Introductory Astronomy

Week 8: Cosmology

Clip 7: Big Bang Nucleosynthesis

Alpher, Gamow 1948

- For a brief time universe was hot and dense as stellar interiors: Fusion everywhere
- Can Big Bang Nucleosynthesis explain abundances of the elements?
- Partially. Triple-alpha process not effective.
- Predict Helium abundance
- Assume: Thermal equilibrium in expanding flat universe
- High T: number densities of relativistic particles similar (Stefan-Boltzmann) $n_A \sim (k_B T)^3$
- Low T: number densities of nonrelativistic particles $n_A \sim e^{-m_A c^2/k_B T}$

Who's Radiation?

Particle	Q	N_e	N_μ	N_τ	Mass	Mc^2/k_B	g
p	1	0	0	0	935	10^{13}	2
n	0	0	0	0	938	$T_p + 1.5 \times 10^{10}$	2
e	-1	1	0	0	0.511	5.93×10^9	2
ν_e	0	1	0	0	?	$0?$	1
μ	-1	0	1	0	106	1.22×10^{12}	2
ν_μ	0	0	1	0	?	$0?$	1
π	1,0,-1	0	0	1	1777	1.6×10^{12}	1
γ	0	0	0	0	0	0	2

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Cosmic Neutrinos

- At $T > 10^{12}\,\mathrm{K};\ t \leq 10^{-4}\,\mathrm{s}$ all species in thermal equilibrium with antiparticles present.

  $$\frac{N_n}{N_p} = e^{-(m_n - m_p)c^2/k_B T} = e^{-1.5\times 10^{10}\,\mathrm{K}/T} \sim 1$$

- By $T \sim 10^{11}\,\mathrm{K};\ t \sim 10^{-3}\,\mathrm{s}$ muons annihilate $N_n/N_p \sim 0.86$
- By $T \sim 3\times 10^{10}\,\mathrm{K};\ t \sim 0.1\,\mathrm{s}$ neutrinos decouple $N_n/N_p \sim 0.6$
- By $T \sim 5\times 10^{9}\,\mathrm{K};\ t \sim 10\,\mathrm{s}$ electrons annihilate producing photons $T_\gamma/T_\nu = 1.4$

Alpher, Bethe, Gamow 1948

- In a hot $10^{12}\,\mathrm{K}$ dense early $10^{-4}\,\mathrm{s}$ universe, protons and neutrons in chemical equilibrium under

$$
\begin{aligned}
n + e^+ &\leftrightarrow p + \overline{\nu}_e \\
n + \nu_e &\leftrightarrow p + e^-
\end{aligned}
$$

- Below $10^{10}\,\mathrm{K}$ these slow as neutrinos decouple and soon thereafter most electrons gone

$N_n/N_p \sim 0.223$

Nuclei

- Deuterium stable after $T \sim 10^9\,\mathrm{K};\ t \sim 180\,\mathrm{s}$
- Neutrons have decayed ($t_{1/2} = 614\,\mathrm{s}$) $N_n/N_p = 0.122$
- Essentially all remaining neutrons bind to form deuterium

$$
\begin{aligned}
{}^2_1\mathrm{H} + {}^2_1\mathrm{H} &\leftrightarrow {}^3_1\mathrm{H} + {}^1_1\mathrm{H} \\
{}^3_1\mathrm{H} + {}^2_1\mathrm{H} &\leftrightarrow {}^4_2\mathrm{He} + n
\end{aligned}
$$

  and then Helium

$$
\begin{aligned}
{}^2_1\mathrm{H} + {}^2_1\mathrm{H} &\leftrightarrow {}^3_2\mathrm{He} + n \\
{}^3_2\mathrm{He} + {}^2_1\mathrm{H} &\leftrightarrow {}^4_2\mathrm{He} + {}^1_1\mathrm{H}
\end{aligned}
$$

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Helium Fraction

- Helium fraction is $\frac{0.122/2}{1-(3/2)\times 0.122} = 0.0747$
- Helium mass fraction is $4 \times 0.0747 = 0.299$
- Close to 0.24 observed. More refined calculation produces agreement
- Insensitive to details

Other Nuclei

- Fusion beyond Helium inefficient
- Trace abundances of deuterium that failed to fuse sensitive to

  $\eta = \Omega_{Db,0}/\Omega_{R,0}$
- BBN constrains cosmology and particle physics