4 Section IV: The early Universe

4.1 The Hot Big Bang

In the **hot big bang model** the Universe began with a fireball about 14 billion years ago. Consequently the early phase of the Universe was much hotter and denser than the present day. We could also see this from our derivation of Friedmann's equation in Section III, where we assumed mass conservation, which implies that the density, ρ, increases as the scale factor, R, decreases.

At time $t \rightarrow 0$ we have $R \rightarrow 0$, and the density of the Universe approaches infinity.

4.2 The cosmic microwave background radiation

In 1946 Gamow predicted the existence of relic radiation from the 'Hot Big Bang'. Peebles and Dicke (1964) developed this theoretical work further, and proposed the building of an antenna to detect the radiation. The radiation was predicted to be **isotropic** and to be **blackbody** in form, fully specified by a single temperature T (see Fig. 14 and also A1Y Stellar Astrophysics). **Wien's Law** states

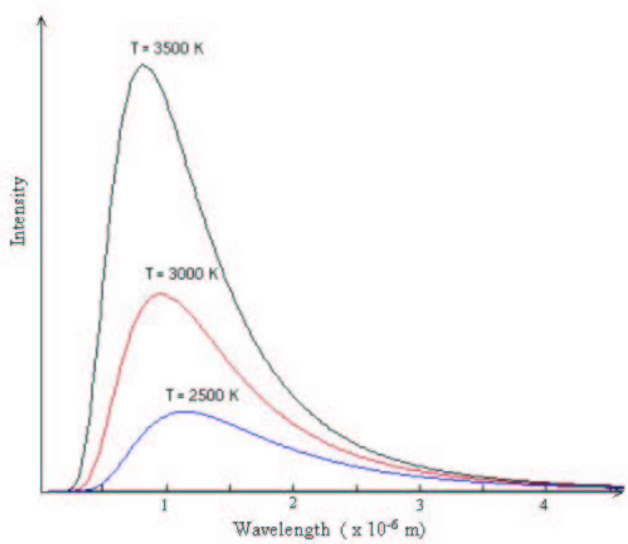

Figure 14: Black body radiation curves for different temperatures. Vertical axis shows the radiation intensity as a function of wavelength.

that the wavelength, λ_{max}, at which the blackbody radiation curve is a maximum is inversely proportional to its temperature [l]. Since the wavelength of photons in this relic radiation should increase with the expansion of the Universe, proportionally to the scale factor $R(t)$, the temperature of the radiation should be *inversely* proportional to the scale factor, i.e.,

$$T \propto R^{-1} \quad \text{and} \quad \frac{T(t)}{T_0} = 1 + z, \tag{51}$$

where $T(t)$ is the temperature of the relic radiation a time t after the Big Bang (corresponding to redshift z) and T_0 is the temperature of the radiation today.

In 1965 Penzias and Wilson discovered the Cosmic Background Radiation by accident as they tried to account for excess noise in their receiving equipment. They found that the radiation was highly isotropic, and appeared to have a uniform temperature of about 3 K. This corresponds to a λ_{max} in the microwave region of the spectrum, and the radiation is now known as the **cosmic microwave background radiation** (CMBR).

The Universe is filled with microwave radiation (the CMBR) that is the highly redshifted glow of the early Universe.

Much later, the CoBE (Cosmic Background Explorer) satellite (launched in 1989) confirmed that the spectrum of the background radiation is blackbody to a remarkable level of precision (see Fig. 15) and refined the mean temperature of the radiation to $T_0 = 2.725$ K. The CoBE results showed that the CMBR is isotropic to better than one part in 10^4 **so, the CMBR provides excellent support for the cosmological principle and the Big Bang model**. [m]

4.3 Where does the CMBR come from?

Gamow's prediction that the Universe should be filled with relic blackbody radiation from the Big Bang was based on the idea that, in the Hot Big Bang model, the Universe was hotter and denser in the past. In particular, the very early Universe was much too hot for neutral atoms to exist – it was **fully ionised** [n], and consisted of a dense mix of free protons and electrons, bathed in blackbody radiation. The free electrons scattered the photons to such an extent, however, that the Universe was effectively **opaque** – analogous to being in a fog. We say that matter and radiation

[l] See A1X notes and A1Y stellar astrophysics handout on blackbody radiation.

