VI. The Thermal History of the Universe

This section roughly parallels §3.5 of Kolb & Turner, for which sections 3.3 and 3.4 are useful background. These three sections are somewhat heavy going, but I highly recommend reading them even if you don't take the time to follow all of the equations (though you will get much more out of them if you do).

Recall that, at redshift z, the temperature of the photon background is

$$T = 2.73 \times (1+z)\ \mathrm{K}, \qquad kT = 2.39 \times 10^{-4} \times (1+z)\ \mathrm{eV}.$$

Particles and anti-particles in the early universe

If the rates of reactions that exchange energy between particles are fast compared to the expansion rate, the populations should relax to thermal equilibrium.

Consider a particle of mass m_K. If $kT > 2m_K$ and the rate of reactions that can create $K\overline{K}$ pairs from other particles (e.g., photons) are fast compared to the expansion rate, maximizing entropy $\Longrightarrow$an abundance of K and $\overline{K}$ particles roughly equal to the photon abundance (up to statistical weight factors).

If the temperature falls below $2m_K$ while the $K\overline{K}$ annihilation rate is high, the particles will annihilate and dump their energy into the background of still-coupled particles. This happens to electrons and positrons.

If the $K\overline{K}$ annihilation rate drops below the expansion rate while $kT > 2m_K$, the particle decouples and redshifts thereafter independent of other species. This happens to neutrinos, and it may happen to other weakly interacting particles. For these species, the abundance should be comparable to the abundance of CMB photons.

WIMP dark matter

In one of the leading scenarios for dark matter, WIMPS (Weakly Interacting Massive Particles) are first suppressed in number as the temperature falls below their rest mass, then decouple once the typical annihilation time (determined by the weak interaction rate) exceeds the age of the universe.

The dark matter would then consist of equal numbers of WIMPS and anti-WIMPS.

For reasonable assumptions about the interaction cross-section and its dependence on mass, the predicted density of dark matter is about right (at the order of magnitude level), making this an attractive model.

In the densest regions of the universe today (at the centers of galaxies), WIMPS and anti-WIMPS might annihilate and produce gamma rays (and other particles) at a detectable rate.

There is not yet a convincing detection of a WIMP-annihilation signature. Searching for one is one of the motivations for GLAST (the Gamma-ray Large-Area Space Telescope).

Baryon asymmetry

The local universe has baryons but almost no anti-baryons.

This asymmetry is small in the sense that the baryon-to-photon ratio is $n_B/n_\gamma = 2.68 \times 10^{-8}\Omega_B h^2$, where $\Omega_B = \rho_B/\rho_c$ and $h \equiv H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Since the particle density in the relativistic era was $\sim n_\gamma$, *almost* all relativistic baryons were annihilated by anti-baryons.

The baryon asymmetry (and corresponding e^+/e^- asymmetry) may be an initial condition of the universe.

Alternatively, the baryon asymmetry may have arisen after the Big Bang. Three conditions are necessary for this to be possible (Sakharov 1968):

(1) Processes exist that do not conserve baryon number (otherwise every B would be produced with an accompanying $\overline{B}$.

(2) There is an asymmetry between reactions involving particles and reactions involving the corresponding anti-particles (technical jargon: CP violation). Such asymmetry is observed experimentally in weak interactions (K_0 mesons), and it is believed to occur in strong interactions.

This makes it possible to statistically favor particle production over antiparticle production.

(3) The universe must be out of thermal equilibrium, otherwise maximizing entropy would lead to equal numbers of particles and anti-particles. Departures from equilibrium can happen because the universe is expanding.

A number of specific models of "baryogenesis" have been proposed, none entirely compelling. Some place baryogenesis at the strong-electroweak ("GUT") symmetry breaking, others at electroweak symmetry breaking. Since the level of CP violation observed in the weak interaction is $\sim 10^{-9}$, it is not unreasonable to imagine creating a baryon asymmetry of the observed order.

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Quantum gravity era ends — $t \sim 10^{-43}$ s $\sim (G\hbar/c^5)^{1/2}$, the "Planck time." Inflation?

Grand unification breaks? — $t \sim 10^{-34}$ s, $kT \sim M_{X,Y}$. Baryogenesis? Inflation?

Electroweak unification breaks — $t \sim 10^{-11}$ s, $kT \sim M_{W,Z}$. Baryogenesis?

Quarks combine into hadrons — $t \sim 10^{-6}$ s, $kT \sim$nucleon binding energy

Neutrinos decouple — $t \sim 1$ s $\sim (\sigma_\nu n c)^{-1}$

Electrons and positrons annihilate — $t \sim$ few s, $kT \sim 1$ MeV $\sim 2m_e$. Adds heat (entropy) to radiation background. Residual e^- keep universe opaque.

Light nuclei form — $t \sim 1$ minute, $kT \sim 0.1$ MeV $\sim B_{\text{deuterium}}/20$.

Matter domination begins — $t \sim 10^3(\Omega_{m,0}h^2)^{-2}$ years, $(1+z) = \rho_{m,0}/\rho_{r,0} = 2.39 \times 10^4(\Omega_{m,0}h^2)$. Expansion changes from $a \propto t^{1/2}$ to $a \propto t^{2/3}$. Growth of instabilities possible.

Atoms form, photons decouple — $t \sim 10^5$ years, $(1+z) \sim 1100$, $kT \sim 0.3$ eV ~ 13.6 eV/45.

Stars, galaxies form — Later.

Λ-domination begins (?) — $(1+z) \sim (\Omega_{\Lambda,0}/\Omega_{m,0})^{-1/3}$. Expansion law changes again, towards $a \propto e^{Ht}$. Growth of instabilities slows down. We are in the middle of this transition now.

If dark energy is not a true cosmological constant, the transition may be slower, and the end state may be power-law rather than exponential expansion.