

Discovery of CMB, Sakharov Oscillations and Polarization of the CMB Anisotropy

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In this paper I outline some aspects of the history of the discovery of Cosmic Microwave Background radiation, including theoretical predictions concerning its anisotropy and polarization. I used some materials from the books Zeldovich and Novikov (1983) and Novikov (1990).

Observations show that we live in an expanding, indeed an evolving, universe. Modern cosmology is a vast, rapidly developing field of knowledge. During rather long period in the second quarter of the century its theoretical basis was the set of cosmological models devised by the Soviet mathematician Alexander Friedmann. Its observational basis was the work that led to the discovery by the American astrophysicist Edwin Hubble of the law describing the redshift in the spectra of galaxies.

Though the kinematics of the evolving Universe became known decades ago, only in more recent years did research into the physics of processes occurring in the expanding Universe receive a reliable observational and theoretical basis.

Describing the situation in cosmology at the beginning of the 60's Steven Hawking (Hawking (1993)) wrote: "Cosmology was thought of as a pseudo-science where wild speculation was unconstrained by any possible observations".

Indeed at that period cosmology was only a science about the mechanics of motion of huge mass of matter in the Universe. With very rare exception there was not any physics in cosmology at that period. We can compare that period with the period in astronomy at the beginning of the last century, when there was not any astrophysics at all. Astronomy itself was only the science about the motion of celestial bodies, the motion of planets and their satellites and so on, but there was nothing about the physical processes. Analogous situation was at the beginning of the second half of our century in cosmology. Mainly it was the science about only two values, the speed of the expansion of the Universe - the Hubble parameter, and the deceleration parameter which characterizes the total average density of the matter and the gravity of this matter which leads to deceleration of its motion.

Nevertheless practically just after the discovery of the expansion of the Universe and during the subsequent period some serious attempts to understand the physics of the Universe were done. Proof that the Universe expands appeared

roughly at the same time that modern ideas on nuclear physics arose. Thus, see the works of Friedmann in 1922 and 1924; the announcement in 1919 of the discovery by Rutherford of nuclear reactions; the works of Hubble in 1929; and the notice in 1932 describing the discovery of the neutron by Chadwick. Almost simultaneously there then arose, first, the questions of what the Universe and the matter filling it represent near the singularity and, second what the physical preconditions for the answer to this question are. Already, the most general idea about the singularity, the infinite-density state at the beginning of the expansion, had led to the idea that the original, prestellar matter was more or less homogeneous—in stark contrast to the diverse structure and composition of the stars and of other celestial bodies today. Then, a pleasant-sounding but nebulous formulation appeared: the Universe is a single “primordial atom”, or the entire Universe is a single nucleus or drop of nuclear fluid (G.Lemaitre, the beginning of the 30’s). G.Lemaitre did the first attempt to understand the physics of the birth of the Universe. It is remarkable how some of his ideas are close to the ideas of the modern cosmology. He wrote in 1931, Lemaitre (1931): “I would rather be inclined to think that the present state of quantum theory suggests a beginning of the world very different from the present order of Nature. Thermodynamical principles from the point of view of quantum theory may be states as follows: (1) Energy of constant total amount is distributed in discrete quanta. (2) The number of distinct quanta is ever increasing. If we go back in the course of time we must find fewer and fewer quanta, until we find all the energy of the universe packed in a few or even in a unique quantum.

Now, in atomic processes, the notions of space and time are no more than classical notions; they fade out when applied to individual phenomena involving but a small number of quanta. If the world has begun with a single quantum, the motions of space and time would altogether fail to have any meaning at the beginning; they would only begin to have a sensible meaning when the original quantum had been divided into a sufficient number of quanta. If this suggestion is correct, the beginning of the world happened a little before the beginning of space and time. I think that such a beginning of the world is far enough from the present order of Nature to be not at all repugnant.”

G.Lemaitre had proposed that initial state of the matter in the Universe may be thought of as a sea of neutrons. Later it was found out that this assumption led to a contradiction with observations.

