

Contents

About the Author	vii
Preface	ix
1 Basic Ideas of General Relativity	1
1.1 Inadequacy of Special Relativity	1
1.2 Einstein's Principle of Equivalence	3
1.3 Immediate Consequences of the Principle of Equivalence	7
1.3.1 The Bending of a Light Beam	7
1.3.2 Gravitational Shift of Spectral Lines (Gravitational Redshift)	8
1.4 The Curved Space-Time Concept	8
1.5 The Principle of General Covariance	12
1.6 Distance and Time Intervals	13
1.7 Problems	15
References	17
2 Curvilinear Coordinates and General Tensors	19
2.1 Curvilinear Coordinates	19
2.2 Parallel Displacement and Covariant Differentiation	23
2.3 Symmetry Properties of the Christoffel Symbols	27
2.4 Christoffel Symbols and the Metric Tensor	28
2.5 Geodesics	29
2.6 The Stationary Property of Geodesics	30
2.7 The Curvature Tensor	32
2.8 The Condition for Flat Space	36
2.9 Geodesic Deviation	37
2.10 Laws of Physics in Curved Spaces	38
2.11 The Metric Tensor and the Classical Gravitational Potential	39
2.12 Some Useful Calculation Tools	40
2.13 Problems	43
References	44

3 Einstein's Law of Gravitation	45
3.1 Introduction (Summary of General Principles)	45
3.2 A Heuristic Derivation of Einstein's Equations	46
3.2.1 Vacuum Field Equations	46
3.2.2 Field Equations Where Matter is Present in Space	48
3.3 Energy-Momentum Tensor	51
3.4 Gravitational Radiation	52
3.5 Problems	54
References	54
4 The Schwarzschild Solution	55
4.1 The Schwarzschild Metric	55
4.2 The Schwarzschild Solution of the Vacuum Field Equations	56
4.3 Schwarzschild Geodesics	60
4.4 Quasiuniform Gravitational Field	62
4.5 Problems	63
References	63
5 Experimental Tests of Einstein's Theory	65
5.1 Precession of the Perihelion of Mercury	65
5.2 Deflection of Light Rays in a Gravitational Field	71
5.3 Light Retardation (The Shapiro Experiment)	75
5.4 Test of Gravitational Radiation (Hulse-Taylor's Measurement of the Orbital Decay of the Binary Pulsar PSR-1913+16)	77
5.5 Problems	79
References	79
6 The Physics of Black Holes	81
6.1 The Schwarzschild Black Hole	81
6.2 Inside a Black Hole	84
6.3 How a Black Hole May Form	86
6.4 The Kerr-Newman Black Hole	89
6.4.1 Energy Extraction from a Rotating Black Hole: The Penrose Process	92
6.4.2 The Area Theorem	93
6.4.3 Energy Extraction from Two Coalescing Black Holes	94
6.5 Thermodynamics of Black Holes	95
6.6 Quantum Mechanics of Black Holes: Hawking Radiation	97
6.7 The Detection of Black Holes	101
6.7.1 Detection of Stellar-Mass Black Holes	101
6.7.2 Supermassive Black Holes in the Centers of Galaxies	104
6.7.3 Intermediate-Mass Black Holes	106
6.8 How Do Electrical and Gravitational Fields Get Out of Black Holes?	106
6.9 Black Holes and Particle Physics	107
6.10 Problems	108
References	109

