Fusion powers the stars—14 Oct

- Big questions
  - Does the sun have a finite life or does it last forever?
  - What powers the sun?
  - Where does carbon come from?
  - How long does the sun live?
  - What happens to the sun when it dies?
- Outine
  - Finish “Adams discovers a white dwarf”
  - Fusion
    - $4H \rightarrow {}^4He$

Ast 207 F2011

Sirius A and Sirius B

- Adams found that Sirius A and B have about the same color. Therefore Sirius B is smaller.
  - $L=R^2T^4$
- How much smaller is Sirius B?
- Apparent mag of Sirius A is –1.5
- Apparent mag of Sirius B is 8.7

1. The mag of Sirius B is approximately __ steps of 2.5 fainter than that of Sirius A.
   A. 4
   B. 5
   C. 6
   D. 10
2. The flux of Sirius B is approximately _ fainter.
   A. a factor 10
   B. a factor of 100
   C. a factor of 1000
   D. a factor of 10,000.

http://chandra.harvard.edu/photo/2000/0065/0065_optical.jpg

Discovery of white dwarfs

- Adams found that Sirius A and B have about the same color. Therefore Sirius B is smaller.

$$L = R^2T^4$$

1. The mag of Sirius B is 4 steps of 2.5 fainter than that of Sirius B.
2. The flux of Sirius B is approximately a factor of 10,000 fainter.

- The radius of Sirius B is 1/100 that of Sirius A.
  - Sirius B is about the size of the Earth.
- Tiny stars are called white dwarfs.
- Main-sequence stars and white dwarfs use different laws of physics.

http://chandra.harvard.edu/photo/2000/0065/0065_optical.jpg

Adams discovered white dwarfs

1. We say Adams discovered white dwarfs. What did he actually do?
   A. Adams was the first person to photograph Sirius B
   B. Adams figured out that Sirius B is very small.
   C. Adams figured out that Sirius B is very faint.

Energy production in the sun

- 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

19th 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 = $m\times(E/m)/L$
  - $E/m=9$MJ/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 of sun: L=4×10^{26}Watt
- Mass m=2×10^{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 = ½ 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 19th 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)
  - Energy can change into mass, and mass can change into energy.

$$E = m\,c^2.$$

  - Energy = mass × (speed of light)^2.
- Changing a little mass produces a lot of energy. Compare with kinetic energy

$$\text{KE} = ½\, m\, v^2$$

  - Speed of light c = 300,000 km/s
  - Air in blast furnace moves at 0.2 km/s

$$\frac{KE}{E} = \frac{1}{2}\left(\frac{v}{c}\right) = 2 \times 10^{-13}$$

$E=mc^2$

- 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.
- H fuses to produce He
  - E=m c^2/140. A part in 140 of the 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. Box containing H
   B. Box containing the products: He, neutrinos, and positrons
   C. The two boxes have the same mass.

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 = $m\times(E/m)/L$
  - $m \times(0.007mc^2/m)/L$
  - 100Byr
  - In reality sun uses 10% of fuel. Lifetime is 10Byr

$4\ ^1H$

$^4He+2e^+ +\nu$

Lighter by 0.7%

Fusion chains in main-sequence stars

- Two paths for fusing hydrogen into helium
- Carbon-nitrogen-oxygen cycle (important in more massive stars)
- Proton-proton chain (main process in sun)

Proton-proton chain

- Step 1: Two protons fuse to produce a deuterium nucleus (^{2}H), a positive electron, and a neutrino.

  $p+p \rightarrow d+e^{+}+\upsilon$

  - Deuterium is an isotope of H with one neutron.
  - A neutrino is almost massless, not charged, and interacts very weakly.

1. Did the number of nucleons change? Charge?
   A. YY
   B. YN
   C. NY
   D. NN

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1. Did the number of nucleons change? Charge?

- Nucleons are conserved (except in some exotic interactions in the early universe).
- Charge is absolutely conserved.

Proton-proton chain

- Step 1: p + p → ^{2}H + e^+ + υ
- In the center of the sun, a proton survives collisions without reacting for 10Byr.
  - Electrical repulsion between protons (Coulomb repulsion; Coulomb barrier)
    - Requires fast speed or high temperature to overcome repulsion.
  - Neutrino indicates a "weak" reaction, which is weak.
- Step 2: p+^{2}H→^{3}He+γ (Takes 6s)
  - γ is a photon, a unit of light. This photon has lots of energy.

1. In step 2, did any protons change into neutrons? Is this a weak interaction?
   A. YY. B. YN. C. NY. D. NN.

Proton-proton chain

- Step 1: p+p→^{2}H+e^++υ (Takes 10Byr)
- Step 2: p+^{2}H→^{3}He+γ (Takes 6s)
- Step 3: ^{3}He+^{3}He→^{4}He+p+X (Takes 1Myr)

1. What is X?
   A. Neutron.
   B. Electron.
   C. Neutrino.
   D. Proton.
   E. Positron (positive electron).

Proton-proton chain

- Step 1: $p+p \rightarrow {}^2H+e^+ + \upsilon$ (Takes 10Byr)
- Step 2: $p+{}^2H \rightarrow {}^3He+\gamma$ (Takes 6s)
- Step 3: ${}^3He+{}^3He \rightarrow {}^4He+p+p$ (Takes 1Myr)
- Where is the created energy?
  - A positron meets an electron, and the two annihilate.
    - $e^+ + e^- \rightarrow 2\gamma$
  - Light interacts with matter to heat it up.
  - Moving reactants heat the matter.
  - Neutrinos escape from the sun carrying away energy.