The situation was as follows. A neutron is an unstable particle. When free, it decays in about 15 minutes into a proton, an electron, and an antineutrino. Hence, as the Universe expands, neutrons inevitably decay, and protons appear. A newborn proton would couple to a surviving neutron and form the nucleus of deuterium atom (a deuteron). A deuteron would join with another deuteron, and so forth. The reaction of forming progressively more complex atomic nuclei would rapidly proceed until alpha particles (nuclei of helium atoms) formed. Calculations show that more complex atomic nuclei would practically never be formed. The entire matter would thus convert to helium. This conclusion sharply contradicts observations. We know that young stars and interstellar gas mostly consist of hydrogen, not of helium.

Observations of the abundance of chemical elements in nature thus completely reject the hypothesis of the cold neutrons beginning of the expansion of the Universe.

In the 40s, George Gamov (Gamov (1946)) published papers that suggested a 'hot scenario' of the initial stage of the expansion; this paper was followed by several more written by him and then by his colleagues Ralph Alpher and Robert Herman (references and some details see in Zeldovich and Novikov (1990)). It was assumed that the temperature of matter at the onset of expansion was extremely high.

The main objective of the authors of the hot Universe scenario was to analyze nuclear reactions at the start of the cosmological expansion and to obtain the currently observed ratio of abundances of various chemical elements and their isotopes.

Why was it initially assumed that all chemical elements had to be born at the start of the expansion of the Universe? The fact is that it was erroneously decided in the 1940s that the time that had elapsed since the Big Bang was 1-4 billion (10^9) years (instead of the current estimate of 15 billion years). We are aware now that this error was caused by the underestimation of the distances to galaxies and consequent overestimation of Hubble's constant. Comparing this time $(1 - 4) \times 10^9$ years, with the age of the Earth, that is $(4 - 6) \times 10^9$ years, Gamov and his colleagues concluded that even the Earth and other planets, let alone the Sun and other stars, had to grow from the primary matter and that all chemical elements had formed at the early stage of the expansion of the Universe because they simply could not be formed at any later period.

We know now that the time of expansion of the Universe is 15×10^9 years. The Earth has been formed not from primary matter but from matter that went through the stage of nuclear reactions (nucleosynthesis) in stars. The theory of nucleosynthesis in stars successfully explains the main body of observations of the abundance of chemical elements, assuming that primordial stars grew from matter that mostly consisted of a mixture of hydrogen and helium. The matter of old first-generation stars, enriched in heavier elements, was ejected into space. New stars and planets grew out of this matter. As a result, the need of explain the origin of all elements (including such heavy elements as iron, lead, etc.) at the early stage of expansion disappeared. But the main idea of the hot Universe hypothesis proved to be correct.

The theory suggested by Gamov and his colleagues established that the expanding matter of the Universe turns into a mixture consisting of hydrogen (75 per cent) and helium (25%). This is the material from which stars and galaxies are later formed. What prevents the matter in the hot Universe scenario from turning into helium, as it did in the scenario that started with cold neutron liquid?

The crucial factor is the hot state of the matter. Hot matter contains numerous energetic photons. It also contains protons and neutrons that tend to merge into deuterons. The photons break down the deuterium nuclei formed by paired protons and neutrons, thus interrupting at the very beginning the chain of reactions leading to the synthesis of helium. When the expanding Universe cools down sufficiently (to a temperature of less than a million degrees), a certain amount of deuterium survives and ultimately give helium.

The hot Universe scenario gives definite predictions on the content of helium in prestellar material. We have already mentioned that helium abundance must be about 25% of the total mass.

Gamov's hypothesis was not the last attempt to treat the Big Bang. One attempt, made at the beginning of the 1960s by Ya. Zeldovich (1962) was to modernize the cold Universe scenario: the new version predicted the conversion of all matter not to helium (as in the former version) but to pure hydrogen. It was also assumed that all other elements were generated much later, already in stars.

Originally the hot and cold Universe models were regarded as attempts to give a detailed explanation of elemental abundances in the prestellar matter. Attempts at determining which of the theories is true were mostly oriented at an analysis of the observational data on abundances of chemical elements. Unfortunately, such observations, and especially their analysis, are extremely complicated and depend on a number of assumptions. If abundances of chemical elements in the Universe were the only test for a theory, the truth could be very hard to unearth. Indeed, it is not easy to decide how much helium and other elements had been synthesized in nuclear processes in stars and how much had been left by the processes occurring in the early Universe.

