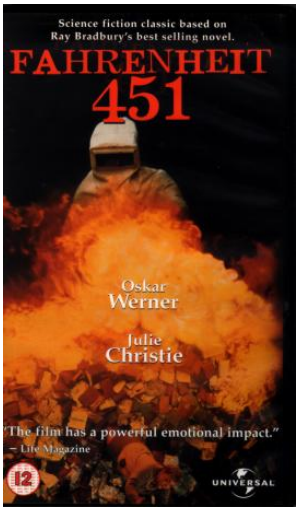
When radiation ruled

- Key idea: When the universe was smaller (when the distance between us and some object was smaller), the temperature was hotter. <u>There is no obvious limit to the temperature.</u>
- Events in the universe's life, when the universe was smaller & hotter.
- Production of the first nuclei other than H (3min) ☜
- Recombination: U changed from opaque to transparent. (300,000yr)☜
- First stars formed (200Myr)



- **Please fill out course evaluation (on front bench)**
  - **Give it to student volunteer at end of class to turn in to ISP office in 100NKL.**
- Please rate your class at
  - rateyourclass.msu.edu
  - Closes on May 8th.
- Homework 7
  - Due 6:00 pm on Tues, April 28th, just before Missouri Club
- Missouri (Show Me) Club
  - Room 1415, Tues, 4/28, 7:00-8:00pm
- Final Exam
  - Wed, May 6th, 3:00-5:00
  - Room 1410 (our classroom)
  - One 8½ ×11 cheat sheet.
  - Covers entire course with more emphasis on galaxies & cosmology.

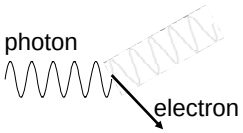
Ionized/un-ionized gas

- Ionization is the loss of an electron.

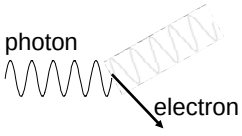
  H atom $\rightarrow$ p + e^-
- Recombination is when electron and nucleus combine.

  p + e^- $\rightarrow$ H atom
- Ionization occurs if the temperature is hot enough.
- Name one thing in this room that is/has ionized gas.
  A. Fluorescent light
  B. Air
  C. Air in my lungs

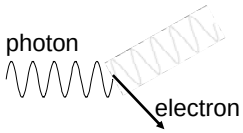
- Light scatters poorly off of electrons bound in an atom or molecule.
- Light scatters readily off of free electrons.



- If the air were ionized, light would travel 500m before it is scattered. Light scatters nearly equally in all directions.
- If the air were ionized, could you, sitting in Spartan Stadium, watch the Spartans beating Purdue? Could you see stars at night?
  - YY
  - YN
  - NY
  - NN



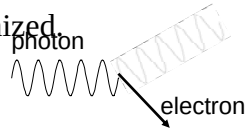
- If the air were ionized, light would travel 500m before it is scattered. Light scatters nearly equally in all directions.
- If the air were ionized, could you, sitting in Spartan Stadium, watch the Spartans beating Purdue? Could you see stars at night?
  - YY
  - YN
  - NY
  - NN



- If the air were ionized, the air would be a fog.

Matter and Radiation Become Decoupled

- History
  - In early, hot universe, hydrogen is ionized.
    - Protons and electrons are free
  - Universe is opaque.
    - Photons travel only short distances.
    - Scattered by free electrons.
  - Decoupling: $p + e^- \rightarrow$ H atom
    - T = 3000 K; universe 300,000 yr old.
  - Universe becomes transparent
    - Photons decouple from matter, continue in whatever direction they were moving.



- Just after matter decoupled from radiation, the temperature was 3000K, the temperature of a cool star. Suppose you lived then. You would have seen
  - A. a faraway, red surface in all directions.
  - B. stars and a faraway, red surface in all directions.
  - C. a nearby, red surface in all directions.
  - D. stars and a nearby, red surface in all directions.

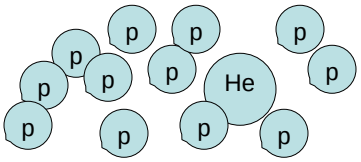
- Just after matter decoupled from radiation, the temperature was 3000K, the temperature of a cool star. Suppose you lived then. There was hydrogen,
  - A. helium, & carbon
  - B. no helium, & no carbon.
  - C. no helium, & carbon.
  - D. helium, & no carbon.

