Lecture 18: The Early Universe II. Nucleosynthesis

- The structure of “normal” matter
- Nucleosynthesis and the hot big bang
- The density of baryonic matter in the Universe, $\Omega_B$
- Stellar nucleosynthesis
- Recombination and matter/radiation decoupling
A brief look at the stages of the Universe’s life...

- Crude overview:
  - $t=0$: The Big Bang
  - First 400,000 yrs, an expanding “soup” of tightly coupled radiation and matter
  - Earliest epochs were “extreme” physics
  - Then more “normal” physics: protons & neutrons form
  - Then came nucleosynthesis
  - After 400,000 yrs, atoms form (“recombination”) and radiation and matter “decouple”
  - Following decoupling, matter and radiation evolve independently
  - Galaxies, stars, planets, etc can then form and evolve
BACKGROUND: THE STRUCTURE OF MATTER

- Atom is made up of...
  - Nucleus (very tiny but contains most of mass)
  - Electrons (orbit around the nucleus)

- Atom held together by attraction between positively-charged nucleus and negatively-charged electrons.

**Atomic nuclei**

- The nucleus is itself made up of:
  - Protons, $p$ (positively charged)
  - Neutrons, $n$ (neutral; no charge)
  - Collectively, these particles are known as **baryons**
  - $p$ is slightly less massive than $n$ (0.1% difference)
  - Protons and neutrons bound together by the strong nuclear force (exchange of “gluons”)
Elements & isotopes

Number of protons determines **element**:
- Hydrogen - 1 proton
- Helium - 2 protons
- Lithium - 3 protons
- Beryllium - 4 protons
- Boron - 5 protons
- Carbon - 6 proton
- ...

Number of neutrons determines the **isotope**
- e.g., for hydrogen (1 proton), there are three isotopes
  - Normal Hydrogen (H or p) - no neutrons
  - Deuterium (d) - 1 neutron
  - Tritium (t) - 2 neutrons

There’s one more level below this, consisting of quarks...
- Protons & Neutrons are made up of trios of quarks
  - Up quarks & Down quarks
  - Proton = 2 up quarks + 1 down quark
  - Neutron = 1 up quark + 2 down quarks
  - There are other kinds of quarks (strange, charm, top, bottom quarks) that make up more exotic types of particles...
Where did all the nuclei of elements come from?

Nuclear fusion

- Heavier nuclei can be built up from lighter nuclei (or free n, p) by fusion
- Need conditions of very high temperature and density to overcome repulsion of protons
- These conditions are present only in cores of stars and... in the early Universe!
- The original motivation of Gamow, Alpher, & Herman in advocating big bang was that it could provide conditions conducive to nuclear reactions
**Fission and fusion**

- **Fission**
  - Nuclei can be split into lighter nuclei (or free n, p) by fission.

- **Fusion**
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Recall timeline for early Universe...

- At $t=1s$, neutrinos began free-streaming
- At $t=14s$, $e^\pm$ stopped being created and destroyed
- Temperature continued to drop until protons and neutrons, if they combined, were not necessarily broken apart

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]
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

\[ D + \gamma \rightarrow n + p \]

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 (\(^4\text{He}\)) formation:

\[ D + D \rightarrow T + p \]
\[ T + D \rightarrow ^4\text{He} + n \]
An alternative pathway to Helium...

\[ D + D \rightarrow ^3\text{He} + n \]
\[ ^3\text{He} + D \rightarrow ^4\text{He} + p \]

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

Further reactions can give Lithium (Li)

\[ ^4\text{He} + T \rightarrow ^7\text{Li} + \gamma \]

Reactions cannot easily proceed beyond Lithium due to the “stability gap”... more about that later.
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 $^4\text{He}$... 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 lower mass thus favored energetically, so they were 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

\[ n \rightarrow p + e + \bar{\nu} \]

- 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, $\Omega_B$ is the density of the baryons (everything made of protons+neutrons) relative to the critical density.

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

From M.White's webpage, UC Berkeley
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 $\Omega_B h^2 = 0.019$.

If $H_0 = 70$ km/s/Mpc,
- $h = 0.70$
- $\Omega_B = 0.04$
- This is far below $\Omega = 1$!
- Baryons alone would give open universe

$\Omega_B h^2$
\[ \Omega_B \approx 0.049 \]

Planck results, 2013

End result of big bang nucleosynthesis
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

Fission and fusion

- Fission
- Fusion
Fission, fusion, and nuclear mass

Fusion of more and more massive nuclei
Elemental abundance in the Sun

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)
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

Proton-electron interaction produces a neutron (and other stuff)
Core collapse

Boom!

(the star explodes)

Supernovae briefly outshine their parent galaxies
The Crab Nebula is the remnant of a SN that exploded in 1054 AD
We directly see a new generation of heavy elements

Where did all the nuclei of elements come from?
After nucleosynthesis

- Nucleosynthesis was essentially completed by $t = 30\text{min}$, with free neutron abundance down to $<1\%$.
- Universe continued to expand, with energy density in radiation dropping more rapidly than energy density in matter.
- After $t = 10^{12}\text{s}$ ($30,000\text{yrs}$), when $\rho_{\text{rad}}$ fell below $\rho_{\text{matter}}$, the Universe ceased to be radiation-dominated era and entered the matter-dominated era.
- At this time, the expansion rate of the Universe changed from $R \propto t^{1/2}$ to $R \propto t^{2/3}$.
- With faster expansion rate, the radiation temperature began to drop more rapidly.

Recombination and beyond

- When radiation temperature reached $T = 3000\text{K}$, at $t = 400,000\text{yrs}$, photons were no longer energetic enough to keep electrons from binding to protons.
- This marked the time of “recombination”: ionized plasma of electrons and protons (with some Helium nuclei) combined into mostly neutral hydrogen atoms (with some Helium atoms).
- Photons interact less with bound electrons than free electrons, so radiation began to stream freely after recombination.
- This marked the event of decoupling of matter and radiation.
- After decoupling, radiation has been freely-streaming through Universe. CBR is the redshifted remnant of radiation that was last “in contact” with matter at $z = 1100$.
- Matter also began to evolve freely at that time; when it finally became cool enough, galaxies began to form (more later!)
Next time...

• What do more observations tell us about the parameters for the real Universe?