Fortunately, another method of testing was found. The hot Universe theory gives a most important observational prediction that is a direct corollary of being hot. This is a prediction of the electromagnetic radiation that has survived in the Universe till our epoch from the time in the past when the matter was dense and hot.

The temperature of matter decreases in the process of cosmological expansion, and the radiation also cools off, but nevertheless electromagnetic radiation with a temperature from (in different versions of the theory) a fraction of one degree to 20-30 degrees of the Kelvin scale must survive until today.

This radiation that must have been left to cool from the ancient epochs of the evolution of the Universe, if the Universe had really been hot at that time, is known as the Cosmic Microwave Background (CMB) radiation: the Soviet astrophysicist I.Shklovsky suggested calling it the relic radiation. The electromagnetic radiation at such a low temperature consists of radio waves in the centimeter and millimeter wavelength ranges. Correspondingly, the crucial test of whether the Universe had been hot or cold was a search for such a radiation. If found, then the Universe had been hot; otherwise it had been cold.

The prediction of existence of the CMB radiation was done by G.Gamov and his collaborators. Unfortunately nobody tried to search for CMB. Later we will discuss why it so happened.

The subsequent history is well known. Penzias and Wilson (1965) stumbled across unexplained, regular radio noise at a wavelength of 7.3cm. At the same time Dicke, Peebles, Roll, and Wilkinson (1965) were preparing an apparatus for the measurement of the radio background at a wavelength of 3cm with the deliberate intention of verifying the theory of the hot Universe and determining the temperature of CMB radiation. At that time they had made corresponding theoretical estimates. (see the book of Dicke (1970)). Then hearing of the results of Penzias and Wilson, Dicke and his group quickly interpreted their results as

confirmation of the theory of the hot Universe and assigned a temperature of about 3 K.

It was in this accidental manner that Penzias and Wilson made the spectacular discovery of the twentieth century, the discovery proving that the Universe had been hot at the beginning of its expansion. In 1978, they won the Nobel Prize for Physics for this discovery.

Let us return now to a problem that belongs to the history of science but that still also excites interest in physicists and astrophysicists. The brilliant American scientist Steven Weinberg (1977) wrote in his book "The first three minutes: A modern view of the origin of the Universe": "I want especially to grapple here with a historical problem that I find both puzzling and fascinating. The detection of the cosmic microwave radiation 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 was there no systematic search for this radiation, years before 1965?"

I remind that the prediction of the radiation at a temperature of several kelvins that fills the Universe was made by Gamov 15 years before the discovery by Penzias and Wilson, at the end of the 1940s and the beginning of the 1950s.

Could it be that sufficiently sensitive radiotelescopes, capable of detecting this radiation, were simply nonexistent? We will see later that this is a rather unlikely reason. Weinberg expresses this opinion too. But the crux of the matter lies elsewhere.

Physics offers numerous examples in which prediction of a new phenomenon was made long before the discovery could become technically feasible. Nevertheless, if the prediction had solid ground and was important, physicists never let it out of sight. The prediction used to be tested immediately after the technical possibility arose. Weinberg gives an example of the prediction of the antiproton in the 1930s. At that period, physicists could not even dream of the equipment needed for its experiment discovery. In the 1950s, however, it became possible, and a special accelerator was constructed in Berkeley to test this problem.

In the case of the cosmic microwave background, however, radioastronomers knew nothing about it or about the possibilities of detecting it until the middle of 1960s.

Why did it happen?

Weinberg gives three reasons. The first is that the hot Universe theory was developed by Gamov and his colleagues to explain the abundances of all chemical elements in nature by their synthesis at the very beginning of expansion. As we mentioned above, this hypothesis had to be abandoned since heavy elements were synthesized in stars. Only the lightest elements date back to the earliest moments of expansion. First version of the theory contained other imperfections as well. Later all shortcomings were corrected for but at the end of the 1940s and in the 1950s the theory as a whole was not regarded as quite reliable.