1. A fossil is a remnant or trace of the past. What is a fossil from the Big Bang?

Fossil from Burgess Shale

Helium Production in Big Bang

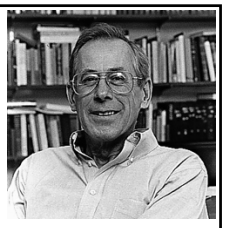
- A fossil is a remnant or trace of the past. What is a fossil from the Big Bang?
  - There are 7 protons for every neutron
  - The surface of the sun is 25% He and 75% H.
- What does that fossil tell about the BB?



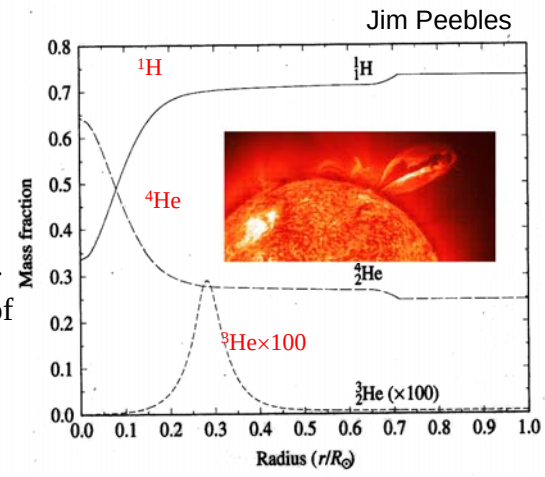
Fossil from Big Bang


Fossil from Burgess Shale

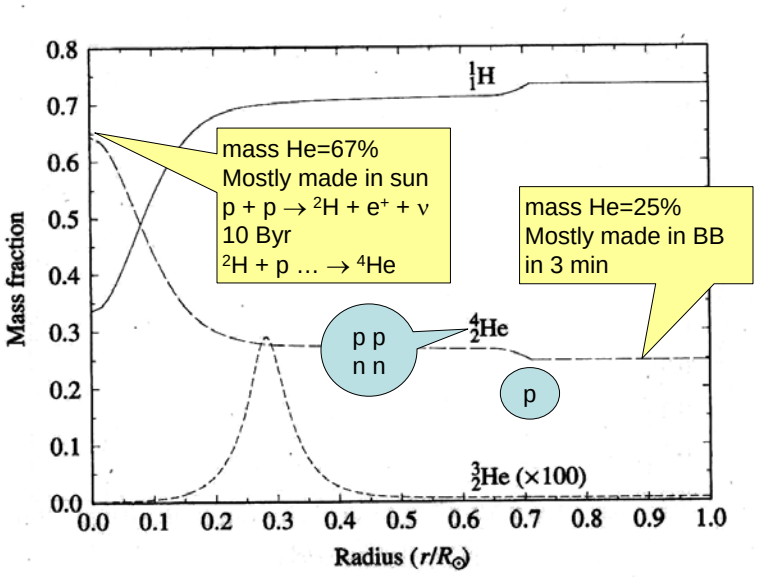
Helium Formed When Universe Was 3 Minutes Old


Jim Peebles

- How & where were the elements made?
  - Carbon, Iron, Calcium in stars
  - Hydrogen is primordial
  - Helium is too abundant to have been made in stars.
  - Helium was made at 3min.
- Evidence: Observations of ^{4}He (and ^{3}He, ^{7}Li, ^{2}H)



Helium in the Sun

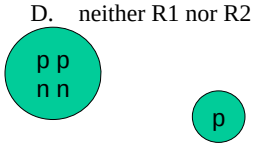


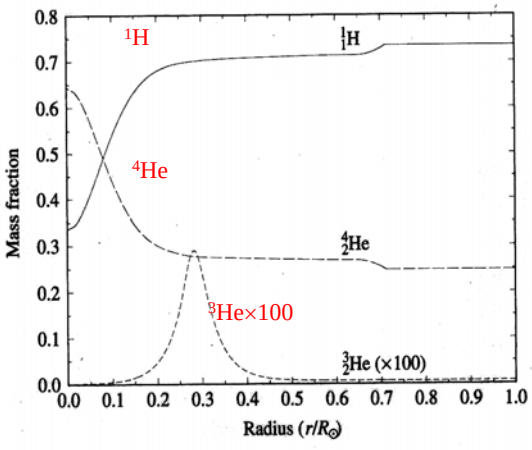
Key is to follow the neutrons

1. When hydrogen fuses to become helium in the sun, does the ratio #n/#p change? Yes

- The reactions in the sun
  - R1: p+p→²H+e⁺+υ (10Byr)
  - R2: ²H+p →³He (6s)
  - R3: ³He+ ³He →⁴He+2p (1Myr)
  - ppn + ppn → ppnn + pp