[m] More recently (2003) the WMAP satellite has made even more precise measurements of the CMBR, but these are primarily of the *fluctuations* in the radiation (see below)

[n] We will see later that, for a tiny fraction of a second after the Big Bang, the Universe was too hot for even sub-atomic particles to exist.

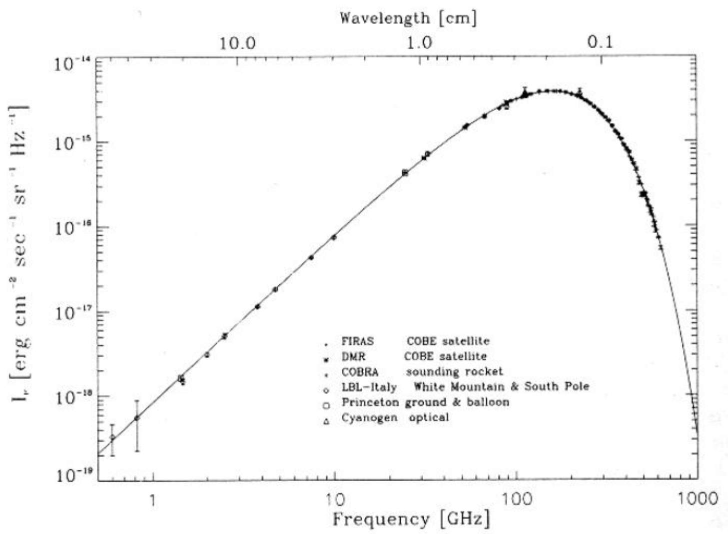

Figure 15: Measurements of the CMBR. The fit to a blackbody curve is very good.

were **coupled**, since the photons interacted so strongly with the free electrons.

As the Universe expanded and cooled, eventually its mean temperature dropped to about 3 000 K. At this temperature the free protons and electrons could combine to form neutral hydrogen, which was hugely less effective at scattering the blackbody photons. As a result the 'fog' cleared, and photons could propagate freely through space without any further scattering by the matter in the Universe (see Fig. 16). We call this time the **epoch of recombination**; at this epoch matter and radiation are said to have **decoupled**. The CMBR consists of photons which were emitted at the epoch of recombination, and which have been travelling towards us ever since – cooling as the Universe continued to expand, but no longer being scattered. For this reason the CMBR is

The CMBR comes to us from the time when the Universe had cooled to about 3 000 K and became transparent to the radiation.

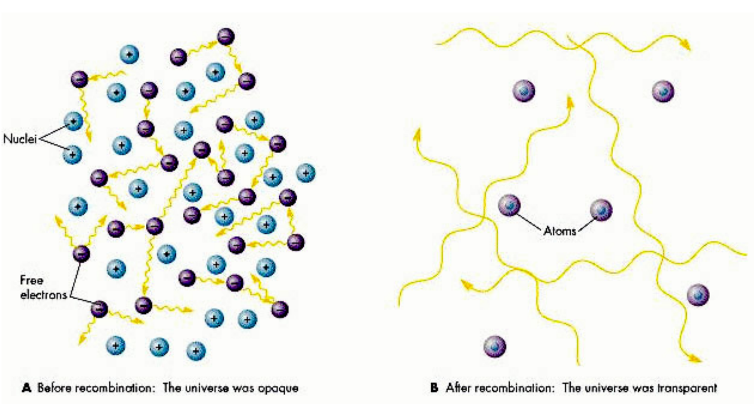

Figure 16: The Universe at recombination.

often referred to as coming from the **surface of last scattering**. The CMBR photons were emitted about 3.8×10^5 yr after the Big Bang, although the exact time depends on details of the cosmological model. So the CMBR gives us a glimpse of the Universe when it was only about 0.003% of its present age. The redshift of the CMBR is $z_{\rm CMBR} \simeq 1\,000$ (following from Eq. 51, above).

