

# Contents

		page
30	2.4.2 Rotation curves of disk galaxies	27
31	2.4.3 Estimation of total mass	28
34	2.4.4 Destruction of D	28
34	2.4.5 Formation of D	28
35	2.4.6 Formation of $H\alpha$	28
35	2.4.7 The virial theorem	28
35	2.4.8 Clusters of galaxies	28
39	2.5.1 Overview	28
39	2.5.2 Further reading	28
40	2.5.3 Cosmic expansion and large-scale structure	28
40	2.5.4 The expansion of the Universe	28
42	2.5.5 The cosmological constant	28
42	2.5.6 Reaction rates	28
42	<i>Preface</i>	xiii
<b>Part I</b>	<b>Classical mechanics</b>	<b>1</b>
1	Orbital mechanics	3
1.1	Universal gravitation	3
1.1.1	Center of mass	3
1.1.2	Reduced mass	4
1.2	Kepler's laws	5
1.2.1	Planetary orbits	9
1.3	Binary stars	11
1.3.1	Visual binaries	11
1.3.2	The apparent orbit	11
1.3.3	The true orbit	12
1.3.4	Determining the orbital elements	14
1.3.5	Spectroscopic binaries	14
1.3.6	The mass function	17
1.3.7	Summary of binary star studies	18
1.3.8	Mass–luminosity relation	19
1.4	Extrasolar planets	20
1.4.1	The astrometric method	21
1.4.2	The radial velocity method	22
1.4.3	The transit method	24
1.5	References	25
1.6	Further reading	25
2	Galaxy dynamics	26
2.1	Potentials of arbitrary matter distributions	26
2.2	Dynamics of thin disks	27

2.3	Rotation curves of disk galaxies	30
2.3.1	Rotation curves of real spiral galaxies	31
2.4	<i>N</i> -body gravitational systems	34
2.4.1	Equation of motion	34
2.4.2	The Virial theorem	35
2.4.3	Clusters of galaxies	36
2.5	References	39
2.6	Further reading	39
3	Cosmic expansion and large scale structure	40
3.1	The expansion of the Universe	40
3.1.1	The cosmological constant	42
3.2	Large-scale cosmic structure	45
3.2.1	Overview	45
3.2.2	Correlation functions of galaxies	46
3.2.3	Dark matter and large-scale structure	47
3.2.4	Hot and cold dark matter	51
3.2.5	The Jeans' mass and gravitational stability	52
3.2.6	Possible models of structure formation	54
3.3	References	55
3.4	Further reading	55
<b>Part II Statistical mechanics</b>		57
4	Overview of statistical mechanics	59
4.1	Thermodynamics	59
4.2	Classical statistical mechanics	61
4.3	Quantum statistical mechanics	63
4.3.1	Bose–Einstein statistics	64
4.3.2	Fermi–Dirac statistics	64
4.4	Photon distribution function	65
4.5	Thermodynamic equilibrium	66
4.6	Further reading	68
5	The early Universe	69
5.1	The 3 K background radiation	69
5.1.1	History of the background radiation	69
5.1.2	Evolution of energy density	70
5.2	Galaxy formation	71
5.3	Local cosmology and nucleosynthesis	72
5.3.1	Overview	72
5.3.2	Primordial helium	73
5.4	Reaction rates	75
5.4.1	Introduction	75

