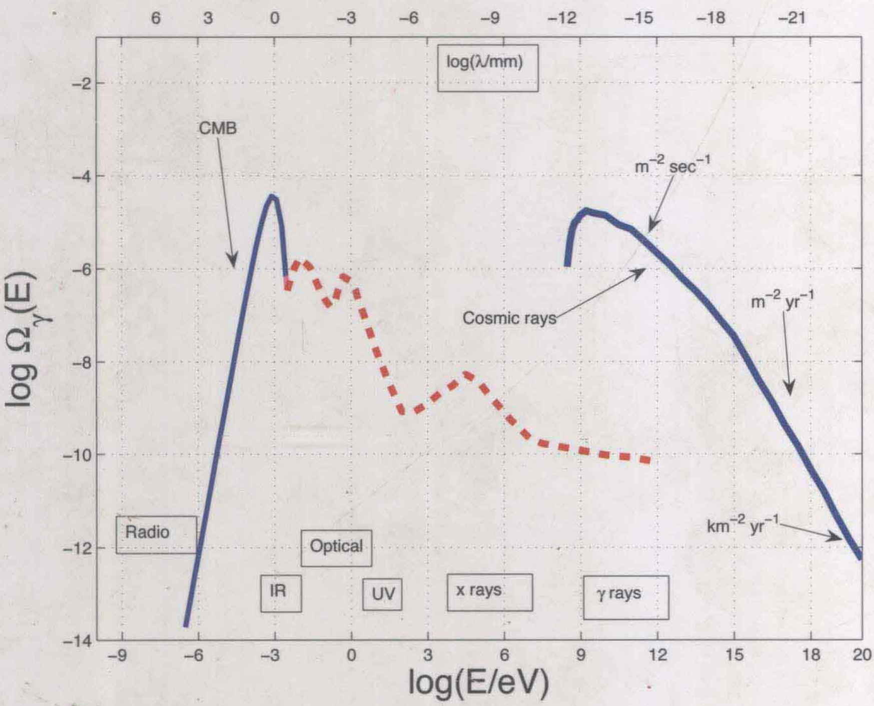
A Primer on the Physics of the Cosmic Microwave Background



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To Sergio Fubini

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Preface

More than three score years ago, high-energy physicists were driven to scrutinize the properties of the cosmic radiation then available (i.e. cosmic rays). Today the same situation is realized not only with cosmic rays but also with different cosmological data: most notably, with the Cosmic Microwave Background (CMB in what follows). While I am writing this preface, European science is at the forefront of the developments in high-energy physics and cosmology thanks to the Large Hadron Collider program and thanks also to the Planck explorer mission. Today laboratory physics and celestial physics give us contradictory indications: it seems that all the matter accessible to terrestrial laboratory experiments contributes only 5% to the total energy budget of the Universe.

Cosmologists and astrophysicists today cannot ignore the knowledge of the micro-world provided by high-energy physics. In similar terms, high-energy physicists cannot avoid being exposed to some of the key concepts in modern gravitation and cosmology. While grand unifications of all fundamental forces are one of the intriguing hopes suggested by current theoretical speculations, the opportunity of a small unification lies already before us in the years to come: the construction of a common language which will allow, in the near future, a more effective exchange of information and ideas between contiguous branches of the physics community. The present book seeks to be a modest contribution to this mighty endeavor.

This book grew through the last decade because of various series of lectures that were either directly or indirectly connected to CMB physics and, more generally, to gravitation. In the last couple of years I came to the conclusion that an effective way of presenting a cosmology course (either for last year undergraduate or for PhD students) is to use CMB as a guiding theme. While lecturing to PhD students I have been confronted with the problem of giving a sufficiently accurate and updated information to an audience that was, very often, rather composite. Not all PhD students were exposed to General Relativity or field theory in their undergraduate courses. Similarly, not all PhD students have a preliminary knowledge of astrophysics. I have tried, therefore, to present the material in a reasonably self-contained manner also in view of the time limitations imposed by a PhD course.

