

## The Sun

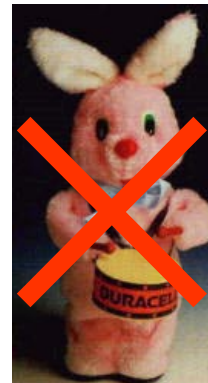
- We know the most about the sun
  - We can see surface details.
    - Other stars are points of light.
  - Magnetic fields, wind, flares
- How does the sun produce energy?
- Inside the sun
- Models of the solar interior



Sun viewed with X rays

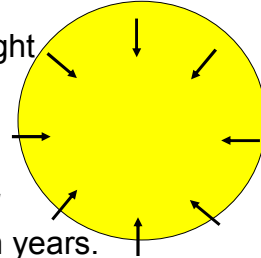
## How does the sun produce energy?

- Lord Kelvin (William Thomson) in Glasgow, Scotland in 1860s.
- Observations: Sun ( $2 \times 10^{30}$  kg) produces  $4 \times 10^{26}$  watts for 4.5 Byrs.
- Batteries (chemical reactions)
  - 0.5 watts/battery  $\Rightarrow$   $8 \times 10^{26}$  batteries required. Battery lasts 40 hours.
  - Sun can shine for 100 years
  - Far too short.
- Kelvin has a better idea
  - Contraction of the sun
  - Led him to maintain that solar system is 100Myrs old, which is incorrect.



## Gravitational contraction?

- Converts gravitational potential energy into kinetic energy
- Kinetic energy in a gas = heat
- Collisions between atoms convert heat to light
- Kelvin-Helmholtz contraction
- To provide  $4 \times 10^{26}$  watts
  - sun must contract by 40 meters per year
  - 40m x 2000 years of observations: *undetectable!*
- Sun shrinking by half => shine for 80 million years.
- 800,000 x better than batteries & chemical reactions. 😊
- *But not good enough.* We need > 4.5 billion years, 60 times longer. 😞



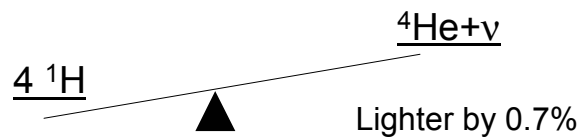
## How does the sun produce energy? $E=mc^2$

- Einstein's theory of relativity (1906)
- Energy can change into mass, and mass can change into energy.
  - Mass disappears & energy appears
  - Energy disappears & mass appears
  - $E = m c^2$ .
    - Energy = mass  $\times$  (speed of light)<sup>2</sup>.
    - Speed of light  $c = 300,000$  km/s
- Chemical reactions convert little mass into energy.
  - Every person on Earth runs a battery for 1 hr.
    - Mass of all batteries is less by  $E/c^2 = 1$  mg.
  - A hydrogen atom absorbs a photon from level 1 to level 2. The mass increases by
    - 1 part in  $10^8$ ; 1 in 100 Million.



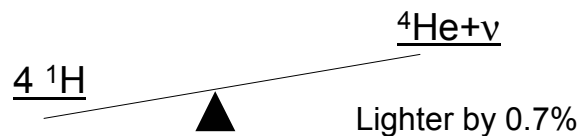
## Nuclear fusion

- $4 \times {}^1\text{H} \rightarrow {}^4\text{He} + \text{neutrinos} + \text{electrons} + \text{energy}$ 
  - 4 hydrogen nuclei fuse to produce one helium nucleus.
- Q: Why does RHS have less mass than LHS?
  - a. You are not weighing the energy.
  - b. Helium is a lighter gas.
  - c. Some of the mass changed into energy.
  - d. The balance is faulty.



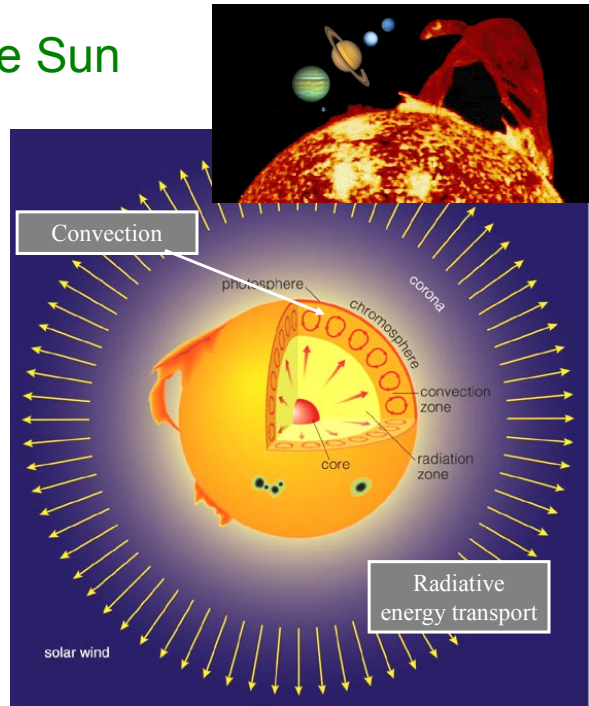
## Sun produces energy by nuclear fusion