1. For which reactions does #n/#p change?
   A. R1 & R2
   B. R1 only
   C. R2 only
   D. neither R1 nor R2



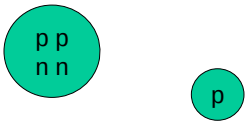


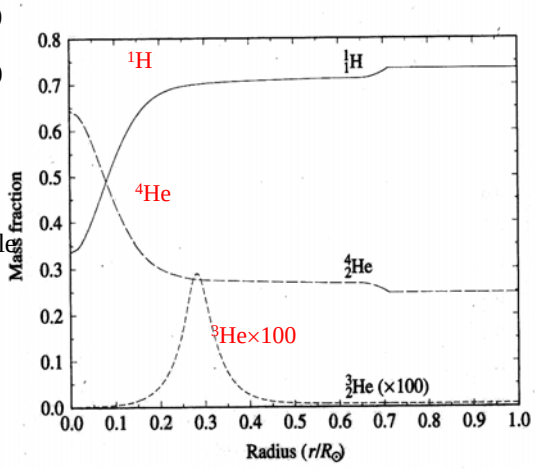
Key is to follow the neutrons

- The reactions in the sun
  - R1: $p+p \rightarrow {}^2H+e^+ + \upsilon$ (10Byr)
  - R2: $^2H+p \rightarrow {}^3He$ (6s)
  - $^3He+ {}^3He \rightarrow {}^4He+2p$ (1Myr)

1. For which reactions does #n/#p change? R1

- Reaction 1 takes a very long time because a neutrino & electron are produced.
- In Big Bang, the only possible reactions are ones that occur quickly.
- In BB, the ratio #n/#p is nearly preserved.

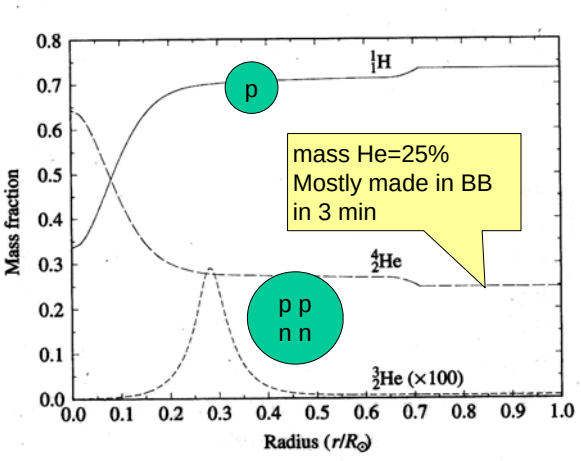




Key is to follow the neutrons

- In the outer parts of the sun, the material is nearly primordial.
- He is 25% of the mass, H is 75%. 12 H atoms for every He atom
  - Mass He = 4
  - Mass H = 12
  - Total mass = 16

1. #n / #p =
   a. 1:1
   b. 1:12
   c. 2:14
   d. 4:12
   e. 2:3



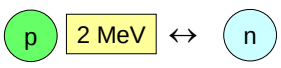
Follow the neutrons

- #n/#p=2/14=1/7 now
- Processing in stars changes #n/#p only slightly because H is much more abundant than other elements.
- #n/#p has been 1/7 from 3min to now.
- #n/#p=1 at 1 ms.
- How do neutrons change into protons?

Changing neutrons & protons

- Proton changes into neutron
  - $p + e^- + \text{energy} \rightarrow n + \nu$
  - E = 2MeV
- Neutron changes into proton
  - $n + e^+ \rightarrow p + \text{energy} + \nu$ (positron must hit neutron)
  - $n \rightarrow p + e^- + \text{energy} + \nu$ (happens spontaneously in 1000s)

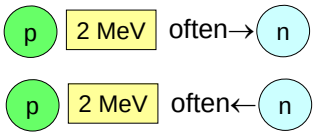
- 1electron-Volt is the typical energy of a chemical reaction.
- $1eV = 1.6\times10^{-19}J$
- 1MeV is the typical energy of a nuclear reaction.
- Radiation in the universe
  - 2.7K
  - E=eV/4000
- At 3 min
  - 1 BK
  - E=0.1MeV
- At 0.001s
  - 400 BK
  - E=40 MeV



Changing neutrons & protons

- When the energy of the photons (light) is much bigger than 2MeV, protons change into neutrons as easily as neutrons changing into protons, because the cost is slight.

2. When the energy of the universe drops to 1 MeV, the reaction p → n
   a. becomes rarer than n → p
   b. becomes more common than n → p
   c. stays the same.



Photon energy is much greater than 2 MeV