# Lifetime of the Sun

- Newton's law of gravity plus his 3rd law of motion gives the mass of the Sun
  - $2 \times 10^{30}$ kg
- Apparent size of the Sun (32 arc-minutes=0.0093 radian) times the distance to the Sun (150 million km) gives the diameter of the Sun
  - 1.4 million km
- Apparent brightness of the Sun and the distance give the solar luminosity
  - $3.8 \times 10^{26}$ watts
- How long could the Sun shine?
  - Gravitational energy is not enough
  - The Sun lasts for only **20 million years** (Helmholtz in 1854; Kelvin in 1887)
  - Something other than gravitational energy was necessary

# Nuclear Energy

- If the Sun could convert *all* of its mass into energy via Einstein's formula, $E=mc^2$…
  - The Sun would shine for about **15 trillion years**!
  - In reality, nuclear reaction in the Sun can convert only a tiny fraction (~0.07%) of the total mass into energy.
    - Only 0.7% of hydrogen gets converted to energy.
    - Not all mass is hydrogen (H:75%, He:25%)
    - Nuclear reaction occurs only in the central region.
- Calculations show that the Sun shines for about **10 billion years** by burning hydrogen.

# p-p chain (0.7% efficiency)

- $^1H + {}^1H \rightarrow {}^2H + e^+ + \nu_e$
- $^2H + {}^1H \rightarrow {}^3He + \gamma$
- $^3He + {}^3He \rightarrow {}^4He + {}^1H + {}^1H$
  - $^1H$: proton, $^2H$: deuteron
  - $^3He$: Helium-3, $^4He$: Helium-4
  - $e^+$: positron, $\nu_e$: neutrino, $\gamma$: gamma ray
- In total, four protons are fused into one helium-4 and produce energy:
  - $^1H + {}^1H + {}^1H + {}^1H \rightarrow {}^4He$ + "binding energy"
  - One proton weighs $1.6726 \times 10^{-27}$ kg
  - One helium-4 weighs $6.643 \times 10^{-27}$ kg
  - Four protons minus one helium = $4.7 \times 10^{-29}$ kg -> energy
    - This is only 0.7% of the original mass of four protons.

# Nuclear Reaction Close-up

- p-p chain is a slow process because…
  - Electric repulsive force prevents one proton from colliding another one. **Quantum tunneling** (or "barrier penetration") takes a long time to occur.
  - The first reaction, $^1H + {}^1H \rightarrow {}^2H + e^+ + \nu_e$, involves **weak interaction**, which is a very slow process.
- Nuclear reaction occurs only in the central region of the Sun because…
  - Density is high (protons easier to meet)
  - Temperature is high (protons easier to penetrate the barrier)
  - Fusion occurs within 2% of the total volume

# Hydrostatic Equilibrium

- Gas is pushed outward by pressure.
  - Nuclear energy heats up gas -> high pressure
  - Pressure = $k_B$ x (number density) x (temperature)
  - Pressure is highest at the center and decreases at larger distances.
- Gas is pulled inward by gravity.
- "Hydrostatic equilibrium" = "Pressure force balances gravitational force"
  - Gravity = $GM^2/R^2$
  - Pressure = $k_B nT$
  - Calculations show that temperature should be ~20 million K
  - High temperature is necessary to balance gravity.

# Energy Transfer

- Core (0-0.25 $R_{solar}$): ~15 million K
  - Energy is produced by fusion
- Radiative zone (0.25-0.70 $R_{solar}$): 2 to 8 million K
  - Energy is carried by radiation (photons) up to near the surface of the Sun
  - Photons frequently scattered by electrons (random walk)
- Convective zone (0.70-1 $R_{solar}$): < 2 million K
  - Photons are absorbed by atoms near the surface; unable to carry energy
  - Energy is then carried by "convection" (clue:boiled water)
- Surface: 5,800 K
  - It takes about a million years from the core to the surface.
- Depth of convective zone depends on stellar mass. (Low mass stars have deeper convective zone.)