The second reason was the poor communication between theorists and experimentators. The former had no idea whether the microwave background was detectable by the available observational equipment; the latter never heard that one would be advised to search for this radiation.

The third reason is psychological. It was extremely difficult for physicists and astrophysicists to accept that calculations dealing with the very first minutes

after the beginning of expansion could indeed describe the true picture. Indeed, the contrast of durations was too striking: the first several minutes against the tens of billions of years that separate that epoch from ours.

Another reason, which I consider to be the most important, was formulated by Penzias (1979) in his Nobel lecture. The point is that neither the first nor subsequent papers by Gamov and his coworkers ever mentioned that the cosmic radiation background could be detected, even in principle. Moreover, it seems that Gamov and the others were of the opinion that the detection was completely unfeasible! Penzias(1979) says:

"As for detection, they appear to have considered the radiation to manifest itself primarily as an increased energy. 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 approximative equal additive energies could not be separated may be found in letter by Gamov 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 relic radiation would set it apart from the other effects."

It so happened that I played my part at the next stage of this story. I started to work in physical cosmology at the beginning of the 1960s, shortly before the microwave background was discovered. I had just completed the postgraduate course at the Moscow University; my science adviser was Professor Zelmanov. My adviser was mostly interested in the mechanics of motion of masses in cosmological models when no simplifying assumption are made about their uniform distribution. He was less interested in specific physical processes in the expanding Universe. At that time, I knew almost nothing about the hot Universe model.

Not long before the end of my postgraduate term, I was attracted to the following problem. We know how different types of galaxies are radiated in different ranges of wavelength of electromagnetic radiation. With certain assumption about the evolution of galaxies in the past and having taken into account the reddening of light from remote galaxies owing to the expansion of the Universe, one can calculate today's distribution of galactic emission over such wavelengths. In this calculation, one has to remember that stars are not the only sources of radiation, and that many galaxies are extremely powerful sources of radio waves in the meter and decimeter wavelength ranges.

I began the necessary calculations. Having completed the postgraduate term, I joined the group of Professor Zel'dovich; our interests focused mostly on the physics of processes in the Universe.

All calculations were carried out jointly with A.Doroshkevich. As a result, we obtained the calculated spectrum of galactic radiation, that is, of the radiation that must fill today's Universe if one takes into account only the radiation produced when galaxies were born and stars began to shine. This spectrum predicted a high radiation intensity in the meter wavelength range (such wavelengths are strongly emitted by radio galaxies) and in the visible light (stars are

powerful emitters in the visible range), while the intensity in the centimeter, millimeter and some still shorter wavelength ranges of electromagnetic radiation must be considerably lower.

Since the hot and cold Universe scenarios were eagerly discussed in our group (consisting of Zel'dovich, Doroshkevich and myself), the paper that Doroshkevich and I prepared for publication added to the total the putative radiation surviving from the early Universe if it indeed had been hot. This hot Universe radiation was expected to lie in the centimeter and millimeter ranges and thus fell into the very interval of wavelengths in which the radiation from galaxies is weak! Hence, the relic radiation (provided the Universe had been hot!) was predicted to be more intensive, by a factor of many thousands or even millions, than the radiation of known sources in the Universe in this range of wavelengths.

This background could, therefore, be observed! Even though the total amount of energy in the microwave background is comparable with the visible light energy emitted by galaxies, the relic radiation would be in very different range of wavelengths and thus could be observed. Here is what Penzias (1979) said about our work with Doroshkevich (Doroshkevich & Novikov (1964)) in his Nobel lecture:

"The first published recognition of the relic radiation as a detectable microwave phenomenon appeared in a brief paper entitled 'Mean Density of Radiation in the Metagalaxy and Certain Problems in Relativistic Cosmology' by A.G. Doroshkevich and I.D. Novikov in the spring of 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 other workers in this field. This remarkable paper not only points out the spectrum of the relic radiation as a blackbody microwave phenomenon, but also explicitly focuses upon the Bell Laboratories 20-ft horn reflector at Crawford Hill as the best available instrument for its detection!"

