THE PHYSICS OF THE COSMIC MICROWAVE BACKGROUND

Spectacular observational breakthroughs by recent experiments, and particularly the WMAP satellite, have heralded a new epoch of CMB science 40 years after its original discovery.

Taking a physical approach, the authors probe the problem of the ‘darkness’ of the Universe: the origin and evolution of dark energy and matter in the cosmos. Starting with the observational background of modern cosmology, they provide an up-to-date and accessible review of this fascinating yet complex subject. Topics discussed include the kinetics of the electromagnetic radiation in the Universe, the ionization history of cosmic plamas, the origin of primordial perturbations in light of the inflation paradigm, and the formation of anisotropy and polarization of the CMB.

This timely and accessible review will be valuable to advanced students and researchers in cosmology. The text highlights the progress made by recent experiments, including the WMAP satellite, and looks ahead to future CMB experiments.

PAVEL NASELSKY is a research scientist and associate professor at the Niels Bohr Institute and at the Rostov State University, Russia. He has written over 100 papers on CMB physics and cosmology, and has taught an advanced course on ‘Anisotropy and polarization of the CMB’. He is a member of the ESA technical working group of the PLANCK project.

DMITRY NOVIKOV is an astronomer and research associate at the Astrophysics Group of Imperial College London and also a research scientist at the Astro Space Center of the P. N. Lebedev Physics Institute, Moscow. His main research interests and publications are in cosmology and astrophysics.

IGOR NOVIKOV is a professor at Copenhagen University and was Director of the Theoretical Astrophysics Center prior to its transfer to the Niels Bohr Institute. He is also a research scientist at the Astro Space Center of the P. N. Lebedev Physics Institute, Moscow. His main research has been on gravitation, physics and astrophysics of black holes, cosmology and physics of the CMB. He has been actively involved in the theory of the anisotropy of the CMB and development of the theory with applications to the observations from space- and ground-based telescopes.

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PAVEL D. NASELSKY
Niels Bohr Institute, Copenhagen and the Rostov State University

DMITRY I. NOVIKOV
Imperial College London and the P. N. Lebedev Physics Institute, Moscow

IGOR D. NOVIKOV
Niels Bohr Institute, Copenhagen and the P. N. Lebedev Physics Institute, Moscow

Translated by Nina Iskandarian and Vitaly Kisin

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The evolution of the Universe can be compared to a display of fireworks that has just ended: some few wisps, ashes and smoke. Standing on a well-chilled cinder, we see the slow fading of the suns, and try to recall the vanished brilliance of the origin of the worlds.

Abbé George-Henri Lemaître, the late 1920s

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Preface to the Russian edition

We wrote this book in 2001–2002. These years saw the launch and start of operations of the American satellite WMAP (Wilkinson Microwave Anisotropy Probe), which began a new stage in the study of the primordial electromagnetic radiation in the Universe. This stage brought a qualitative change to the status of modern cosmology which, using a metaphor suggested by Malcolm Longair, entered the phase of 'precision cosmology' in which the level of progress in theory and experiment was so high that the interpretation of observational data became relatively less urgent than the problem of measuring the most important parameters that characterize the state of gravitation and matter as they were long before the current phase of the cosmological expansion.