5.4.2	Barrier penetration	77
5.4.3	Estimating reaction rates	81
5.4.4	Destruction of D	82
5.4.5	Formation of D	82
5.4.6	Formation of $^4\text{He}$	83
5.5	Particle equilibria in the early Universe	83
5.5.1	Overview	83
5.5.2	Chemical equilibrium	86
5.5.3	The early Universe	87
5.5.4	The neutron–proton ratio	87
5.5.5	Reaction freeze-out	88
5.5.6	Reaction timescale	90
5.5.7	Formation of deuterium	91
5.6	Further reading	93
6	Stellar structure and compact stars	94
6.1	Hydrostatic equilibrium	94
6.2	Fermion degeneracy	97
6.2.1	White dwarf equation of state	100
6.2.2	Mass–radius relation for white dwarfs	100
6.3	Internal structure of white dwarfs	100
6.3.1	Relationship between pressure and energy density	101
6.3.2	Relating electron number density to the mass density	104
6.3.3	Other sources of pressure	105
6.3.4	Equation of state	105
6.3.5	Internal structure of white dwarfs	105
6.3.6	Estimating the radius and mass of a white dwarf	107
6.4	Stability of compact stars	109
6.4.1	Total energy	109
6.4.2	Electron capture	110
6.4.3	Maximum density	111
6.5	Structure of neutron stars	114
6.5.1	Overview	114
6.5.2	Liquid layer	115
6.5.3	The crust	117
6.5.4	The core	119
6.6	Pulsars	119
6.7	Further reading	121

<b>Part III Electromagnetism</b>		123
7 Radiation from accelerating charges		125
7.1 The Lienard–Wiechert potential		125
7.1.1 Scalar and vector potentials		125
7.1.2 Green’s function solution		126
7.1.3 The L–W potentials		127
7.2 Electric and magnetic fields of a moving charge		128
7.2.1 Moving charge at constant velocity		129
7.2.2 Radiation from accelerating charges – the far zone		131
7.2.3 Angular distribution of radiation		131
7.2.4 Total emitted power		133
7.3 Further reading		134
8 Bremsstrahlung and synchrotron radiation		135
8.1 Bremsstrahlung		135
8.1.1 Single particle collisions		135
8.1.2 Radiation from an ensemble of particles		137
8.2 Synchrotron radiation		138
8.2.1 Total power		139
8.2.2 The received spectrum		140
8.2.3 Spectrum of a power-law energy distribution		141
8.3 Further reading		143
9 High energy processes in astrophysics		144
9.1 Neutron stars		144
9.2 Supernova remnants		145
9.2.1 Particle acceleration		145
9.3 Radio galaxies		148
9.4 Galactic X-ray sources		152
9.4.1 The energy source		153
9.4.2 Maximum luminosity/Eddington limit		153
9.4.3 Characteristic temperature		154
9.4.4 Mass transfer		154
9.5 Accretion disks		154
9.5.1 Disk hydrodynamics		156
9.5.2 The emission spectrum of the disk		157
9.6 Pulsars revisited		159
9.6.1 The radiation field		160
9.6.2 Radiated power		161
9.6.3 The Braking Index		162
9.6.4 The static magnetic field		162
9.6.5 The static electric field		162

9.7	Reference	163
9.8	Further reading	163
10	Electromagnetic wave propagation	164
10.1	EM waves in an un-magnetized plasma	165
10.1.1	Dispersion measure	166
10.2	EM waves in a magnetized medium	167
10.2.1	Rotation measure	170
10.3	Reference	172
10.4	Further reading	172
<b>Part IV Quantum mechanics</b>		173
11	The hydrogen atom	175
11.1	Structure of the hydrogen atom	175
11.1.1	Case 1 $r \rightarrow \infty$	177
11.1.2	Case 2 $r \rightarrow 0$	177
11.1.3	What about the in-between?	178
11.1.4	Normalizing $R(r)$	179
11.2	Total wave function	181
11.3	Probability functions	181
11.4	Energy eigenstates and transitions	185
11.5	Further reading	185
12	The interaction of radiation with matter	187
12.1	Non-relativistic treatment	187
12.2	Single particle Hamiltonian	188
12.3	Separation of static and radiation fields	189
12.3.1	Relative importance of $H_0$ , $H_1$ and $H_2$	189
12.4	Radiative transitions	190
12.4.1	Semi-classical approach	190
12.4.2	The Hamiltonian of the radiation field	191
12.4.3	The perturbation Hamiltonian	192
12.4.4	Time-dependent perturbation theory	193
12.5	Absorption of photons	194
12.5.1	Absorption cross-sections	196
12.5.2	Dipole transition probability	197
12.5.3	Bound-bound absorption cross-section	198
12.6	Spontaneous emission	199
12.7	Photoionization	200
12.7.1	Bound-free cross-sections	202
12.8	Selection rules	203
12.8.1	Dipole selection rules	204
12.8.2	Electric quadrupole transitions	205

