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BOOK REVIEW

Ruth Durrer: The cosmic microwave background

Cambridge University Press, 2008, 424 p., GBP 40.00 USD 80.00, ISBN-13: 9780521847049

Matthias Bartelmann

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Professor Durrer has undertaken the admirable endeavour to explain the theory of the cosmic microwave background (CMB) in a textbook, aimed at graduate students and researchers. She has done so hoping that "the subject is mature enough" for a textbook (p. 325). A high-level introduction to the physics of the CMB and the statistics of its analysis is certainly timely in an era of cosmology in which precise CMB observations play a key role in the development of the emerging cosmological standard model, and in which more sensitive, better resolved observations of the CMB temperature and polarisation fluctuations in wider frequency ranges are forthcoming. As the CMB is thus turning into one of the most solid pillars of modern cosmology, there is a clear need for a textbook capable of introducing advanced students into the field, bringing researchers up to speed, and providing authoritative material for lecturers.

The beauty of CMB physics is that the CMB arose when the universe was in a relatively simple state when fluctuations were still small, such that well-understood linear perturbation theory can be applied. Its challenge is that it combines many aspects of widely different areas of physics and mathematics. General relativity and the Friedmann–Lemaître models derived from it form the background on which everything develops. Statistical and thermal physics define how the universe and its ingredients evolve thermally. Relativistic perturbation theory provides the foundation for any treatment of the CMB. Relativistic kinetic theory describes how photons propagate in a curved, perturbed space-time. The study of the CMB polarisation requires the representation theory of the SO(3) group. Structures in the CMB are modified by gravitational lensing, foreground sources imprint secondary signals, and both effects need to be quantified and removed. High-level statistics is needed not only to derive

M. Bartelmann (✉)
Institute of Theoretical Astrophysics,
Albert-Überle-Str. 2, 69120 Heidelberg, Germany
e-mail: mbartelmann@ita.uni-heidelberg.de

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CMB temperature and polarisation power spectra, but in particular to extract cosmological parameters and their uncertainties from them. Thus, a thorough study of the CMB needs to cover and combine a wide range of subjects.

Professor Durrer structures her book into eight chapters and ten appendices. The first chapter introduces Friedmann–Lemaître cosmological models and their main properties, starting with their geometry and including their thermal evolution, primordial nucleosynthesis and the arguments for cosmological inflation. Most readers are likely to be familiar with the contents of this chapter, but for those it serves as a brief reminder and to fix terminology and notation.

The second chapter lays the foundation for everything to follow, as it introduces and discusses relativistic perturbation theory. It begins discussing the choice of gauge and the importance of working with gauge-invariant variables, then proceeds with the harmonic decomposition of perturbed scalar, vector and tensor quantities, derives the respective perturbation equations, discusses special cases and ends with the derivation of power spectra.

The generation of scalar, vector and tensor perturbations during inflation and thus of the initial conditions for perturbation theory is the subject of the short third chapter. Power spectra are derived, and the two main types of initial conditions, adiabatic and iso-curvature, are discussed.

Together with chapter two, chapters four and five form the core of the book. The largest part of chapter four is devoted to relativistic kinetic theory. Its origins are briefly summarised and the Liouville equation and the energy–momentum tensor are derived for scalar, vector and tensor perturbations. The chapter proceeds with the Boltzmann equation with Thomson scattering causing the collision term, and ends with Silk damping and a summary of the perturbation equations. Chapter five turns to the polarisation of the CMB. First, polarisation is transformed to its E and B-mode components, which do not depend on the particular reference frame, but require the spin-2 spherical harmonics for their decomposition on the sphere. Polarisation power spectra are being derived before the Boltzmann equation for the transport of the CMB polarisation is set up and solved.

Chapter six addresses the problem how cosmological parameters can be extracted from measured CMB temperature and polarisation power spectra. It begins by summarising the influence of physical parameters on the CMB observables and proceeds discussing the effects of antenna beams, window functions, and cosmic variance. Statistical methods are described next, emphasising Bayesian statistics, the Fisher information matrix and Monte-Carlo Markov chains. The chapter ends with a discussion of parameter degeneracies and the combination of CMB with other cosmological data.

Chapter seven introduces cosmological gravitational lensing and studies its effect on the CMB temperature and polarisation patterns, deriving the characteristic distortions of their power spectra both on the full sky and in the flat-sky limit.

Finally, a short eighth chapter concludes the main part of the book describing distortions of the electromagnetic CMB spectrum away from its Planck shape. Compton scattering, the Kompaneets equation and thermal bremsstrahlung form a major part of it, followed by constraints on the chemical potential and an introduction to the Sunyaev-Zel'dovich effect.

The book has a rich appendix of almost 70 pages, structured into ten sections. The first three essentially clarify the notation, the fourth mainly explains the normal and spin-weighed spherical harmonics, the following five fill gaps in derivations of the main part of the book and offer additional explanations and background, and the tenth section gives solutions to selected exercises.

Professor Durrer's book is an admirable achievement. First of all, it is a pleasure to read in its very clear, lucid and sometimes laconic style. It is full of remarkably deep insights, showing up in many places where conceptual difficulties are usually swept under the rug. Not so in this book, which clearly articulates them together with their solution.

It is among the great virtues of this book that the derivations are traced back to elementary or fundamental concepts. They are sometimes not carried out in all steps, but then references are given to where the full derivations can be found. The level of understanding facilitated by the book is enormous, as it traces all of CMB physics back to its roots in General Relativity, thermal physics, kinetic theory and classical electrodynamics.

Arguably the most difficult chapter is the second, where gauge-invariant, relativistic perturbation theory is developed. However, it remains enjoyable because of its stringent and elegant way of proceeding, which culminates towards the end in the special cases discussed. This chapter is characteristic for the entire book. The foundations are always laid on fundamental principles and concepts, clarifying their origins in the most comprehensible way. The following mathematics is elegant even where the calculations are lengthy, which becomes particularly visible in chapters two and five. The summaries of the physics following long calculations allow the reader to follow the main ideas of the development even if some steps should have remained unclear.

This is not an easy book, and working through it requires time and patience. It also requires solid knowledge at least of General Relativity and statistical physics, and some representation theory of groups certainly helps. However, the reward is enormous, since the book clarifies all aspects of CMB physics by tracing them back to their roots in fundamental theory, and at the same time branches out into practically most relevant issues of CMB statistics.

On the whole, I believe that Professor Durrer's book is a masterpiece which appears at exactly the right time. Although it superbly covers a remarkably broad range of subjects, it leaves the impression of being written with ease. From the first to the last page, it is a pleasure to read, and it is an extremely rich source of knowledge and insight. It illustrates and summarises the physics of one of the cornerstones of modern cosmology, and it will certainly serve generations of graduate students and researchers as an inspiring guide to CMB physics.