×(0.007mc^2/m)/L
  - 100Byr
  - In reality sun uses 10% of fuel. Lifetime is 10Byr



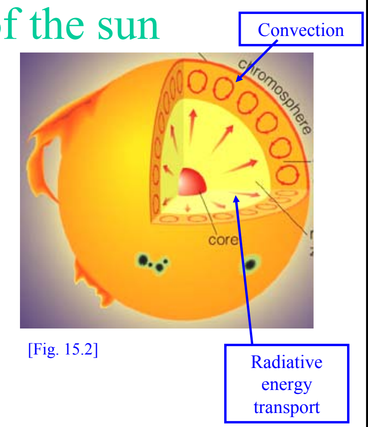
Proton-proton chain

- 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 replusion.
  - Neutrino indicates a "weak" reaction, which is weak.



Interior of the sun

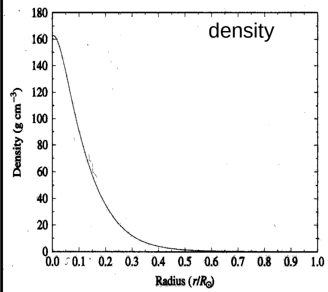
- Use physics to construct models
- Energy is generated by nuclear fusion, which depends on temperature and composition.
- Energy moves from center, where fusion occurs, to outside, where it radiates into space.
- Gas pressure holds the mass of the parts above.

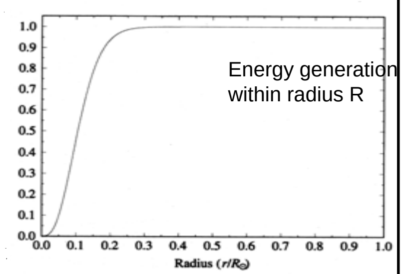


[Fig. 15.2]

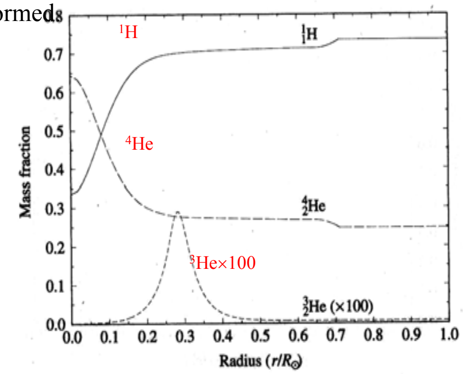
Model of the Sun

1. At what radius is the density of the sun that of water (1gm/cm^3)? Same for gold (19gm/cm^3)
2. 90% of the energy is produced within ___ R_{sun} of the center.





3. Why is there so much helium at the center of the sun?
   A. It used to be hydrogen.
   B. It sunk because it is heavier than hydrogen.
   C. The heavier helium collected in the center when the sun formed



3. The sun loses 4 million tons of mass every second. Can you capture some of that mass?
   A. Yes. Put up a windmill.
   B. You cannot capture mass that has disappeared.