My warm acknowledgment goes to the Enrico Fermi center for a senior research grand entitled *From the Planck Scale to the Hubble Radius*. Without this support my efforts would have been forlorn. In commencing this script I wish also to express my very special and sincere gratitude to Prof. G. Cocconi and Prof. E. Picasso. I am indebted to G. Cocconi for his advice in the preparation of the first section. I am indebted to E. Picasso for delightful discussions which have been extremely relevant both for the selection of topics and for the overall quality of the manuscript.

Massimo Giovannini

Contents

Preface vii

Part I **1**

1. Why CMB Physics? 3

1.1 The blackbody spectrum and its physical implications . 8
1.2 A bit of history of CMB observations 12
1.3 The entropy of the CMB and its implications 14
1.4 The time evolution of the CMB temperature 16
1.5 A quick glance to the Sunyaev-Zeldovich effect 18
1.6 Cosmological parameters 22

2. From CMB to the Standard Cosmological Model 29

2.1 The Standard Cosmological Model (SCM) 30
2.1.1 Homogeneity and isotropy 31
2.1.2 Perfect barotropic fluids 32
2.1.3 General Relativity 37
2.2 Friedmann-Lemaître equations 40
2.3 Matter content of the SCM 44
2.4 The future of the Universe 47
2.5 The past of the Universe 51
2.5.1 Hydrogen recombination 54
2.5.2 Coulomb scattering: the baryon-electron fluid . . 59
2.5.3 Thompson scattering: the baryon-photon fluid . 60
2.6 Simplified numerical estimates 64

Part II 67

3. Problems with the SCM 69

3.1 The horizon problem 70
3.2 The spatial curvature problem 74
3.3 The entropy problem 75
3.4 The structure formation problem 76
3.5 The singularity problem 79

4. SCM and Beyond 81

4.1 The horizon and the flatness problems 81
4.2 Classical and quantum fluctuations 88
4.3 The entropy problem 93
4.4 The problem of geodesic incompleteness 97

5. Essentials of Inflationary Dynamics 101

5.1 Fully inhomogeneous Friedmann-Lemaître equations . . . 101
5.2 Homogeneous evolution of a scalar field 108
5.3 Classification(s) of inflationary backgrounds 112
5.4 Exact inflationary backgrounds 116
5.5 Slow-roll dynamics 120
5.6 Slow-roll parameters 123

Part III 127

6. Inhomogeneities in FRW Models 129

6.1 Decomposition of inhomogeneities in FRW Universes . . 131
6.2 Gauge issues for the scalar modes 133
6.3 Super-adiabatic amplification 136
6.4 Quantum mechanical description of the tensor modes . . 141
6.5 Spectra of relic gravitons 150
6.6 Quantum state of cosmological perturbations 151
6.7 Digression on different vacua 156
6.8 Numerical estimates of the mixing coefficients 164

7. The First Lap in CMB Anisotropies 171

7.1 Tensor Sachs-Wolfe effect 172

7.2 Scalar Sachs-Wolfe effect 175
7.3 Scalar modes in the pre-decoupling phase 179
7.3.1 Scale crossing and CMB initial conditions 182
7.4 CDM-radiation system 183
7.5 Adiabatic and non-adiabatic modes: an example 188
7.6 Sachs-Wolfe plateau: mixture of initial conditions 196

8. Improved Fluid Description of Pre-Decoupling Physics 205

8.1 The general plasma with four components 206
8.2 CDM component 208
8.3 Tight-coupling between photons and baryons 216
8.4 Shear viscosity and silk damping 218
8.5 The adiabatic solution 220
8.6 Pre-equality non-adiabatic initial conditions 223
8.6.1 The CDM-radiation mode 224
8.6.2 The baryon-entropy mode 228
8.6.3 The neutrino-entropy mode 229
8.7 Numerics in the tight-coupling approximation 232
8.7.1 Interpretation of the numerical results 237
8.7.2 Numerical estimates of diffusion damping 242

