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Pavel D. Naselsky , Dmitry I. Novikov , Igor D. Novikov
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1

Observational foundations of modern cosmology

1.1 Introduction

In a way, the entire history of cosmology from Ptolemy and Aristotle to the present day can be divided into two stages: a period before and a period after the discovery of the cosmic microwave background (CMB). The first period was the subject of hundreds of volumes of literature; now it is not only an integral part of science, but also marks a step in the progress of mankind. The second stage started in 1965 when two American researchers, A. Penzias and R. Wilson published their famous article in the *Astrophysical Journal*, 'A measurement of excess antenna temperature at 4080 Mc/s' (Penzias and Wilson, 1965), in which they announced the discovery of a previously unknown background radio noise in the Universe. Another article, in the same issue of the *Astrophysical Journal*, preceded the one by Penzias and Wilson; this was by R. Dicke, P. J. E. Peebles, P. Roll and D. Wilkinson (Dicke *et al*., 1965) and discussed the preparation of a similar experiment at a different wavelength, but also interpreted the Penzias–Wilson results as confirming the predictions of the 'hot universe' theory. The radiation with a temperature close to 3 K discovered by Penzias and Wilson was described as the remnant of the hot plasma that existed at the very onset of expansion which then cooled down as a result of expansion.

Formally, the new stage in the study of the Universe was catalysed by several pages in one volume of a journal and began in this non-dramatic and almost routine way. Note that the 'child' wasn't born all that unexpectedly for astrophysicists. In the mid 1940s George Gamow had already published a paper (Gamow, 1946) in which he proposed a model of what became known as the 'hot' starting phase of cosmological expansion; this work stimulated the work of R. Alpher and R. Herman (Alpher and Herman, 1953), offering an explanation of the chemical composition of pre-galactic matter (see a review and references in Novikov (2001)).

The starting point for motivating all these authors was an attempt to explain specific features of the abundances of chemical elements and isotopes in the Universe. It was assumed that these were all produced at the very first moments of expansion of the Universe. Tables of the abundances of different isotopes show that isotopes with an excess of neutrons typically dominate. It followed that free neutrons should have existed in the primordial matter for a sufficiently long time – something that is only possible at extremely high temperatures. This stimulated the idea of the hot initial phase of expansion of the Universe. The first publications of the theory of the hot Universe contained a number of inconsistencies on which we will not dwell here. The reader can find the details in Weinberg (1977) and Zeldovich and Novikov (1983).

According to our current understanding, in the first three minutes of expansion of the Universe only the lightest elements were 'cooked', whereas the heavier ones were produced much later by nuclear processes in stars; the heaviest elements were born when supernovas exploded. It is important to note that Gamow, Alpher and Herman's main idea about the need for high temperatures of the primordial matter proved to be correct. For details on the modern theory of nucleosynthesis in the early Universe, see, for example, Kolb and Turner (1989) and Zeldovich and Novikov (1983). There was, however, another altogether funnier reason why the authors of the theory of the 'hot Universe' considered it necessary 'to cook' (literally) all the chemical elements in the very first seconds of the cosmological expansion. Namely that, in the 1940s, the value of the Hubble constant, H_0, and, consequently, the age of the Universe, were evaluated incorrectly. The Hubble constant was thought to be several times larger than the value deduced from modern measurements, so that the age of the Universe was as low as (1–4) $\times$ 10^9 years, as against the value of (13.5–14) $\times$ 10^9 years accepted now. This duration would not be enough for the synthesis of chemical elements in stars; consequently, Gamow and his colleagues came to the conclusion that all chemical elements must have been 'cooked' from the primeval matter.

We now know, owing to the available cosmochronological data, that the age of the Universe is far greater than the age of the Earth (4×10^9 years), and that the Earth was formed from the protoplanetary material that had been enriched by products of thermonuclear synthesis deep inside stars. Therefore the need to find an explanation for the chemical composition of matter, including elements heavier than iron, within the limits of the 'hot Universe' model has simply gone up in smoke, but the principal idea of the founders of this theory – the idea of high initial temperature and high density of cosmic plasma – passed the test of time.

