The hot big bang

The thermal history

We have already introduced the idea that the density of the universe is **radiation dominated** at early times. This does not perhaps emphasize strongly enough the key fact: the early universe was a very *hot* place. The **Wien law** says that black-body radiation peaks at a frequency $\propto T$. So, suppose we put some black-body radiation in an expanding universe. The frequency of photons falls $\propto 1/R$ through the redshift, so the radiation still looks thermal, but with a lower temperature:

$$\boxed{T \propto 1/R(t).}$$

At early enough times, the typical photons become energetic enough that they interact strongly with matter – so the whole universe sits at a temperature dictated by the radiation. The behaviour of matter changes as a function of its temperature, and so a number of key events in the history of the universe happen according to a schedule dictated by the temperature – time relation. From the solution of the Friedmann equation, we can obtain this relation for a photon-dominated universe:

$$\boxed{t/\mathrm{seconds} = \left(T/10^{10.18}\,\mathrm{K}\right)^{-2}.}$$

This is independent of the present-day temperature (which we will soon see to be very small: a mere 2.73 K). The present temperature does however set the redshift above which the universe is radiation-dominated: this is roughly $z = 10^4$.

We can now make a table of the time at which some key events happen. Note that, for very high temperatures, energy units for kT are often quoted instead of T. The conversion is $kT = 1$ eV for $T = 10^{4.06}$ K. Some of these epochs will be explained below. Some of the numbers are rounded, rather than exact; also, some of them depend a little on Ω and H. We won't worry about this here.

Event	T	kT	redshift	time
Now	2.73 K	0.0002 eV	0	13 Gyr
Distant galaxy	16 K	0.001 eV	5	1 Gyr
Recombination	3000 K	0.3 eV	1000	$10^{5.6}$ years
Radiation domination	8000 K	0.7 eV	3000	$10^{4.6}$ years
Nucleosynthesis	10^{10} K	1 MeV	10^{10}	1 s
Nucleon pair creation	10^{13} K	1 GeV	10^{13}	10^{-6} s
Grand unification	10^{28} K	10^{15} GeV	10^{28}	10^{-34} s
Quantum gravity	10^{32} K	10^{19} GeV	10^{32}	10^{-43} s

The microwave background

Looking further away is the same as looking back in time, suggesting that we should be able to see these hot early phases directly. This sounds too good to be true, and it is: we can only see back a certain distance, because light can only propagate if the universe is transparent. When the universe is hot enough that typical thermal photons can **ionize** a Hydrogen atom, it undergoes a phase change, becoming a **plasma** of free protons and electrons. The free electrons scatter radiation very effectively, so there is a barrier that we can't see through. This is rather like the surface of the sun: the sun isn't a solid body, and the apparent surface (or **photosphere**) is where it is dense enough to scatter light. This key era in the universe's history is called **recombination**; the cosmic photosphere is called the **last-scattering surface**.

The characteristic ionization temperature for Hydrogen is given by $kT = 13.6$ eV, so $T = 10^{5.2}$ K. In reality, the last-scattering surface is at a somewhat lower temperature: about 3000 K. This is because even a small degree of ionization is very effective at scattering radiation. This is still a very hot surface – about the same temperature as the sun. The reason we don't get cooked when we go outside is that the surface is highly redshifted. Just how redshifted was discovered (by accident) in 1965 by **Penzias & Wilson**. They were trying to map the galaxy at 7.3 cm wavelength and kept measuring an excess signal. Astronomers in Princeton university had predicted that there should be relic radiation in the microwave band, and were planning to search for it – so they were able to tell Penzias & Wilson what they had found. Subsequent experiments, culminating in the 1989 launch of the **COBE** satellite (of which more later) measured this radiation at a wide range of frequencies and showed it to be a very accurate black body:

$$\boxed{T = 2.728 \pm 0.004\,\mathrm{K}.}$$

The redshift of last scattering is thus close to $z = 1000$.

Primordial nucleosynthesis

Although $z = 1000$ is as far as we can see, earlier and hotter times still leave measurable traces in the universe. At very high temperatures, the universe is a rather simple place. If $kT > m_p c^2$, where m_p is the proton mass, then typical photons have enough energy to produce pairs of protons and anti-protons. Since the mass of the neutron is nearly the same as that of the proton, there are also neutrons and anti-neutrons, all participating in reactions like $p + \bar{p} \leftrightarrow 2\gamma$. The mass-energy of the proton is 938 MeV, so the corresponding temperature is $T = 10^{13}$ K. Above this temperature, nucleons and anti-nucleons behave rather like photons: both will be relativistic particles, and they will have a similar number density and a similar energy density.

As the universe cools, it becomes energetically favourable for the nucleon and anti-nucleon pairs to **annihilate**, leaving just photons. This leaves a big puzzle: if we look around the universe now, it is clear that there are quite a few protons about, but where are the anti-protons? **Antimatter** would annihilate violently with ordinary matter; since even the space between galaxies is filled with tenuous **intergalactic gas**, there can't be significant amounts of antimatter anywhere in the universe. If the numbers of protons and anti-protons started out equal, how did things get to be like this? We will shortly see that there are now about 10^9 photons for each proton in the universe. This says that, at early times, the number densities of protons and anti-protons couldn't have been quite equal:

$$\boxed{n(p) \,/\, n(\bar{p}) \simeq 1 + 10^{-9}.}$$

Pair creation and annihilation processes can't change this slight excess of protons, so they survive to the present, making the matter in the universe (and us). The origin of this **matter – antimatter asymmetry** is one of the big outstanding questions in cosmology. It seems likely that the answer lies in particle physics, since there are some observed reactions where the properties of particles and anti-particles are very slightly different (the technical term for this is **CP violation**). One of the great aims of the subject is to use measurements of such effects in terrestrial particle accelerators to predict the matter – antimatter asymmetry.

