Lecture 17

Big Bang Nucleosynthesis

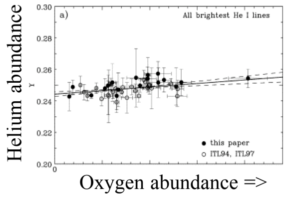
"The First Three Minutes" by Steven Weinberg

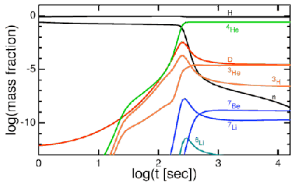
1975: Big Bang Nuclear Fusion

Big Bang + 3 minutes
T ~ 10^9 K
First atomic nuclei forged.
Calculations predict:
75% H and 25% He
AS OBSERVED !

+ traces of light elements
D, ^{3}H, ^{3}He, ^{7}Be, ^{7}Li

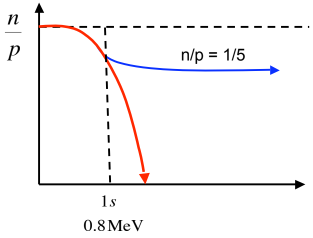
=> normal matter only 4% of critical density.





Neutron / Proton Ratio

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



0.1% mass difference is critical !

LTE :

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p}\right)^{3/2} \exp\left(-\frac{Q_n}{kT}\right)$$
$$m_n = 939.6\,\mathrm{MeV} \quad m_p = 938.3\,\mathrm{MeV}$$
$$Q_n \equiv \left(m_n - m_p\right)c^2 = 1.29\,\mathrm{MeV}$$

Freeze-out:

$$\sigma_w \sim 10^{-47} m^2 \left(kT/1\,\mathrm{MeV}\right)^2$$
$$n\sigma_w c \sim H$$
$$t \approx 1\mathrm{s} \quad kT \approx 0.8\,\mathrm{MeV}$$
$$\frac{n}{p} = \exp\left(-\frac{1.29}{0.8}\right) \approx \frac{1}{5}$$

Neutron / Proton => He / H

Deuterium production: $n + p \rightarrow D + \gamma$

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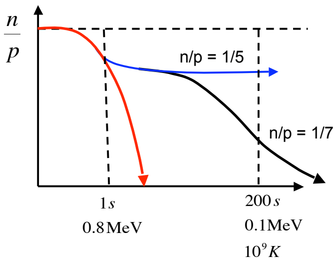
$$B_D = 2.2\,\mathrm{MeV} \quad \eta = 10^9 \frac{\text{photons}}{\text{baryon}}$$
$$\ln\eta = \ln(10^9) \sim 20$$
$$t \approx 200s \quad kT \approx \frac{B_D}{\ln\eta} = 0.1\,\mathrm{MeV}$$



Neutron decay:

$$n_n = n_0 e^{-t/\tau} \quad \tau = 890\mathrm{s}$$
$$\frac{n}{p} = \frac{1}{5} e^{-\left(\frac{200}{890}\right)} \approx \frac{1}{7}$$

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Primordial Abundances :

$$X_p \equiv \frac{\text{mass in H}}{\text{total mass}} = 0.75 \quad Y_p \equiv \frac{\text{mass in He}}{\text{total mass}} = 0.25$$

Onset of Big Bang Nucleosynthesis

Deuterium production

● ● $n + p \rightarrow D + \gamma$ ●●

delayed until the high energy tail of blackbody photons can no longer break up D. Binding energy: $B_D = 2.2$ MeV.

$$B_D / kT \sim \ln\left(N_\gamma / N_B\right) = \ln\left(10^9\right) \sim 20$$

$$kT \sim 0.1 \text{ MeV} \quad (T \sim 10^9 \text{ K} \quad t \sim 200 \text{ s})$$

Thermal equilibrium ● ● ● ● ● ● ● ●

+ neutron decay: $N_p / N_n \sim 7$ ●● ● ● ● ● ● ●

Thus, at most, $N_D / N_p = 1/6$

Deuterium readily assembles into heavier nuclei.

Key Fusion Reactions

	product:	binding energy:
$n + p \rightarrow D + \gamma$	Deuterium (pn) ●●	2.2 MeV
$D + D \rightarrow {}^3He^{++} + n$ $p + D \rightarrow {}^3He^{++} + \gamma$	^3He (ppn) ●●●	7.72 MeV
$n + D \rightarrow T + \gamma$ $D + D \rightarrow T + p$ $n + {}^3He^{++} \rightarrow T + p$	Tritium (pnn) ●●●	8.48 MeV
$n + {}^3He^{++} \rightarrow {}^4He^{++} + \gamma$ $D + {}^3He^{++} \rightarrow {}^4He^{++} + p$ $p + T \rightarrow {}^4He^{++} + \gamma$ $D + T \rightarrow {}^4He^{++} + n$ ${}^3He^{++} + {}^3He^{++} \rightarrow {}^4He^{++} + 2p$	^4He (ppnn) ●●●●	28.3 MeV

Deuterium Bottleneck

Note:
1) D has the lowest binding energy (2.2 MeV)
   (D easy to break up)
2) Nuclei with A > 2 can't form until D is produced.
   (would require 3-body collisions)

→ **Deuterium bottleneck**
- Nucleosynthesis is delayed until D forms.
- Then nuclei immediately form up to ^{4}He.

^{4}He + Traces of Light Elements

The main problem:
^{4}He very stable, 28 MeV binding energy.
Nuclei with A = 5 are unstable!