Let us return, however, to the history of the discovery of the cosmic microwave background. Using somewhat inconsistent estimates, Gamow and his colleagues concluded that, owing to the hot birth of the Universe, the space that exists during this epoch must be filled with equilibrium radiation at a temperature of several kelvin. It would seem likely to us now that once a major prediction had been formulated, it demanded immediate testing, and that radioastronomers would have tried to detect this radiation. This, however, failed to happen. An outstanding American scientist, winner of a Nobel prize for physics, Steven Weinberg, wrote in *The First Three Minutes: A Modern View of the Origin of the Universe* (Weinberg, 1977) 'This detection of the cosmic microwave background in 1965 was one of the most important scientific discoveries of the twentieth century. Why did it have to be made by accident? Or to put it another way, why there was no systematic search for this radiation, years before 1965?' We mentioned above that Gamow and his colleagues predicted the probable presence of electromagnetic radiation with a temperature of several kelvin more than 15 years before its detection. Perhaps special radiotelescopes were required, with sensitivity unattainable at the moment? Apparently not; the necessary receivers were available. The main reason, in our opinion, was probably of a psychological nature. There is convincing evidence to support this view, and we will discuss this later.

In fact, numerous examples can be found in the history of science when predictions of novel phenomena, and in particular ground-breaking discoveries, occurred long before experimental confirmations were obtained. Weinberg (1977) provides us with an excellent example: the prediction, made in 1930, of the existence of the antiproton. Immediately after this theoretical prediction, physicists could not even imagine what kind of physical experiment would be capable of confirming or, as often happens, disproving this fundamental inference of the theory. It only became possible almost 20 years later when a suitable particle accelerator was built in Berkeley that provided impeccable confirmation of the prediction of the theory.

However, as we shall see below, in the case of this particular prediction the suitable receivers necessary to start searching for the microwave background already existed. Alas, radioastronomers simply did not know what it was they should search for. There was no proper communication between theorists and observers, and theorists did not really trust the not yet perfect theory of the hot Universe. Ideas on how it would be possible to detect the electromagnetic 'echo of the Big Bang' started to appear only in the mid 1960s, and even then only accidentally. Another reason why radioastronomers did not attempt to discover the CMB, and perhaps the most important one, was formulated by Arno Penzias in his Nobel lecture of 1979 (Penzias, 1979). The fact was that none of the work published by Gamow and his colleagues pointed out that the microwave radiation that reaches us from the epoch of cosmological nucleosynthesis, having cooled down to several kelvin owing to the expansion of the Universe, could be detectable, even in principle. In fact, the general feeling was quite the opposite; Penzias, in his Nobel lecture, formulated the widespread impression: 'As for detection, they appear to have considered the radiation to manifest itself primarily as an increased energy density.[1] This contribution to the total energy flux incident upon the earth would be masked by cosmic rays and integrated starlight, both of which have comparable energy densities. The view that the effects of three components of approximately equal additive energies could not be separated may be found in a letter by Gamow written in 1948 to Alpher (unpublished, and kindly provided to me by R. A. Alpher from his files). "The space temperature of about 5 K is explained by the present radiation of stars (C-cycles). The only thing we can tell is that the residual temperature from the original heat of the Universe is not higher than 5 K." They do not seem to have recognized that the unique spectral characteristics of the relict radiation would set it apart from the other effects.'

This, however, was understood by A. Doroshkevich and I. Novikov, who, in 1964, published a paper in *The Academy of Sciences of the USSR Doklady* entitled 'Mean density of radiation in the metagalaxy and certain problems in relativistic cosmology' (Doroshkevich and Novikov, 1964). The basic idea formulated in this paper has not lost its relevance even 40 years later. We shall assume for the moment that we know how galaxies of different type emit electromagnetic radiation in different wavelength bands. Choosing certain assumptions concerning the evolution of galaxies in the past and taking into account the redshifting of the wavelength of light from distant galaxies because of the expansion of the Universe, it is possible to calculate the intensity of radiation from galaxies in today's Universe for each wavelength. What we need to consider is that stars are not the only sources of radiation: indeed, many galaxies are powerful emitters of radio waves on the metre and decimetre wavelengths. Gas and dust in the galaxies also radiate. The nontrivial aspect of this is that if the Universe had been 'hot' at some point, the primordial radiation background has to be added to the radiation spectrum one wishes to calculate, and this is what Doroshkevich and Novikov (1964) accomplished. The wavelength of this radiation should be on the order of centimetres and millimetres and should fall within that range of spectrum where the contribution of galaxies is practically zero. Therefore, the cosmic microwave background in this wavelength range should exceed the radiation of known sources of radio emission by a factor of tens of thousands, even millions. Hence, it should be observable! Here is how Arno Penzias formulated it in his Nobel lecture: 'The first published recognition of the relict radiation as a detectable microwave phenomenon appeared in a brief paper entitled "Mean density of

