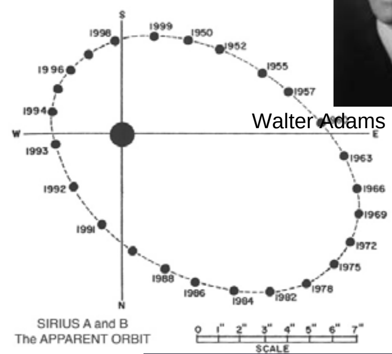
Fusion Powers the Sun—12 Oct

- 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
  - $4H \rightarrow {}^{4}He$

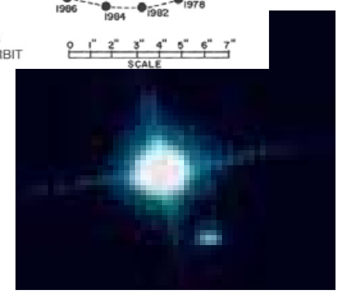
- Course grade is on angel.
  - Weights: Hwk 25%, Clicker 9%, Test 1 64%
    - Set so that the relative weights of hwk, clicker, & tests are the same as at the end of the term.
  - Lowest hwk & lowest 2 clickers are dropped.
  - 85% of the final course grade is in the future.
- Test 2 is Wed, Oct 21.
  - 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.



Walter Adams 1876-1956



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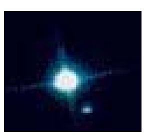
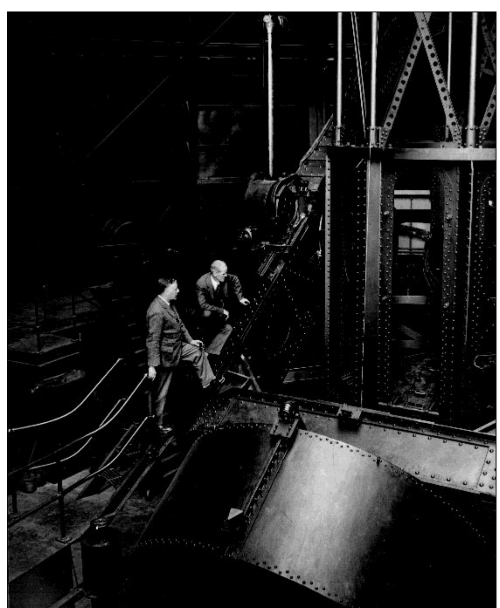
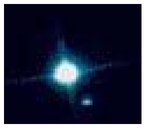
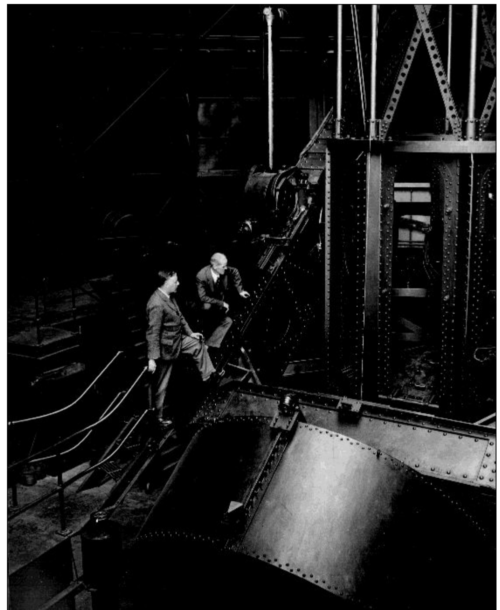


1. Sirius B may be faint for two reasons. It may be small or it may be
   A. farther away
   B. closer
   C. cooler
   D. hotter

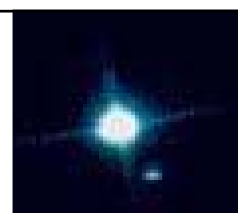




1. Sirius B may be faint for two reasons. It may be small or it may be
   A. farther away
   B. closer
   C. cooler
   D. hotter
- Adams found that Sirius A and B have about the same color. Therefore Sirius B is smaller.



Sirius A and Sirius B

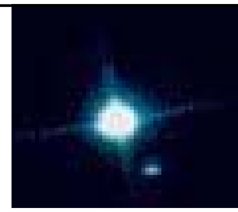


- Adams found that Sirius A and B have about the same color. Therefore Sirius B is smaller.
  - $L=R^2T^4$
- How much smaller is Sirius B?
- Apparent mag of Sirius A is –1.5
- Apparent mag of Sirius B is 8.7

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

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 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.

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

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?
  - 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

19^{th} 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=9MJ/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: $L=4\times10^{26}$Watt
- Mass $m=2\times10^{30}$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 = $\frac{1}{2}$ 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 kinetic energy $\frac{1}{2}$ m v^2 with m c^2.
  - Speed of light c = 300,000 km/s
  - Air in blast furnace moves at 0.2 km/s
- 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

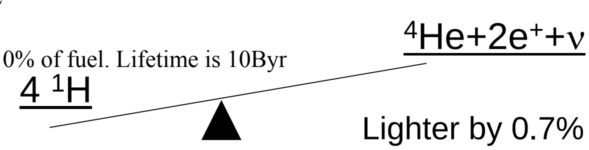
- In a nuclear reaction, converting a significant fraction of the mass to energy is possible.
- Hans Bethe figured out the nuclear physics of how this happens.
- $4\ {}^{1}H \rightarrow {}^{4}He$ + neutrinos $+2e^{+}$+ energy
  - 4 hydrogen nuclei fuse
  - One helium nucleus is produced

1. Which is heavier? A box of hydrogen and a box of helium, neutrinos, and positrons made from the hydrogen?
   A. <u>Box containing H</u>
   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.
- $4\ {}^{1}H \rightarrow {}^{4}He$ + neutrinos $+2e^{+}$+ energy
  - 4 hydrogen nuclei fuse
  - One helium nucleus is produced
- $4\ {}^{1}H$ weighs 0.7% more than ${}^{4}He$ + 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



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 (^2H), 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. <u>NN</u>

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1. Did the number of nucleons change? Charge?

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