- $4 \times {}^1\text{H} \rightarrow {}^4\text{He} + \text{neutrinos} + \text{energy}$ 
  - 4 hydrogen nuclei fuse to produce one helium nucleus.
  - 0.7% of mass becomes energy
  - Hans Bethe figured out the nuclear reactions in 1930s.
- Sun can potentially produce  
 $0.007 \times (2 \times 10^{30} \text{ kg}) \times (3 \times 10^8 \text{ m/s})^2 = 10^{45} \text{ Joules of energy}$
- Sun can shine for
  - $10^{45} \text{ Joules} / (4 \times 10^{26} \text{ J/s}) = 100 \text{ Billion years}$
  - Sun will actually last 10 Byr, because 10% of mass is used before sun becomes a dead star.



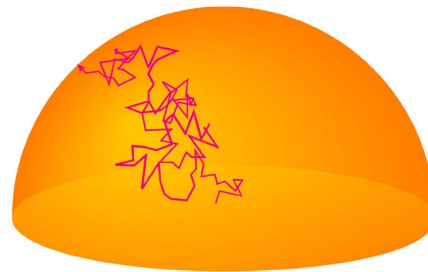
## Parts of the Sun

- 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

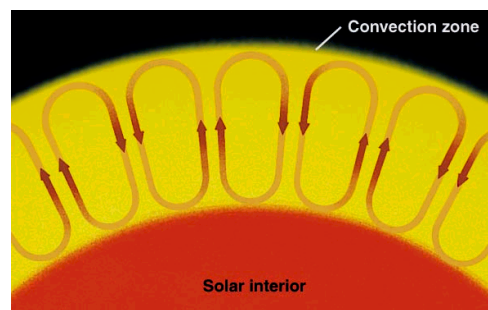


## Energy transfer

- 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

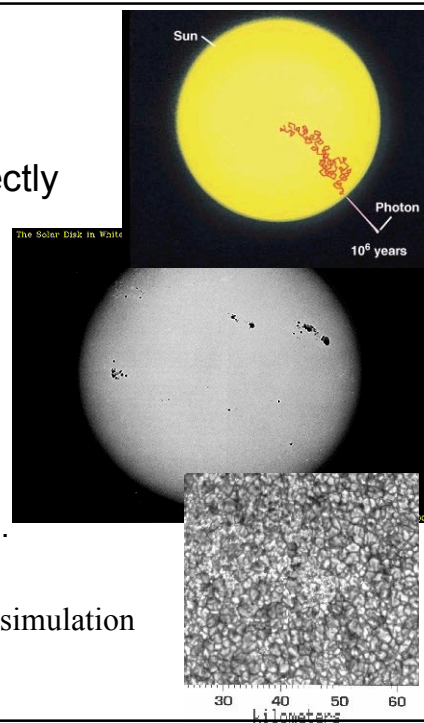


[Fig. 10.7]



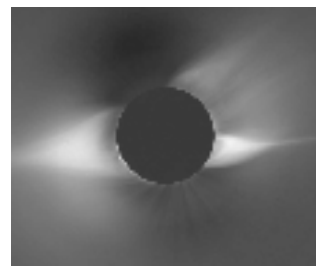
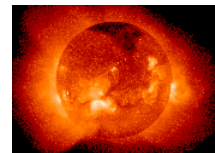
## Photosphere

- Layer from which light directly escapes into space.
- Low density and pressure
  - $10^{-4}$  density in this room
  - 0.1 pressure in this room
- *Hot* (5800 K)
- Granules
  - Tops of convection currents.



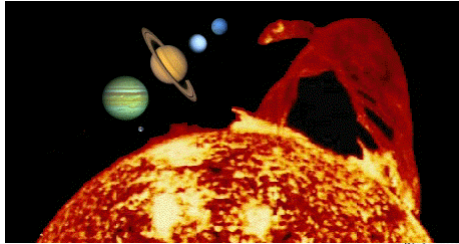
Bob Stein's simulation  
[movie](#)

- Chromosphere
  - Transparent gas layer, reaches 2000-3000 km above photosphere.
  - Hotter than photosphere  $T \sim 5,000-10,000^\circ \text{K}$
  - Emission lines
- Corona
  - $T > 1,000,000^\circ \text{K}$
  - Very low density:  $10^{-10}$  bar.
  - Heated by magnetic energy.
  - Several x diameter of photosphere.
- Solar wind
  - Particles streaming from sun
  - Extends beyond the planets