[1] Penzias referred here to work by Alpher and Herman dated 1949.

radiation in the metagalaxy and certain problems in relativistic cosmology", by A. G. Doroshkevich and I. D. Novikov (1964). Although the English translation appeared later the same year in the widely circulated *Soviet Physics–Doklady*, it appears to have escaped the notice of the other workers in this field. This remarkable paper not only points out the spectrum of the relict radiation as a blackbody microwave phenomenon, but also explicitly focuses upon the Bell Laboratories twenty-foot horn reflector at Crawford Hill as the best available instrument for its detection!'

Note that the cosmic microwave background was indeed discovered in 1965 using precisely this facility.

The paper by Doroshkevich and Novikov was not noticed by observer astronomers. Neither Penzias and Wilson, nor Dicke and his coworkers, were aware of it before their papers were published in 1965. We wish to mention a strange mistake involving the interpretation of one of the conclusions in Doroshkevich and Novikov (1964). Penzias (1979) wrote: 'Having found the appropriate reference [Ohm, 1961], they [Doroshkevich and Novikov] misread its result and concluded that radiation predicted by the "Gamov theory" was contradicted by the reported measurements.'

Also, in Thaddeus (1972) one can read: 'They [Doroshkevich and Novikov] mistakenly concluded that studies of atmospheric radiation with this telescope (Ohm, 1961) already ruled out isotropic background radiation of much more than 0.1 K.' Actually, Doroshkevich and Novikov's paper contains no conclusion stating that the observational data exclude the CMB with temperature predicted by the hot Universe model. In fact, it states: 'Measurements reported in Ohm (1961) at a frequency $\nu = 2.4 \times 10^9$ cycles s^{-1} give a temperature 2.3 ± 0.2 K, which coincides with theoretically computed atmospheric noise (2.4 K). Additional measurements in this region (preferably on an artificial earth satellite) will assist in obtaining a final solution of the problem of the correctness of the Gamow theory'. Thus, Doroshkevich and Novikov encouraged observers to perform the relevant measurements! They did not discuss in their paper the interpretation of the value 2.4 K obtained by Ohm (1961), who used a technique developed specifically for measuring the atmospheric temperature (see discussion in Penzias (1979)).

This is not the end, however, of the dramatic episodes in the history of the prediction and discovery of the cosmic microwave background. It is now clear that astronomers came across indirect manifestations of the CMB long before the 1960s. In 1941, a Canadian astronomer, Andrew McKellar, discovered cyanide molecules (HCN) in interstellar space. He used the following method of studying interstellar gases. If light travelling from a star to the Earth propagates through a cloud of interstellar gas, atoms and molecules in the gas absorb this light only at certain wavelengths. This creates the well known absorption lines that are successfully used not only for studying the properties of interstellar gas in our Galaxy, but also in other fields of astrophysics. The positions of absorption lines in the emission spectrum of radiation depend on what element or what molecule causes this absorption, and also on the state in which they were at the moment of absorption. As the object of research, McKellar chose absorption lines caused by cyanide molecules in the spectrum of the star 'ε' of Ophiuchus. He concluded that these lines could only be caused by absorption of light by rotating molecules. Relatively simple calculations allowed McKellar to conclude that the excitation of rotational degrees of freedom of cyanide molecules required the presence of external radiation with an effective temperature of 2.3 K. Neither McKellar himself, nor anyone else, suspected that he had stumbled on a manifestation of the cosmic microwave background. Note that this happened long before the ground-breaking work of Gamow and his colleagues! Only after the discovery of the CMB, in 1966 were the following three papers published in one year: Field and Hitchcock (1966), Shklovsky (1966) and Thaddeus and Clauser (1966); later, Thaddeus (1972) showed that the excitation of rotational degrees of freedom of cyanide was caused by CMB quanta. Thus, an indication, even if indirect, of the existence of a survivor from the 'hot' past of the Universe was available as early as 1941.

Even now we are not at the end of our story. We shall return to the question of whether the experimental radiophysics was ready to discover the microwave background long before the results of Penzias and Wilson. Weinberg (1977) wrote that 'It is difficult to be precise about this but my experimental colleagues tell me the observation could have been made long before 1965, probably in the mid 1950s and perhaps even in the mid 1940s.' Was this indeed possible?

