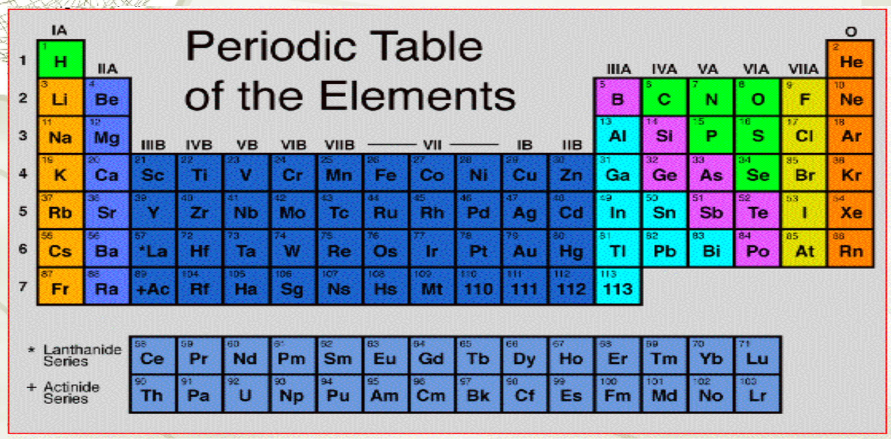
Class 19 : Where did the elements come from?



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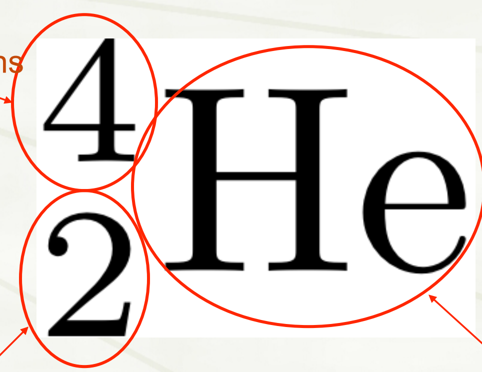
Notation… we need some compact way of discussing nuclei

Total number of nucleons = protons+neutrons



Atomic number = number of protons

Symbol for element (set by atomic number)

NUCLEOSYNTHESIS IN THE EARLY UNIVERSE

- Nucleosynthesis: the production of different elements via nuclear reactions
- Consider universe at t=180s
  - i.e. 3 minutes after big bang
  - Universe has cooled down to 1 billion (10^9) K
  - Filled with
    - Photons (i.e. parcels of electromagnetic radiation)
    - Protons (p)
    - Neutrons (n)
    - Electrons (e)
    - [also Neutrinos, but these were freely streaming]

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The first three minutes…

- Protons and Neutrons can **fuse** together to form deuterium (d)

$$n + p \rightarrow D + \gamma$$

- But, deuterium is quite fragile…
- Before t=180s, Universe is hotter than 1 billion degrees.
  - High-T means that photons carry a lot of energy
  - Deuterium is destroyed by energetic photons as soon as it forms

$$D + \gamma \rightarrow n + p$$

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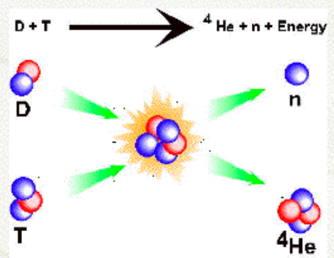
After the first 3 minutes…

- But, after t=180s, Universe has cooled to the point where deuterium can survive
- Deuterium formation is the first step in a whole sequence of nuclear reactions:
  - e.g. Helium-4 (^{4}He) formation:

$$D + D \rightarrow T + p$$

$$T + D \rightarrow {}^4He + n$$



- An alternative pathway to Helium…

$$D + D \rightarrow {}^3He + n$$

$${}^3He + D \rightarrow {}^4He + p$$

- This last series of reactions also produces traces of left over “light” helium (^{3}He)

- Further reactions can give Lithium (Li)

$$^{4}He + T \rightarrow {}^{7}Li + \gamma$$

- Reactions cannot easily proceed beyond Lithium

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- If this were all there was to it, then the final mixture of hydrogen & helium would be determined by initial number of p and n.
  - If equal number of p and n, everything would basically turn to ^{4}He… Pairs of protons and pairs of neutrons would team up into stable Helium nuclei.
  - Would have small traces of other species
  - But we know that most of the universe is hydrogen… why are there fewer n than p? What else is going on?

