

Particle Astrophysics

Second Edition

D. H. PERKINS

*Particle and Astrophysics Department
Oxford University*

Contents

Part 1 Particles and Interactions

1	Quarks and leptons and their interactions	3
1.1	Preamble	3
1.2	Quarks and leptons	4
1.3	Fermions and bosons: the spin-statistics theorem; supersymmetry	9
1.4	Antiparticles	9
1.5	The fundamental interactions: boson exchange	11
1.6	The boson couplings to fermions	14
1.7	The quark–gluon plasma	21
1.8	The interaction cross section	21
1.9	Examples of elementary particle cross sections	24
1.10	Decays and resonances	30
1.11	Examples of resonances	32
1.12	New particles	34
1.13	Summary	35
	Problems	36
2	Relativistic transformations and the equivalence principle	39
2.1	Coordinate transformations in special relativity	39
2.2	Invariant intervals and four-vectors	41
2.3	The equivalence principle: clocks in gravitational fields	42
2.4	General relativity	47
2.5	The Schwarzschild line element, Schwarzschild radius, and black holes	49
2.6	The gravitational deflection of light by a point mass	51
2.7	Shapiro time delay	52
2.8	Orbital precession	53
2.9	The Robertson–Walker line element	54
2.10	Modifications to Newtonian gravity?	55
2.11	Relativistic kinematics: four-momentum; the Doppler effect	56
2.12	Fixed-target and colliding-beam accelerators	57
	Problems	59

3	Conservation rules, symmetries, and the Standard Model of particle physics	60
3.1	Transformations and the Euler–Lagrange equation	60
3.2	Rotations	62
3.3	The parity operation	62
3.4	Parity conservation and intrinsic parity	63
3.5	Parity violation in weak interactions	65
3.6	Helicity and helicity conservation	67
3.7	Charge conjugation invariance	69
3.8	Gauge transformations and gauge invariance	69
3.9	Superstrings	73
3.10	Gauge invariance in the electroweak theory	74
3.11	The Higgs mechanism of spontaneous symmetry breaking	75
3.12	Running couplings	77
3.13	Vacuum structure in gauge theories	83
3.14	CPT theorem and CP and T symmetry	83
3.15	CP violation in neutral kaon decay	84
3.16	CP violation in the Standard Model: the CKM matrix	87
3.17	Summary	89
	Problems	90
4	Extensions of the Standard Model	92
4.1	Neutrinoless double beta decay	92
4.2	Neutrino masses and flavour oscillations	94
4.3	Grand unified theories: proton decay	97
4.4	Grand unification and the neutrino see-saw mechanism	100
4.5	Hierarchies and supersymmetry	102
4.6	Summary	103
	Problems	104
Part 2 The Early Universe		
5	The expanding universe	107
5.1	The Hubble expansion	107
5.2	Olbers' paradox	113
5.3	The Friedmann equation	114
5.4	The sources of energy density	117
5.5	Observed energy densities	120
5.6	The age and size of the universe	123
5.7	The deceleration parameter	126
5.8	Cosmic microwave background radiation (CMB)	127
5.9	Anisotropies in the microwave radiation	130
5.10	Particles and radiations in the early universe	131
5.11	Photon and neutrino densities	134
5.12	Radiation and matter eras	135

5.13	The eras of matter–radiation equality	138
5.14	Summary	139
	Problems	140
6	Nucleosynthesis and baryogenesis	142
6.1	Primordial nucleosynthesis	142
6.2	Baryogenesis and matter–antimatter asymmetry	146
6.3	The baryon–photon ratio in the Big Bang	148
6.4	The Sakharov criteria	150
6.5	The baryon–antibaryon asymmetry: possible scenarios	151
6.6	Summary	154
	Problems	155
7	Dark matter and dark energy components	156
7.1	Preamble	156
7.2	Dark matter in galaxies and clusters	157
7.3	Gravitational lensing	159
7.4	Evidence for dark matter from gravitational lensing	160
7.5	Microlensing and MACHOs	163
7.6	The lensing probability: optical depth	165
7.7	Baryonic dark matter	166
7.8	Neutrinos	167
7.9	Axions	168
7.10	Axion-like particles	169
7.11	Weakly interacting massive particles	170
7.12	Expected WIMP cross-sections and event rates	173
7.13	Experimental WIMP searches	174
7.14	Dark energy: high redshift supernovae and Hubble plot at large z	176
7.15	Vacuum energy: the Casimir effect	182
7.16	Problems with the cosmological constant and dark energy	184
7.17	Summary	186
	Problems	187
8	Development of structure in the early universe	188
8.1	Preamble	188
8.2	Galactic and intergalactic magnetic fields	189
8.3	Horizon and flatness problems	190
8.4	Inflation	192
8.5	Chaotic inflation	196
8.6	Quantum fluctuations and inflation	198
8.7	The spectrum of primordial fluctuations	200
8.8	Gravitational collapse and the Jeans mass	202
8.9	The growth of structure in an expanding universe	205
8.10	Evolution of fluctuations during the radiation era	206

8.11	Cosmological limits on neutrino mass from fluctuation spectrum	210
8.12	Growth of fluctuations in the matter-dominated era	212
8.13	Temperature fluctuations and anisotropies in the CMB	213
8.14	The Angular spectrum of anisotropies: 'acoustic peaks' in the distribution	216
8.15	Experimental observation and interpretation of CMB anisotropies	222
8.16	Polarization of the cosmic microwave radiation	223
8.17	Summary	224
	Problems	226

Part 3 Particles and Radiation in the Cosmos

9	Cosmic particles	229
9.1	Preamble	229
9.2	The composition and spectrum of cosmic rays	230
9.3	Geomagnetic and solar effects	233
9.4	Acceleration of cosmic rays	237
9.5	Secondary cosmic radiation: pions and muons	239
9.6	Passage of charged particles and radiation through matter	240
9.7	Development of an electromagnetic cascade	243
9.8	Extensive air showers: nucleon- and photon-induced showers	245
9.9	Detection of extensive air showers	245
9.10	Point sources of γ -rays	247
9.11	γ -Ray bursts	249
9.12	Ultra-high-energy cosmic ray showers: the GZK cut-off	251
9.13	Point sources of ultra high energy cosmic rays	253
9.14	Radio galaxies and quasars	253
9.15	Atmospheric neutrinos: neutrino oscillations	257
9.16	Solar neutrinos	260
9.17	Neutrino oscillations in matter	263
9.18	Point sources of high-energy neutrinos	263
9.19	Gravitational radiation	264
9.20	The binary pulsar	267
9.21	Detection of gravitational waves	269
9.22	Summary	270
	Problems	271
10	Particle physics in stars and galaxies	273
10.1	Preamble	273
10.2	Stellar evolution—the early stages	273
10.3	Hydrogen burning: the p-p cycle in the Sun	276

10.4	Helium burning and the production of carbon and oxygen	278
10.5	Production of heavy elements	280
10.6	Electron degeneracy pressure and stellar stability	281
10.7	White dwarf stars	284
10.8	Stellar collapse: type II supernovae	285
10.9	Neutrinos from SN 1987A	288
10.10	Neutron stars and pulsars	291
10.11	Black holes	294
10.12	<i>Hawking radiation from black holes</i>	295
10.13	Summary	297
	Problems	298
A	Table of physical constants	299
B	Yukawa theory and the boson propagator	301
C	Perturbative growth of structure in the early universe	303
C.1	Growth in the matter-dominated era	306
D	The MSW mechanism in solar neutrino interactions	308
	Answers to problems	312
	References	329
	Bibliography	333
	Index	335