VI. Big Bang Nucleosynthesis (BBN)

This subject is covered in Chapter 7 of Huterer.

The lecture discussion will be complemented by working through a simplified BBN calculation in Problem Set 3.

To test/constrain the big bang theory at $z > 10^7$, we must turn to nucleosynthesis, "archeology" based on element abundances

The Basic Physics

After electron-positron annihilation at $t \sim 1$ second, the constituents of the universe are photons, neutrinos, and (at an abundance smaller by a factor $\sim 10^9$) protons, neutrons, and electrons.

The energy density is dominated by the photons and neutrinos. The relation between the age of the universe and the photon temperature is determined by the radiation-dominated Friedmann equation, which yields:

$$t(T) \approx 1.32 \left(\frac{kT}{1\ \mathrm{MeV}}\right)^{-2}\ \mathrm{s}. \tag{6.1}$$

(as shown in PS 3 and PS 4).

While interconversion between neutrons and protons (by weak interactions involving neutrinos) is fast compared to the expansion time, the neutron-to-proton ratio is pinned to its thermal equilibrium value

$$\frac{n}{p} = e^{-Q/kT}, \quad Q \equiv (m_n - m_p)c^2 = 1.2934\,\mathrm{MeV}.$$

The conversion reactions become slow compared to the expansion at $t \sim 3$ seconds, $kT \sim 0.7$ MeV.

The neutron-to-proton ratio "freezes in" at $n/p \sim 1/6$.

Synthesis of elements heavier than hydrogen has to start with deuterium formation ($n+p \rightarrow D + \gamma$).

The binding energy of deuterium is $B_D = 2.22$MeV.

Naively one expects deuterium synthesis to begin when the temperature falls to $kT \sim B_D$. However, the baryon-to-photon ratio is $\eta \sim 5 \times 10^{-10}$, so the exponential tail of the blackbody distribution can still dissociate deuterium even when kT is significantly below B_D.

Synthesis of deuterium actually begins when $kT \sim B_D / -\ln\eta \sim 0.1$ MeV, at time $t \sim$2 minutes.

The decay time for free neutrons is ~ 900 sec, so in two minutes a small but non-negligible fraction of the neutrons left over from "freeze-out" have decayed.

The neutron-to-proton ratio at the time of deuterium synthesis is $n/p \sim 1/7$.

The reaction rate for $n + p \rightarrow D + \gamma$ is fast, so when the temperature falls below 0.1 MeV, all neutrons are quickly processed into deuterium.

The reactions that process D into ^{4}He are also fast, and to first order all neutrons go into ^{4}He .

A small fraction ($\sim 10^{-5}$) of D "escapes" and is never processed into heavier nuclei.

A comparable fraction is processed into ^{3}He but not into ^{4}He .

A small amount ($\sim 10^{-10}$) of ^{7}Li is produced.

There are no stable elements of atomic number 5 or 8.

Starting with protons and neutrons, there is no way to bridge the gap at atomic number 8 to build heavier nuclei.

Stars do it by the "triple-α" reaction: ^{4}He + ^{4}He + ^{4}He $\longrightarrow {}^{12}$C*, but this requires high temperature *and* density.

Consequence: only light elements are made in the early universe. All elements heavier than ^{7}Li are made in stars.

The "standard" nucleosynthesis calculation

Assume particle content of the standard particle physics model.

Assume GR, homogeneity, use measured interaction rates.

Integrate reaction network in cosmological background, predict abundances.

Primary free parameter is baryon-to-photon ratio η, which is proportional to $\Omega_B h^2$.

Number of neutrino species N_ν can be treated as a second free parameter.

$N_\nu > 3$ can represent actual additional neutrino species or some other form of energy density that affects the cosmic expansion rate at early times.

^{4}He production depends mainly on weak interaction cross sections vs. expansion rate.

Weakly sensitive to η, thus a robust prediction of the standard model (at the 10% level).

Some dependence on η because of free neutron decay.

Quite sensitive to N_ν (Steigman, Schramm, & Gunn 1977), thus a probe of the relativistic degrees of freedom present at $t \sim 1$ sec.

Other light element abundances depend on fusion rates rates vs. expansion rate, hence sensitive to density.

D and ^{3}He result from "incomplete" processing to ^{4}He $\Longrightarrow$abundances decrease as η increases.