Our paper was not noticed by observers. Neither Penzias and Wilson, nor Dicke and his coworkers were aware of it before their papers were published in 1965; Penzias told me several times that this was very unfortunate.

We are not yet through the chain of missed opportunities that plagued the discovery of the relic radiation.

It is found that the microwave background could have been discovered as early as in 1941.

In 1941, MacKellar was analyzing absorption lines in the spectrum of the light coming from the star ζ Ophiuchi; the absorption was caused by cyan molecules (compounds of carbon and nitrogen). MacKellar concluded that these lines (in the visible part of the spectrum) could have arisen only if the light was absorbed by rotating cyan molecules. The rotation must be excited by radiation at a temperature about 2.3K. Of course, neither MacKellar nor anybody else thought at that moment about the possibility that the rotation of molecules is excited by the relic radiation. In fact, the theory of the hot Universe has not even been developed yet!

It was only after the cosmic microwave background had been discovered, that Shklovsky, Field, Hitchcock, Wolf and Thaddeus published their papers, in 1966 and later, which showed that the rotation of interstellar cyan molecules

observed in the stellar spectra of the ζ Ophiuchi and three other stars was indeed excited by the relic radiation.

This shows that one manifestation of the microwave radiation background, even though indirect, was observed in 1941; its effect on the rotational state of interstellar cyan molecules.

But even this is not yet final chapter of the story. Let us return to the question about the technical feasibility of detecting the cosmic microwave background. At what time did this become possible? Weinberg writes: 'It is difficult to be precise about this, but my experimental colleagues tell me that the observation could have been made long before 1965, probably in mid-1950s and perhaps even in mid-1940s.' Is this correct?

In the autumn of 1983, Dr. J. Shmaonov of the Institute of General Physics, with whom I was not previously acquainted, telephoned me and said that he would like to talk to me about things relevant to the discovery of the cosmic microwave background. We met the same day and Shmaonov described how, in the middle of the 1950s, he had been doing postgraduate research in the group of well-known Soviet radioastronomers S. Khaikin and N. Kaidanovsky: he was measuring radio waves coming from space at a wavelength of 3.2cm. Measurements were done with a horn antenna similar to that used many years later by Penzias and Wilson. Shmaonov carefully studied possible sources of noise. Of course, his instrument could not have been as sensitive as those with which the American astronomers worked in the 1960s. Results obtained by Shmaonov were reported in 1957 in his Ph.D. Thesis and published in a paper Shmaonov (1957) in the Soviet journal *Pribory i Tekhnika Eksperimenta* (Instruments and experimental methods). The conclusion of the measurements was: 'The absolute effective temperature of radiation background ... appears to be 4 ± 3 K'. Shmaonov emphasized the independence of the intensity of radiation on direction and time. Errors in Shmaonov's measurements were high and his 4K estimate was absolutely unreliable, but nevertheless we now realize that what he recorded was nothing other than the cosmic microwave background. Unfortunately, neither Shmaonov himself, nor his science advisors, nor other astronomers who saw the results of his measurements, knew anything about the possibility of the existence of the relic radiation and so failed to pay the results the attention that they deserved. They were soon forgotten. When Doroshkevich and I, having completed our calculations, were calling in 1963 and 1964 on several Soviet radioastronomers with the question 'Do you know any measurements of the cosmic background in the centimeter and shorter wavelength ranges?' not one of them remembered Shmaonov's work.

It is rather amusing that even the person who made these measurements failed to appreciate their significance, not only in the 1950s - this is easy to explain - but even after the discovery of the microwave background by Penzias and Wilson in 1965. True, at that time Shmaonov was working in very different field. His attention turned to old results only in 1983, in response to semiaccidental remarks, and Shmaonov gave a talk on the subject at the Bureau of the Section of General Physics and Astronomy of the USSR Academy of Sciences. This event took place 27 years after the measurements and 18 years after the publication of the results of Penzias and Wilson.

But even this is not the final chapter. Some years ago I was informed that measurements by Japanese radioastronomers at the beginning of the 1950s may also have detected the radiation background. This work, as well as that of Shmaonov, went unnoticed then, was not realized later, and remained practically unknown to the scientific community.