Paradoxically, the entire period of explosive development of cosmology happened virtually within the last three decades of the twentieth century; however, it brought together thousands of years of mankind's attempts to comprehend the basic laws governing the structure and evolution of the Universe. Regarded formally, this period coincided – although realistically it was genetically connected – on one hand with the penetration into the mysteries of structure of matter at the microscopic level and on the other hand with the sending of humans into space and with progress in space technologies that revolutionized the experimental basis of the observational astrophysics. One of the authors of this book (Igor Novikov) was involved in the creation of the modern physical cosmology and remembers very well the hot discussions raging in the 'era of the 1960s and 1970s' about the nature of the primordial fluctuations that gave rise to galaxies and galaxy clusters, about the possible anisotropic 'start' of the expansion of the Universe and about the 'hidden mass' whose status was for a long time underestimated by most cosmologists. Another aspect that attracted huge interest was the problem of pregalactic chemical composition of matter which was most closely connected with the 'hot' past of the cosmological plasma and which highlighted for the first time the paramount role played by neutrinos and other hypothetical weakly interacting particles in the thermal history of the Universe; in a wider sense, though, it also connected with the problem of the birth of life in the cosmos. Finally, a brief list of 'hot spots' of astrophysics and cosmology since the late 1970s cannot avoid the eternal questions: How and why did the Universe 'explode'? What was the 'first push' that triggerred the expansion of matter? What was there (if anything) prior to this moment? And how will the expansion of the Universe continue to unfold?

We should add that working on answers to some questions has inevitably generated new ones – for instance, was space-time always four-dimensional? Is it possible that we actually face here manifestations of more complex topology of the space-time continuum and, among other things, the existence of the yet unknown remnants of the early Universe, for example primordial black holes or other mysterious particles? And so forth. These and a whole range of other problems were reflected in the pioneer studies by Peebles (1971), Weinberg (1972, 1977), Zeldovich and Novikov (1983), and in some later works (see, for example, Kolb and Turner (1989), Melchiori and Melchiori (1994), Padmanabhan (1996), Partridge (1995) and Smoot and Davidson (1993)). Some of these problems acquired new status and took their rightful places among the so-called 'eternal' problems of natural sciences that will excite subsequent generations of cosmologists and will await the arrival of new Newtons, Einsteins and Hubbles. As could be expected, some of the hypotheses failed the test of time and sunk into the realm of the history of science, leaving behind a sort of monument to mankind's thinking. But a smaller fraction of hypotheses were verified experimentally and ascended to the sanctum of science, having changed our comprehension of the Universe and of the properties of space-time and matter.

One spectacular example of this sort of achievement of modern cosmology is the problem of the origin of the primordial electromagnetic radiation, better known as the cosmic microwave background (CMB), which covers the aspects of its spectral distribution, anisotropy and polarization. This book is mostly devoted to discussing this range of problems; it was written immediately after the completion of a number of successful ground-based and balloon experiments closely connected with the satellite project COBE, which was successfully completed in the mid 1990s. This project was preceded by a Russian project, RELIKT, that was the first dedicated space mission for the investigation of the CMB anisotropy. The COBE mission became part of the history of cosmology not only as the first experiment that measured the CMB anisotropy with the maximum angular resolution achievable at the time (about 7 degrees of arc), but also as an experiment that put an end to numerous discussions on the possible non-equilibrium of the CMB spectrum and on its deviations from Planck's law of the blackbody frequency distribution of quanta predicted by the theory of the 'hot Universe'.[1]

Metaphorically speaking, the post-COBE cosmology entered a new phase in its development, switching from a search for, let us say, the most probable evolutionary 'treks' to a detailed clarification of the causes of why one reliably established (within a certain time span, of course) particular mode of cosmological evolution of matter had been realized.

The relay race to create a realistic picture of the evolution of the Universe by measuring the CMB anisotropy was continued after COBE by the next generation of experiments (CBI, DASI, BOOMERANG, MAXIMA-1, and quite a few others), all of which provided conclusive proof of the existence of the CMB anisotropy on small angular scales of about 10 minutes of arc. At first glance, the progress of the experiment towards smaller angular scales looks modest at best. Indeed, we still lack 1.5–2 orders of magnitude in order to gauge the typical sizes of galaxy clusters recalculated to the moment of hydrogen recombination at which the Universe became transparent to radiation ($\sim$300 000 years after the onset of the expansion of the Universe). The reality is that it was with the CMB anisotropy and polarization that we were connecting the possibility of 'peeking' into the remote past of the Universe and of 'discovering' the signs of the future clusters on what we now refer to as maps of distribution of the CMB temperature fluctuations on the celestial sphere. Unfortunately this problem was

