

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?
- Outline
 - Finish “Adams discovers a white dwarf”
 - Fusion
 - $4\text{H} \rightarrow ^4\text{He}$

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.

$$L = R^2 T^4$$
 1. The mag of Sirius B is 4 steps of 2.5 fainter than that of Sirius A.
 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 $L=4 \times 10^{26}$ Watt
- Mass $m=2 \times 10^{30}$ 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

- Luminosity of sun: $L=4 \times 10^{26}$ Watt
- Mass $m=2 \times 10^{30}$ kg
- How long will the sun last if the energy is produced by the sun contracting?
- If material falls from R_{sun} to $0.9R_{\text{sun}}$,
 - Energy = $\frac{1}{2} m v^2 = m g h = m (GM_{\text{sun}}/R_{\text{sun}})(0.1R_{\text{sun}})$
 - Life time = $m \times (E/m)/L$
 - 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.



William Thomson
Lord Kelvin
1824-1907
www-history.mcs.st-andrews.ac.uk/history/PictDisplay/Thomson.html/

$$E = mc^2$$

- Crisis: No solution with physics of 19th century.
- Einstein's new theory (1906)
 - Energy can change into mass, and mass can change into energy.
- Changing a little mass produces a lot of energy. Compare with kinetic energy

$$E = m c^2.$$

- Energy = mass \times (speed of light)².

- Changing a little mass produces a lot of energy. Compare with kinetic energy

$$KE = \frac{1}{2} m v^2$$

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

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



$$E=mc^2$$



- Chemical reaction $C+O_2 \rightarrow CO_2$
 - $E=mc^2/100,000,000,000$. One part in 100 billion of mass disappears and changes into energy.
- Sun contracts by 10%
 - $E=mc^2/1,000,000$. One part in a million of mass disappears and changes into energy.
- H fuses to produce He
 - $E=mc^2/140$. A part in 140 of the mass disappears and changes into energy.

Nuclear fusion



Hans Bethe
1906-2005

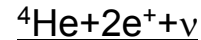
- In a nuclear reaction, converting a significant fraction of the mass to energy is possible.
- Hans Bethe figured out the nuclear physics of how this happens.
- $4\ ^1\text{H} \rightarrow\ ^4\text{He} + \text{neutrinos} + 2e^+ + \text{energy}$
 - 4 hydrogen nuclei fuse
 - One helium nucleus is produced
- 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.
- $4\ ^1\text{H} \rightarrow\ ^4\text{He} + \text{neutrinos} + 2e^+ + \text{energy}$
 - 4 hydrogen nuclei fuse
 - One helium nucleus is produced
- $4\ ^1\text{H}$ weighs 0.7% more than $^4\text{He} + \text{neutrinos} + 2e^+$
 - 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 14% of fuel. Lifetime is 10Byr



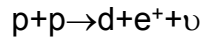
Lighter by 0.7%

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 (${}^2\text{H}$), a positive electron, and a neutrino.

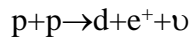


- Deuterium is an isotope of H with one neutron.
- A neutrino is almost massless, not charged, and interacts very weakly.

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

Proton-proton chain

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- Deuterium is an isotope of H with one neutron.
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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: $p + p \rightarrow {}^2\text{H} + e^+ + \nu$
 - 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: $p + {}^2\text{H} \rightarrow {}^3\text{He} + \gamma$ (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: $p + p \rightarrow {}^2\text{H} + e^+ + \nu$ (Takes 10Byr)
 - Step 2: $p + {}^2\text{H} \rightarrow {}^3\text{He} + \gamma$ (Takes 6s)
 - Step 3: ${}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + p + X$ (Takes 1Myr)
1. What is X?
- A. Neutron.
B. Electron.
C. Neutrino.
D. Proton.
E. Positron (positive electron).

Proton-proton chain

- Step 1: $p+p \rightarrow {}^2\text{H}+e^++\nu$ (Takes 10Byr)
- Step 2: $p+{}^2\text{H} \rightarrow {}^3\text{He}+\gamma$ (Takes 6s)
- Step 3: ${}^3\text{He}+{}^3\text{He} \rightarrow {}^4\text{He}+p+p$ (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.