

# Table of Contents

<b>1</b>	<b>The Observable Universe</b> .....	1
1.1	Introduction .....	1
1.2	Baryonic Matter .....	2
1.3	Antimatter .....	3
1.4	The Expansion of the Universe .....	4
1.5	Dark Matter .....	6
1.6	The Age of the Universe.....	9
1.7	The Left-Overs from the Big Bang.....	10
1.8	New Windows to Cosmology and Particle Physics .....	10
1.9	Problems .....	12
<b>2</b>	<b>Special Relativity</b> .....	15
2.1	Introduction .....	15
2.2	Frames, Coordinates and Metric .....	15
	2.2.1 Coordinates .....	16
	2.2.2 Metric and Transformations .....	17
2.3	Minkowski Space .....	18
	2.3.1 Causal Structure of Space-Time .....	22
	2.3.2 Vectors, Scalars and Tensors .....	22
2.4	Relativistic Kinematics.....	23
	2.4.1 Kinematics for $2 \rightarrow 2$ Processes .....	26
	2.4.2 System of Units .....	28
	2.4.3 Some Relativistic Kinematics for $2 \rightarrow 2$ Processes ...	28
2.5	Relativistic Optics .....	29
	2.5.1 Aberration .....	29
	2.5.2 Doppler Effect.....	31
2.6	Electromagnetic Vectors and Tensors .....	32
2.7	Summary.....	34
2.8	Problems .....	35
<b>3</b>	<b>General Relativity</b> .....	37
3.1	Introduction .....	37
3.2	The Equivalence Principle .....	37
3.3	Gravitational Redshift and Bending of Light .....	39
3.4	Curved Spaces .....	42

## XII Table of Contents

3.5	Coordinates and Metric . . . . .	43
3.5.1	Measures of Curvature . . . . .	45
3.5.2	Three-Dimensional Space . . . . .	48
3.6	Curved Space-Time . . . . .	49
3.6.1	The Energy-Momentum Tensor . . . . .	52
3.7	Einstein's Equations of Gravitation . . . . .	54
3.7.1	The Schwarzschild Solution . . . . .	55
3.8	Summary . . . . .	56
3.9	Problems . . . . .	56
<b>4</b>	<b>Cosmological Models . . . . .</b>	<b>59</b>
4.1	Space without Matter – the de Sitter Model . . . . .	59
4.2	The Standard Model of Cosmology . . . . .	61
4.3	The Expanding Universe . . . . .	65
4.3.1	The Deviation from the Linear Hubble Law . . . . .	68
4.3.2	The Fate of the Universe . . . . .	69
4.3.3	Particle Horizons . . . . .	71
4.4	Cosmological Distances: Low Redshift . . . . .	73
4.4.1	Luminosity Distance . . . . .	74
4.4.2	Angular Distance . . . . .	75
4.5	Cosmological Distances: High Redshift . . . . .	76
4.5.1	The Lookback Time and the Age of the Universe . . . . .	76
4.5.2	Measuring Cosmological Parameters . . . . .	78
4.5.3	Redshift Dependence of the Particle Horizon . . . . .	79
4.6	Observations of Standard Candles . . . . .	80
4.7	Meaning of the Cosmological Constant . . . . .	82
4.8	Summary . . . . .	85
4.9	Problems . . . . .	86
<b>5</b>	<b>Gravitational Lensing . . . . .</b>	<b>89</b>
5.1	The Bending of Light . . . . .	89
5.2	Observation of Gravitational Lensing . . . . .	94
5.2.1	Galactic Dark Matter Searches: Lensing of Stars . . . . .	94
5.2.2	Lensing of Objects at Cosmological Distances . . . . .	97
5.2.3	The Mass Density in Galaxy Clusters . . . . .	100
5.2.4	Weak Gravitational Lensing . . . . .	101
5.3	Black Holes . . . . .	103
5.3.1	Primordial Black Holes . . . . .	104
5.4	Summary . . . . .	105
5.5	Problems . . . . .	105