[1] To be precise, the COBE data limit the degree of non-equilibrium of the primordial radiation at the level of 10^{-4}–10^{-5}, which is practically equivalent to a complete absence of distortions. Nevertheless, even this small but possible degree of non-equilibrium proves to be very informative in that it places constraints on energy releases in the early Universe, especially during the period of non-equilibrium ionization of hydrogen and helium. This aspect of the problem is analysed in more detail in several chapters of the book.

found to lie beyond the technical possibilities of radioastronomy, not so much because today's receivers of primordial radiation lack sensitivity, but rather owing to the disruptive effect of various types of noise connected with the activity primarily within our Galaxy, with hot gas in galaxy clusters, the emission from intergalactic dust, and a number of other factors that safely shield the CMB anisotropy from us. However, from the standpoint of CMB physics, this negative outcome is still an outstanding positive result for the adjacent fields of cosmology and astrophysics, which achieved excellent progress in studying the manifestations of activities of various structural forms of matter in the Universe. It was the symbiosis of the adjacent fields of astrophysics that made it possible at the very beginning of the twenty-first century to come very close to solving one of the key problems of cosmology: the determination of the most important parameters that characterize the evolution of the Universe in the past, present and future, namely the Hubble constant, H_0, the current density of the baryonic fraction of matter, the density of the invisible cold component (the so-called 'cold hidden mass'), the value of the cosmological constant, Λ, the type and characteristics of the spectrum of primordial fluctuations of density, velocity and gravitational potential of matter, and other important parameters that will be discussed in the book. As applied to CMB physics, this symbiosis made it possible not only to outline the contours, but also to start a practical implementation of the PLANCK satellite mission – an experiment unique in the extent of pre-launch analysis of the anticipated effects and noise, capable of mapping the CMB anisotropy and polarization with unique angular resolution (on the order of 6 minutes of arc) with a record low level of internal noise of the receiving electronics, less by approximately an order of magnitude than in all currently operational grand-based, balloon and satellite experiments.

It should be noted that the PLANCK project will launch in 2007–2008. Although the objectives, namely the mapping of the CMB anisotropy and polarization with maximum possible coverage of the celestial sphere, are shared by the two missions, the PLANCK project is meant to provide the maximum possible sensitivity of the receiver electronics and to achieve it with a unique selection of frequency ranges for the observation of the CMB anisotropy and polarization. Furthermore, the objectives of the project include compilation of a catalogue of radio and infrared pointlike sources that would cover the frequency range 30–857 GHz in 19 frequency channels, mapping of galaxy clusters, plus a number of other tasks whose solution became possible thanks to the unique theoretical and experimental studies of the CMB anisotropy and the noise of galactic and extragalactic origin that accompanies it.

The following legitimate questions may be asked. Is it justifiable to present the CMB physics now, before the completion of these two new space missions which may drastically change our ideas about the evolution of the Universe and about the formation of anisotropy and polarization of cosmic microwave background and, who knows, about the formation of its large-scale structure? Would it be advisable to wait perhaps seven or ten years until the situation concerning the distribution of anisotropy on the celestial sphere has been clarified and then summarize the era of studying the CMB with certainty, being supported by the data of literally 'the very last experiments'? Answers to the above questions seem to us surprisingly simple. First – and this point is perhaps the most important – we are absolutely sure that no subsequent experiments will act as 'foundation destroyers' for modern cosmology. The foundations of the theory are too solid for that, and its implications are very well developed and carefully checked against observations. Secondly, the preparation stage for the WMAP and PLANCK missions stimulated unprecedented progress in the theory that needs further digeston and systematization. Suffice it to say that compared with the situation at the beginning of the 1990s, the CMB physics has progressed greatly, coming very close to predicting effects with an accuracy of better than 5%, requiring for their simulation modern computer networks and the development of new mathematical techniques for data processing. Finally, placed third in sequence but not in significance, the future space experiments, the PLANCK mission among them, have one obvious peculiar feature: they have been mostly prepared under the guidance of the generation of 'veterans', whereas the results will mostly be used by the generation of 'pupils'. We think that in this relay race of generations it is extremely important not to lose sight of the subject, not to disrupt the connection between the days of 'Sturm und Drang' of the 1970s–1990s when the foundations of the CMB physics were laid and, let us say, the 'days of bliss' that we all anticipate to arrive roughly by the end of the first decade of this century when the WMAP and PLANCK projects will have been successfully completed. This is the reason why we attempted in the book to stand back from discussing the general aspects of cosmology and to focus mostly on specific theoretical problems of the formation of the CMB frequency spectrum, its anisotropy and polarization and their observational aspects; we assume the reader to have at least some general familiarity with the foundations of the theory of the 'hot Universe', physical cosmology, probability theory and mathematical statistics, the theory of random fields and atomic physics.

