

Contents

<i>Preface</i>	<i>page</i> xiii
<i>Acknowledgements</i>	xvii

Part I Astronomical background

1 High energy astrophysics – an introduction	3
1.1 High energy astrophysics and modern physics and astronomy	3
1.2 The sky in different astronomical wavebands	4
1.3 Optical waveband	5
1.4 Infrared waveband	9
1.5 Millimetre and submillimetre waveband	14
1.6 Radio waveband	17
1.7 Ultraviolet waveband	21
1.8 X-ray waveband	22
1.9 γ -ray waveband	25
1.10 Cosmic ray astrophysics	27
1.11 Other non-electromagnetic astronomies	32
1.12 Concluding remarks	34
2 The stars and stellar evolution	35
2.1 Introduction	35
2.2 Basic observations	35
2.3 Stellar structure	39
2.4 The equations of energy generation and energy transport	43
2.5 The equations of stellar structure	47
2.6 The Sun as a star	50
2.7 Evolution of high and low mass stars	59
2.8 Stellar evolution on the colour–magnitude diagram	68
2.9 Mass loss	70
2.10 Conclusion	75
3 The galaxies	77
3.1 Introduction	77
3.2 The Hubble sequence	78

3.3	The red and blue sequences	80
3.4	Further correlations among the properties of galaxies	86
3.5	The masses of galaxies	89
3.6	The luminosity function of galaxies	95
4	Clusters of galaxies	99
4.1	The morphologies of rich clusters of galaxies	99
4.2	Clusters of galaxies and isothermal gas spheres	102
4.3	The Coma Cluster of galaxies	106
4.4	Mass distribution of hot gas and dark matter in clusters	109
4.5	Cooling flows in clusters of galaxies	110
4.6	The Sunyaev–Zeldovich effect in hot intracluster gas	114
4.7	Gravitational lensing by galaxies and clusters of galaxies	116
4.8	Dark matter in galaxies and clusters of galaxies	123
Part II Physical processes		
5	Ionisation losses	131
5.1	Introduction	131
5.2	Ionisation losses – non-relativistic treatment	131
5.3	The relativistic case	136
5.4	Practical forms of the ionisation loss formulae	141
5.5	Ionisation losses of electrons	145
5.6	Nuclear emulsions, plastics and meteorites	146
5.7	Dynamical friction	151
6	Radiation of accelerated charged particles and bremsstrahlung of electrons	154
6.1	Introduction	154
6.2	The radiation of accelerated charged particles	154
6.3	Bremsstrahlung	163
6.4	Non-relativistic bremsstrahlung energy loss rate	166
6.5	Thermal bremsstrahlung	167
6.6	Relativistic bremsstrahlung	173
7	The dynamics of charged particles in magnetic fields	178
7.1	A uniform static magnetic field	178
7.2	A time-varying magnetic field	180
7.3	The scattering of charged particles by irregularities in the magnetic field	184
7.4	The scattering of high energy particles by Alfvén and hydromagnetic waves	187
7.5	The diffusion-loss equation for high energy particles	189
8	Synchrotron radiation	193
8.1	The total energy loss rate	193
8.2	Non-relativistic gyroradiation and cyclotron radiation	195

8.3	The spectrum of synchrotron radiation – physical arguments	198
8.4	The spectrum of synchrotron radiation – a fuller version	202
8.5	The synchrotron radiation of a power-law distribution of electron energies	212
8.6	The polarisation of synchrotron radiation	214
8.7	Synchrotron self-absorption	217
8.8	Useful numerical results	222
8.9	The radio emission of the Galaxy	224
9	Interactions of high energy photons	228
9.1	Photoelectric absorption	228
9.2	Thomson and Compton scattering	231
9.3	Inverse Compton scattering	237
9.4	Comptonisation	243
9.5	The Sunyaev–Zeldovich effect	257
9.6	Synchrotron–self-Compton radiation	260
9.7	Cherenkov radiation	264
9.8	Electron–positron pair production	270
9.9	Electron–photon cascades, electromagnetic showers and the detection of ultra-high energy γ -rays	272
9.10	Electron–positron annihilation and positron production mechanisms	275
10	Nuclear interactions	279
10.1	Nuclear interactions and high energy astrophysics	279
10.2	Spallation cross-sections	282
10.3	Nuclear emission lines	287
10.4	Cosmic rays in the atmosphere	292
11	Aspects of plasma physics and magnetohydrodynamics	298
11.1	Elementary concepts in plasma physics	298
11.2	Magnetic flux freezing	304
11.3	Shock waves	314
11.4	The Earth’s magnetosphere	319
11.5	Magnetic buoyancy	321
11.6	Reconnection of magnetic lines of force	323
Part III High energy astrophysics in our Galaxy		
12	Interstellar gas and magnetic fields	333
12.1	The interstellar medium in the life cycle of stars	333
12.2	Diagnostic tools – neutral interstellar gas	333
12.3	Ionised interstellar gas	340
12.4	Interstellar dust	347
12.5	An overall picture of the interstellar gas	353