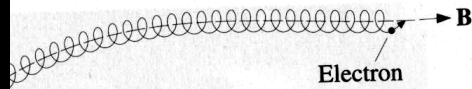


Corona

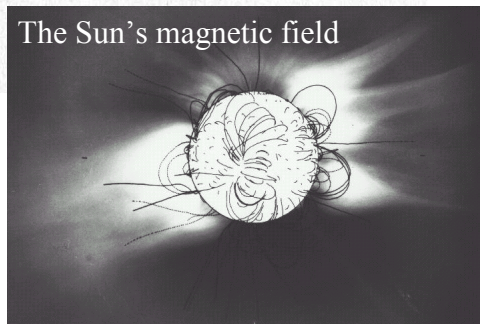
## Magnetic Field



Electrons move in tight spiral around magnetic field lines

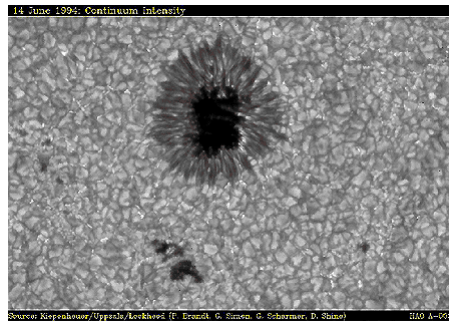
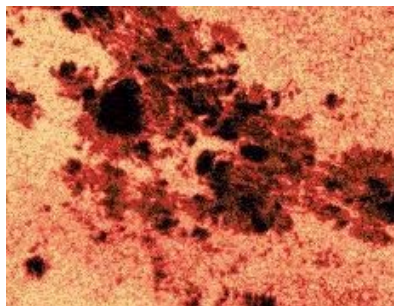
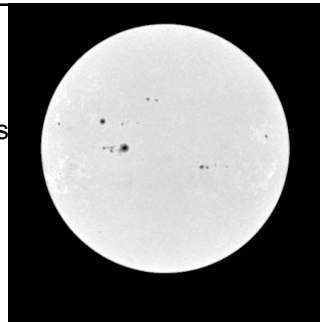


The Sun's magnetic field



## Sunspots

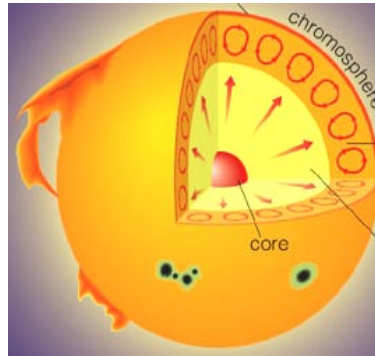
- Magnetic hernias
  - Magnetic field exits at one sunspot & reenters at another.
- Cooler areas
  - Magnetic field prevents hotter gas from entering these regions.
  - As much as 1500K less than photosphere.
  - Looks dark, but they glow at 4300K instead of 5800K





## Interior of the sun

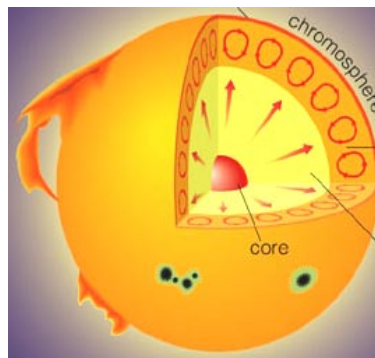
- Q How do we know what is inside the sun?
  - a. NASA sent a probe inside the sun.
  - b. We observe a type of radiation that is not absorbed by the sun.
  - c. We use physics and surface observations to construct models.
  - d. We cut away part of the sun and look.



[Fig. 10.3]

## Interior of the sun

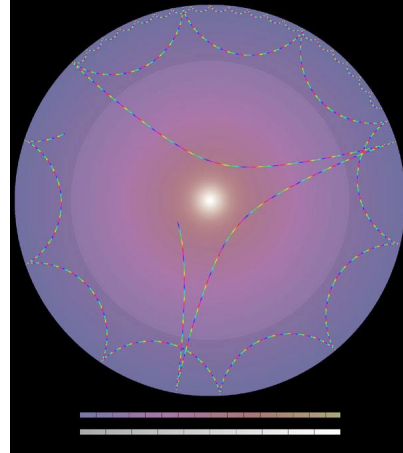
- Use observations of the surface and physics to construct models.
- Physics
  - Energy is generated by nuclear fusion, which depends on temperature and composition.
  - Energy moves from center, where fusion occurs, to outside, where it radiates into space.
  - Gas pressure holds the mass of the parts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



[Fig. 10.3]