We have attempted to demonstrate in what way the modern apparatus of theoretical physics can be applied to studying the properties of cosmic plasma and how the limits of our knowledge of such fundamental natural phenomena as gravitation, relativity and relativism can be expanded owing to their symbiotic relationship with astrophysics.

We are grateful to all our colleagues in the Astrocosmic Centre of the P. N. Lebedev Physics Institute (FIAN, Moscow), Rostov State University, Copenhagen University, the Theoretical Astrophysics Centre (Copenhagen) and Oxford University for supporting our work and for numerous discussions.

We are especially grateful to E. V. Kotok for her enormous work preparing the manuscript of this book, and also for her participation in a number of research papers quoted in it.

Preface to the English edition

The English translation of our book appears three years after the first Russian edition, which was published in 2003. Cosmology, and specifically the cosmology of the cosmic microwave background (CMB), is the most rapidly evolving branch of science in our time, so there have been several important advances since the first edition of this book. Some extremely important developments – the publication of new observational results (particularly the observations of the Wilkinson Microwave Anisotropy Probe (WMAP) space mission), the discussion of these results in numerous papers, the formulation of new ideas on the physics of the CMB, and the creation of new mathematical and statistical methods for analysing CMB observations – have arisen since the completion of the Russian edition, originally entitled *Relic Radiation of the Universe.* The term 'cosmic microwave background' used in publications in the West (and now often in Russia) is rather clumsy. 'Relic radiation', introduced by the Russian astronomer I. S. Shklovskii, is an impressive name that appealed to many astrophysicists; however, since CMB is used in the specific literature in the field, we had to call the English version of our book *The Physics of the Cosmic Microwave Background*, and we continue using this term throughout the book.

In the original Russian edition, we tried to give a complete review of all the important topics in CMB physics. In preparing this edition, we tried hard to incorporate most of the new developments; however, we preserve the original spirit of the book in not striving to encompass the entire recent literature on the subject (especially as this now seems to be impossible, even in such an inflated volume). Nevertheless, we hope that the English edition presents the current situation in CMB physics.

This edition also includes a new eighth chapter, entitled 'The Wilkinson Microwave Anisotropy Probe (WMAP).' This chapter describes in detail the primary results of the most important CMB project of the last few years. In addition to the references recommended in the Preface to the Russian edition, we recommend the following books devoted to the subject: de Oliveira-Costa and Tegmark (1999), Freedman (2004), Lachiez-Rey and Gunzig (1999), Liddle (2003), Partridge (1995), Peacock (1999) and Peebles (1993).

We also used this opportunity to correct misprints and some imperfections detected when rereading the Russian edition. We are grateful to our translators, Nina Iskandarian and Vitaly Kisin, for their valuable help in preparing the English edition.

And last but not least, while working on the English edition we enjoyed unfailing support from the Niels Bohr Institute, Copenhagen, and Imperial College London. We wish to express our sincere thanks to these institutions and the wonderful people there who helped make this edition possible.