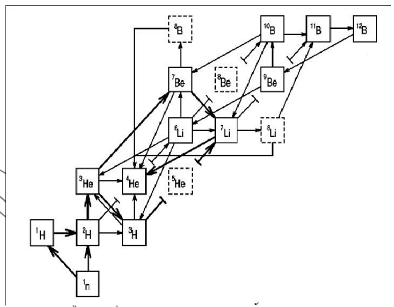
Cosmology AS7009, 2009
Lecture 8



Outline

- Origin of the elements
- Big Bang Nucleosynthesis
- Measuring Abundances
- Lingering discrepancies
- Baryon-Antibaryon asymmetry

Covers chapter 10 in Ryden + extra stuff

The Elements

Atomic nuclei:

Z = Number of protons

N = Number of neutrons

A = Nucleons = Mass number = Z + N

^{1}H = Normal hydrogen nucleus (proton)

^{2}H = Deuterium (hydrogen isoptope)

^{4}He = Normal Helium

X, Y, Z

- X: Mass fraction of Hydrogen (most common element in the Universe).
  Here, now: $X \approx 0.71$
- Y: Mass fraction of Helium (second most common element in the Universe)
  Here, now: $Y \approx 0.27$
- Z: Mass fraction of all heavier elements combined. Also known as "Metallicity".
  Here, now: $Z \approx 0.02$

Abundances in Astronomy

$$[A/B] = \log_{10}\left(\frac{(\text{number of A atoms / number of B atoms})_{\text{object}}}{(\text{number of A atoms / number of B atoms})_{\text{sun}}}\right)$$

- Common examples:
  - [Fe/H], [O/H] – These two are often carelessly referred to as 'metallicities'
- [Fe/H] = -1 means that the object you're looking at only has 10% Iron (relative to hydrogen) compared to the Sun.

The Light Elements

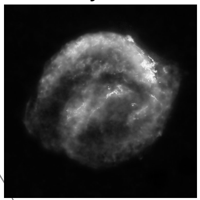
Created during Big Bang Nucleosynthesis, roughly in the first three minutes after the Big Bang:

- ^{2}H (Deuterium, D), ^{3}H (Tritium)
- ^{3}He, ^{4}He
- ^{6}Li, ^{7}Li
- ^{7}Be, ^{8}Be (Unstable, decays back into Li)

Note: BBNS required to explain abundances of ^{4}He and Deuterium!

The Heavy Elements

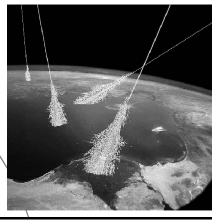
- Essentially all elements with A>7 are created through
  - Stellar nucleosynthesis
  - Supernova nucleosynthesis



Fusion: H → He → Heavier elements

Cosmic Ray Spallation

- Nucleosynthesis due to high-energy impacts of cosmic rays
- Can form ^{3}He + certain isotopes of Li, Be, B, Al, C, Cl, I and Ne



Important BBNS Reactions I: Proton-neutron freezeout

Consider the Universe at t ≈ 0.1 s…

Pair production:

$$\gamma + \gamma \Leftrightarrow e^- + e^+$$

n and p are held in equlibrium with each other:

$$n + \nu_e \Leftrightarrow p + e^-$$

$$n + e^+ \Leftrightarrow p + \bar{\nu}_e$$

Neutrinos freeze out of these reactions at t ~1 s →
Neutron-to-proton ratio frozen at $n_n/n_p \approx 0.2$
Then follows neutron decay:

$$n \Rightarrow p + e^- + \bar{\nu}_e$$

Important BBNS Reactions II: Deuterium and Helium synthesis

Consider the Universe at t ≈ 2—300 s…

$$p + n \Leftrightarrow d + \gamma$$

The rightward direction starts to dominates once the photon temperature has dropped below the 2.22 MeV binding energy of Deuterium.
Serious production of D does not start until t ≈ 300 s.
Once we have Deuterium, several routes allow the formation of Helium:

$d + n \longrightarrow H^3 + \gamma$

$H^3 + p \longrightarrow He^4 + \gamma$

$d + p \longrightarrow He^3 + \gamma$

$He^3 + n \longrightarrow He^4 + \gamma$

$d + d \longrightarrow He^3 + n$

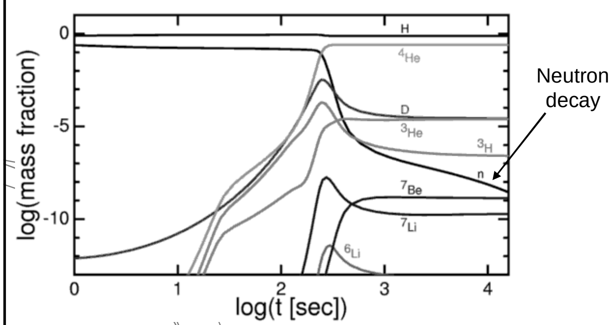
$d + d \longrightarrow H^3 + p$

$H^3 + d \longrightarrow He^4 + n$

$He^3 + d \longrightarrow He^4 + p$

$d + d \longrightarrow He^4 + \gamma$

The Detailed Solution



The Beryllium Bottleneck

- No stable nuclei with A=8 → Prevents formation of heavier elements during BBNS

Even though you can form:

