The thermal history of the Universe - Summary

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This summary is based on the book Chapter 11 from Arnab Rai Choudhuri: Astrophysics for physicists.

1 Primordial nucleosynthesis

Basic timeline of the earliest phase of the Universe:

1. When the temperatures were higher than 1GeV, we enter the particle physics era
2. energies of order MeV. During the epoch from about t = 1 - 100 s → nuclear reactions
3. a few thousand years → changed from being radiation-dominated to being matter-dominated
4. 1 eV and formation of atoms took place → recombination → CMB

Thermodynamical or chemical equilibrium when the concentrations of various elements is such that the **backward reaction rate balances the forward reaction rate** and the concentrations do not change.

As the Universe expanded at the rate $H = \dot{a}/a$, the condition for chemical equilibrium kept changing. Only if a reaction proceeded at a rate faster than this expansion rate, can we expect the reaction to reach equilibrium. Γ is the interaction rate per particle. If $\Gamma << H$, then the reaction would be able to reach chemical equilibrium, if $\Gamma >> H$ there is no chemical equilibrium. → Γ decreases with the expansion of the Universe. We then expect the condition $\Gamma << H$ to change over to the condition $\Gamma >> H$ as the Universe evolves. → The concentrations of the particles involved in the reaction are not expected to change after the reaction goes out of equilibrium.

Based on the number chemical equilibrium consideration and the CMB we can calculate the number density of photons and estimate the number density of baryons. The ratio of the number density of baryons to photons is an important cosmological parameter:

$$\eta = \frac{n_{B,0}}{n_{\gamma,0}}$$

After the CMB was created η should not change significantly.

1 s to 10^2 s after the Big Bang was suitable for nuclear reactions. This was the time when the primordial He, ^2H and Li was synthesized.

At $\sim$ 0.8 MeV the chemical equilibrium for the n^0 broke, which in combination with the nuclear reaction timescale approximately determines the overall amount of n^0 in the universe, which is basically all inside He in the early Universe → the calcualted mass fraction of He is 0.25. Measurements indicate between 0.23 - 0.27.

We can get constrains on η by measuring the primordial ^2H → deuterium fraction falls sharply with the increase in η. → upper bound on $\Omega_{B,0} < 0.09$. In contrast $\Omega_{mass,0} \sim 0.3$. → this clearly indicates that the 'dark matter' can not be baryons.

1.1 Neutrinos

We would expect a background of neutrinos because neutrinos were created in the early Universe. In the early Universe, photons, neutrinos and matter particles must all have been in thermodynamic equilibrium and must have had the same temperature. When the temperature fell, the electrons and positrons would have annihilated each other creating photons, thereby putting more energy in the photon background. → we can estimate the temperature of the cosmic background neutrinos to be $T_{\nu,0} = 1.95K$, a bit colder than the CMB. Unfortunately this is currently impossible to detect.

2 Dark matter

Evidence for dark matter:

- rotation curves of galaxies
- application of the virial theorem to galaxy clusters
- Primordial nucleosynthesis calculations

There are two main types of dark matter based on the particle mass:
- **hot dark matter:** with particle masses < 10 eV (Cowsik-McClelland limit) and very high kinetic energy (ultra relativistic) $\rightarrow$ these particles would not be gravitationally bound to galaxies or galaxy clusters which is a problem
- **cold dark matter:** with particle masses > 3 GeV (Lee-Weinberg limit) and low kinetic energy $\rightarrow$ currently believed to be more realistic

Candidates for dark matter: **Weakly interacting massive particles (WIMPs)** are hypothetical particles that are one of the proposed candidates for dark matter. There exists no formal definition of a WIMP, but broadly, it is an elementary particle which interacts via gravity and any other force (or forces), which are as weak as or weaker than the weak force, but also non-vanishing in strength.

3 Problems related to the early Universe

3.1 The horizon problem

Photons in the CMBR reach us after travelling through space for time comparable to the age of the Universe. Consider CMBR photons coming from two diametrically opposite regions in the sky. These two regions are causally connected to us, but are not causally connected to each other because the information from one of the regions had just time enough to reach us and did not yet have time to reach the other region. The isotropy of CMBR, however, suggests that these two regions which apparently had never been in causal contact have the same physical characteristics, since they produce CMBR of exactly the same nature. How is it possible that regions which are out of each other's horizons and which have never been in causal contact are so homogeneous? This is known as the horizon problem in cosmology.

To solve the horizon problem, it was suggested that there was a brief phase in the very early Universe when the Universe expanded very rapidly and became larger by several orders of magnitude. This is called **inflation**. the Universe before inflation must have been much, much smaller than what we would expect it to be if inflation had not taken place. Different parts of the Universe could have been causally connected if the Universe was very small before inflation and thereby the homogeneity of the Universe could have been established.

Possible observables of the inflation:
- gravitational waves
- density waves

3.2 Baryogenesis

The value of η suggests that there are many more photons than baryons in the Universe, but why?

In the early Universe when the temperature was higher than a few GeV and baryon-antibaryon pairs could be formed, the number of either baryons or antibaryons would have been comparable to the number of photons. But the number of baryons must have been slightly larger than the number of antibaryons to ensure that some baryons were left over after the baryon-antibaryon annihilation. In the present Universe we mostly have baryons and almost no antibaryons.