In the autumn of 1983, one of authors of this volume (I. Novikov) received a call from T. Shmaonov, a researcher with The Institute of General Physics, with whom Novikov was not previously acquainted. Shmaonov explained that he would like to discuss some details concerning the discovery of the cosmic microwave background. When they met, Shmaonov described how, in the middle of the 1950s, working under the guidance of the well known radioastronomers S. E. Khaikin and N. L. Kaidanovsky, he conducted measurements of the intensity of radio emission from space at the wavelength of 3.2 cm using a horn antenna similar to the one that Penzias and Wilson worked with many years later. Shmaonov very carefully measured the inherent noise of his receiver electronics, which was certainly not as good as the future American equipment (do not forget the time factor, which in those years was decisive as far as the quality of receivers was concerned), and concluded that he had detected a useful signal. Shmaonov published his results in 1957 in *Pribory i Tekhnika Eksperimenta* and also included them in his Ph.D. thesis (Shmaonov, 1957). The conclusion drawn from these measurements was as follows: 'We find that the absolute effective temperature of the radioemission background ... is 4 ± 3 K.' Moreover, measurements showed that radiation intensity was independent of either time or direction of observations. Even though temperature measurement errors were quite considerable, it is now clear that Shmaonov did observe the cosmic microwave background at a wevelength of 3.2 cm; alas, neither the author nor other radioastronomers with whom he discussed the results of his experiments have given this effect the attention it deserved. Furthermore, even after the work of Penzias and Wilson was published, Shmaonov failed to realize that the source of the signal was the same; in fact, at the time, Shmaonov was working in a very different branch of physics. Only 27 years after he published those measurements did Shmaonov make available a special report on his discovery (see the discussion in Kaidanovsky and Parijskij (1987)).

Even this is not the last piece of the jigsaw puzzle! More recently, we have learnt that at the very beginning of the 1950s Japanese physicists made attempts to measure the cosmic microwave background. Unfortunately we were unable to find reliable contemporary or more recent references to these studies.

It is obvious that the drama of ideas and 'random walks' of the 1940s to the 1950s in search of manifestations of the cosmic microwave background is still waiting for its historian, while the period from 1965 to the present day is a well planned and orchestrated attack on the secrets of cosmic radiation, not only at radio wavelengths, but also in the optical, infrared, ultraviolet, x-ray and gamma radiation ranges.

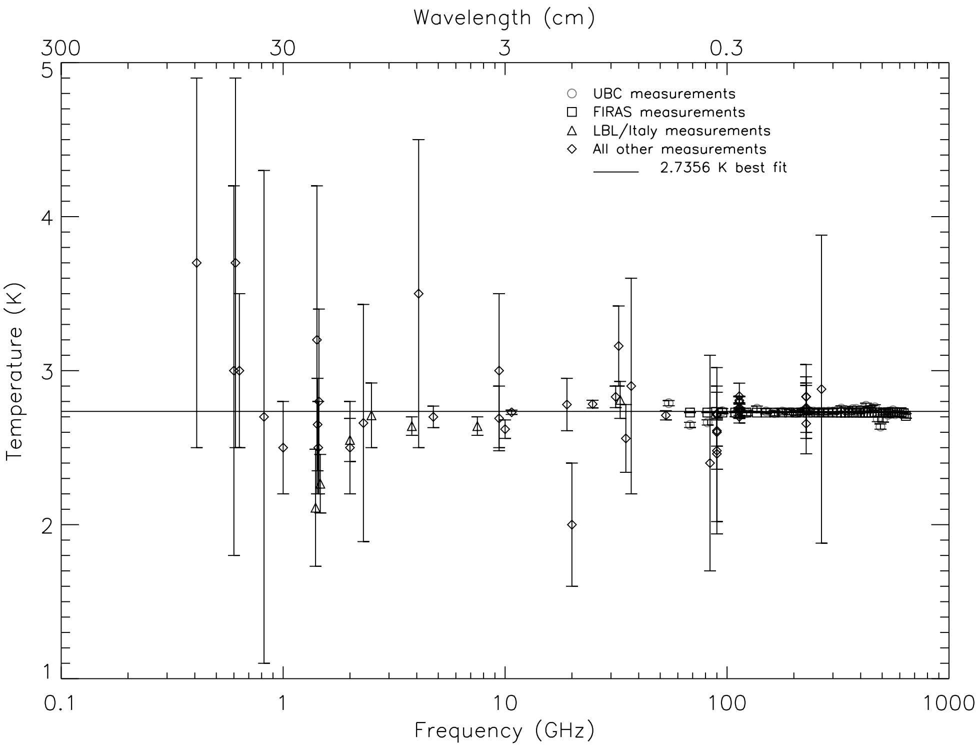

Figure 1.1 Thermodynamic temperature of the CMB as a function of radiation frequency and wavelength. Data from the FIRAS instrument are shown in the 100 to 600 GHz range. The horizontal line corresponds to $T_0 = 2.736$ K – the best approximation of the COBE data. For comparison, the data from other experiments are marked by squares and triangles. Adapted from Nordberg and Smoot (1998) and Scott (1999a).