<b>6</b>	<b>Particles and Fields</b> .....	107
6.1	Introduction .....	107
6.2	Review of Particle Physics .....	107
6.3	Quantum Numbers .....	109
6.4	Degrees of Freedom in the Standard Model .....	110
6.5	Mesons and Baryons .....	110
6.6	Gauge Fields .....	112
6.7	Massive Gauge Bosons and the Higgs Mechanism .....	115
6.8	Gluons and Gravitons .....	119
6.9	Beyond the Standard Model .....	120
6.9.1	Supersymmetry .....	121
6.10	Some Particle Phenomenology .....	123
6.10.1	Estimates of Cross-Sections .....	124
6.11	Examples of Cross-Section Calculations .....	126
6.11.1	Definition of the Cross-Section .....	128
6.11.2	Neutrino Interactions .....	128
6.11.3	The $\gamma\gamma ee$ System .....	129
6.12	Processes Involving Hadrons .....	132
6.13	Vacuum Energy Density .....	135
6.14	Summary .....	136
6.15	Problems .....	137
<b>7</b>	<b>Phase Transitions</b> .....	139
7.1	Introduction .....	139
7.2	Phase Transitions in Condensed Matter .....	139
7.2.1	The Landau Description of Phase Transitions .....	140
7.3	Domain Walls, Strings and other Defects .....	143
7.4	Summary .....	146
<b>8</b>	<b>Thermodynamics in the Early Universe</b> .....	147
8.1	Introduction .....	147
8.2	Equilibrium Thermodynamics .....	149
8.3	Entropy .....	153
8.4	Summary .....	158
8.5	Problems .....	160
<b>9</b>	<b>Thermal Relics from the Big Bang</b> .....	161
9.1	Matter Antimatter Asymmetry .....	161
9.2	Freeze-Out and Dark Matter .....	163
9.3	Nucleosynthesis .....	167
9.4	Photon Recombination and Decoupling .....	170
9.4.1	Ionization Fraction – the Saha Equation .....	170
9.5	Summary .....	175
9.6	Problems .....	176

<b>10</b>	<b>The Accelerating Universe</b> .....	177
10.1	Problems of the Standard Big Bang Model .....	177
10.2	The Inflation Mechanism .....	180
10.3	Models for Inflation .....	183
10.4	Dark Energy .....	185
10.5	Summary .....	188
10.6	Problems .....	189
<b>11</b>	<b>The Cosmic Microwave Background Radiation and Growth of Structure</b> .....	191
11.1	The First Revolution: the 2.7 K Radiation .....	191
11.1.1	Thermal Nature of the CMBR .....	192
11.2	The Second Revolution: the Anisotropy .....	196
11.2.1	Temperature Fluctuations and Density Perturbations .....	196
11.3	The New Generation of Observations .....	198
11.4	Fluid Equations .....	199
11.5	The Jeans Mass .....	202
11.6	Structure Growth in the Linear Regime .....	202
11.7	Connection to Fluctuations in the CMBR .....	204
11.8	Primordial Density Fluctuations .....	206
11.9	Present Experimental Situation .....	207
11.10	Summary .....	208
11.11	Problems .....	211
<b>12</b>	<b>Cosmic Rays</b> .....	213
12.1	Introduction .....	213
12.2	The Abundance of Cosmic Rays .....	214
12.3	Ultra-High Energies .....	217
12.3.1	Extensive Air-Showers .....	217
12.3.2	Interaction with CMBR .....	219
12.4	Particle Acceleration .....	221
12.5	Summary .....	225
12.6	Problems .....	225
<b>13</b>	<b>Cosmic Gamma-Rays</b> .....	227
13.1	The Sky of High-Energy Photons .....	227
13.2	Gamma-Ray Bursts .....	228
13.2.1	What Are GRB? .....	229
13.3	Very High-Energy Gamma-Rays .....	232
13.3.1	Resolved Sources .....	233
13.3.2	Interaction with IR Photons .....	234
13.4	Summary .....	236
13.5	Problems .....	236