If the Universe had equal numbers of baryons and antibaryons in the beginning, then the net baryon number Δn_B (the difference between the number of baryons and anti baryons) was initially zero and it had to change to a non-zero value later. We find the baryon number to be a conserved quantity in all particle interactions we study at the present time. If the Universe was created with equal numbers of baryons and antibaryons, then the small excess of baryons over antibaryons could arise only if baryon number conservation was violated in the very early Universe. This is known as the problem of baryogenesis and has been of some interest to theoretical particle physicists.

4 CMB

Photons interact with electrons through Thomson scattering. As long as electrons are free, we expect Thomson scattering to keep matter and radiation in equilibrium. Radiation gets decoupled from matter when atoms form and all electrons get locked up inside atoms.

The ionization potential for hydrogen is $\xi = 13.6$ eV, corresponding to a temperature of 1.5×10^5 K. However, a simple application of the Saha equation shows that the number of free electrons becomes insignificant only when the temperature falls to a much lower value of about 3000K. We thus the Universe becomes transparent to photons when the temperature falls below **3000 K,** causing radiation to get decoupled from matter. The Universe became transparent after this decoupling and photons no longer interacted with matter.

All the CMBR photons which reach us today last interacted with matter at the era of redshift $z_{dec} = 1100$. These photons started as blackbody radiation of temperature 3000 K. The redshift of 1100 has made them the present blackbody radiation of temperature 2.735 K.

The CMBR photons coming from all directions show us a surface of primordial matter surrounding us as it existed at redshift $z_{dec} = 1100$. This is called the **last scattering surface**.

If there were inhomogeneities in the last scattering surface, they would manifest themselves as angular anisotropies in the CMBR. The typical angular size of anisotropies can be used to put important constraints on various cosmological parameters. The anisotropies in CMBR resulting from irregularities in the last scattering surface are often called **primary anisotropies**. The rms variations are only 18 μK (very tiny).

4.1 Sunyaev-Zeldovich effect

Galaxy clusters contain hot gas, which is ionized and has free electrons. So CMBR photons passing through galaxy clusters can interact with the free electrons in the hot gas. In normal Thomson scattering, photons scatter off electrons without any significant change in energy. Thomson scattering involving an energy exchange between photons and electrons is called the **Compton effect or Compton scattering**.

The Compton effect becomes important when the photon energy is not negligible compared to the rest mass energy of the electron. When an **electron with high kinetic energy interacts with a low-energy photon, we can have the inverse Compton effect** in which energy is transferred from the electron to the photon. This happens when CMBR photons interact with the free electrons in a galaxy cluster, which are highly energetic because of the high temperature of the cluster gas. This **transfer of energy from the electrons in the hot cluster gas to the CMBR photons is known as the Sunyaev-Zeldovich effect**. This results in a depletion of CMBR intensity in radio frequencies in the directions of galaxy clusters.

From this depletion in intensity, one can estimate the optical depth (usually $<< 1$) of CMBR photons through the cluster gas. For a spherical cluster of radius R_c and internal electron density n_e, the maximum optical depth at the centre would be of order $2\sigma_T n_e R_c$, where σ_T is the Thomson scattering cross-section. One important application of the Sunyaev-Zeldovich effect is that it **can be used to estimate the distances of galaxy clusters, thereby leading to a determination of the Hubble constant.**

5 The first galaxies

After the matter-radiation decoupling (CMBR), however, the matter in the Universe became transparent and did not emit any more radiation until stars and galaxies formed long afterwards.

The 'oldest' most distant galaxy was recently detected with the James Web Space Telescope at redshift 14.179. This is a galaxy with intense star formation.

Another type of objects that can be detected at high redshift are quasars. The most distant quasar has been detected at redshift 7.54. Since quasars are very bright, they can be detected at relatively high redshifts. We see a change in the number of detected quasars with redshift with few quasars above redshift 4, a peak of quasars at redshift 2, and fewer quasars at lower redshift. This suggest that the peak of galaxy activity was at redshift 2 and is decreasing since than.

The star formation rate was maximum during redshifts z $\sim$ 1-1.5.

6 The intergalactic medium

We can measure the intergalactic medium (gas between galaxies) using absorption lines in quasar spectra. Often we find a large number of narrowly spaced hydrogen absorption lines. These absorption lines are collectively referred to as the **Lyman-α forest**. The Lyman-α forest probes the hydrogen between galaxies. We do not have a uniform distribution of neutral hydrogen gas along the line of sight. There must be many clouds of neutral hydrogen lying on the path at different redshifts, which are causing the absorption lines.

When the first stars, galaxies and quasars started forming, the ionizing radiation from these objects presumably ionized the intergalactic medium again. This is called the **reionization.** In addition to neutral hydrogen clouds there is also ionized hydrogen between galaxies.

7 Structure formation

The very small density perturbations present in era z = 1100 grew by gravitational instability to become the first stars and galaxies before z > 6. Understanding the details of how this happened is the subject of **structure formation**.

1. It is found that the perturbations remained frozen and could not grow as long as the Universe was radiation-dominated.

2. Only after the Universe becomes matter-dominated, can those perturbations grow.

We expect only the baryonic matter to interact with radiation and to be coupled with it till the formation of atoms. Since the cold dark matter can have only the weak interaction, it must have become decoupled from the other components of the Universe when the temperature fell below MeV values.

The perturbations in the cold dark matter would have grown considerably and would have produced gravitational potential wells in the regions where the cold dark matter got clumped. Once the baryonic perturbations are allowed to grow after the formation of atoms, the baryonic matter would quickly fall in the gravitational potential wells created by the cold dark matter.

Simulations indicate that structures like what we see today may indeed form if the Universe contains a significant amount of cold dark matter in addition to baryonic matter.