

Contents

Part I The Standard Big-Bang Model

1. The Cosmological Models	3
1.1 The Friedmann-Lemaître (FL) Space-Times	4
1.2 The Initial Singularity	10
1.3 Light Propagation in a FL Model	14
1.4 Explicit Solutions	18
1.5 A Special Anisotropic Homogeneous Model	22
2. Facts – Observations of Cosmological Significance	26
2.1 Age Determinations	33
2.1.1 The Age of the Solar System	33
2.1.2 The Age of the Elements	36
2.1.3 The Age of Globular Clusters	40
2.2 The Hubble Constant H_0 – How Big is the Universe?	44
2.2.1 The Cosmic Distance Scale and H_0	45
2.2.2 Evidence for a Local Anisotropy of the Hubble Flow	53
2.2.3 A Cosmological Redshift-Distance Square Law?	57
2.2.4 Other Methods of Determining H_0	58
a) Supernovae and the Distance Scale	58
b) Direct Estimate from the Double Quasar 0957 + 61	59
2.2.5 Conclusion	60
2.3 The Mean Density	61
2.3.1 M/L Ratios for Galaxies	63
a) Elliptical Galaxies	63
b) Disk Galaxies	65
c) The Luminosity Function of Galaxies	68
2.3.2 The Cosmic Virial Theorem	70
2.3.3 Infall to the Virgo Cluster	72
2.3.4 Ω_0 from the IRAS Galaxies	72
2.3.5 An Upper Limit to Ω_0	74
2.3.6 Conclusion	74
2.4 Evolutionary Effects	74
2.4.1 Counts of Radio Sources	75
2.4.2 The Luminosity-Volume Test for Quasars	79
2.4.3 Conclusion, q_0 Measurement	79
2.5 The 3-K Cosmic Black-Body Radiation	80
2.5.1 The Spectrum	81

2.5.2 Isotropy of the Background	82
2.5.3 Possible Distortions of the 3-K Background	86
2.6 The X-Ray Background	87
3. Thermodynamics of the Early Universe in the Classical Hot-Big-Bang Picture	90
3.1 Thermodynamic Equilibrium	91
3.1.1 Statistical Equilibrium Distributions	91
3.1.2 The Neutrino Temperature	96
3.2 Nucleosynthesis	101
3.2.1 The Neutron-to-Proton Ratio	101
3.2.2 Nuclear Reactions	104
3.3 Observations of Cosmic Abundances	108
3.3.1 The Abundance of ^4He	108
3.3.2 The Deuterium Abundance	110
3.3.3 The ^3He Abundance	111
3.3.4 The ^7Li Abundance	112
3.3.5 Conclusion	112
3.4 Helium Abundance and Neutrino Families	113
4. Can the Standard Model be Verified Experimentally?	115
4.1 Ideal Galactic Observations	115
4.2 Realistic Observations	120
4.2.1 Observational Methods	121
4.2.2 Observational Limits	122
4.2.3 Effects of Evolution	124
4.2.4 Selection Effects	124
4.2.5 Uncertainty Increases with Redshift	127
4.3 Verification of the FL Universes	127
4.3.1 Isotropy	128
4.3.2 Homogeneity	128
4.3.3 The Mixmaster Universe	132
4.4 Concluding Remarks	133

Part II Particle Physics and Cosmology

5. Gauge Theories and the Standard Model	137
5.1 Introduction – The Concept of Gauge Invariance	137
5.2 Yang-Mills Theory	141
5.3 Spontaneous Symmetry-Breaking	145
5.4 The Higgs-Mechanism	149
5.5 The Salam-Weinberg Theory of Electroweak Interactions	154
5.6 The Colour Gauge Theory of Strong Interactions – Quantum Chromodynamics (QCD)	161
5.7 Successes and Problems of the Standard Model	166