Once the pairs have annihilated, the remaining nucleons can undergo nuclear reactions. The result of these reactions illustrates a critical point about the early universe: it is a **non-equilibrium** system. Consider the simplest nuclear reactions that might be used to produce nuclei:

$$\boxed{p + n \to \mathrm{D}; \quad \mathrm{D} + \mathrm{D} \to {}^4\mathrm{He},}$$

where D stands for a deuterium nucleus, with one proton and one neutron, and He stands for Helium, with two protons and two neutrons. Energy is given out when these nuclei form: the **binding energy per nucleon** is 1 MeV for deuterium, and 7 MeV for helium. This number increases for bigger nuclei, reaching a maximum of about 9 MeV for iron. Suppose the early universe works in equilibrium: if it is cool enough for helium to start forming, the reactions should go all the way to iron. They don't, because deuterium has to form first, then helium and so on. While this is happening, the universe is expanding and cooling: the time between each interaction, τ, increases – until it becomes longer than the age of the universe at that redshift. Once this happens, the nuclear reactions switch off, and we are left with a snapshot of conditions as they were when the reactions were last in equilibrium. This process is known as **freeze-out**, and the criterion is

$$\boxed{\mathrm{freeze-out} : \tau(z) > t(z).}$$

In practice, freeze-out happens after helium has formed, before significant amounts of more massive elements have been created. This happens at a temperature of about 10^9 K, or a time of 3 minutes. There is something missing in this story, since studies of the stars have told us since the 1930s that 75% of the mass in the universe is hydrogen, and about 25% is helium. This can be understood, because the neutron is an **unstable particle**, with a half-life of about 3 minutes. The number of neutrons that are available to be fixed into nuclei is therefore lower than the number of protons; the helium fraction should be large, but less than unity.

This is an incredible calculation: the debris of the first few minutes of the life of the universe are all around us; think of this next time you see someone selling helium balloons.

The prediction of the helium abundance depends on knowing the present radiation temperature. For a lower temperature, there would be more nucleons per photon at a given time, so nuclear reactions would keep going longer; freeze-out would happen later and there would be less helium. Historically, this argument was presented the other way around, by **Gamow** in 1948. He used the observed helium abundance to *predict* the existence of relic radiation in the microwave band. It is a pity that this prediction made little impact; it indicates that few people in those days saw the early universe as a fit subject for serious science.

Since the discovery of the microwave background, Gamow's ideas have been elaborated into one of the key ingredients of the big bang. The prediction of 25% helium is a relatively robust calculation, but other nuclear reactions are more sensitive. Deuterium is the most important example: the deuterium that remains in the universe today (about 10^{-5} the abundance of hydrogen) is the residue that escaped being mopped up into Helium. The larger the density of normal (or **baryonic**) material, the smaller the proportion of deuterium that survives. This fact can be used to infer the baryon density of the universe, a calculation that was first done in the mid-1970s. The answer is that the number of baryons per photon has to be very low:

$$\boxed{n_{\rm B}/n_\gamma \simeq 10^{-9.5} \quad \text{or} \quad \Omega_{\rm B} \simeq 0.036.}$$

If the universe is to be closed, **non-baryonic matter** will be required. This result is one of the cornerstones of modern cosmology.

The quantum gravity limit

In principle, $T \to \infty$ as $R \to 0$, but this extrapolation of classical physics eventually breaks down. When the thermal energy of typical particles is such that their **de Broglie wavelength** ($\lambda = h/mv$) is smaller than their **Schwarzschild radius** ($r = 2Gm/c^2$), classical spacetime dissolves into a foam of quantum black holes. Equating these two lengths yields a characteristic mass for quantum gravity known as the **Planck mass**, together with the corresponding length $\hbar/(m_{\rm P}c)$ and time $\ell_{\rm P}/c$:

$$\boxed{m_{\rm P} \equiv \sqrt{\frac{\hbar c}{G}} \simeq 10^{19}\,\text{GeV}; \quad \ell_{\rm P} \equiv \sqrt{\frac{\hbar G}{c^3}} \simeq 10^{-35}\,\text{m}; \quad t_{\rm P} \equiv \sqrt{\frac{\hbar G}{c^5}} \simeq 10^{-43}\,\text{s}.}$$

The Planck time therefore sets the origin of time for the classical phase of the big bang. A common question about the big bang is 'what happened at $t < 0$?', but in fact it is not even possible to get to zero time without adding new physical laws. The initial singularity does not indicate some fatal flaw with the whole big bang idea; rather, we should be reassured that the model gives sensible results everywhere except the one place where we know in advance that it will be invalid.

Later, we will discuss **inflationary cosmology**, which aims to understand the classical initial conditions for the big bang in terms of **grand unification** physics operating below the Planck scale, but even so energies of $\sim 10^{-4} E_{\rm P}$ are involved.