4.4 Why does the CMBR have a temperature of 3000 K?

The typical energy of a black body photon of temperature T is given by $E_{\rm typical} = kT$, where k is Boltzmann's constant. Taking $T \simeq 3000$ K we find that $E_{\rm typical} \simeq 4.14 \times 10^{-20}$ J, or $E_{\rm typical} \simeq 0.26$ eV. However, we know from A1Y Stellar Astrophysics that the **ionisation energy** of hydrogen is $E_{\rm ion} = 13.6$ eV. This presents us with something of a puzzle: we see that, for $T \simeq 3000$ K, $E_{\rm typical} << E_{\rm ion}$.

Expressing this puzzle another way, suppose we ask at what black body temperature does the the *mean* energy of a photon equal the ionisation energy of hydrogen? Plugging in the numbers we see that $T \simeq 15800$ K. Hence, for all $T < 15800$ K, the mean photon energy is *less* than the ionisation energy of hydrogen. Why, then, wasn't the CMBR emitted when the Universe had a mean temperature of 15800 K?

An answer follows from the fact that black body photons have a *distribution* of energies, as discussed in A1Y Stellar Astrophysics. In particular, at any black body temperature there is a long 'tail' of photons with energies $E > kT$. This tail falls off rapidly at large E – i.e. the fraction of photons with energy $E >> kT$ is very small. However, in the very early Universe there were about 10^9 photons for every proton and electron. This means that for $T \leq 15800$ K, although the *mean* photon energy was insufficient to ionise a hydrogen atom, there were enough high energy photons in the tail of the distribution to keep the Universe ionised.

It was only once the temperature of the Universe reached about 3000 K that the fraction of high energy photons, with $kT \geq 13.6$ eV, became sufficiently small that effectively *none* of the hydrogen in the Universe was left in ionised form.

4.5 Matter-dominated and radiation-dominated epochs

From Einstein's famous formula, $E = mc^2$, we can define the **energy density** of matter in the Universe to be

$$u_{\rm matter} = \rho_{\rm matter} c^2 \qquad (52)$$

where ρ_{matter} is the matter density of the Universe. The energy density of blackbody radiation of temperature T is given by the equation

$$u_{\mathrm{radiation}} = \frac{4\sigma}{c} T^4 \tag{53}$$

where σ is the Stefan-Boltzmann constant (see A1Y Stellar astrophysics).

The Universe is currently **matter dominated**, meaning simply that $u_{\mathrm{matter}} \gg u_{\mathrm{radiation}}$. The dependence of the matter and radiation energy density on the scale factor is different however. From mass conservation it follows that $\rho_{\mathrm{matter}} \propto R^{-3}$ and therefore $u_{\mathrm{matter}} \propto R^{-3}$, while from $T \propto R^{-1}$ it follows that $u_{\mathrm{radiation}} \propto R^{-4}$. Therefore

$$\eta = \frac{u_{\mathrm{radiation}}}{u_{\mathrm{matter}}} \propto R(t)^{-1}. \tag{54}$$

The present-day value of η is roughly 3.2×10^{-4}, so $\eta = 1$ for $R \simeq 3.2 \times 10^{-4} R_0$. We call that the epoch of **matter-radiation equality**. It is the epoch at which the mean energy densities of matter and radiation are equal. It follows that

The energy in matter is presently greater than the energy in radiation (the CMBR). In the early Universe, radiation energy dominated.

$$\frac{R_0}{R_{\mathrm{eq}}} \simeq 3.2 \times 10^3 \qquad \text{i.e.,} \qquad z_{\mathrm{eq}} \simeq 3.2 \times 10^3. \tag{55}$$

Also

$$T_{\mathrm{eq}} \simeq 3.2 \times 10^3\, T_0 \simeq 9000\,\mathrm{K} \tag{56}$$

For $T > T_{\mathrm{eq}}$ the Universe is **radiation dominated**. Therefore, when the CMBR photons were emitted the Universe was matter dominated but only about 160,000 years earlier [0] the Universe had been radiation dominated. It is something of a coincidence that both the epochs of recombination and matter-radiation equality occur within a short space of time, relative to the current age of the Universe.