Further fusion is rare (lower binding energies):

$$^3He^{++} + ^4He^{++} \rightarrow ^7Li^{+++} + e^+ + \gamma$$
$$^3He^{++} + ^4He^{++} \rightarrow ^7Be^{4+} + \gamma$$
$$^7Be^{4+} + n \rightarrow ^7Li^{+++} + p$$
$$^7Li^{+++} + p \rightarrow 2\ ^4He^{++}$$

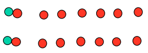
In stars, fusion proceeds because high density and temperature overcomes the ^{4}He binding energy.

Primordial Abundances

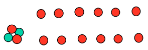
Because ^{4}He is so stable, all fusion pathways lead to ^{4}He, and further fusion is rare.

Thus almost all neutrons end up in ^{4}He, and residual protons remain free. [p+p -> ^{2}He does not occur]

To first order, with $N_p / N_n \sim 7$,



$$\boxed{\begin{aligned} X_p &\equiv \frac{\text{mass in H}}{\text{total mass}} = \frac{N_p - N_n}{N_p + N_n} = \frac{6}{8} = 0.75 \\ Y_p &\equiv \frac{\text{mass in He}}{\text{total mass}} = \frac{2N_n}{N_p + N_n} = \frac{2}{8} = 0.25 \end{aligned}}$$

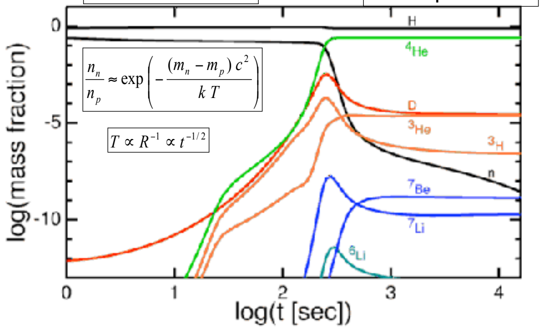


Primordial abundances of H & He (by mass, not number).

Big Bang Nucleosynthesis

Thermal equilibrium

Reactions "freeze out" due to expansion



$$\frac{n_n}{n_p} \approx \exp\left(- \frac{(m_n - m_p)\, c^2}{k\, T} \right)$$

$$T \propto R^{-1} \propto t^{-1/2}$$

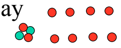
Sensitivity to Parameters

Abundances depend on two parameters:

1) cooling time vs neutron decay time
(proton - neutron ratio)

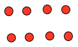
2) photon-baryon ratio
(T at which D forms)

If cooling much faster, no neutrons decay and $N_p / N_n \sim 5$



→ $X_p = 4/6 = 0.67$ $Y_p = 2/6 = 0.33$.

If cooling much slower, all neutrons decay



→ $X_p = 1$ $Y_p = 0$.

Baryon Density Constraint

Abundances (especially D) sensitive to these 2 parameters.

Why?

Fewer baryons/photon, D forms at lower T, longer cooling time, more neutrons decay ==> less He.

At lower density, lower collision rates, D burning incomplete ==> more D.

Conversely, higher baryon/photon ratio
==> more He and less D.

Photon density is well known, but baryon density is not.

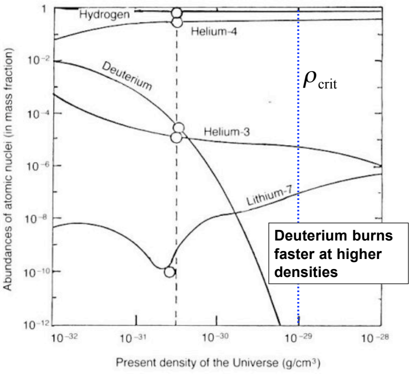
→ The measured D abundance constrains the baryon density!!
A very important constraint. $\Omega_b \approx 0.04$

Big Bang Nucleosynthesis

$$\Omega_b \left(\frac{h}{0.7}\right)^2 = 0.040 \pm 0.004$$

~4% baryons

consistent with CMB

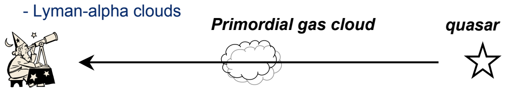


Deuterium burns faster at higher densities

Primordial gas

Observations can check the predictions,
but must find places not yet polluted by stars**.**

- Lyman-alpha clouds



Quasar spectra show absorption lines. Line strengths give abundances in primordial gas clouds (where few or no stars have yet formed).

- nearby dwarf galaxies

High gas/star ratio and low metal/H in gas suggest that interstellar medium still close to primordial

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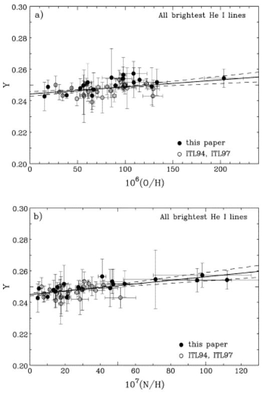
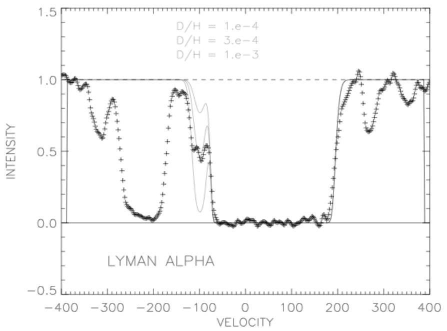
Primordial He/H measurement

- **Emission lines from H II regions in low-metalicity galaxies.**
- **Measure abundance ratios: He/H, O/H, N/H, …**
- **Stellar nucleosynthesis increases He along with metal abundances.**
- **Find Y_p by extrapolating to zero metal abundance.**



Primordial D/H measurement

Lα (+Deuterium Lα) line in quasar spectrum:



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