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Balance of p and n

Protons are more common than neutrons (86% of baryons are p, 14% are n) because:

1. Protons are slightly lower mass thus favored energetically, so they were somewhat more abundant to begin with
2. Free neutrons decay quickly

Neutron decay

- Free neutrons (i.e., neutrons that are not bound to anything else) are unstable!
  - Neutrons spontaneously and randomly decay into protons, emitting electron and neutrino

$$n \rightarrow p + e + \overline{\nu}$$

  - Half life for this occurrence is 10.5 mins (i.e., take a bunch of free neutrons… half of them will have decayed after 10.5 mins).

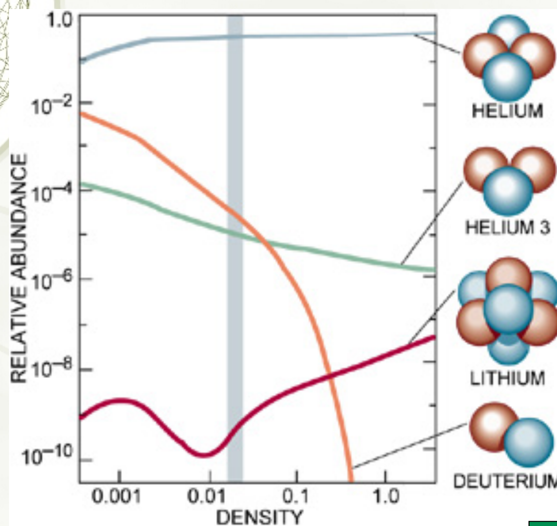
- While the nuclear reactions are proceeding, supply of "free" neutrons is decaying away.
- So, speed at which nuclear reactions occur is crucial to final mix of elements
- What factors determine the speed of nuclear reactions?
  - Density (affects chance of p/n hitting each other)
  - Temperature (affects how hard they hit)
  - Expansion rate of early universe (affects how quickly everything is cooling off and spreading apart).

- Full calculations are complex. Need to:
  - Work through all relevant nuclear reactions
  - Take account of decreasing density and decreasing temperature as Universe expands
  - Take account of neutron decay
- Feed this into a computer…
  - Turns out that relative elemental abundances depend upon the quantity $\Omega_B H^2$
  - Here, Ω_B is the density of the baryons (everything made of protons+neutrons) relative to the critical density.

$$\Omega_B = \frac{\rho_B}{\rho_{crit}} = \frac{\rho_B}{3H_0^{\ 2}/(8\pi G)}$$

Dependence of abundances on $\Omega_B H^2$

From M.White's webpage, UC Berkeley



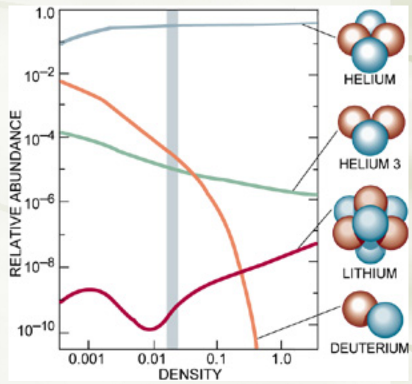
$\Omega_B h^2$

$$h = \frac{H_0}{100 km/s/Mpc}$$

- We can use the spectra of stars and nebulae to measure abundances of elements
  - These need to be corrected for reactions in stars
- By measuring the abundance of H, D, ^{3}He, ^{4}He, and ^{7}Li, we can
  - Test the consistency of the big bang model -- are relative abundances all consistent?
  - Use the results to measure the quantity $\Omega_B h^2$

Results

- All things considered, we have $\Omega_B h^2 \approx 0.019$.
- If H_0=72km/s/Mpc,
  - h=0.72
  - $\Omega_B \approx 0.04$
- This is far below Ω=1!
- Baryons alone would give open universe



$\Omega_B h^2$

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How are other elements formed?