4.6 The Primordial Universe

Although the Universe is opaque to photons beyond the CMBR, the success of the Big Bang model does not stop at recombination. The Big Bang model remains an accurate description of how matter and radiation evolve at much earlier times, and therefore at much higher densities and temperatures. Our ideas about the *primordial Universe* lie at the interface between cosmology and particle physics. Formally, as $t \to 0$, the density and temperature of the Universe in the Big Bang model tend to infinity – an

[0] As with recombination, the exact time depends on details of the cosmological model.

indication that the Big Bang model (and indeed what is known as the 'Standard Model' of particle physics, which describes all elementary particles) breaks down. Both models are, nonetheless, valid from $t \simeq 10^{-40}$ seconds after the Big Bang, when the temperature of the Universe was $T \simeq 10^{27}$ K. **The Big Bang can, therefore, be thought of as a natural particle accelerator, able to test particle physics theories beyond terrestrial limits.**

Present theories of the Universe can only get to within about 10^{-40} s of the Big Bang.

The physics of the primordial Universe lies mainly beyond the scope of this course, but we will pick out a few highlights.

4.6.1 GUT scale: $T \simeq 10^{27}$ K; $t \simeq 10^{-35}$ s

This is the approximate energy scale above which **grand unified theories** hold, so that three of the four fundamental forces of nature (the electromagnetic force and the strong and weak nuclear forces) behave as if they are a single unified force. Only gravity does not fit within this unified picture. (To unify gravity too would require a so-called 'Theory of Everything' or full theory of quantum gravity, which still eludes us – although we have some clues as to what that theory might be).

At this time the Universe consists of a 'soup' of fundamental particles: **quarks** and **leptons**, and radiation. There are six different types of quarks, and these are believed to be the real indivisible building blocks of all matter. Quarks can combine together to form **hadrons** such as protons and neutrons which each consist of a triplet of quarks, but above the GUT scale the Universe is still too hot for this to happen. Leptons are light, elementary particles including electrons and positrons.

Above the GUT scale there is spontaneous conversion of particle antiparticle pairs into radiation and vice versa. The Universe contains equal amounts of matter and antimatter during this time. Below the GUT scale, the strong nuclear force breaks off from the unified picture, and a tiny imbalance between matter and antimatter arises. The remaining, equal, amounts of matter and antimatter annihilate each other, leaving the Universe consisting of matter that we see today.

4.6.2 'Electroweak transition': $T \simeq 10^{15}$ K; $t \simeq 10^{-12}$ s

Below this energy scale the Universe has cooled sufficiently that the weak nuclear and electromagnetic forces are no longer unified. From now on there are four distinct fundamental forces (as today!).

4.6.3 'Quark-hadron transition': $T \simeq 10^{12}$ K; $t \simeq 10^{-6}$ s

At this energy scale the 'quark soup' condenses. The Universe has cooled enough to form stable hadrons such as protons and neutrons. The quarks are now confined inside hadrons, and no longer exist as free particles. The Universe now consists of hadrons and leptons, bathed in a background of blackbody radiation (as today, only much hotter!).

4.6.4 Primordial nucleosynthesis: $T \simeq 10^9 - 10^8$ K; $t \simeq 1 - 100$ s

At this time the Universe has cooled sufficiently to allow protons and neutrons to combine together and form stable light atomic nuclei: deuterium and tritium (isotopes of hydrogen), helium and lithium. As we remarked in Section III, the relative amounts of these elements 'cooked' during the first 100 s or so after the Big Bang depends strongly on the density of baryons (ρ_B) since this determines the rates of the nuclear reactions which take place. We call the formation of these light atoms **primordial nucleosynthesis**.

Note that since we can write $\rho_B = \Omega_B \rho_{\rm crit}$ and $\rho_{\rm crit} \propto H_0^2$ (see Section III), it follows that $\rho_B \propto \Omega_B h^2$.

