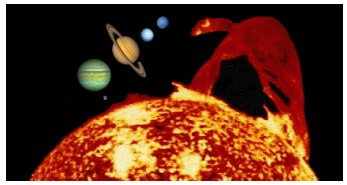
The Sun–March 2

- Test 2 is not graded yet.
- See me if you need provisional grade immediately.
- How does the sun produce energy?
- Inside the sun

We know the most about one star

- We know the most about the sun because we can see surface details. (Other stars are points of light.)
  - Magnetic fields, wind, flares
  - Seismology => sound waves probe interior
- How do we know?
  - Make observations
  - Make theories
  - Compute models
  - Do models agree with observations?
  - Repeat process



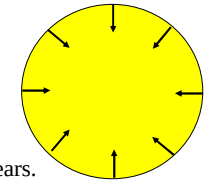
- How does the sun produce energy?
  - Question first asked in 19th century. Theories failed.
  - Bethe found answer in 1930s
  - Today: new questions of detail

How does the sun produce energy?

- Lord Kelvin (William Thomson) in Glasgow, Scotland in 1860s.
- Observations: Sun (2×10^{30} kg) produces 4×10^{26} watts for 4.5 Byrs.
- Batteries (chemical reactions)
  - 0.5 watts/battery => 8×10^{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 4×10^{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?

- 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
  - Speed of light c = 300,000 km/s
  - Nitrogen in air moves at 0.1 km/s.
  - Air in blast furnace moves at 0.2 km/s
- Chemical reaction
  - Chemical: v=10km/s (two H atoms make H molecule)
  - E=m/1,000,000,000 c^2. One part in billion of mass disappears and changes into energy.

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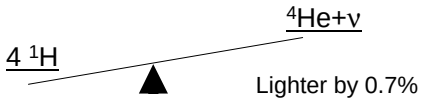
  - Speed of light c = 300,000 km/s
- Q: A hydrogen atom falling from 1 AU hits the sun at 300 km/s. How much of the mass is converted into energy?
  a. 100%
  b. 1/1000
  c. 1/1,000,000

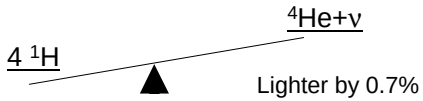
Nuclear fusion

- $4 \times {}^1H \rightarrow {}^4He$ + neutrinos + energy
  - 4 hydrogen nuclei fuse
  - One helium nucleus is produced
- 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.



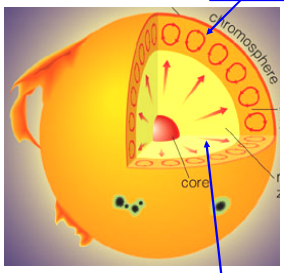
Sun produces energy by nuclear fusion

- $4 \times {}^1H \rightarrow {}^4He$ + neutrinos + energy
  - 4 hydrogen nuclei fuse
  - One helium nucleus is produced
  - 0.7% of mass becomes energy
- Sun can potentially produce
  $0.007 \times (2\times10^{30}\ \text{kg}) \times (3\times10^{8}\ \text{m/s})^2 = 10^{45}$ Joules of energy
- Sun can shine for
  - 10^{45} Joules/$(4\times10^{26}$J/s)=100 Billion years
  - Sun will actually last 10 Byrs, because 10% of mass is used before sun becomes a dead star.



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.
- Gas pressure holds the mass of the parts above.



[Fig. 10.3]

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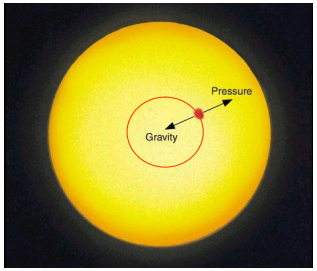

[See Fig 10.2]