<b>14</b>	<b>The Role of Neutrinos</b> .....	237
14.1	Introduction .....	237
14.2	The History of Neutrinos .....	238
14.3	Neutrino Interactions with Matter .....	239
14.3.1	The Cross-Sections .....	240
14.4	Neutrino Masses .....	242
14.5	Stellar Neutrinos .....	243
14.5.1	Solar Neutrinos .....	245
14.5.2	Supernova Neutrinos .....	251
14.6	Neutrino Oscillations .....	254
14.6.1	Neutrinos Propagating Through Matter .....	258
14.7	Atmospheric Neutrinos .....	259
14.8	Neutrinos as Tracers of Particle Acceleration .....	261
14.9	Indirect Detection of CDM Particles .....	264
14.10	Neutrino Telescopes: the <i>Cherenkov</i> Effect .....	265
14.10.1	Water and Ice Cherenkov Telescopes .....	267
14.11	Potential Sources of High-energy Neutrinos .....	269
14.12	Status of High-energy Neutrino Telescopes .....	269
14.13	Summary .....	270
14.14	Problems .....	270
<b>15</b>	<b>Gravitational Waves</b> .....	273
15.1	Introduction .....	273
15.2	Derivation of the Gravitational Wave Equation .....	273
15.3	Properties of Gravitational Waves .....	276
15.4	The Binary Pulsar .....	278
15.5	Gravitational Wave Detectors .....	280
15.6	Summary .....	283
15.7	Problems .....	283
<b>A</b>	<b>Some More General Relativity</b> .....	285
A.1	Metric for Curved Space-Time .....	285
A.2	The Newtonian Limit .....	288
A.3	The Curvature Tensor .....	289
A.4	Summary .....	293
A.5	Problems .....	294
<b>B</b>	<b>Relativistic Dynamics</b> .....	297
B.1	Classical Mechanics .....	297
B.2	Classical Fields .....	300
B.3	Relativistic Quantum Fields .....	302
B.3.1	The Klein Gordon Field .....	302
B.3.2	Electromagnetic Field .....	304
B.3.3	Charged Scalar Field .....	304
B.4	Summary .....	306

<b>C</b>	<b>The Dirac Equation</b> .....	309
C.1	Introduction .....	309
C.2	Constructing the Dirac Equation .....	310
C.3	Plane-Wave Solutions .....	314
C.4	Coupling to Electromagnetism .....	317
C.5	Lorentz Invariance .....	318
C.6	Bilinear Forms .....	319
C.7	Spin and Energy Projection Operators .....	321
C.8	Non-Relativistic Limit .....	324
C.9	Problems with the Dirac Equation .....	325
	C.9.1 The Dirac Sea .....	325
C.10	Central Potentials .....	327
C.11	Coulomb Scattering .....	328
C.12	Trace Formulae .....	330
C.13	Quantization of the Dirac Field .....	332
C.14	Majorana Particles .....	333
C.15	Lagrangian Formulation .....	334
C.16	Summary .....	335
<b>D</b>	<b>Cross-Section Calculations</b> .....	337
D.1	Definition of the Cross-Section .....	337
D.2	The Process $e^+e^- \rightarrow \mu^+\mu^-$ .....	339
D.3	The Process $\bar{\nu}_e e^- \rightarrow \bar{\nu}_\mu \mu^-$ .....	341
D.4	The Processes $ee\gamma\gamma$ .....	342
<b>E</b>	<b>Quantum Fluctuations of the Inflaton</b> .....	345
E.1	Quantum Fields in General Relativity .....	345
E.2	Evolution in de Sitter Space-Time .....	346
E.3	The Vacuum State .....	347
E.4	Connection to Observations .....	349
<b>F</b>	<b>Suggestions for Further Reading</b> .....	353
	<b>References</b> .....	355
	<b>Index</b> .....	357