We can compute the *relative abundances* of helium, deuterium and lithium to hydrogen predicted in the Big Bang model as a function of $\Omega_B h^2$, and compare each ratio with the observed limits, based on the abundances measured today. Fig. 17 shows schematically the current limits on the baryon density from primordial element abundances. Each light element provides an independent check of the Big Bang model. The solid curves denote the theoretically predicted abundances, for different values of $\Omega_B h^2$. The dotted lines denote the observational limits on the relative abundances.

There is consistent agreement between observations and predictions *for all the light elements* over a narrow range of values of $\Omega_B h^2$ (as shown by the vertical grey bands in Fig. 17). This is one of the major successes of the Big Bang and places strong constraints on the value of ρ_B.

The relative abundance of helium is about 25%; other light elements are very rare. **All heavier elements are manufactured inside stars and supernovae – see A1Y Stellar Astrophysics**. It is interesting to note that we can now also check the nucleosynthesis constraints at high redshift, by deducing the light element abundances at (for example) $z \sim 1$ from quasar absorption spectra – we mentioned this point at the end of Section I.

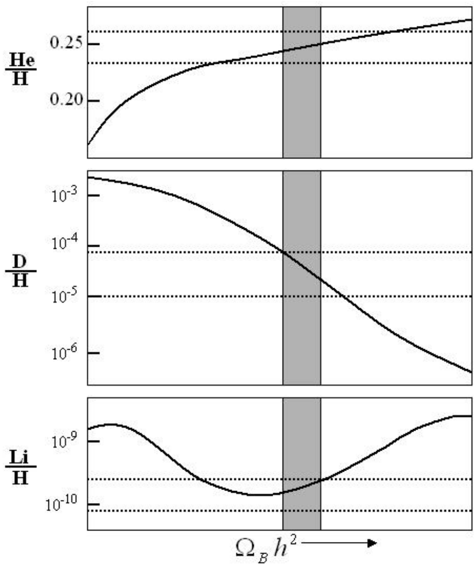

Figure 17: Primordial nucleosynthesis and the baryon density. The grey band shows the value of $\Omega_B h^2$ consistent with the observations.

4.7 Microwave background anisotropies and galaxy formation

The CMBR is not *perfectly* smooth. In 1992, CoBE first detected temperature variations of about 10^{-5} K on angular scales of about 10° (see Fig. 18). Previously, CoBE had confirmed the existence of what we call a **dipole** temperature variation in the CMBR, of the form

$$T(\theta) = T_0(1 + \delta T \cos\theta), \qquad (57)$$

where T_0 is the mean temperature of the CMBR, averaged over the whole sky and where $T(\theta)$ is the temperature of the CMBR at an angle θ away from the 'CMBR hotspot' direction – the direction in which the temperature is $T_0(1 + \delta T)$. CoBE measured

$$\Delta T = 3.35 \times 10^{-3}\,\mathrm{K}. \qquad (58)$$

This dipole anisotropy is *not* believed to be intrinsic to the CMBR, but instead is due to our peculiar motion with respect to the CMBR, which causes a Doppler Shift of the radiation of an amount which varies with direction according to the above dipole formula. The Doppler formula gives

$$\frac{\Delta T}{T_0} = \frac{v_{\mathrm{pec}}}{c}. \qquad (59)$$

Taking $T_0 = 3\,\mathrm{K}$ gives $v_{\mathrm{pec}} = 330\,\mathrm{km\,s^{-1}}$. In 2003 the WMAP satellite confirmed the earlier CoBE measurement of the CMBR dipole temperature and direction.

After removing the dipole anisotropy, and also the contaminating effect of the microwave emission from stars and dust in our own Milky Way galaxy, the CoBE map reveals intrinsic temperature fluctuations of about 10^{-5} K. These variations have now been confirmed (and improved) by a large number of other experiments, which make measurements of the temperature variation on a range of different angular scales – most notably the new results from the WMAP (Wilkinson Microwave Anisotropy Probe) Satellite in 2003 and other ground-based results, which show fluctuations on much smaller angular scales than in the CoBE maps.