Fate takes unexpected and tortuous turns. Nevertheless, the entire story is very instructive. To hit upon a phenomenon is not yet equivalent to discovering it. One has to realize the significance of the find, and give the correct explanation. A combination of circumstances and sheer luck do play a role here - no doubt about it. Nevertheless, success does not come by accident. Success requires lots and lots of work, vast knowledge, and persistence in the work itself and in bringing the results to the attention and recognition of others.

The discovery of CMB was one of the most unexpected astronomical discoveries of the century. In contrast to that the existence of the “ripples” (the tiny variations that are seen in the background radiation temperature) in the CMB radiation had been predicted and the corresponding proposal to search for them submitted to NASA in the 70s. These “ripples” have been discovered by COBE - satellite in 1992, see Smoot (1992) ¹.

The “ripples” contain the key to the mystery why cosmic structure finally developed. Observations of the ripples provide data to investigate process of birth of the Universe, origin of primordial small irregularities in the matter distribution in the Universe and they allow us to estimate main cosmological parameters (Hubble constant, total amount of matter in the Universe, amount of baryonic matter and other parameters). All this information can be extracted from the angular power spectrum of the CMB anisotropy. It is the dependence of the intensity of the variations of the CMB temperature on the angular scale (or corresponding multipole number l of spherical harmonics). The theoretical power spectrum has clear peaks. In the standard cosmological model the matter is ionized until a redshift $z_{rec} \approx 1000$. Fluctuations in the hot matter-radiation fluid before z_{rec} oscillate like sound waves. The peaks in the power spectrum are a consequence of these sound waves which we see at the epoch of recombination $z_{rec} \approx 1000$ when the Universe became transparent for radiation. We call these peaks in the power spectrum Sakharov oscillations because a corresponding effect had been pointed out by A.Sakharov (1965), see Zeldovich and Novikov (1983), Naselsky and Novikov (1993), Jørgensen et al (1995). The first Sakharov peak (it is called also “Doppler peak”) at $\theta \approx 0.5^\circ$ corresponds to the distance that a sound wave can travel at the time of recombination. Other peaks are at smaller angular scales. The COBE satellite mapped the sky with an angular resolution of $\approx 7^\circ$. This was not enough for the measurement even the first peak. Since then, experiments with finer angular resolution have detected CMB anisotropy on smaller angular scales and have produced evidence for the presence of the first Sakharov peak. Finally two groups (De Bernardis (2000) (BOOMERANG experiment) and Hanany (2000) (MAXIMA-I experiment) announced about the discovery of the first Sakharov peak.

¹I don't discuss here the large scale dipole anisotropy related with the motion of our Galaxy through the microwave background radiation

These rather recent observational data by BOOMERANG and MAXIMA-I opened a new epoch in the investigation of the CMB power spectrum at large multipole numbers l . As we mentioned above, the angular power spectrum of the CMB (in particular the position and amplitudes of the first, second and subsequent Sakharov peaks) provides a unique chance to construct the most likely cosmological model. This model includes information about the Hubble constant, baryonic and CMB densities, Cosmological constant Ω_Λ , ionization history and so on. In the coming years the measurements of the angular anisotropy of CMB by satellite missions will provide CMB maps with high resolution and sensitivity.

In addition to the anisotropy of the intensity it is possible, though more difficult, to measure polarization of the radiation. Polarization is a secondary effect induced by the scattering of anisotropic radiation on electrons in the cosmic plasma. Importance of the polarization measurements of the relic radiation was pointed out by Rees (1968) and this problem has since been discussed in many papers, see for example Basko and Polnarev (1979), Polnarev (1985). Polarization contains an addition to the anisotropy information about the nature of primordial cosmological perturbations and different types of foregrounds. The polarization field is a combination of two randomly distributed Stokes parameters (Q and U) while the anisotropy is just a scalar. In particular, this field is quite sensitive to the presence of tensor perturbations (primordial gravitational waves) and a deviation from zero of the so called pseudo scalar or 'magnetic' part of polarization would be an indicator of gravitational waves or vector perturbations.

But all these points are related with the future observations. Our conference is devoted to the history. So I have to stop here.

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