1.2 Current status of knowledge about the spectrum of the CMB in the Universe

Only a year after the publication of the paper by Penzias and Wilson, their colleagues, F. Howell and J. Shakeshaft (Howell and Shakeshaft, 1966) measured the temperature of the cosmic microwave background at a wavelength of 20.7 cm and found it to be 2.8 ± 0.6 K. Similar values of temperature, but in the wavelength range 3.2 cm ($T = 3.0 \pm 0.5$ K), were reported in the same year by Roll and Wilkinson (1966) and by Field and Hitchcock (1966) ($T = 3.2 \pm 0.5$ K at a wavelength 0.264 cm), and by a number of other researchers in subsequent years.

Table 1.1 gives a complete list of published measurements of the CMB temperature from 408 MHz up to 300 GHz (Nordberg and Smoot, 1998). In spite of a large number of experiments (∼60) that measured the CMB temperature, not all of them are equally informative. Quite often a high level of systematic errors led to considerable spreads of the average values of T_R. In this connection, Fig. 1.1 presents selective data for a number of experiments carried out over a period from the end of the 1980s to the beginning of the 1990s and manifesting an extremely low noise level (references to these experiments are given in Table 1.1).

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Table 1.1. *Measurements of the CMB temperature*

Frequency (GHz)	Wavelength (cm)	Temperature (K)	Reference
0.408	73.5	3.7 ± 1.2	Howell and Shakeshaft (1967)
0.6	50	3.0 ± 1.2	Sironi *et al.* (1990)
0.610	49.1	3.7 ± 1.2	Howell and Shakeshaft (1967)
0.635	47.2	3.0 ± 0.5	Stankevich, Wielebinski and Wilson (1970)
0.820	36.6	2.7 ± 1.6	Sironi, Bonelli and Limon (1991)
1.4	21.3	2.11 ± 0.38	Levin *et al.* (1988)
1.42	21.2	3.2 ± 1.0	Penzias and Wilson (1967)
1.43	21	$2.65^{+0.33}_{-0.30}$	Staggs *et al.* (1996a,b)
1.45	20.7	2.8 ± 0.6	Howell and Shakeshaft (1966)
1.47	20.4	2.27 ± 0.19	Bensadoun *et al.* (1993)
2	15	2.55 ± 0.14	Bersanelli *et al.* (1994)
2.5	12	2.71 ± 0.21	Sironi *et al.* (1991)
3.8	7.9	2.64 ± 0.06	de Amici *et al.* (1991)
4.08	7.35	3.5 ± 1.0	Penzias and Wilson (1965)
4.75	6.3	2.70 ± 0.07	Mandolesi *et al.* (1986)
7.5	4.0	2.60 ± 0.07	Kogut *et al.* (1990)
7.5	4.0	2.64 ± 0.06	Levin *et al.* (1992)
9.4	3.2	3.0 ± 0.5	Roll and Wilkinson (1966)
9.4	3.2	$2.69^{+0.26}_{-0.21}$	Stokes, Partridge and Wilkinson (1967)
10	3.0	2.62 ± 0.06	Kogut *et al.* (1990)
10.7	2.8	2.730 ± 0.014	Staggs *et al.* (1996a,b)
19.0	1.58	$2.78^{+0.12}_{-0.17}$	Stokes *et al.* (1967)
20	1.5	2.0 ± 0.4	Welch *et al.* (1967)
24.8	1.2	2.783 ± 0.025	Johnson and Wilkinson (1987)
31.5	0.95	2.83 ± 0.07	Kogut *et al.* (1996b)
32.5	0.924	3.16 ± 0.26	Ewing, Burke and Staelin (1967)
33.0	0.909	2.81 ± 0.12	De Amici *et al.* (1985)
35.0	0.856	$2.56^{+0.17}_{-0.22}$	Wilkinson (1967)
53	0.57	2.71 ± 0.03	Kogut *et al.* (1996b)
90	0.33	$2.46^{+0.40}_{-0.44}$	Boynton, Stokes and Wilkinson (1968)
90	0.33	2.61 ± 0.25	Millea *et al.* (1971)
90	0.33	2.48 ± 0.54	Boynton and Stokes (1974)
90	0.33	2.60 ± 0.09	Bersanelli *et al.* (1989)
90	0.33	2.72 ± 0.04	Kogut *et al.* (1996b)
90.3	0.332	< 2.97	Bernstein *et al.* (1990)
113.6	0.264	2.70 ± 0.04	Meyer and Jura (1985)
113.6	0.264	2.74 ± 0.05	Crane *et al.* (1986)
113.6	0.264	2.75 ± 0.04	Kaiser and Wright (1990)
113.6	0.264	2.75 ± 0.04	Kaiser and Wright (1990)
113.6	0.264	2.834 ± 0.085	Palazzi *et al.* (1990)
113.6	0.264	2.807 ± 0.025	Palazzi, Mandolesi and Crane (1992)
113.6	0.264	$2.279^{+0.023}_{-0.031}$	Roth, Meyer and Hawkins (1993)
154.8	0.194	< 3.02	Bernstein *et al.* (1990)
195.0	0.154	< 2.91	Bernstein *et al.* (1990)
227.3	0.132	2.656 ± 0.057	Roth *et al.* (1993)
227.3	0.132	2.76 ± 0.20	Meyer and Jura (1985)
227.3	0.132	$2.75^{+0.24}_{-0.29}$	Crane *et al.* (1986)
227.3	0.132	2.83 ± 0.09	Meyer, Cheng and Page (1989)
227.3	0.132	2.832 ± 0.072	Palazzi *et al.* (1990)
266.4	0.113	< 2.88	Bernstein *et al.* (1990)
Broad range	Broad range	2.728 ± 0.002	Fixsen *et al.* (1990)
300	0.1	2.736 ± 0.017	Gush, Halpern and Wishnow (1990)

