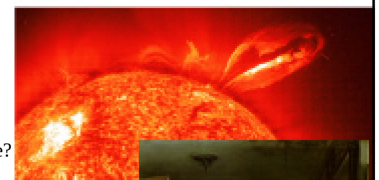
Fusion Powers the Sun—10 Oct



- 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
  - 4H? ^{4}He

19^{th} Century "Energy Crisis"

- Luminosity $L=4\times10^{26}$Watt
- Mass $m=2\times10^{30}$kg
- How long will the sun last if the energy is produced by burning coal? $C+O_2$? CO_2
  - Life time = $m\times(E/m)/L$
  - 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 $L=4\times10^{26}$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 = $m\times(E/m)/L$
  - 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 19^{th} century, age of earth was shown to be much larger.

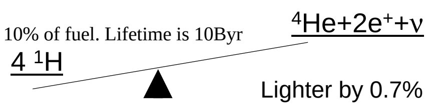
$E=mc^2$

- Crisis: No solution with physics of 19^{th} century.
- Einstein's new theory (1906)
  - $E = m c^2$.
  - Energy = mass $\times$ (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 $C+O_2$? 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

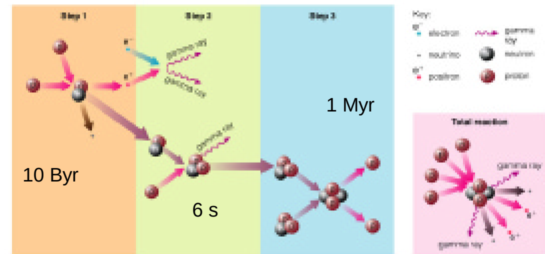
Hans Bethe
1906-2005

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



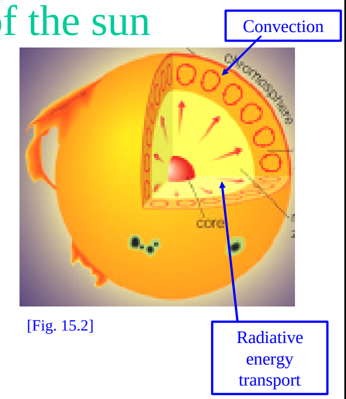
Proton-proton chain

- 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

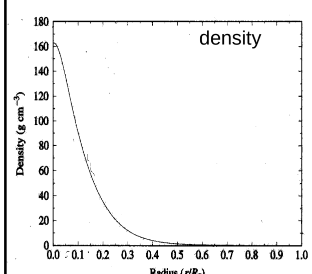
- Use physics to construct models
- Energy is generated by nuclear fusion, which depends on temperature and composition.
- Energy moves from center, where fusion occurs, to outside, where it radiates into space.
- Gas pressure holds the mass of the parts above.

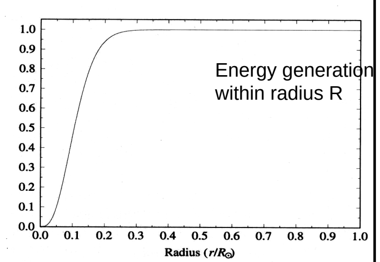


[Fig. 15.2]

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