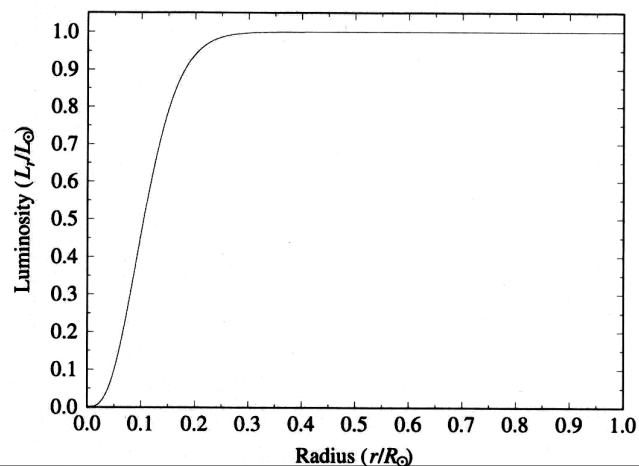
## Solar oscillations with GONG

- 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: Where is energy produced?

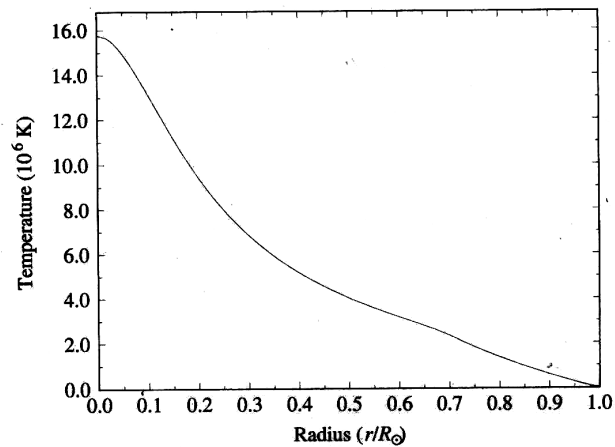
- Where is energy produced? Within central 10% (of radius)





## Model: What is temperature of center?

- 16 MK (million degrees Kelvin)



## Composition of the Sun

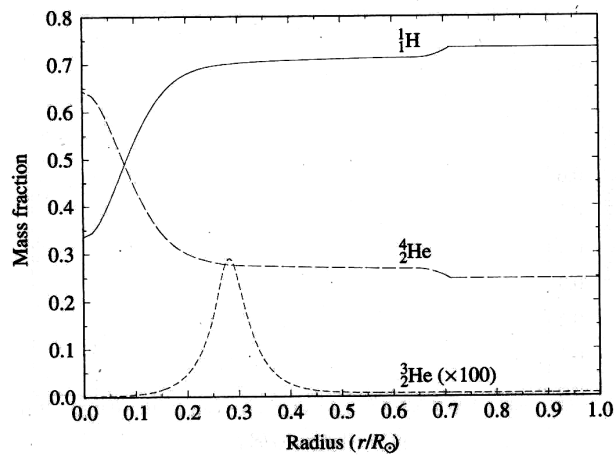
- From spectroscopy of outer layers

The Abundance of Elements in the Sun

Element	Percentage by Number of Atoms	Percentage by Mass
Hydrogen	92.0	73.4
Helium	7.8	25.0
Carbon	0.02	0.20
Nitrogen	0.008	0.09
Oxygen	0.06	0.8
Neon	0.01	0.16
Magnesium	0.003	0.06
Silicon	0.004	0.09
Sulfur	0.002	0.05
Iron	0.003	0.14

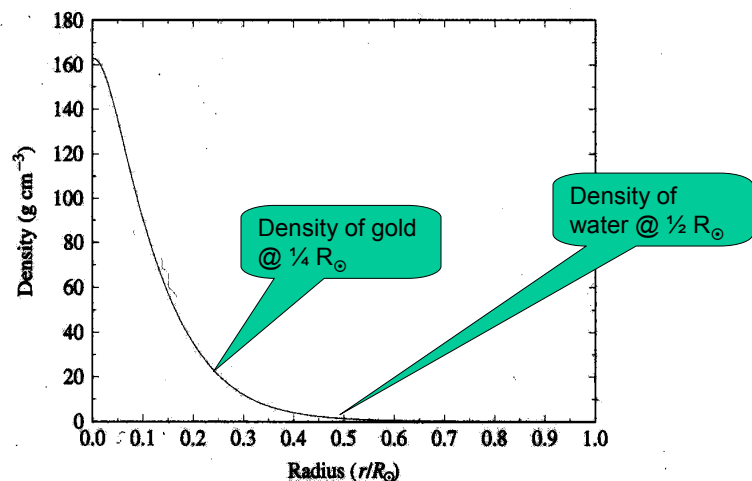
## Model: What is composition of sun?

- Q: Why is there more helium than hydrogen in the center?
  - The heavier helium sunk to the center
  - Helium was made there



## Model: Density of sun

- In center, sun is 160 times denser than water, 8 times denser than gold.



Have a safe spring break