9. Kinetic Hierarchies 247

9.1 Collisionless Boltzmann equation 248
9.2 Boltzmann hierarchy for massless neutrinos 251
9.3 Brightness perturbations of the radiation field 255
9.4 Evolution equations for the brightness perturbations . . 257
9.4.1 Visibility function 259
9.5 Line of sight integrals 261
9.5.1 Angular power spectrum and observables 267
9.6 Tight-coupling expansion 270
9.7 Zeroth order in tight-coupling: acoustic oscillations . . . 272
9.7.1 Solutions of the evolution of monopole and dipole 274
9.7.2 Estimate of the sound horizon at decoupling . . 276
9.8 First order in tight-coupling: polarization 278
9.8.1 Improved estimates of polarization 278
9.8.2 Polarization power spectra 281

9.9 Second order in tight-coupling: diffusion damping 287
9.10 Semi-analytical approach to Doppler oscillations 292

10. Early Initial Conditions? 305

10.1 Minimally coupled scalar field 307
10.1.1 Gauge-invariant description 308
10.1.2 Curvature perturbations and scalar normal modes 310
10.2 Spectral relations 312
10.2.1 Some slow-roll algebra 312
10.2.2 Tensor power spectra 315
10.2.3 Scalar power spectra 318
10.2.4 Consistency relation 319
10.3 Curvature perturbations and density contrasts 320
10.4 Hamiltonians for the scalar problem 322
10.5 Trans-Planckian problems? 324
10.5.1 Minimization of canonically related Hamiltonians 327
10.5.2 Back-reaction effects 331
10.6 How many adiabatic modes? 334

Part IV **339**

11. Surfing on the Gauges 341

11.0.1 Generalities on scalar gauge transformations . . 342
11.1 The longitudinal gauge 346
11.1.1 Gauge-invariant generalizations 347
11.2 The synchronous gauge 349
11.2.1 Evolution equations in the synchronous gauge . . 352
11.2.2 The adiabatic mode in the synchronous gauge . . 357
11.2.3 Entropic modes in the synchronous gauge 359
11.3 Comoving orthogonal hypersurfaces 362
11.4 Uniform density hypersurfaces 364
11.5 The off-diagonal gauge 367
11.5.1 Evolution equations in the off-diagonal gauge . . 369
11.6 Mixed gauge-invariant treatments 372

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12. Interacting Fluids 377

12.1 Interacting fluids with bulk viscous stresses 379
12.2 Evolution equations for the entropy fluctuations 381
12.3 Specific physical limits 385
12.4 Mixing between entropy and curvature perturbations . . 386

13. Spectator Fields 391

13.1 Spectator fields in a fluid background 393
13.2 Unconventional inflationary models 400
13.3 Conventional inflationary models 403

Appendix A The Concept of Distance in Cosmology 409

A.1 The proper coordinate distance 409
A.2 The redshift 411
A.3 The distance measure 413
A.4 Angular diameter distance 415
A.5 Luminosity distance 416
A.6 Horizon distances 417
A.7 Few simple applications 417

Appendix B Kinetic Description of Hot Plasmas 421

B.1 Generalities on thermodynamic systems 421
B.2 Fermions and bosons 423
B.3 Thermal, kinetic and chemical equilibrium 425
B.4 An example of primordial plasma 427
B.5 Electron-positron annihilation and neutrino decoupling . 429
B.6 Big-bang nucleosynthesis (BBN) 431

Appendix C Scalar Modes of the Geometry 435

C.1 Fluctuations of the Einstein tensor 435
C.2 Fluctuations of the energy-momentum tensor(s) 437
C.3 Fluctuations of the covariant conservation equations . . . 439
C.4 Some algebra with the scalar modes 441

Appendix D Metric Fluctuations: Gauge-Independent Treatment 445

D.1 The scalar problem 446
D.2 The vector problem 447

D.3 The tensor problem 448
D.4 Inhomogeneities of the sources 449

Bibliography 455

Index 467

Part I

Cosmic Microwave Background Physics and the Formulation of the Standard Cosmological Model

Chapter 1

Why CMB Physics?

