

Contents

1. Introduction	1
1.1 The Start of Cosmic Ray Research	1
1.2 The Scope of Cosmic Ray Research	1
1.3 Organization of the Book	3
2. Cosmic Rays as Part of the Universe	7
2.1 Our Present View of the Structure of the Universe	7
2.2 Interstellar Medium	10
2.3 Cosmic Photon Fields	17
2.4 Cosmic Magnetic Fields	19
2.5 Intergalactic Medium	23
2.6 Interlude	24
3. Direct Observations of Cosmic Rays	25
3.1 The Cosmic Ray Landscape	26
3.2 Solar Modulation	29
3.3 Solar and Heliospheric Cosmic Rays	36
3.3.1 Solar Flare Cosmic Ray Particles	38
3.3.2 The Anomalous Cosmic Ray Component	46
3.4 Extrasolar Cosmic Rays	46
3.4.1 Elemental Composition	46
3.4.2 Isotopic Composition	57
3.4.3 Anisotropy	64
3.4.4 Time History from Cosmogenic Nuclei	69
3.4.5 Ultrahigh Energy Cosmic Rays	70
4. Interactions of Cosmic Ray Electrons	73
4.1 Synchrotron Radiation	74
4.1.1 Synchrotron Power	74
4.1.2 Emission and Transfer of Synchrotron Radiation	76
4.1.3 Synchrotron Radiation from Cosmic Ray Electrons in the Interstellar Medium	78
4.1.4 Synchrotron Energy Loss of Relativistic Electrons	80
4.2 Inverse Compton Scattering	80

4.2.1	Inverse Compton Power	81
4.2.2	Inverse Compton Scattering of Target Photons in the Interstellar Medium by Cosmic Ray Electrons .	84
4.2.3	Inverse Compton Energy Loss of Relativistic Electrons	88
4.3	Triplet Pair Production	89
4.4	Nonthermal Relativistic Electron Bremsstrahlung	93
4.4.1	Nonthermal Bremsstrahlung Power	93
4.4.2	Nonthermal Bremsstrahlung of Cosmic Ray Electrons in the Interstellar Medium .	95
4.4.3	Bremsstrahlung Energy Loss of Relativistic Electrons	97
4.5	Ionization and Coulomb Interactions	98
4.6	Total Energy Loss Rate	99
4.7	Continuum Radiation Processes of Relativistic Electrons	102
5.	Interactions of Cosmic Ray Nuclei	105
5.1	Relativistic Kinematics of Inelastic Collisions	105
5.1.1	Threshold Energy	106
5.1.2	The Energy of One Particle Seen from the Rest System of Another	107
5.2	Interactions Between Cosmic Ray Nuclei and Cosmic Photons	107
5.2.1	Photo-Pair Production	109
5.2.2	Photo-Hadron Production	109
5.2.3	Photo-Disintegration	112
5.3	Interactions Between Cosmic Ray Nuclei and Matter	114
5.3.1	Gamma-Ray, Electron, Positron and Neutrino Source Functions	115
5.3.2	Pion Production Spectra	116
5.3.3	π^0 Decay γ -Rays	120
5.3.4	Secondary Electrons and Positrons	123
5.3.5	Secondary Neutrinos	125
5.3.6	Energy Loss by Pion Production	128
5.3.7	Excitation of Nuclei	128
5.3.8	Coulomb and Ionization Interactions	130
5.3.9	Catastrophic Losses from Fragmentation and Radioactive Decay	135
5.3.10	Total Energy Loss Rate from Interactions with Matter	138
5.3.11	Ionization and Heating Rate of Interstellar Matter by Cosmic Rays	139
5.3.12	Continuum Radiation Processes of Relativistic Nuclei	140

6. Indirect Observations of Cosmic Rays	143
6.1 Clues from Radio Astronomy	143
6.1.1 Free-Free Emission	143
6.1.2 Radio Continuum Surveys	145
6.2 Clues from γ -Ray Astronomy	154
6.2.1 γ -Ray Emission Above 10 MeV	155
6.2.2 Continuum γ -Ray Emission Below 10 MeV	162
6.2.3 γ -Ray Line Emission Below 10 MeV from the Orion Region	163
6.2.4 Interlude	164
6.3 γ -Ray Point Sources	165
6.3.1 γ -Ray Observations of Active Galactic Nuclei	165
6.3.2 Nonthermal γ -Ray Emission Processes in the Jets of Active Galactic Nuclei	172
6.3.3 Interlude	176
6.3.4 Galactic γ -Ray Sources	177
7. Immediate Consequences of Galactic Cosmic Ray Observations	179
7.1 Cosmic Ray Energetics	179
7.2 Global Cosmic Ray Source Energetics	180
7.3 Cosmic Ray Scattering, Confinement and Isotropy	182
8. Statistical Mechanics of Charged Particles	183
8.1 Basic Equations	183
8.1.1 Plasma Parameter	183
8.1.2 Kinetic Description of Plasmas	187
8.1.3 Magnetohydrodynamics of Plasmas	190
8.2 The Relativistic Vlasov Equation and Maxwell Equations	194
8.3 Kinetic Theory of Plasma Waves	195
8.3.1 Linearization of Kinetic Plasma Equations	195
8.3.2 Solution of the Linearized Vlasov Equation	196
8.3.3 Dispersion Relation	197
8.3.4 The Landau Contour	200
8.3.5 Polarization Vector	203
8.3.6 Conductivity Tensor in a Homogeneous Hot Magnetized Plasma	204
8.3.7 Energy Transfer in Dispersive Media	208
9. Test Wave Approach 1. Waves in Cold Magnetized Plasmas	211
9.1 Plasma Waves in a Cold Moving Magnetized Plasma	211
9.2 Plasma Waves in a Cold Magnetized Plasma at Rest	213
9.2.1 Cold Unmagnetized Plasma at Rest	215
9.2.2 Cold Electron-Proton Plasma	217