An important feature of these data is an extremely low absolute measurement error, which makes possible the calculation of the amplitude of today's temperature of the microwave background at the 95% confidence limit:

$$T_0 = 2.7356 \pm 0.038\,\mathrm{K}. \tag{1.1}$$

It is well known that this temperature (T_0) determines all spectral characteristics of radiation (see, for example, Landau and Lifshits (1984)). For instance, the spectral intensity of radiation, defined as energy per unit area element in unit solid angle and unit frequency interval, is given by the expression

$$I_\nu = \frac{2h\nu^3}{c^2} n_\nu, \tag{1.2}$$

where h is Planck's constant, c is the speed of light in vacuum, ν is frequency and n_ν is the spectral density of the number of quanta. For the Planck radiation, n_ν is a function of only one parameter, namely temperature:

$$n_\nu = \left(e^{h\nu/kT} - 1\right)^{-1}, \tag{1.3}$$

where k is the Boltzmann constant, and the corresponding spectral brightness is given by

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\left(e^{h\nu/kT_0} - 1\right)^{-1}. \tag{1.4}$$

Note that the dependence of I_ν on frequency will be different for non-equilibrium radiation, but in general it should not necessarily be characterized by a single universal parameter, i.e. temperature. Equation (1.4) readily leads to asymptotics for $B_\nu(T)$ in the limit $\left(\frac{h\nu}{kT} \ll 1\right)$

$$B_\nu^{\mathrm{RJ}}(T) \simeq \frac{2\nu^2}{c^2} kT \tag{1.5}$$

for the Rayleigh–Jeans interval, and, for high energies of quanta $\left(\frac{h\nu}{kT} \gg 1\right)$,

$$B_\nu^{\mathrm{W}}(T) \simeq \frac{2h\nu^3}{c^2} e^{-h\nu/kT} \tag{1.6}$$

for Wien's interval. We see that $B_\nu^{\mathrm{RJ}}(T)$ describes the classical (non-quantum) part of the spectrum, which is independent of the value of Planck's constant. The Rayleigh–Jeans formula is well known in radioastronomy for determining the brightness temperature of a radiation source with spectral intensity I_ν:

$$T_{\mathrm{A}} = \frac{c^2}{2k\nu^2} I_\nu(T). \tag{1.7}$$

As we see from Eq. (1.7), the relation between the thermodynamic and brightness temperatures for blackbody radiation has the form