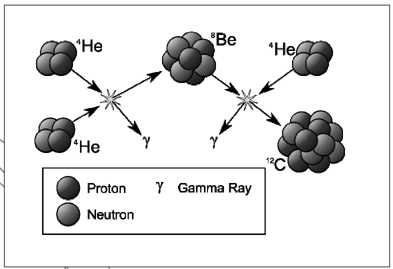
$$^4He + ^4He \Rightarrow ^8Be$$

^{8}Be will decay back into He after just 3×10^{-16} s

Yet we know that the Universe has somehow managed to make heavier elements…

The Beryllium Bottleneck II

How do you make carbon?
Solution: The Triple-Alpha process can take place in stars because of high temperatures (fast fusion of Helium)



The Beryllium Bottleneck III

Triple-Alpha works because ^{4}He, ^{8}Be and ^{12}C happen to have finely tuned energy levels.
Fred Hoyle (1950s) predicted a so far unknown excited level of ^{12}C, to explain why Carbon-based entities such as ourselves exist. Experimentalists later proved him right!

Suggestion for Literature Exercise: The Anthropic Principle in Cosmology

- Anthropic Reasoning:
  "If things were different, we wouldn't be here to observe them!"
- Has been advocated to crack tough nuts like:
  - The "why now?" problem
    Why is $\rho_M \sim \rho_\Lambda$ at the current epoch?

Primordial Abundances

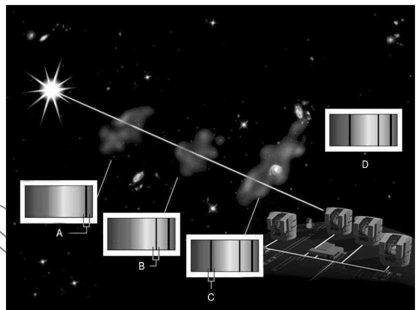
To test BBNS, one needs to measure the primordial abundances of the light elements, i.e. measure the abundances in environments unaffected by chemical evolution

- Helium: Low-metallicity HII regions
- Deuterium: Quasar absorption lines
- Lithium: Low-metallicitiy stars

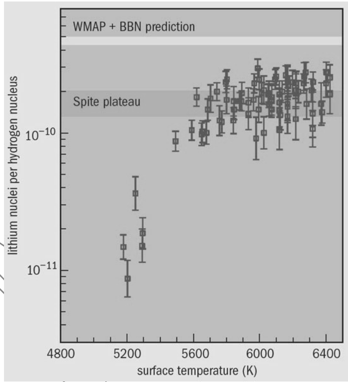
Primordial Helium

The blue compact galaxy IZw18

Primordial Deuterium



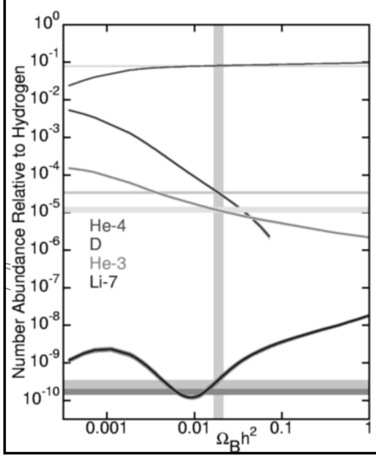
Primodrial Lithium



BBNS – A Big Bang Success Story

- Big Bang explains primordial abundances of the light elements
- The abundances of the light elements agree with predictions over 9 orders of magntiude!
- The resulting Ω_b is in accord with the result from other methods

This is how the success story is usually told – but there may be more to this than meets the eye…



Impressive agreement over 9 orders of magnitude → Big picture probably correct

But beware:
The logaritmic scale hides discrepancies…

Lingering discrepancies

Tracer	Ω_b
Deuterium	0.038±0.005
Helium	0.021±0.008
Lithium	0.028±0.005
CMBR	0.046±0.007

McGaugh (2008)

Something's wrong here…

Suggestion for Literature Exercise: The Lithium Problem

- Why does Lithium-7 not agree with BBNS predictions?
  - Exotic particles decayed around t_{BBNS}?
  - Stars used as probes destroy lithium through mixing?

The Baryon-Antibaryon Asymmetry

Why is there so little antimatter?

- At the time of BBNS, $n_{bar} >> n_{antibar}$
- When the energy of the Universe was higher than 150 MeV: Quark soup

Pair production and annihilation

$$q + \bar{q} \Leftrightarrow \gamma + \gamma$$

At lower temperatures:

$$q + \bar{q} \Rightarrow \gamma + \gamma$$

The Baryon-Antibaryon Asymmetry II

- Slight overweight of quarks compared to antiquarks:

$$n_{\mathrm{q}} > n_{\bar{\mathrm{q}}} \text{ by 3 parts in a billion}$$

- This leads to current baryon-antibaryon asymmetry and large photon-to-baryon ratio at BBNS

Problem: Mechanism behind quark-antiquark asymmetry poorly understood…