2

The Cosmic Microwave Radiation Background

Before the mid-1960s by far the greatest part of our information about the structure and evolution of the universe came from observations of the red-shifts and distances of distant galaxies, discussed in the previous chapter. In 1965 a nearly isotropic background of microwave radiation was discovered, which has provided a wealth of new cosmological data. After reviewing the expectations and discovery of this radiation, this chapter will explore some of its implications. We will only be able to give a first look at the anisotropies in this radiation in this chapter. In Chapter 7 we will return to this very important topic, applying the analysis of the evolution of cosmological perturbations presented in Chapters 5 and 6, and in Chapter 10 we will consider the origin of these perturbations in the very early universe.

2.1 Expectations and discovery of the microwave background

The work done by pressure in an expanding fluid uses heat energy drawn from the fluid. The universe is expanding, so we expect that in the past matter was hotter as well as denser than at present. If we look far enough backward in time we come to an era when it was too hot for electrons to be bound into atoms. At sufficiently early times the rapid collisions of photons with free electrons would have kept radiation in thermal equilibrium with the hot dense matter. The number density of photons in equilibrium with matter at temperature T at photon frequency between ν and $\nu + d\nu$ is given by the *black-body spectrum*:

$$n_T(\nu)d\nu = \frac{8\pi\nu^2\,d\nu}{\exp\left(h\nu/k_BT\right) - 1}\,, \qquad (2.1.1)$$

where h is the original Planck's constant (which first made its appearance in a formula equivalent to this one), and k_B is Boltzmann's constant. (Recall that we are using units with $c = 1$.)

As time passed, the matter became cooler and less dense, and eventually the radiation began a free expansion, but *its spectrum has kept the same form.* We can see this most easily under an extreme assumption, that there was a time t_L when radiation suddenly went from being in thermal equilibrium with matter to a free expansion. (The subscript L stands for "last scattering.") Under this assumption, a photon that has frequency ν at some later time t when photons are traveling freely would have had frequency

$\nu a(t)/a(t_L)$ at the time the radiation went out of equilibrium with matter, and so the number density at time t of photons with frequency between ν and $\nu + d\nu$ would be

$$n(\nu, t)\, d\nu = \Big(a(t_L)/a(t)\Big)^3 n_{T(t_L)}\Big(\nu a(t)/a(t_L)\Big)\, d(\nu a(t)/a(t_L))\,, \quad (2.1.2)$$

with the factor $\Big(a(t_L)/a(t)\Big)^3$ arising from the dilution of photons due to the cosmic expansion. Using Eq. (2.1.1) in (2.1.2), we see that the redshift factors $a(t)/a(t_L)$ all cancel except in the exponential, so that the number density at time t is given by

$$n(\nu, t) d\nu = \frac{8\pi \nu^2\, d\nu}{\exp(h\nu/k_B T(t)) - 1} = n_{T(t)}(\nu)\, d\nu\,, \qquad (2.1.3)$$

where

$$T(t) = T(t_L) a(t_L)/a(t)\,. \qquad (2.1.4)$$

Thus the photon density has been given by the black-body form even after the photons went out of equilibrium with matter, but with a redshifted temperature (2.1.4).

This conclusion is obviously unchanged if the transition from opacity to transparency occupied a finite time interval, as long as the interactions of photons with matter during this interval are limited to elastic scattering processes in which photon frequencies are not changed. This is a very good approximation. We will see in Section 2.3 that the last interaction of photons with matter (until near the present) took place at a time when the cosmic temperature T was of order 3,000 K, when by far the most important interaction was the elastic scattering of photons with electrons, in which the fractional shift of photon frequency was of order $k_B T/m_e c^2 \approx 3 \times 10^{-7}$. In the following section we shall show that, because of the large photon entropy, even the small shift of photon frequency in elastic scattering and the relatively infrequent inelastic interactions of photons with hydrogen atoms had almost no effect on the photon spectrum.

It was George Gamow and his collaborators who first recognized in the late 1940s that the universe should now be filled with black-body radiation.[1] The first plausible estimate of the present temperature of this radiation was

[1] G. Gamow, *Phys. Rev.* **70**, 572 (1946); R. A. Alpher, H. A. Bethe, and G. Gamow, *Phys. Rev.* **73**, 803 (1948); G. Gamow, *Phys. Rev.* **74**, 505 (1948); R. A. Alpher and R. C. Herman, *Nature* **162**, 774 (1948); R. A. Alpher, R. C. Herman, and G. Gamow, *Phys. Rev.* **74**, 1198 (1948); *ibid* **75**, 332A (1949); *ibid* **75**, 701 (1949); G. Gamow, *Rev. Mod. Phys.* **21**, 367 (1949); R. A. Alpher, *Phys. Rev.* **74**, 1577 (1948); R. A. Alpher and R. C. Herman, *Phys. Rev.* **75**, 1089 (1949).