9.2.3	Propagation Along the Static Magnetic Field	219
9.2.4	Propagation Across the Static Magnetic Field	224
9.2.5	Oblique Propagation of Low-Frequency Waves	228
9.2.6	Oblique Propagation of High-Frequency Waves	231
9.2.7	More Rigorous Treatment of Dispersion Relation and Polarization of Low-Frequency Waves	234
9.2.8	Faraday Rotation	238
10.	Test Wave Approach 2.	
	Waves in Hot Magnetized Isotropic Plasmas	241
10.1	Conductivity Tensor for Isotropic Distribution Functions	241
10.2	The Longitudinal Mode	244
10.2.1	Superluminal Waves	247
10.2.2	Subluminal Waves	249
10.3	Illustrative Example: Longitudinal Waves in an Equilibrium Electron Plasma	250
10.3.1	Superluminal Waves	252
10.3.2	Subluminal Waves	253
10.3.3	Non-relativistic Plasma Temperatures	254
10.3.4	Infinitely Large Speed of Light, $c \rightarrow \infty$	257
10.3.5	Solution of the Non-relativistic Dispersion Relation	257
10.3.6	Landau Damping of Subluminal Solutions	262
10.3.7	Weak Damping Approximation	262
10.4	The Transverse Modes	263
10.4.1	Collisionless Damping of Transverse Oscillations	265
10.4.2	An Illustrative Example	266
11.	Test Wave Approach 3.	
	Generation of Plasma Waves	269
11.1	Two-Stream Instability	269
11.2	Cosmic-Ray-Induced Instabilities	273
11.2.1	Parallel Propagating Waves	274
11.2.2	Growth Rates at Arbitrary Angles of Propagation	283
11.2.3	Cosmic Ray Self-Confinement in Galaxies	286
11.3	Competition of Wave Growth and Damping	287
11.3.1	Damping by Ion-Neutral Collisions	287
11.3.2	Nonlinear Landau Damping	287
11.3.3	Wave Cascading	289
11.3.4	Super-Alfvénic Cosmic Ray Propagation?	290
12.	Test Particle Approach 1.	
	Hierarchy of Transport Equations	293
12.1	Quasilinear Theory	293
12.2	Quasilinear Fokker-Planck Coefficients	298
12.2.1	Unperturbed Particle Orbits	298

12.2.2	Fokker-Planck Coefficients for Plasma Wave Turbulence	302
12.3	The Diffusion Approximation	306
12.3.1	Cosmic Ray Anisotropy	309
12.3.2	The Diffusion-Convection Transport Equation	310
13.	Test Particle Approach 2.	
	Calculation of Transport Parameters	313
13.1	Linearly Polarized Alfvén Waves	313
13.1.1	Alfvén Wave Fokker-Planck Coefficients	315
13.1.2	Magnetic Turbulence Tensors	315
13.1.3	Slab Linearly Polarized Alfvén Turbulence	318
13.1.4	Isotropic Linearly Polarized Alfvén Waves	319
13.2	Parallel Propagating Magnetohydrodynamic Waves	320
13.2.1	Undamped Waves	322
13.2.2	Undamped Non-dispersive Alfvén Waves	322
13.2.3	Influence of Damping and Dissipation	337
13.2.4	Numerical Test of Quasilinear Theory	340
13.3	Magnetosonic Waves	342
13.3.1	Fast Mode Wave Fokker-Planck Coefficients	343
13.3.2	Isotropic Fast Mode Waves	345
13.3.3	Cosmic Ray Mean Free Path from Fast Mode Waves	357
13.3.4	Cosmic Ray Momentum Diffusion Coefficient from Fast Mode Waves	359
13.3.5	Fast Mode Time Scale Relation	361
13.4	Cosmic Transport Parameters from Fast Mode Waves and Slab Alfvén Waves	361
13.4.1	Modifications Due to Slab Alfvén Waves	361
13.4.2	Transport Parameters in the Case of Admixture of Slab Alfvén Waves to Fast Mode Waves	362
14.	Acceleration and Transport Processes of Cosmic Rays	365
14.1	Structure of the Cosmic Ray Transport Equation	365
14.1.1	Inclusion of Momentum Losses	367
14.1.2	Continuous and Catastrophic Momentum Losses	368
14.2	Steady-State and Time-Dependent Transport Equations	370
14.3	Scattering Time Method: Separation of Spatial and Momentum Problem	371
14.3.1	Formal Mathematical Solution	371
14.3.2	Leaky-Box Equations	372
14.3.3	Illustrative Example: Galactic Cosmic Ray Diffusion 1	373
14.3.4	Momentum Problem	375
14.4	Solutions Without Momentum Diffusion	378