Contents	xiii
7 Introduction to Cosmology	
7.1 Introduction	111
7.2 The Development of Western Cosmological Concepts	112
7.2.1 Ancient Greece	112
7.2.2 The Renaissance of Cosmology	113
7.2.3 Newton and the Infinite Universe	114
7.2.4 Newton's Law of Gravity and a Nonstationary Universe	115
7.2.5 Olbers' Paradox	118
7.3 The Discovery of the Expansion of the Universe	119
7.4 The Big Bang	123
7.5 The Microwave Background Radiation	124
7.6 Additional Evidence for the Big Bang	128
7.7 Problems	130
References	131
8 Big Bang Models	
8.1 The Cosmic Fluid and Fundamental Observers	133
8.2 Properties of the Robertson-Walker Metric	135
8.3 Cosmic Dynamics and Friedmann's Equations	139
8.4 The Solutions of Friedmann's Equations	142
8.4.1 Flat Model ($k = 0$)	143
8.4.2 Closed Model ($k = 1$)	144
8.4.3 Open Model ($k = -1$)	146
8.5 Dark Matter and the Fate of the Universe	148
8.6 The Beginning, the End, and Time's Arrow	152
8.7 An Accelerating Universe?	156
8.8 The Cosmological Constant	158
8.9 Problems	161
References	161
9 Particles, Forces, and Unification of Forces	
9.1 Particles	163
9.1.1 Spin	163
9.1.2 Fermions	164
9.1.3 Bosons	165
9.1.4 Hadrons and Leptons	165
9.1.5 Quarks	167
9.1.6 Quark Colors	168
9.1.7 Quark Confinement	169
9.2 Fundamental Interactions and Conservation Laws	171
9.3 Spontaneous Symmetry Breaking	177
9.4 Unification of Forces (Interactions)	180
9.5 The Negative Vacuum Pressure	184
References	186

10	The Inflationary Universe	187
10.1	The Flatness Problem	187
10.2	The Horizon Problem	188
10.3	Alan Guth's Inflationary Theory	191
10.4	The Successes of Guth's Inflationary Theory	195
10.4.1	The Horizon Problem Resolved	195
10.4.2	The Flatness Problem Resolved	196
10.5	Problems with Guth's Theory and the New Inflationary Theory	197
10.6	Problems	199
	References	199
11	The Physics of the Very Early Universe	201
11.1	Introduction	201
11.2	Cosmic Background Radiation	202
11.2.1	Conservation of Photon Numbers	206
11.2.2	The Transition Temperature T_t	207
11.2.3	The Photon-to-Baryon Ratio	207
11.3	The Creation of Matter and Photons	208
11.4	A Brief History of the Early Universe	211
11.4.1	The Planck Epoch	211
11.4.2	The GUTs Era	213
11.4.3	The Inflationary Era	213
11.4.4	The Hadron Era	214
11.4.5	The Lepton Era	215
11.4.6	The Nuclear Era	216
11.5	The Mystery of Antimatter	218
11.6	The Dark Matter Problem	221
11.7	The Primordial Magnetic Fields	227
11.8	Problems	228
	References	229
A	Classical Mechanics	231
A.1	Newtonian Mechanics	231
A.1.1	The Three Laws of Motion	231
A.1.2	The Galilean Transformation	233
A.1.3	Newtonian Relativity and Newton's Absolute Space	233
A.1.4	Newton's Law of Gravity	235
A.1.5	Gravitational Mass and Inertial Mass	237
A.1.6	Gravitational Field and Gravitational Potential	238
A.1.7	Gravitational Field Equations	239
A.2	Lagrangian Mechanics	240
A.2.1	Hamilton's Principle	240
A.2.2	Lagrange's Equations of Motion	242
A.3	Problems	243
	Reference	244

Contents	xv
B The Special Theory of Relativity	245
B.1 The Origins of Special Relativity	245
B.2 The Michelson-Morley Experiment	246
B.3 The Postulates of the Special Theory of Relativity	249
B.4 The Lorentz Transformations	251
B.4.1 Relativity of Simultaneity and Causality	253
B.4.2 Time Dilation and Relativity of Co-locality	254
B.4.3 Length contraction	255
B.4.4 Velocity Transformation	257
B.5 The Doppler Effect	259
B.6 Relativistic Space-Time and Minkowski Space	260
B.6.1 Interval ds^2 as an Invariant	262
B.6.2 Four Vectors	265
B.6.3 Four-Velocity and Four-Acceleration	268
B.6.4 Four-Momentum Vector	268
B.6.5 The Conservation Laws of Energy and Momentum	270
B.6.6 Equivalence of Mass and Energy	272
B.7 Problems	274
References	275
Index	277