

Contents

Part I. The Standard Big-Bang Model

1. The Cosmological Models	3
1.1 Friedmann–Lemaître Space-Time	4
1.2 The Initial Singularity	11
1.3 Light Propagation in an FL Model	16
1.4 Explicit Solutions	20
Exercises	25
2. Facts – Observations of Cosmological Significance	29
2.1 Age Determinations	46
2.1.1 The Age of the Solar System	46
2.1.2 The Age of the Elements	50
2.1.3 The Age of Globular Clusters	55
2.2 The Hubble Constant H_0 – How Big is the Universe?	60
2.2.1 Cepheids in Virgo	64
2.2.2 Type Ia Supernovae as Standard Candles	67
2.2.3 Some Statistical Aspects	72
2.2.4 Other Methods to Determine H_0	76
2.2.5 Evidence for a Local Anisotropy of the Hubble Flow	78
2.2.6 Side Remarks	81
2.2.7 Conclusion	82
2.3 The Mean Density	84
2.3.1 M/L Ratios for Galaxies	87
2.3.2 Estimates of Ω_m from Galaxies	96
2.3.3 Estimates of Ω_m from Clusters of Galaxies	98
2.3.4 The Cosmic Virial Theorem	106
2.3.5 Infall to the Virgo Cluster	108
2.3.6 Large-Scale Peculiar Motions	108
2.3.7 An Upper Limit to $\Omega_{0,B}$	111
2.3.8 Conclusion	112
2.4 Ω_Λ Estimates	112
2.5 The 3 K Cosmic Black-Body Radiation	113
2.5.1 The Spectrum	114

2.5.2	Isotropy of the Background.....	118
2.5.3	A Limit to Cosmic Ray Energies.....	125
2.5.4	The Sunyaev–Zel’dovich Effect.....	125
2.6	The X-ray Background.....	128
2.7	Evolutionary Effects.....	129
2.7.1	Counts of Radio Sources.....	129
2.7.2	The Luminosity–Volume Test for Quasars.....	134
2.7.3	Direct Evidence for Cosmic Evolution.....	134
	Exercises.....	136
3.	Thermodynamics of the Early Universe in the Classical Hot Big-Bang Picture.....	141
3.1	Thermodynamic Equilibrium.....	142
3.1.1	Statistical Equilibrium Distributions.....	142
3.1.2	The Neutrino Temperature.....	148
3.2	Nucleosynthesis.....	153
3.2.1	The Neutron-to-Proton Ratio.....	154
3.2.2	Nuclear Reactions.....	157
3.3	Observations of Cosmic Abundances.....	162
3.3.1	The Abundance of ^4He	163
3.3.2	The Deuterium Abundance.....	165
3.3.3	The ^3He Abundance.....	166
3.3.4	The ^7Li Abundance.....	167
3.3.5	Conclusion.....	169
3.4	Helium Abundance and Neutrino Families.....	171
3.5	Non-standard Scenarios.....	172
	Exercises.....	173
4.	Can the Standard Model Be Verified Experimentally?....	175
4.1	Ideal Galactic Observations.....	175
4.2	Real Observations.....	179
4.2.1	Observational Methods.....	180
4.2.2	Observational Limits.....	182
4.2.3	Effects of Evolution.....	183
4.2.4	Selection Effects.....	184
4.2.5	Uncertainty Increases with Redshift.....	187
4.3	Outline of a Procedure to Verify the FL Universe.....	188
4.3.1	Isotropy.....	188
4.3.2	Homogeneity.....	189
4.3.3	The Mixmaster Universe.....	193
4.4	The Classical Cosmological Tests.....	194
4.4.1	Observational Relations.....	194
4.4.2	Cosmological Tests.....	196
4.5	Concluding Remarks.....	198
	Exercises.....	200

