1.6 Cosmic background radiation

In the thermodynamic equilibrium of the electromagnetic field with its emitters/absorbers, the space is filled by radiation, the density and spectrum of which is described for each thermodynamic temperature T by the Planck law for the black-body radiation

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{\mathrm{e}^{\frac{h\nu}{kT}}-1} \; . \tag{32}$$

In an expanding universe, the thermodynamic equilibrium is generally violated due to the different dependence of the temperature T of a relativistic gas (e.g. photons) and a non-relativistic gas (e.g., standard baryonic matter) on the volume in the course of their adiabatic expansion.[22] However, as it was shown in 1946 by G. Gamow, the conditions in the early stages of the cosmological expansion were similar to those in the stellar nuclei, i.e., there was not only a large density but also a high temperature, which described both the radiations as well as the baryonic matter, because the relaxation time in which the thermodynamic equilibrium can be achieved was much shorter than the age of the Universe at that time. In the course of the cosmological expansion, the relaxation time increased (due to the decreasing density and energy of the particles) more than the age of the Universe, and starting from the moment of the so-called *decoupling of radiation from matter* when the hydrogen recombined, the radiation almost ceased to interact with baryonic matter. The photon density decreases as $n \sim R^{-3}$ during the subsequent expansion of the Universe, and due to the redshift (i.e., the Doppler effect) also the frequency ν of each photon decreases as $\nu \sim R^{-1}$. The radiation thus preserves the Planckian distribution with the temperature T inversely proportional to the radius of the Universe ($T \sim R^{-1}$; the total energy of the radiation field is decreasing due to the work exerted by its pressure – cf. Eqs. (6) and (15)) despite it is no more in thermodynamic equilibrium with the matter.[23] This so-called *cosmic background radiation* (CBR) is observed at present time as a homogeneous and isotropic radiation with the temperature $T \simeq 2.73\mathrm{K}$ (Gamow predicted $T \simeq 10\mathrm{K}$). The density of energy of this radiation field is now smaller (in ratio $\simeq 1 : 10^4$) than that of the rest-mass energy of baryonic matter. However, in the past during the so called radiation-dominated epoch, the density of the mass-energy of radiation was larger than the density of the baryonic matter. The existence of CBR is, in principle, a confirmation of the hot big-bang cosmological model. The present observational and theoretical investigation of the deviations of CBR from the exact isotropy, homogeneity and the Planckian spectrum, enables us to improve the scenario of the early evolution of the Universe and of the formation of galaxies.

CBR was discovered in 1965 by A.A. Penzias and R.W. Wilson during tests of a microwave radiometer at the wavelength $\simeq$ 7cm. The direct measurements are experimentally difficult and they require the use of cryogenic technique. The main source of the noise is thermal radiation from the Earth and its atmosphere. This is why the measurements are often performed from airplanes, balloons and satellites (Relikt, COBE). Next, it is necessary to subtract in the data-processing the radiation of local sources like planets, stars, the Galaxy (i.e., interstellar matter) or discrete extragalactic sources. As an indirect method of the measurement of CBR can be used determination of the excitation temperature of interstellar molecules (e.g., CN) from the observation of strengths of absorption lines in the optical spectrum of stars. Due to the irradiation of molecules by nearby stars, this method yields an upper limit on the intensity of CBR only. However, it is the only test of the homogeneity of the CBR in space on a relatively large scale.

The largest observed deflection of CBR from the exactly isotropic equilibrium distribution is the dipole component of the dependence of the intensity or the temperature T

$$\Delta T \sim \frac{vT}{c}\cos\vartheta \; , \tag{33}$$

[22] This different behavior of relativistic and non-relativistic gas is caused by their different equations of state. The thermodynamic equilibrium in the Universe is also violated by the existence of local inhomogeneities like galaxies and stars, which have higher densities and temperatures and which thus emit hot radiation into their cooler environment.

[23] The mean temperature of baryonic matter, which is already nonrelativistic at this stage, starts to decrease much faster from this moment. However, the decoupling enables clustering of matter, and the temperature of local condensations (e.g., stars) can increase and their high-energy radiation can cause a re-ionization of the surroundings.

which arise by the Doppler effect (and the aberration) in the case of the motion of the observer (with the velocity v in the direction containing the angle ϑ with the line of sight) with respect to the inertial system in which the radiation is isotropic. CBR thus defines a "local rest system" of the Universe (which is for its privilege sometimes mentioned as a "new ether"). The measured velocity of the Sun with respect to CBR is about 380 km/s in the direction with galactic coordinates $l = 253°$, $b = 47°$, the velocity of the Galaxy with respect to CBR is thus about 600 km/s.

A quadrupole deflection (for which the direction characteristics has the form of a three-axial elipsoid) could arise if the cosmological expansion (and hence also the Hubble constant) would not be the same in all directions. Fluctuations with smaller angular dimensions could arise at the epoch of the decoupling of the matter from the radiation on possible inhomogeneities in the spatial distribution of the density and the velocity field, which were the seeds of the later formed galaxies (the so-called *Sachs – Wolfe effect*). In the case of *adiabatic perturbations* any local enhancement of the density $\Delta\rho > 0$ (which produces some local depression in the gravity potential $\Delta\Phi < 0$) is accompanied also by an increase of temperature $\Delta T > 0$. The photons emitted in these regions are thus hotter, however, before reaching the observer they are gravitationally redshifted (in the matter-dominated universe $\Delta T = -\frac{1}{3}c^{-2}T\Delta\Phi$). These perturbations of isotropy of CBR have been observed by COBE and some other instruments on angular scale $\sim 1°$ and amplitude $\frac{\Delta T}{T} \sim 10^{-5}$.

The observed smallness of the amplitude of such perturbations is in fact also a cosmological paradox (the so-called *paradox of the horizon*) because it means that there was the same temperature and density, e.g. in the events at the opposite directions on the sky in the same time, despite these events were still causally disconnected, i.e., they could not exchange any information about the values of these quantities. A possibility to solve this paradox is offered by the inflation cosmologies, in which the true horizon is many orders larger than the apparent one corresponding to the epoch of the decoupling – cf. Eq. (27). An additional distortion of CBR could take place also in later epochs of the evolution of the Universe, e.g., after the re-ionization of the intergalactic matter by the high-energy radiation from the first formed quasars and stars, or by the inverse Compton scattering[24] on high-energy particles in the clusters of galaxies (the so-called *Zel'dovitch – Sunyaev effect*), or due to the gravitational interaction with the density perturbations (*Rees – Sciama effect*). The variety of these effects can influence not only the intensity but also the spectrum and polarization of CBR.

[24]This particular effect tends to establish a more general Bose–Einstein distribution with non-zero chemical potential instead of the Planckian distribution for the CBR- photons.