12.6	Star formation	361
12.7	The Galactic magnetic field	369
13	Dead stars	378
13.1	Supernovae	378
13.2	White dwarfs, neutron stars and the Chandrasekhar limit	394
13.3	White dwarfs	401
13.4	Neutron stars	401
13.5	The discovery of neutron stars	406
13.6	The Galactic population of neutron stars	419
13.7	Thermal emission of neutron stars	421
13.8	Pulsar glitches	422
13.9	The pulsar magnetosphere	424
13.10	The radio and high energy emission of pulsars	427
13.11	Black holes	429
14	Accretion power in astrophysics	443
14.1	Introduction	443
14.2	Accretion – general considerations	443
14.3	Thin accretion discs	451
14.4	Thick discs and advective flows	461
14.5	Accretion in binary systems	464
14.6	Accreting binary systems	473
14.7	Black holes in X-ray binaries	486
14.8	Final thoughts	492
15	Cosmic rays	493
15.1	The energy spectra of cosmic ray protons and nuclei	493
15.2	The abundances of the elements in the cosmic rays	496
15.3	The isotropy and energy density of cosmic rays	502
15.4	Gamma ray observations of the Galaxy	503
15.5	The origin of the light elements in the cosmic rays	507
15.6	The confinement time of cosmic rays in the Galaxy and cosmic ray clocks	515
15.7	The confinement volume for cosmic rays	517
15.8	The Galactic halo	520
15.9	The highest energy cosmic rays and extensive air-showers	522
15.10	Observations of the highest energy cosmic rays	524
15.11	The isotropy of ultra-high energy cosmic rays	529
15.12	The Greisen–Kuzmin–Zatsepin (GKZ) cut-off	531
16	The origin of cosmic rays in our Galaxy	536
16.1	Introduction	536
16.2	Energy loss processes for high energy electrons	536

16.3	Diffusion-loss equation for high energy electrons	540
16.4	Supernova remnants as sources of high energy particles	545
16.5	The minimum energy requirements for synchrotron radiation	549
16.6	Supernova remnants as sources of high energy electrons	553
16.7	The evolution of supernova remnants	554
16.8	The adiabatic loss problem and the acceleration of high energy particles	556
17	The acceleration of high energy particles	561
17.1	General principles of acceleration	561
17.2	The acceleration of particles in solar flares	562
17.3	Fermi acceleration – original version	564
17.4	Diffusive shock acceleration in strong shock waves	568
17.5	Beyond the standard model	574
17.6	The highest energy cosmic rays	580
Part IV Extragalactic high energy astrophysics		
18	Active galaxies	585
18.1	Introduction	585
18.2	Radio galaxies and high energy astrophysics	585
18.3	The quasars	586
18.4	Seyfert galaxies	592
18.5	Blazars, superluminal sources and γ -ray sources	596
18.6	Low Ionisation Nuclear Emission Regions – LINERs	598
18.7	Ultra-Luminous InfraRed Galaxies – ULIRGs	598
18.8	X-ray surveys of active galaxies	600
18.9	Unification schemes for active galaxies	602
19	Black holes in the nuclei of galaxies	610
19.1	The properties of black holes	610
19.2	Elementary considerations	611
19.3	Dynamical evidence for supermassive black holes in galactic nuclei	613
19.4	The Soltan argument	623
19.5	Black holes and spheroid masses	625
19.6	X-ray observations of fluorescence lines in active galactic nuclei	626
19.7	The growth of black holes in the nuclei of galaxies	633
20	The vicinity of the black hole	637
20.1	The prime ingredients of active galactic nuclei	637
20.2	The continuum spectrum	637
20.3	The emission line regions – the overall picture	640
20.4	The narrow-line regions – the example of Cygnus A	641
20.5	The broad-line regions and reverberation mapping	646

20.6	The alignment effect and shock excitation of emission line regions	653
20.7	Accretion discs about supermassive black holes	656
21	Extragalactic radio sources	661
21.1	Extended radio sources – Fanaroff–Riley types	661
21.2	The astrophysics of FR2 radio sources	666
21.3	The FR1 radio sources	675
21.4	The microquasars	676
21.5	Jet physics	678
22	Compact extragalactic sources and superluminal motions	681
22.1	Compact radio sources	681
22.2	Superluminal motions	683
22.3	Relativistic beaming	686
22.4	The superluminal source population	693
22.5	Synchro-Compton radiation and the inverse Compton catastrophe	697
22.6	γ -ray sources in active galactic nuclei	699
22.7	γ -ray bursts	704
23	Cosmological aspects of high energy astrophysics	714
23.1	The cosmic evolution of galaxies and active galaxies	714
23.2	The essential theoretical tools	715
23.3	The evolution of non-thermal sources with cosmic epoch	720
23.4	The evolution of thermal sources with cosmic epoch	729
23.5	Mid- and far-infrared number counts	737
23.6	Submillimetre number counts	740
23.7	The global star-formation rate	743
23.8	The old red galaxies	746
23.9	Putting it all together	749
	Appendix Astronomical conventions and nomenclature	753
A.1	Galactic coordinates and projections of the celestial sphere onto a plane	753
A.2	Distances in astronomy	755
A.3	Masses in astronomy	759
A.4	Flux densities, luminosities, magnitudes and colours	760
A.5	Diffraction-limited telescopes	764
A.6	Interferometry and synthesis imaging	771
A.7	The sensitivities of astronomical detectors	774
A.8	Units and relativistic notation	779
	<i>Bibliography</i>	783
	<i>Name index</i>	825
	<i>Object index</i>	829
	<i>Index</i>	831