15. Interplanetary Transport of Cosmic Ray Particles	383
15.1 Solar Flare Events	383
15.1.1 Observations	383
15.1.2 Comparison with Quasilinear Theory	387
15.2 Solar Modulation of Galactic Cosmic Rays	388
16. Acceleration of Cosmic Ray Particles	
at Shock Waves	391
16.1 Astrophysical Shock Waves	391
16.2 Magnetohydrodynamic Shock Discontinuities	392
16.2.1 Stationary Discontinuities	395
16.2.2 Shock Waves	397
16.3 Alfvén Wave Transmission Through a Parallel Fast Shock ...	402
16.3.1 Basic Equations	403
16.3.2 Reflection and Transmission Coefficients	405
16.3.3 Only Forward Moving Waves Upstream	405
16.3.4 Only Backward Moving Waves Downstream	409
16.3.5 Alternative Notation	410
16.3.6 Shock Effect on Wavenumbers	410
16.3.7 Precursor Streaming Instability	413
16.4 Cosmic Ray Transport and Acceleration Parameters	415
16.4.1 Upstream Cosmic Ray Transport Equation	416
16.4.2 Downstream Cosmic Ray Transport Equation	417
16.4.3 Scattering Center Compression Ratio	418
16.4.4 Importance of Downstream Momentum Diffusion ...	419
16.4.5 Interlude	420
16.5 Solution of the Transport Equations	421
16.5.1 Basic Equations	422
16.5.2 Upstream Solution	424
16.5.3 Downstream Solution	424
16.6 Qualitative Results	428
16.6.1 Zero Momentum Diffusion	429
16.6.2 Finite Momentum Diffusion	431
16.7 Maximum Particle Energy	433
17. Galactic Cosmic Rays	435
17.1 Galactic Cosmic Ray Diffusion 2	435
17.2 Cosmic Ray Propagation in the Leaky-Box Approximation ...	436
17.2.1 Secondary/Primary Ratio	437
17.2.2 Secondary Cosmic Ray Clocks	438
17.3 Cosmic Ray Propagation Including Interstellar Acceleration ..	439
17.3.1 Mathematical Solution	441
17.3.2 Sources of Cosmic Ray Primaries	443
17.3.3 Steady-State Primary Particle Spectrum Below $R_{\max}$...	445

17.3.4	Influence of Source Spectral Index Dispersion on the Steady-State Primary Particle Spectrum Below $R_{\max}$	450
17.3.5	Steady-State Primary Particle Spectrum Above $R_{\max}$	452
17.4	Time-Dependent Calculation	455
17.4.1	General Values $\chi \neq 0$	455
17.4.2	Special Case $\chi = 0$	457
17.5	Secondary/Primary Ratio Including Interstellar Acceleration ..	458
18.	Formation of Cosmic Ray Momentum Spectra	461
18.1	Fundamental Physical Picture	461
18.2	Some Exact Solutions for $q = 2$	464
18.2.1	Shock Acceleration of Relativistic Electrons Undergoing Radiation Losses	465
18.2.2	Shock Acceleration of Relativistic Electrons Undergoing Ionization and Coulomb Losses	467
18.3	Bessel Function Solutions	467
18.4	Interlude	468
19.	Summary and Outlook	469
19.1	Cosmic Ray Sources	470
19.2	Cosmic Ray Isotropy	471
19.3	Cosmic Ray Isotopic and Elemental Composition	472
19.4	Electron/Nucleon Ratio	472
19.5	Formation of Particle Momentum Spectra	474
19.6	Conclusion	474
 Appendix		
A.	Radiation Transport	475
B.	Conductivity Tensor in a Hot Magnetized Plasma	479
B.1	The General Case	481
B.2	Isotropic Distribution Functions	482
C.	Calculation of the Integral (10.3.10)	485
C.1	The Integral J for Imaginary Values of y	486
C.2	The Integral J for Non-imaginary Values of y	487
C.3	A Second Form of the Integral J	490
C.4	The Integral J for Non-relativistic Temperatures	491
References		495
Illustration Credits		511
Index		513