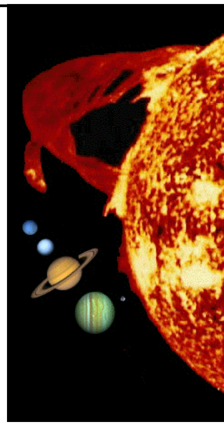
The Sun

- We know the most about the sun
  - We can see surface details.
    - Other stars are points of light.
  - Magnetic fields, wind, flares
- 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
  - $4H \rightarrow {}^4He$



Sun viewed with X rays

- Astronomical Horizons Public Talks
  - Telescopes of the Future
    - Jack Baldwin
    - Abrams Planetarium
    - Thursday at 7:30pm
  - First Light for the Spartan Infrared Camera
    - Ed Loh
    - Thursday, 16 April
- Homework 5
  - Chapters 6, 8, & 9
  - Jovian planets, comets, asteroids, formation of the solar system, extra-solar planets.
  - Due 6:00am, Wed, 25 March
- Test 2
  - Results on www.loncapa.msu.edu
  - Read announcement on angel for instructions.
  - Average 21/35, 61%
  - Average Test 1: 58%
- Overall grades
  - On angel, "Reports" tab
  - Excused absences have not been entered
  - Curve on angel announcements
    - Average 2.9
  - More than half of the course grade is left.
    - 17% for Test 3
    - 35% for Final Exam

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 for burning coal
  - 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 19th 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

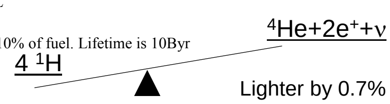
- In a nuclear reaction, converting a significant fraction of the mass to energy is possible.
- Hans Bethe figured out the nuclear physics of how this happens.
- $4\ {}^1H \rightarrow {}^4He$ + neutrinos $+2e^+$+ energy
  - 4 hydrogen nuclei fuse
  - One helium nucleus is produced

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
   C. Mass is the same

Nuclear fusion

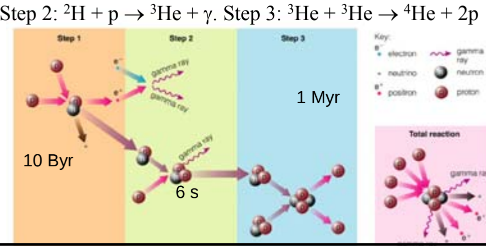
Hans Bethe
1906-2005

- In a nuclear reaction, converting a significant fraction of the mass to energy is possible.
- $4\ {}^1H \rightarrow {}^4He$ + neutrinos $+2e^+$+ energy
  - 4 hydrogen nuclei fuse
  - One helium nucleus is produced
- $4\ {}^1H$ weighs 0.7% more than ${}^4He$ + 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



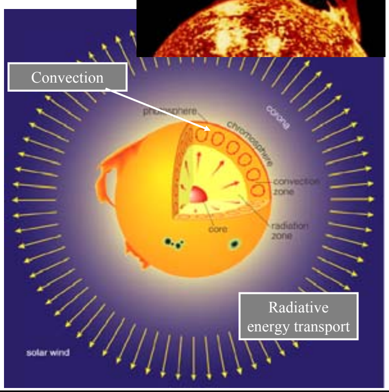
Proton-proton chain

- Watch a proton for an average of 10 Byr before reaction in step 1 occurs. $p + p \rightarrow {}^2H + e^+ + \upsilon$
  - Electrical repulsion; Coulomb repulsion; Coulomb barrier
    - Requires fast speed or high temperature to overcome repulsion.
  - Neutrino is not charged & has very small mass. It exits the sun without scattering.
- Step 2: ${}^2H + p \rightarrow {}^3He + \gamma$. Step 3: ${}^3He + {}^3He \rightarrow {}^4He + 2p$



Parts of the Sun

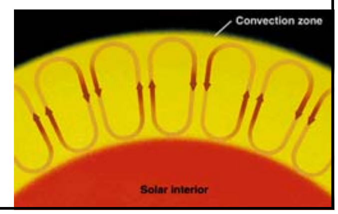
- Core
  - Energy is generated here
- Radiation zone
  - Energy moves by radiation
- Convection zone
  - Energy moves by movement of gas
- Photosphere
  - What we see
- Chromosphere
- Corona
- Wind



Energy transfer

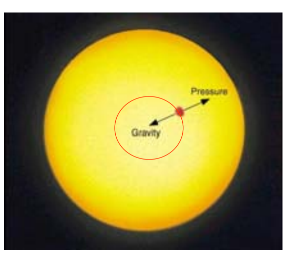
- Radiation
  - photons (light) travel a short distance.
    - absorbed by atoms.
    - re-emitted.
    - Repeat
  - Photons do a random walk & eventually get to convection zone
- Convection
  - hot bubbles rise.
  - cooler bubbles fall.
- Conduction
  - Not important in Sun

[Fig. 10.7]



Interior of the sun

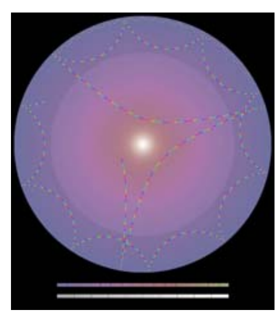
- Use physics to construct models
- Energy is generated by nuclear fusion, which depends on temperature and composition.
- Energy move from center, where fusion occurs, to outside, where it radiates into space.
- <u>Gas pressure holds the mass of the parts above.</u>



[See Fig 10.2]

Solar oscillations with GONG

- Observe motion of the surface caused by sound waves that go deep in the sun
  - Solar seismology
    - Similar to analysis of Earth's interior.
  - Wave pattern reveals interior structure
    - Wave speed depends on composition & temperature

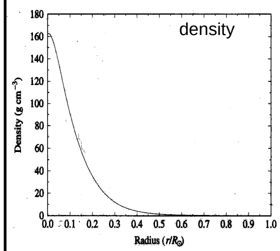


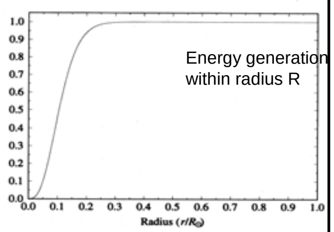
Model of the Sun

1. At what radius is the density of the sun that of water (1gm/cm^3)? Same for gold (19gm/cm^3)

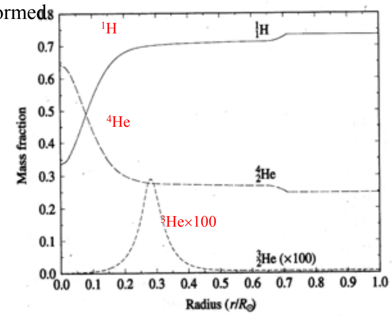
   A: 0, B: 0.25, C: 0.5, D:0 .75, E: surface

is produced within



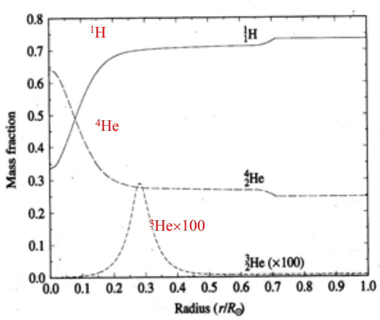


3. Why is there so much helium at the center of the sun?
   - A. It is the "ash" from burning hydrogen.
   - B. It sunk because it is heavier than hydrogen.
   - C. The heavier helium collected in the center when the sun formed.



Composition of the sun

- In center, hydrogen is half used up.



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.