$$T_{\mathrm{A}}(\nu) = T_0 \frac{x^2 e^x}{(e^x - 1)^2}, \tag{1.8}$$

where $x = \frac{h\nu}{kT}$. Therefore, in the low-frequency limit, $x \ll 1$, Eq. (1.8) immediately implies the equality $T_{\mathrm{A}} = T_0$, and if $x \gg 1$ then the brightness temperature is found to be systematically below the thermodynamic temperature. In what follows we require integral characteristics of the CMB in addition to spectral ones: energy density, ε_γ; concentration of quanta, n_γ;

entropy density, S_γ; and quantum energy averaged over the spectrum, $\overline{E}_\gamma$. These quantities are defined for the CMB in the standardized manner (Landau and Lifshits, 1984), regardless of its cosmological nature:

$$\begin{aligned} \varepsilon_\gamma &= \sigma T_0^4 = 4.24 \times 10^{-13}\ \text{erg cm}^{-3}; & n_\gamma &= 0.244\left(\tfrac{kT_0}{\hbar c}\right)^3 = 414\ \text{cm}^{-3}; \\ S_\gamma &= \tfrac{4}{3}\tfrac{\varepsilon_\gamma}{kT_0} = 1.496 \times 10^3\ \text{cm}^{-3}; & \bar{E}_\gamma &= \tfrac{\varepsilon_\gamma}{n_\gamma} = 1.02 \times 10^{-15}\ \text{erg}, \end{aligned} \tag{1.9}$$

where $\sigma = (\pi^2 k^y / 15\hbar^3 c^3) = 7.5640 \times 10^{-15}$ erg cm^{-3} K^{-1} is the emission constant and $\hbar = h/2\pi$.

1.2.1 Electromagnetic emission from space

We mentioned at the beginning of this chapter that the pioneers of CMB research considered various types of electromagnetic emission coming from space as sources of very undesirable noise. However, in contrast to the CMB, electromagnetic radiation in the optical, ultraviolet, x-ray, γ and also long-wavelength ranges ($\lambda > 1$ m) are of non-cosmological origin. The most important characteristics of these electromagnetic backgrounds are, as in the case of the CMB, the intensity and degree of anisotropy of distribution over the sky. In this section we are mostly interested in the isotropic extragalactic component which is obtained by subtracting the component generated by the activities within the Milky Way Galaxy from the total signal. Figure 1.2 (Halpern and Scott, 1999) shows the combined distribution of various electromagnetic backgrounds published in Dwek and Arendt (1998), Hauser *et al.* (1998), Kappadath *et al.* (1999), Lagache *et al.* (1998), Miyaji *et al.* (1998), Pozzetti *et al.* (1998), and Sreekumar *et al.* (1998). In the long-wavelength limit ($\lambda > 10^3$ mm), we clearly see a contribution from extragalactic radio sources that is characterized by a power-law spectrum:

$$I_\nu \simeq 6 \times 10^3 \left(\frac{\nu}{1\text{GHz}}\right)^\alpha \ \text{Jy ster}^{-1}, \tag{1.10}$$

with the spectrum exponent $\alpha = -0.8 \pm 0.1$ (Longair, 1993) and 20% uncertainty in amplitude. The total contribution of this component to the total energy density of the radiation is extremely small, but the role of this background is found to be very significant in clarifying the origin of the so-called superhigh-energy cosmic rays ($E \geq 10^{20}$ eV) (Bhattacharjee and Sigl, 2000; Blasi, 1999; Doroshkevich and Naselsky, 2002).

Note, however, that as $\nu \to 0$, the intensity increases ($I_\nu \propto \nu^{-0.8}$) only up to frequencies $\nu \sim$ 1–3 MHz. The data of Clark, Brown and Alexander (1970), Longair (1993) and Simon (1978) point to this behaviour. The slope I_ν changes at $\nu \leq 3$ MHz and the effective exponent becomes $\alpha \simeq 1$. The causes of this behaviour may be traced to synchronous self-absorption of radiation in the sources responsible for the formation of long-wavelength radio background (Longair, 1993).