12.9	Numerical evaluation of transition probabilities	206
12.9.1	The Lyman $\alpha$ transition	207
12.9.2	Bound-free absorption cross-section	209
12.10	HII regions	210
12.10.1	Ionizing stars	211
12.11	Ionization of a pure hydrogen nebula	212
12.11.1	Radius of HII region	216
12.12	Quasars and the Lyman $\alpha$ forest	216
12.12.1	Correlation studies	218
12.12.2	Column density of the HI responsible for the Ly- $\alpha$ forest	220
12.13	Reference	220
12.14	Further reading	221
13	Atomic fine structure lines	222
13.1	Electron spin	222
13.1.1	Relativistic Hamiltonian	222
13.2	Dirac's postulate	223
13.2.1	The Dirac equation	224
13.2.2	Free particle at rest	224
13.2.3	Non-relativistic limit of Dirac's equation	225
13.3	Radiative transitions involving spin	227
13.3.1	Zeeman effect	228
13.4	Relativistic correction with $A = 0$	228
13.5	Atomic fine structure	229
13.5.1	Spin-orbit interaction	230
13.5.2	Time-independent perturbation theory	230
13.5.3	The $jm$ representation	231
13.5.4	Solution for $E_{SO}$	232
13.6	Further reading	234
14	Atomic hyperfine lines	235
14.1	The 21 cm line of hydrogen	235
14.1.1	Transition rate	238
14.1.2	The 21 cm line profile	239
14.2	The Doppler effect	240
14.2.1	Doppler broadening of the 21 cm line	241
14.3	Neutral hydrogen in galaxies	242
14.3.1	Equation of transfer for HI emission	242
14.3.2	Emission or absorption?	244

14.4	Measuring HI in external galaxies	244
14.4.1	Integral properties of galaxies	245
14.4.2	Kinematics of the HI	245
14.5	Probing galactic mass distributions	246
14.5.1	HI rotation curves	247
14.6	References	253
14.7	Further reading	253
15	Transitions involving multi-electron atoms	254
15.1	Symmetry of multi-particle wave functions	254
15.2	The helium atom	255
15.2.1	The ground state	255
15.2.2	Lowest excited states	257
15.2.3	Summary	258
15.3	Many-electron atoms	259
15.3.1	The Hartree–Fock procedure	260
15.4	Forbidden lines in astrophysics	261
15.4.1	Collisional equilibria	261
15.4.2	Line emission and cooling of nebulae	263
15.4.3	Statistical equilibrium for $N$ levels	265
15.4.4	OIII lines as probes of temperature	266
15.4.5	Line ratios as density probes	269
15.4.6	Observations of nebulae	270
15.4.7	Observations of active galactic nuclei	270
15.5	Further reading	272
16	Molecular lines in astrophysics	273
16.1	Diatomic molecules	273
16.1.1	Inter-nuclear potential	273
16.1.2	Electronic transitions	273
16.1.3	Vibrational transitions	274
16.1.4	Rotational transitions	274
16.1.5	Summary	275
16.2	Diatomic molecules with two valence electrons	275
16.2.1	The Born–Oppenheimer Approximation	276
16.3	Translational and internal degrees of freedom	278
16.3.1	Vibrations and rotations	279
16.3.2	Vibrations – harmonic oscillator approximation	280
16.4	Dipole transition probability	281
16.4.1	Pure rotational spectra	282
16.5	Transitions between vibrational levels	283

284	16.6	Transitions between electronic levels	284
285	16.7	The H <sub>2</sub> molecule	285
287	16.8	The CO molecule	287
290	16.9	Other molecules	290
291	16.10	Life in the Universe	291
291	16.10.1	The building blocks of life	291
293	16.10.2	Communicating with other civilizations	293
293	16.11	Further reading	293
294	<i>Index</i>		294