6. Grand Unification Schemes	169
6.1 $SU(5)$ – GUT	170
6.1.1 The Group Structure	170
6.1.2 Spontaneous Symmetry-Breaking	177
6.2 Evolution of the Coupling Constants	181
6.3 Nucleon Decay in $SU(5)$ – GUT	185
6.4 Beyond $SU(5)$	188
6.4.1 Critical Remarks	188
6.4.2 Larger Gauge Groups	189
6.4.3 Neutrino Masses	190
6.5 Axions	192
6.6 SUSY-GUT	197
6.6.1 Supersymmetry	197
6.6.2 Particle Masses	201
6.6.3 Effects of the Photino in Astrophysics	202
6.6.4 Effects of the Gravitino	203
6.6.5 A Few Comments	205
6.7 Monopoles, Strings, and Domain Walls	206
6.7.1 Magnetic Monopoles	209
6.7.2 Strings	213
6.7.3 Domain Walls	217
6.8 Further Developments	218
6.8.1 Kaluza-Klein Theories	220
6.8.2 Superstrings	222
7. Relic Particles from the Early Universe	224
7.1 Introductory Remarks	225
7.2 Production, Destruction, and Survival of Particles	227
7.3 Massive Neutrinos	233
7.3.1 Experimental Limits	233
7.3.2 The Solar Neutrino Puzzle	237
a) Neutrinos from Supernova 1987 A in the Large Magellanic Cloud	239
7.3.3 Theoretical Possibilities	240
7.3.4 Cosmological Limits for Stable Neutrinos	241
7.3.5 Asymmetric Neutrinos	243
7.3.6 Unstable Neutrinos	243
7.3.7 Neutrino Generations	246
7.4 Axions	247
7.5 Domain Walls, Strings, Monopoles	250
7.5.1 Domain Walls	250
7.5.2 Strings	252
7.5.3 Monopoles	252
7.6 Gravitinos and Photinos	253
7.7 QCD Transition Relics – The Aborigines of the Nuclear Desert	253

8. Baryon Synthesis	257
8.1 Evidence for B -Asymmetry	258
8.2 Some Qualitative Remarks	259
8.3 GUTs and Thermodynamic Equilibrium	261
8.4 A Mechanism for Baryon Synthesis	264
9. The Inflationary Universe	272
9.1 Some Puzzles of the Standard Big-Bang Model – or – Uneasiness About Certain Initial Conditions	272
9.2 The Inflationary Universe – A Qualitative Account	278
9.3 The Old and the New Inflationary Cosmology	281
9.4 Model for the Transition from $\varphi = 0$ to $\varphi = \sigma$ in the Context of the “New” Inflationary Universe	285
9.5 The Spectrum of Fluctuations	289
9.6 Chaotic Inflation	291
9.7 Summary of a Few Difficulties	291
9.7.1 Tunnelling Probabilities	291
9.7.2 Inflation in Anisotropic, Inhomogeneous Cosmological Models	293
9.7.3 The Reheating Problem	295
9.7.4 Convexity and Gauge-Dependence of V_{eff}	295
9.8 Concluding Remarks	297

Part III Dark Matter and Galaxy Formation

10. Typical Scales – From Observation and Theory	303
10.1 The Clustering of Galaxies	304
10.1.1 Visual Impressions	304
10.1.2 Orientation Effects	312
10.1.3 Correlation Functions	313
10.1.4 Distribution of Dark Matter	317
10.2 Typical Scales Derived from Theory	319
10.2.1 The Jeans Mass for an Adiabatic Equation of State	319
10.2.2 The ‘Jeans Mass’ for Collisionless Particles	323
10.2.3 The Adiabatic Damping Scale	325
10.2.4 The Horizon Scale	328
10.2.5 Damping by Free Streaming and Directional Dispersion	329
11. The Evolution of Small Perturbations	330
11.1 Some Remarks on the Case of Spherical Symmetry	330
11.1.1 Spherical Fluctuations in a Friedmann Universe	330
11.1.2 Linearized Spherical Perturbations	331
11.1.3 Non-linear Spherical Fluctuations	332
11.2 Newtonian Theory of Small Fluctuations	334
11.2.1 The Evolution with Time	334