Let us return, however, to discussing background radiation outside the range in which the CMB dominates. The most complete review of the available observational data in the infrared (IR) range of wavelengths from 1 mm to 10^{-3} mm is given in Hauser (1998) and Gispert, Lagache and Puget (2000). Note that the study of the defuse cosmic IR radiation is relatively recent, even though the data on the intensity of this background radiation make it possible to extract unique information on the evolution of pregalactic matter and on the dynamics of the formation of galaxies and stars. It appears that the first indications of the

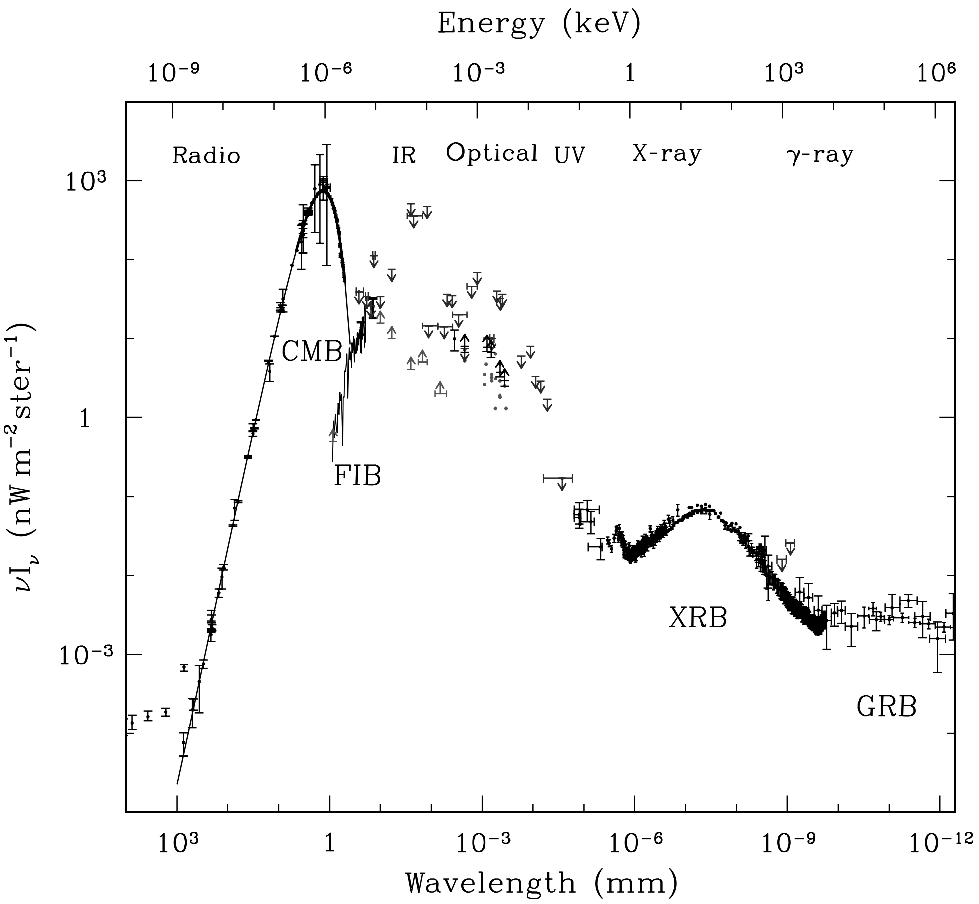

Figure 1.2 Spectral density of extragalactic electromagnetic radiation in the Universe. From Scott (1999a).

existence of this background were obtained in rocket experiments (see, for example, Hauser *et al*. (1991)). The IR background was later studied specifically using the DIRBE tool in the framework of the Cosmic Background Explorer (COBE) project that we have mentioned earlier. In combination with FIRAS – an instrument in the same project (Gispert *et al*., 2000) – it was possible to obtain unique data on the spectral characteristics of IR radiation in the range from 100 μm to 1 cm, as shown in Fig. 1.3. The same figure shows the data for the optical and ultraviolet (uv) ranges that follow the IR range in the order of increasing energy of quanta. An important feature of these ranges, as in the case of the IR background, is their genetic relation to young galaxies being formed in the process of evolution of the Universe (the optical range 0.15–2.3 μm), to the diffuse thermal emission of intergalactic medium and to the integral ultraviolet luminosity of galaxies and quasars (UV range; $\lambda \simeq 1000$–2500 Å) (see Gispert *et al*. (2000) and the relevant references therein).

In the optical range in the interval $\lambda \simeq 3200$–$24\,000$ Å, the intensity distribution is described sufficiently well by the following expression:

$$\lambda F_\lambda \simeq A^{(\lambda)} 10^{-6}\,\text{erg cm}^{-2}\,\text{s}^{-1}\,\text{ster}^{-1}, \tag{1.11}$$