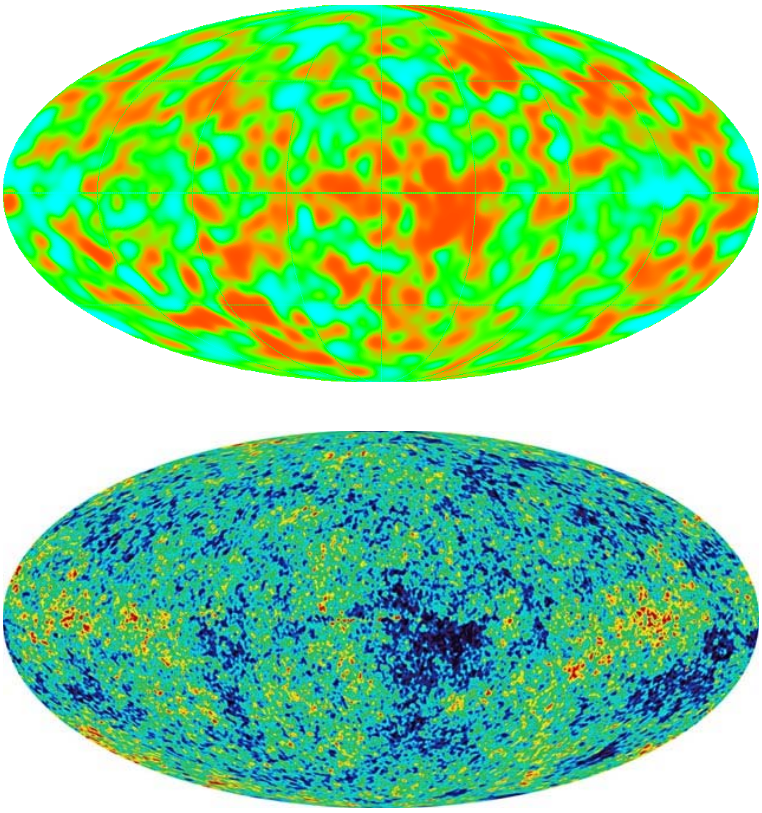

Figure 18: Maps of CMBR temperature fluctuations. The upper panel (from Jan 1996) shows results from the first four years of CoBE data. The lower panel (from Feb 2003) shows results from the first year of data from the WMAP satellite.

These intrinsic anisotropies are *very* important for cosmology, since they indicate density inhomogeneities in the Universe at $t = 3.8 \times 10^5$ yr after the Big Bang. These density fluctuations are the seeds of the cosmic structure which we observe today, such as galaxies, clusters and superclusters. The fluctuations are believed to have been created very soon after the Big Bang itself, during a period known as **inflation** when the Universe expanded extremely rapidly.

The mechanism for structure formation is **gravity**, which causes the density inhomogeneities to grow as the Universe expands. Structure evolves under the influence of gravity, and the amount and nature of the dark matter determines how structure forms at different times and on different scales. By comparing model predictions for different structure formation scenarios with the observed Universe, we can determine which model is correct. For example, **hot dark matter** smooths out clustering on small scales, so that in models with hot dark matter one expects large structures to form first and then later fragment. On the other hand, in models where the dark matter is cold structures form on both small and large scales from the outset. More specifically we can also determine very precisely how much dark matter there is and how it is distributed by careful study of the pattern of temperature variations in the CMBR and in the clustering of galaxies. Recall from Section III that we mentioned that these measurements can also reveal the **curvature** of the Universe; the results from WMAP seem to indicate that the Universe is **flat**.

4.8 Understanding the formation of galaxies and larger structures

This is one of the biggest challenges facing modern cosmology. The task is to explain how the Universe got from the (nearly) smooth CMBR which we observe at $z = 1\,000$ to the 'lumpy' galaxies and clusters which we observe at $z = 0$ (now). One can think of this task as trying to find the correct recipe for galaxy formation. The ingredients are known to be

- CMBR temperature fluctuations,
- dark and luminous matter, and
- gravity,

and the cooking time is about 14 billion years! While a definitive model for structure formation which matches the observations on *all* scales and at all epochs has yet to be found, it is likely that a solution to this problem will be found within the next decade.