- Big Bang Nucleosynthesis produces most of the hydrogen & helium observed today.
- But what about other elements?
  - There are naturally occurring elements as heavy as Uranium
  - Some elements (e.g., Carbon, Nitrogen, Oxygen) are rather plentiful (1 atom in every 10^5 atoms)
  - Astronomers believe these elements were formed in the cores of stars long after the big bang
    - Theory of stellar nucleosynthesis was first worked out by Burbidge, Burbidge,Folwer, & Hoyle in 1957

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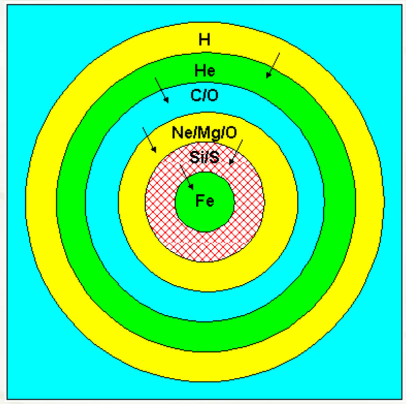
Stellar "burning"

- In the normal life of a star (main sequence)…
  - nuclear fusion turns Hydrogen into Helium
- In the late stages of the life of a massive star…
  - Helium converted into heavier elements (carbon, oxygen, …, iron)
  - "Triple-alpha" process bridges stability gap from Be to C
  - At end of star's life, get an onion-like structure (see picture to right)



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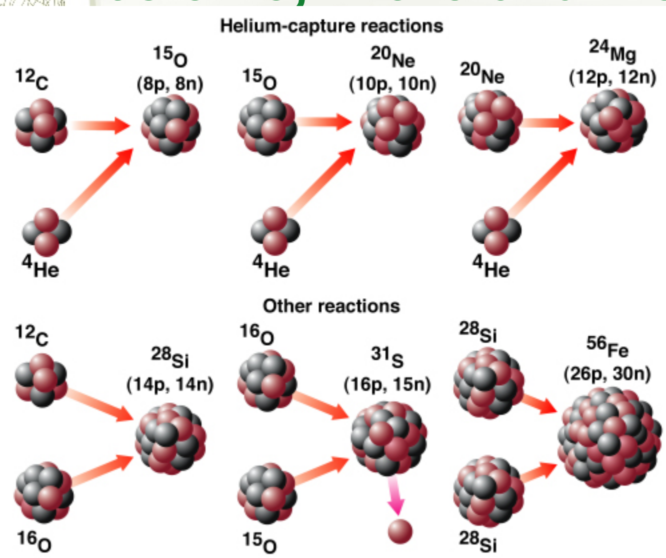
Fusion of more and more



Iron, the most stable nucleus

- What's special about iron?
  - Iron has the most stable nucleus
  - Fusing hydrogen to (eventually) iron releases energy (thus powers the star)
  - Further fusion of iron to give heavier elements would require energy to be put in…
  - Can only happen in the energetic environment of a **supernova** explosion

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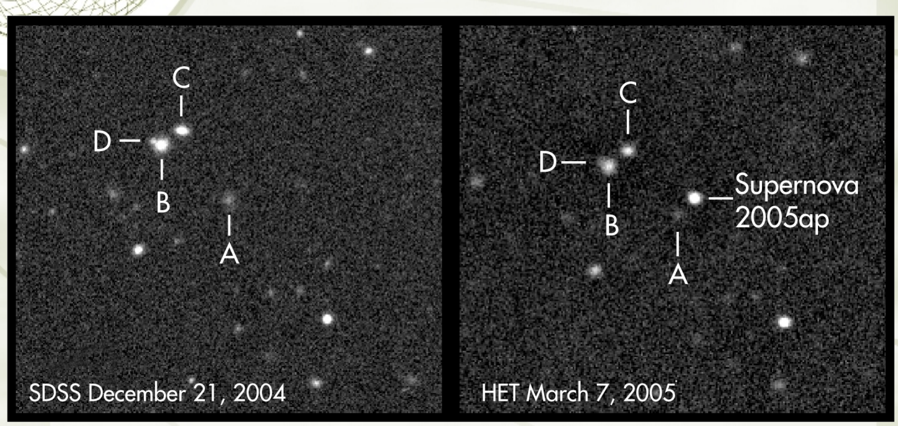
Supernovae briefly outshine their parent galaxies



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- The Crab Nebula is the remnant of a SN that exploded in 1054 AD
- We directly see a new generation of heavy elements

Elemental abundance in the Sun