Part II. Particle Physics and Cosmology

5. Gauge Theories and the Standard Model	203
5.1 Introduction – The Concept of Gauge Invariance	204
5.2 Yang–Mills Theory	208
5.3 Spontaneous Symmetry-Breaking	212
5.4 The Higgs Mechanism	216
5.5 The Salam–Weinberg Theory of Electroweak Interactions	222
5.6 The Colour Gauge Theory of Strong Interactions – Quantum Chromodynamics	230
5.7 Successes and Problems of the Standard Model	236
Exercises	238
6. Grand Unification Schemes	241
6.1 $SU(5)$ GUT	242
6.1.1 The Group Structure	242
6.1.2 Spontaneous Symmetry-Breaking	250
6.2 Evolution of the Coupling Constants	253
6.3 Nucleon Decay in $SU(5)$ GUT	258
6.4 Beyond $SU(5)$	261
6.4.1 General Remarks	261
6.4.2 Larger Gauge Groups	262
6.4.3 Neutrino Masses	263
6.5 Axions	264
6.6 SUSY GUT	270
6.6.1 Supersymmetry	270
6.6.2 Particle Masses	275
6.6.3 Effects of the Photino in Astrophysics	276
6.6.4 Effects of the Gravitino	277
6.6.5 A Few Comments	278
6.7 Monopoles, Strings, and Domain Walls	279
6.7.1 Magnetic Monopoles	283
6.7.2 Strings	287
6.7.3 Domain Walls	291
6.7.4 Textures	293
6.8 Further Developments	293
6.9 Superstrings	296
6.10 Quantum Gravity	298
Exercises	302

7. Relic Particles from the Early Universe	305
7.1 Introductory Remarks	306
7.2 Production, Destruction, and Survival of Particles	308
7.3 Massive Neutrinos	314
7.3.1 Experimental Limits	314
7.3.2 The Solar Neutrino Puzzle	319
7.3.3 Atmospheric Neutrinos	322
7.3.4 Neutrinos from Supernova 1987A in the Large Magellanic Cloud	323
7.3.5 Theoretical Possibilities	324
7.3.6 Cosmological Limits for Stable Neutrinos	325
7.3.7 Asymmetric Neutrinos	326
7.3.8 Unstable Neutrinos	327
7.3.9 Neutrino Generations	328
7.4 Axions	329
7.5 Domain Walls, Strings, Monopoles	331
7.5.1 Domain Walls	331
7.5.2 Strings	332
7.5.3 Monopoles	332
7.5.4 Textures	333
7.6 Gravitinos, Photinos, and Neutralinos	333
7.7 QCD Transition Relics – The Aborigines of the Nuclear Desert	334
Exercises	337
8. Baryon Synthesis	339
8.1 Evidence for B -Asymmetry	340
8.2 Some Qualitative Remarks	341
8.3 GUTs and Thermodynamic Equilibrium	343
8.4 A Mechanism for Baryon Synthesis	347
8.5 The Electroweak Phase Transition and Baryon Synthesis	353
Exercises	355
9. The Inflationary Universe	357
9.1 Some Puzzles of the Standard Big-Bang Model, or Uneasiness About Certain Initial Conditions	357
9.2 The Inflationary Universe – A Qualitative Account	363
9.3 The Old and the New Inflationary Cosmology	364
9.4 Model for the Transition from $\varphi = 0$ to $\varphi = \sigma$ in the Context of the “New” Inflationary Universe	371
9.5 Chaotic Inflation	373
9.6 Other Models	378
9.6.1 Power Law Inflation	379
9.6.2 Extended Inflation	379
9.6.3 R^2 Inflation	379
9.6.4 Others	379

9.7	The Spectrum of Fluctuations	380
9.7.1	Basic Features	380
9.7.2	A Detailed Calculation	381
9.8	Summary of a Few Difficulties	384
9.8.1	Tunnelling Probabilities	384
9.8.2	Inflation in Anisotropic, Inhomogeneous Cosmological Models	386
9.8.3	The Reheating Problem	387
9.8.4	Convexity and Gauge-Dependence of V_{eff}	388
9.9	Concluding Remarks	391
	Exercises	395

Part III. Dark Matter and Galaxy Formation

10.	Typical Scales – From Observation and Theory	399
10.1	The Clustering of Galaxies	400
10.1.1	Visual Impressions	400
10.1.2	Correlation Functions	411
10.1.3	Distribution of Dark Matter	414
10.2	Typical Scales Derived from Theory	417
10.2.1	The Jeans Mass for an Adiabatic Equation of State	417
10.2.2	The “Jeans Mass” for Collisionless Particles	421
10.2.3	The Adiabatic Damping Scale	423
10.2.4	The Horizon Scale	426
10.2.5	Damping by Free Streaming and Directional Dispersion	427
	Exercises	428
11.	The Evolution of Small Perturbations	431
11.1	Some Remarks on the Case of Spherical Symmetry	431
11.1.1	Spherical Fluctuations in a Friedmann Universe	431
11.1.2	Linearized Spherical Perturbations	432
11.1.3	Non-linear Spherical Fluctuations	433
11.2	Newtonian Theory of Small Fluctuations	436
11.2.1	Evolution with Time	436
11.2.2	Observational Constraints on Adiabatic Fluctuations	441
11.2.3	Non-linear Newtonian Perturbations	442
11.3	Relativistic Theory of Small (Linearized) Fluctuation	443
11.3.1	Gauge-Invariant Formalism	443
11.3.2	Adiabatic Perturbations of a Single Ideal Fluid	444
11.3.3	Perturbation Modes	447
11.4	The Power Spectrum of the Density Fluctuations	448
11.4.1	The rms Fluctuation Spectrum	448
11.4.2	Change in the Linear $P(k)$ at $t = t_{\text{eq}}$	451
11.4.3	Normalization	452

