Fusion Powers the Sun—12 Oct

• Finish Walter Adams & white dwarfs
• 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
  – $4H \rightarrow ^4He$

• Course grade is on angel.
  – Weights: Hwk 25%, Clicker 9%, Test 1 64%
    • Set so that the relative weights of hwk, clicker, & tests are the same as at the end of the term.
  – Lowest hwk & lowest 2 clickers are dropped.
  – 85% of the final course grade is in the future.
• Test 2 is Wed, Oct 21.
  – Covers material though Adams’ discovery of white dwarfs (today).
  – One cheat sheet.
• Hwk 5 is due at start of class on Mon, Oct 19. No late papers.
Sirius A and Sirius B (from 9/11)

• We are Walter Adams of the Mt. Wilson Observatory in 1914. We are studying the double star Sirius A and B. (Sirius A & B orbit each other.)
• Sirius B is much fainter than Sirius A.

1. Sirius B may be faint for two reasons. It may be small or it may be
   A. farther away
   B. closer
   C. cooler
   D. hotter
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Sirius A and Sirius B

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  - \( L = R^2 T^4 \)
- 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
Sirius A and Sirius B

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  - $L = R^2 T^4$
- 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 4 steps of 2.5 fainter than that of Sirius B.
2. The flux of Sirius B is approximately 10,000 fainter.
- The radius of Sirius B is 1/100 that of Sirius A.
  - Sirius B is about the size of the Earth.

Summarizing question

- Why was finding of Sirius B’s spectral class crucial to discovery of white dwarfs?
Energy production in stars

• Big questions
  – What powers the sun?
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  – How long does the sun live?
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• Lifetime of the sun
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• 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

- Luminosity of sun: \( L = 4 \times 10^{26} \text{Watt} \)
- Mass \( m = 2 \times 10^{30} \text{kg} \)
- How long will the sun last if the energy is produced by the sun contracting?
  - If material falls from \( R_{\text{sun}} \) to \( 0.9R_{\text{sun}} \):
    - Energy = \( \frac{1}{2} m v^2 = mgh = m \left( \frac{GM_{\text{sun}}}{R_{\text{sun}}} \right)^2 (0.1R_{\text{sun}}) \)
    - Life time = \( m \times \frac{(E/m)}{L} \)
    - 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.
  - \( E = mc^2 \).
  - Energy = mass \times (speed of light)^2.
- Changing a little mass produces a lot of energy. Compare kinetic energy \( \frac{1}{2} m v^2 \) with \( mc^2 \).
  - Speed of light \( c = 300,000 \text{ km/s} \)
  - Air in blast furnace moves at 0.2 km/s
- Chemical reaction \( \text{C} + \text{O}_2 \rightarrow \text{CO}_2 \)
  - \( E = m c^2/100,000,000,000 \). 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

- 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.
- $^4_1\text{H} \rightarrow ^4_2\text{He} + \text{neutrinos} + 2e^+ + \text{energy}$
  - 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.

Hans Bethe
1906-2005

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  - 4 hydrogen nuclei fuse
  - One helium nucleus is produced
- $^4_1\text{H}$ weighs 0.7% more than $^4_2\text{He} + \text{neutrinos} + 2e^+$.
  - Part of the mass has been converted into energy.
  - Amount of energy is $E=0.007m c^2$. Most of mass remains.
- Life time = $m \times (E/m)/L$
  - $m \times (0.007m c^2/m)/L$
  - 100Byr
  - In reality sun uses 10% of fuel. Lifetime is 10Byr

$^2_4\text{He} + 2e^+ + \nu$

$^4_1\text{H}$

Lighter by 0.7%
Proton-proton chain

• Two paths for fusing hydrogen into helium
• Carbon-nitrogen-oxygen cycle (important in more massive stars)
• Proton-proton chain (main process in sun)
  – Step 1: Two protons fuse to produce a deuterium nucleus ($^2$H), a positive electron, and a neutrino.
    \[ p + p \rightarrow d + e^+ + \nu \]
    • 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).
• Charge is absolutely conserved.