When approaching a new subject of study, especially within the realm of empirical sciences, the relevant question to ask is always the same: why should we learn about this? So, why should we learn about CMB physics? To answer this kind of questions one might be tempted to invoke either historical or subjective arguments. For instance one could say that, historically, blackbody emission is rather interesting in itself since it represented, at the dawn of the century, one of the fragile bridges that allowed us to pass from a classical description of macroscopic phenomena to the quantum mechanical language which is today the most appropriate for the discussion of microscopic physics. On a more aesthetic (and hence subjective) level, one could also affirm that blackbody emission is beautiful since it depends only upon one crucial parameter, i.e. the temperature. Subjectivity in science is very important since it drives the enthusiasm of researchers towards new and exciting fields of investigation. At the same time any subjective self-excitation should be gauged by more objective elements of judgment. Objectivity, for natural scientists, rhymes with testability. The quest for objectivity does not imply the lack of fantasy but, on the contrary, it just focuses our theoretical endeavor.

In this introductory chapter the theme will be to stress that there are objective elements that make CMB physics one of the most attractive and promising frameworks for gathering indirect informations on the early stages of the life of our own Universe. After a general introduction to blackbody emission, the motivations of this script will be spelled out. The bottom line will be that, indeed, the CMB is cosmological and represents the dominant component of the detected extra-galactic emission.

The whole observable Universe will therefore be approached, in the first approximation, as a system emitting electromagnetic radiation. The topics to be treated in the present chapter are therefore the following:

- electromagnetic emission of the Universe;
- the blackbody spectrum;
- a bit of history of the CMB observations;
- the entropy of the CMB and its implications;
- the time evolution of the CMB temperature;
- a quick glance at the Sunyaev-Zeldovich effect.

All along this script the natural system of units will be adopted. In this system

$$\hbar = c = k_{\rm B} = 1, \tag{1.1}$$

where $\hbar = h/2\pi$, c is the speed of light and $k_{\rm B}$ is the Boltzmann constant. In order to pass from one system of units to the other it is useful to recall that

- $\hbar c = 197.327\,\text{MeV fm}$;
- $\text{K} = 8.617 \times 10^{-5}\,\text{eV}$;
- $(\hbar c)^2 = 0.389\,\text{GeV}^2\,\text{mbarn}$;
- $c = 2.99792 \times 10^{10}$ cm/sec.

In Fig. 1.1 a rather intriguing plot summarizes the electromagnetic emission of our own Universe. Only the extra-galactic emissions are reported.[a] On the horizontal axis we have the logarithm of the energy of the photons (expressed in eV). On the vertical axis we reported the logarithm (to base 10) of $\Omega_{\gamma}(E)$ which is defined as

$$\Omega_{\gamma}(E) = \frac{1}{\rho_{\rm crit}} \frac{d\rho_{\gamma}}{d\ln E}. \tag{1.2}$$

The specific form of $\Omega_{\gamma}(E)$ in the case of the CMB branch of the spectrum will be discussed in the following section (see, for instance, Eq. (1.12)). For the moment it suffices to note that $\Omega_{\gamma}(E)$ measures the energy density of the emitted radiation in critical units. The critical energy density $\rho_{\rm crit}$ can be understood, grossly speaking, as the mean energy density of the Universe, i.e. for the current values of the cosmological parameters, the energy density equivalent to about six proton masses per cubic meter (see, for instance, Eq. (1.11)).

[a]By extra-galactic emissions we mean radiation coming from the outside of our galaxy. Of course, as stressed later on, it must be borne in mind that our own galaxy is also an efficient emitter of electromagnetic radiation.

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