11.5	Primeval Fluctuation Spectrum	453
11.5.1	Attempts to Derive δ_H	454
11.5.2	Perturbations in the Inflationary Universe	454
11.6	CMB Anisotropies	456
11.6.1	Recombination	458
11.6.2	Anisotropy Formation	459
11.6.3	Dependence on Model Parameters	463
11.7	Non-baryonic “Hot” and “Warm” Dark Matter	467
11.7.1	Neutrino Stars	468
11.7.2	Typical Scales for Hot DM	469
11.7.3	The Hot-DM Fluctuation Spectrum	471
11.7.4	The “Pancake Model” for Galaxy Formation	473
11.7.5	Problems with Massive Neutrinos	476
11.7.6	Candidates for Warm DM	477
11.7.7	Fluctuation Spectrum for Warm DM	477
11.7.8	Problems with Warm DM	479
11.8	Non-baryonic Cold Dark Matter	480
11.8.1	The Growth of Fluctuations	480
11.8.2	Galaxy and Cluster Formation	481
11.8.3	Problems with Cold DM	482
11.9	What’s Wrong with Baryonic Galaxy Formation?	483
11.9.1	Excluding Baryons from Galactic Halos	483
11.9.2	Deuterium Limit	483
11.9.3	The Growth of Fluctuations	483
11.10	Topological Defects and Galaxy Formation	485
11.10.1	Strings and Galaxy Formation	487
	Exercises	490
12.	Non-linear Structure Formation	493
12.1	General Remarks	493
12.2	N -Particle Simulations	495
12.2.1	Equations of Motion	495
12.2.2	The Model of the Simulation	497
12.3	Simulations with Cold Dark Matter	502
12.3.1	Initial Conditions	502
12.3.2	The Simulations	505
12.4	Comparison with Observations	511
12.4.1	Correlation Functions and the Las Campanas Redshift Survey	512
12.4.2	A Phenomenological Bias Model	521
12.4.3	The PSCz Survey	522
12.4.4	Three-Point Correlation Functions	524
12.4.5	A Few More Observations	526
12.4.6	High-Redshift Objects	528
12.4.7	Conclusion	529

12.5	Neutrinos and Large-Scale Structure Formation	529
12.5.1	The Coherence Length	529
12.5.2	The Vlasov Equation for Massive Neutrinos	531
12.5.3	Cooking Pancakes	533
12.5.4	Mixed DM Models	534
12.6	Analytic Approaches	535
12.6.1	Dynamics and Statistics	535
12.6.2	The Cosmic Virial Theorem	539
12.6.3	Analytic Solutions	540
12.6.4	The Press–Schechter Mass Function	542
12.7	How Did Galaxies Form?	544
12.7.1	What Does Galaxy Formation Mean?	544
12.7.2	What Sets the Observed Distributions of Galaxy Properties?	545
12.7.3	What Does Galaxy Evolution Tell Us About Galaxy Formation?	546
12.7.4	What Is Galaxy Bias?	547
12.7.5	How Are Protogalaxies Related to the Intergalactic Medium at High Redshift?	548
	Exercises	548
A.	The Gauge-Invariant Theory of Perturbations	551
A.1	The “3+1” Formalism	551
A.1.1	Unperturbed Solutions	552
A.1.2	Small Perturbations	553
A.2	Perturbations of $g_{\mu\nu}$ and $T_{\mu\nu}$	554
A.3	Gauge-Invariant Variables	555
A.4	Linearized Einstein Equations for Gauge-Invariant Variables	558
A.5	The General Solution	559
B.	Recent Developments	
	First Year Results from WMAP	563
B.1	Temperature Anisotropies	563
B.2	Polarization Signal	565
	References	567
	Index	585