

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	The Composition of the Universe	3
1.1.1	The Visible Universe: Galaxies	3
1.1.2	Baryons	10
1.1.3	Cold Dark Matter	11
1.1.4	Photons	13
1.1.5	Neutrinos	14
1.1.6	Dark Energy	16
1.2	The Evolution of the Universe	18
1.2.1	The Scale Factor $a(t)$	18
1.2.2	Gravitation and the Friedmann Equation	20
1.2.3	Open and Closed Universes	22
1.2.4	The Evolution of the Temperature	24
1.2.5	An Improved Friedmann Equation	29
1.2.6	The Evolution of the $\Omega$ s and Structure Formation	31
1.2.7	The Standard Scenario	33
1.3	Open Questions	35
	Exercises	39
<b>2</b>	<b>Observational Cosmology</b>	<b>41</b>
2.1	Stars and Quasi-stars	41
2.2	Galaxies	53
2.3	Galaxy Clusters	60
2.4	Large-Scale Structure	62
2.5	Dark Matter	64
2.5.1	WIMPs	64
2.5.2	Axions	68
2.5.3	MACHOs	68
2.5.4	Cold Gas	71
2.6	The Cosmological Parameters	73
2.6.1	$H_0$	73
2.6.2	$\rho$ s and $\Omega$ s	78
	Exercises	80

<b>3 Coordinates and Metrics</b>	91
3.1 Relativity and Gravitation	94
3.2 Comoving Coordinates	100
3.3 The Metric I: Mostly Isotropy	102
3.4 The Metric II: Mostly Homogeneity	105
3.5 Photon Propagation	110
3.6 Observable Distances	113
3.7 The Geodesic Equation	116
3.8 Gravitational Lensing	119
Exercises	130
<b>4 The Field Equations</b>	137
4.1 Our Freely Falling Coordinates	138
4.2 A Universe with $\rho = 0$	142
4.3 The Energy-Momentum Tensor	143
4.4 The Friedmann Equation	148
4.5 The Cosmological Parameters	150
4.6 Scalar Fields	152
4.7 The Riemann Tensor	154
4.8 The Einstein Tensor	157
4.9 The General Einstein Equation	158
Exercises	162
<b>5 Friedmannology</b>	165
5.1 The Age of the Universe	167
5.2 Type Ia Supernovae as Standard Candles	170
5.3 The Sound Horizon as a Standard Ruler	175
5.4 The Horizon Problem	181
5.5 The $\Omega$ Problem	186
5.6 Inflation	188
5.7 Intergalactic Scattering and Absorption	191
Exercises	193
<b>6 The Thermal History of the Universe</b>	197
6.1 Equilibrium Distributions	200
6.2 The Boltzmann Equation	204
6.3 Electrons and Positrons	209
6.4 Neutrinos	215
6.5 Primordial Nucleosynthesis	216
6.6 WIMPs	225
6.7 Baryogenesis	227
6.8 Irreversibility	229
6.9 The Future	231
Exercises	232

<b>7 Structure Formation</b>	239
7.1 A Spherical Collapse Model	242
7.1.1 A CDM Universe with Scale Invariant Fluctuations	246
7.1.2 Effects of Baryons and Photons	247
7.2 The Spectrum of Density Fluctuations	248
7.2.1 The Power Spectrum for a CDM-Baryon Universe	252
7.2.2 Measurements of the Power Spectrum	256
7.2.3 The Correlation Function	258
7.2.4 Redshift Distortions	258
7.3 The Primordial Spectrum from Inflation	260
7.4 CMB Temperature Anisotropies	264
7.4.1 The Sources of Anisotropy	267
7.4.2 The Cosmological Parameters	272
7.5 CMB Polarization	274
7.6 Alternatives to $\Lambda$ CDM	278
7.7 Newtonian Evolution	280
7.8 Photon Propagation	283
Exercises	288
<b>A Lorentz Vectors and Tensors</b>	295
<b>B Natural Units</b>	299
<b>C Standard Particles and Beyond</b>	303
<b>D Magnitudes</b>	309
<b>E Solutions and Hints for Selected Exercises</b>	311
<b>F Useful Formulas and Numbers</b>	317
<b>References</b>	321
<b>Index</b>	325