a) $p_1 = 0$ Solutions	336
b) Adiabatic and Isothermal Fluctuations	339
11.2.2 Observational Constraints on Adiabatic Fluctuations	339
11.3 Relativistic Theory of Small (Linearized) Fluctuations	341
11.3.1 The Gauge-Invariant Formalism	341
a) Unperturbed Solutions	343
b) Small Perturbations	343
11.3.2 Adiabatic Perturbations of a Single Ideal Fluid	344
11.3.3 The Radiation-Dust Universe	346
11.3.4 Application to a System of Baryons and Photons – A Physical Interpretation of Adiabatic and Isothermal Perturbations	347
a) Super-Horizon Scales	348
b) Sub-Horizon Scales	350
11.3.5 Baryons in an Uncoupled Radiation Field	351
11.4 The Primeval Fluctuation Spectrum	352
11.4.1 Attempts to Derive δ_H	353
11.4.2 Perturbations in the Inflationary Universe	353
11.5 The Power Spectrum of the Density Fluctuations	357
11.6 Non-Baryonic “Hot” and “Warm” Dark Matter	360
11.6.1 Neutrino Stars	360
11.6.2 Typical Scales for Hot DM	361
11.6.3 The Hot-DM Fluctuation Spectrum	363
11.6.4 The “Pancake Model” for Galaxy Formation	365
11.6.5 Problems with Massive Neutrinos	367
11.6.6 Candidates for Warm DM	368
11.6.7 The Fluctuation Spectrum for Warm DM	369
11.6.8 Problems with Warm DM	370
11.7 Non-Baryonic Cold Dark Matter	370
11.7.1 The Growth of Fluctuations	371
11.7.2 Galaxy and Cluster Formation	372
11.7.3 Problems with Cold DM	373
11.8 What’s Wrong with Baryonic Galaxy Formation?	373
11.8.1 Excluding Baryons from Galactic Halos	373
11.8.2 Deuterium Limit	373
11.8.3 The Growth of Fluctuations	374
11.8.4 Loopholes	374
11.9 Strings and Galaxy Formation	377
12. Computer Simulations and the Large-Scale Structure	380
12.1 General Remarks	380
12.2 N -Particle Simulations Without Coherence Length	381
12.2.1 Equations of Motion	382
12.2.2 The Model of the Simulation	383
a) PP – the “Particle-Particle” Method (Aarseth Integrator)	384
b) P ³ M: “Particle-Particle-Particle-Mesh” Method	385

c) “PM” Model (Particle-Mesh)	385
d) The Short-Range Force	387
12.2.3 Results	388
a) The Clustering Phenomenon	388
b) Correlation Functions	389
c) Comparison with Observations	390
12.3 <i>N</i> -Particle Simulations with Coherence Length (Structures in a Neutrino-dominated Universe)	392
12.3.1 The Coherence Length	392
12.3.2 The Vlasov Equation for Massive Neutrinos	393
12.3.3 The Model of the Simulation – the PM Model	396
12.3.4 Results	396
a) Cooking Pancakes	397
b) The Correlation Function	399
c) Comparison with Observations	400
12.3.5 Conclusion	403
12.4 Simulations with Cold Dark Matter	403
12.4.1 Initial Conditions	403
12.4.2 The Morphology of Clustering	404
12.4.3 Biased Galaxy Formation	406
12.5 Conclusion	408
Appendix	409
A.1 The Gauge-Invariant Theory of Perturbations	409
A.1.1 Perturbations of $g_{\mu\nu}$ and $T_{\mu\nu}$	409
A.1.2 Gauge-Invariant Variables	411
A.1.3 Linearized Einstein Equations for Gauge-Invariant Variables	413
A.1.4 Some Remarks on Multi-Component Systems	413
References	419
Subject Index	431