^{7}Li vs. η has minimum at $\eta \sim 2.5 \times 10^{-10}$ because of competition between production and destruction mechanisms.

BBN in practice

Goals:

- test the standard model — is there a value of η consistent with all of the inferred abundances?
- constrain the model's free parameters: η and N_ν
- test alternatives, e.g., decaying particles, time-varying gravitational constant, inhomogeneities present at nucleosynthesis, extra energy components

While the calculation itself is improved as inputs become better known, most of the art (and controversy) has to do with inferring primordial abundances from observations.

Deuterium

Cleanest case, because seems impossible to make anywhere other than the big bang (because so weakly bound).

Destroyed in stars $\Longrightarrow$observed abundance is lower limit to primordial abundance $\longrightarrow$upper limit on η

Solar system and ISM estimates give D/H$\sim 1-2\times10^{-5}$.

Estimates from high-redshift QSO absorbers give D/H$\approx 2.5\times10^{-5}$. A weighted average of recent high-quality measurements by Cooke, Pettini, & Steidel (2018) gives

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_P = (2.53\pm0.03)\times10^{-5}\ .$$

where the P subscript denotes "primordial."

This measurement combined with standard BBN implies

$$\Omega_b h^2 = 0.0223\pm0.0004, \qquad \eta=(6.1\pm0.1)\times10^{-10}\ . \tag{6.2}$$

CMB anisotropies now allow an independent estimate of $\Omega_b h^2$ based on completely different physics. The value inferred from CMB anisotropy is

$$\Omega_b h^2 = 0.0224\pm0.0002\ .$$

This consistency of different estimates of the baryon density is an important and striking piece of evidence for the validity of the standard model, of both BBN and CMB anisotropy.

The estimated value is substantially below the estimated value of Ω_m (by a factor ~ 6) $\Longrightarrow$ dark matter is not made of baryons.

Helium-4

Can be measured accurately.

The big question: how accurately? Need to extrapolate to zero metal abundance, correct for an assortment of systematics.

Estimates of primordial mass fraction range from $Y_P \sim 0.23 - 0.25$, though quoted error bars have traditionally been much smaller. Measurements have, arguably, improved markedly in the past several years.

A good value based on the best recent measurements is

$$Y_P = 0.245 \pm 0.003 \ . \tag{6.3}$$

^{4}He /H is a weakly increasing function of η, and the above value is consistent with predictions for the value of η implied by (D/H) and by CMB.

This consistency limits deviations from the standard model, in particular extra degrees of freedom that would increase the expansion rate in the early universe and lead to higher predicted values of Y_P.

This constraint is often expressed in terms of the quantity N_ν, the effective number of neutrino species.

Helium-3 and Lithium-7

Agree with standard model at order-of-magnitude level, providing additional low precision evidence for it.

But ^{3}He and ^{7}Li can both be produced and destroyed in stars.

Inferred primordial ^{3}He abundance depends on chemical evolution modeling, stellar yields.

Inferred primordial ^{7}Li abundance depends on stellar astrophysics, especially rotational mixing mechanisms that might allow destruction in metal poor stars (work by Pinsonneault, Deliyannis, and others).

Probably can't use factor of few discrepancies as cosmological tests, because of uncertainties in chemical evolution and stellar astrophysics.

Similarly, can't use ^{3}He and ^{7}Li to confirm standard model at high precision.

BBN Bottom Line

$\sim 25\%$ ^{4}He is a key piece of evidence for the Big Bang model, at $\sim 10\%$ precision.

D is the "baryometer"; best estimates of D/H imply $\Omega_b h^2 \approx 0.02$.

Consistency with CMB measurements of $\Omega_b h^2 \Longrightarrow$important consistency check of standard model via independent methods.

^{3}He and ^{7}Li give two additional, low precision (factor ~ 3) tests.

Departures from GR, standard particle content at $t \sim 1\,\mathrm{sec} - 3\,\mathrm{mins}$ are tightly constrained.

Improved understanding of "astrophysical" systematics on primordial abundance measurements could yet yield interesting conflicts, but necessary improvements difficult to achieve.

Can instead use “known” primordial abundances and measurements to test astrophysical creation/destruction mechanisms, chemical evolution models.

The Particle Data Group (PDG) review of BBN, updated every two years, is a good way to keep apprised of recent developments.