

Contents

<i>Preface</i>	xi
<i>Acknowledgments</i>	xiii
<i>List of Figures</i>	xv
1 Island Universes	1
1.1 The First Move	1
1.2 Looking Back	4
1.3 Age and Size of the Visible Universe	18
1.4 Expanding Universe	24
1.5 Cosmological Principle	26
1.6 Inflationary Epoch	27
1.7 Beyond the Visible Universe	27
1.8 Boxes 1–3	28
2 The Large and the Small	30
2.1 Face to Face	30
2.2 Space, Time, and Relativity	30
2.3 Physics of the Very Small: Quantum Mechanics	32
2.4 Heisenberg’s Uncertainty Principle	37
2.5 Radiation in the Early Universe	37
2.6 Other Planets Around Other Suns	44
2.7 Life on Other Planets	46
2.8 Different Points of View	49
2.9 Milky Way	52
2.10 Universe Without a Center	55
2.11 Cosmic Horizon as Small as a Nucleon	57
2.12 Box 4	58

3	Big Bang	59
3.1	Hubble's Discovery	59
3.2	Evidence for a Big Bang	61
3.3	A Day Without Yesterday	63
3.4	Temperature Measured at an Earlier Time	68
3.5	Model Universes	69
3.6	Scale Factor of the Universe	73
3.7	Theories of Expansion	77
3.7.1	The big crunch	78
3.7.2	Einstein–de Sitter universe	79
3.7.3	Accelerating universe	79
3.7.4	Recycling universe	80
3.8	Boxes 5–8	81
4	Elementary Particles — Fundamental Forces	84
4.1	The Atom	84
4.2	Vacuum: Particles, Antiparticles, and Dirac	97
4.3	Antiparticles and Antiuniverses	101
4.4	The Particle Explosion	102
4.4.1	Cosmic rays	102
4.4.2	Laboratory beams of particles	104
4.5	So Many Riches	105
4.6	The Quarks and Leptons	109
4.7	The Force Carriers	114
5	The Primeval Fireball	118
5.1	Cosmic Evolution	118
5.2	Heat, Temperature, and Equilibrium	120
5.3	Planck Era ($t < 10^{-43}$ Seconds)	121
5.4	Radiation-Dominated Era ($t = 10^{-11}$ Seconds to 10^6 Years) ...	123
5.4.1	Superradiant era ($t = 10^{-11}$ to 10^{-5} seconds)	126
5.4.2	Hadronic era ($t = 10^{-5}$ to 10^{-3} seconds)	127
5.4.3	Leptonic era ($t = 10^{-3}$ to 1 second)	129
5.4.4	Formation of the light elements ($t = 100$ seconds to 10 minutes)	137
5.4.5	Measurement of primordial abundances of elements ...	142
5.4.6	Decoupling of radiation and matter ($t = 300\,000$ to 1 million years)	144
5.5	Close of the Radiation Era	146
5.6	Matter Dominance	147
5.7	Boxes 9–20	152

6 Galaxy Clusters, Galaxies, and Stars	161
6.1 Structure Formation	161
6.2 Cloud Collapse in the Radiation Era	165
6.3 Matter Era	167
6.4 Galaxy Formation	167
6.5 Galaxy Types	170
6.6 Star Formation	172
6.7 Nova and Supernova	172
6.7.1 Nova: creation of a white dwarf	175
6.7.2 Supernova: creation of a neutron star or black hole	176
6.8 Boxes 21–25	178
7 The Future Universe	183
7.1 Dark Matter, Dark Energy	183
7.2 The Three Ages of the Universe	185
7.3 The Great Cosmology Experiments	186
7.3.1 Supernova cosmology	187
7.3.2 The seed of our galaxy	190
7.4 Boxes 26–29	194
 <i>Books for Further Study</i>	 198
 <i>Index</i>	 201