

Contents

1	Introduction	1
1.1	General Overview	1
1.2	Complexity of the Inner Magnetosphere	5
References		8
2	Kinetic Equations and Particle Collisions	11
2.1	Kinetic and Maxwell Equations	11
2.2	Elastic Collisions	13
2.3	Inelastic Collisions	17
2.4	Plasma Source	20
2.5	Superthermal Electron Kinetic Equation Simplification	24
References		26
3	General Description of Wave–Particle Interaction Phenomena	27
3.1	Plasma Electrodynamics	27
3.2	Energy of the Electromagnetic Field	31
3.3	Electromagnetic Waves	34
3.4	Dielectric Tensor of Collisionless Plasma	36
3.5	Maxwellian Plasma	41
3.6	Cold Plasma Approximation	43
3.7	Wave Damping and Growth	46
3.8	The Quasilinear Approximation	53
3.9	Nonlinear Drift-Kinetic Equation	56
References		62
4	Hydrodynamic Description of Space Plasma	65
4.1	Moments of the Kinetic Equation	65
4.2	General Transport Equations	72
4.3	The 16-Moment Approximation	79
4.4	Coulomb Collision Terms	82

4.4.1 General Expressions	82
4.4.2 Collisions with Superthermal Electrons	86
4.5 Collisions with Neutral Particles	90
4.5.1 Electrons	90
4.5.2 Ions	98
4.6 Wave–Particle Interaction Terms	102
4.6.1 Quasilinear Interaction in Hydrodynamics: General Relationships	103
4.6.2 Moments in a Bi-Maxwellian plasma	108
4.6.3 Moments in the Absence of a Transverse Drift	110
4.7 Heat Balance Equation in the Presence of Temperature Anisotropy	113
4.8 Equations of Anisotropic Hydrodynamics for Modeling the Ionosphere–Magnetosphere Plasma	119
References	121
5 Transport of Superthermal Electrons: General Analysis	125
5.1 Exact Solution of the Collisionless Drift Kinetic Equation	125
5.1.1 Introduction	125
5.1.2 Moments of the Velocity Distribution Function	128
5.1.3 The Generalized Approach	130
5.1.4 Implementation	133
5.2 Legendre Polynomial Expansion	140
5.3 Description of Electron–Electron Collisions in the Lower Ionosphere	146
5.3.1 Lower Energies	146
5.3.2 Fine Structure of Photoelectron Fluxes	149
5.4 Pitch-Angle Distribution in the Upper Ionosphere	154
5.5 Transport in the Plasmasphere	159
5.5.1 Infinite Trapped Zone Approximation	162
5.5.2 The Distribution Function of Superthermal Electrons in the Plasmasphere	165
5.5.3 Plasmaspheric Transparency and Heating Rate	170
5.6 Thermal Electron Heating Rate	174
5.7 The Loss Cone Distribution	184
References	188
6 Analysis of Cold Plasma Transport	193
6.1 Convective Plasma Motion in the Magnetosphere	193
6.2 Density Distribution	194
6.2.1 Model of the Electric Field	194
6.2.2 Effects of Perpendicular Transport on Equatorial Density ...	196
6.2.3 Plasma Distribution Along a Field Line	201
6.3 Effects of Magnetospheric Convection on Temperature	205

6.3.1 Adiabatic Variations	206
6.3.2 Heat Conduction	209
6.4 Plasma Electron Temperature Anisotropy	211
6.4.1 The Effect of Anisotropy on Electron Temperature in the Plasmasphere	212
6.4.2 Electron Temperature Anisotropy Estimations	215
6.4.3 Discussion	229
6.5 Heating and Cooling of the Plasmasphere	232
6.5.1 Electron Energy Equation and Sources of Heating	233
6.5.2 Electron Temperatures in the Upper Ionosphere	234
6.5.3 Plasmaspheric Solution	235
6.5.4 Analysis	237
6.6 Polar Wind	241
6.6.1 Historical Remarks	241
6.6.2 General Relations	244
6.6.3 The Solution of the Kinetic Equation	245
6.6.4 Moments of the Velocity Distribution Function	247
6.6.5 Thermal Electron Fluid Equations	249
6.6.6 The Necessity of a Generalized Model	251
6.6.7 Applications of the General Formulation	256
References	263
7 Kinetic Theory of Superthermal Electron Transport	271
7.1 Superthermal Electron Studies	271
7.2 Ionosphere–Plasmasphere Superthermal Electrons Coupling	272
7.2.1 Mathematical Formulation	272
7.2.2 Steady-State Solution	276
7.2.3 Nonsteady-State Solution	279
7.2.4 Plasmaspheric Transparency	284
7.2.5 Plasmaspheric Energy Interplay	289
7.2.6 Comparison with Observations	292
7.3 Global Superthermal Electron Transport	294
7.3.1 The Field-Aligned and Bounce-Averaged Models	295
7.3.2 Combined Global Model	297
7.3.3 Numerical Implementation	298
7.3.4 The Low-Energy Limit	300
7.3.5 Photoelectron Distribution Function Formation	304
7.3.6 Injection of Plasma Sheet Electrons	309
7.3.7 The Combined Electron Distribution Function	312
7.4 Artificial Relativistic Electrons Injection	317
7.4.1 Interhemispheric Transport	318
7.4.2 Global Transport	325
7.5 Magnetospheric Convection Electric Field Dynamics and Storm-Time Particle Energization	351

7.5.1 Electric Fields Models	351
7.5.2 Model Description	353
7.5.3 The 1–7 May 1998 Storm	355
7.5.4 Results	356
References	368
8 Kinetic Superthermal Electron Instabilities in the Ionosphere	377
8.1 The Generation of Plasma Oscillations by Photoelectrons	377
8.1.1 Dielectric Permittivity of Plasma	377
8.1.2 Cherenkov Resonance	379
8.1.3 Cyclotron Resonance	385
8.1.4 Double Resonance	388
8.2 High-Frequency Fluctuations in the Ionospheric Plasma	390
8.2.1 Fluctuations of a Non-equilibrium Stable Plasma	390
8.2.2 Coulomb Scattering in a Weakly Non-equilibrium Plasma ...	393
8.2.3 Unstable Plasma Fluctuations	396
8.3 Relaxation of Electron Fluxes in the Auroral Ionosphere	399
8.3.1 The Origin of Electron Beams	399
8.3.2 Peculiarities of the Plasma Noise Distribution in the Auroral Ionosphere	406
8.3.3 Instabilities of the Secondary Electrons in the Region of Their Production	409
8.4 Some Radio Physical Effects of Superthermal Electrons	413
8.4.1 The RIS Spectrum in the Presence of Photoelectrons: Diagnostic of Aeronomical Parameters	414
8.4.2 Ground-Based Diagnostic of Photoelectron Fluxes	421
8.4.3 Generation of VLF Emission	423
References	425
9 Kinetic Theory of Ring Current and Electromagnetic Ion Cyclotron Waves: Fundamentals	429
9.1 General Overview	429
9.1.1 Terrestrial Ring Current	429
9.1.2 Electromagnetic Ion Cyclotron Waves	431
9.2 EMIC Wave Generation and Propagation in Magnetosphere	434
9.2.1 EMIC Wave Modes in Multicomponent Plasma	434
9.2.2 Propagation in the Magnetosphere	438
9.2.3 Tunneling Effects	441
9.3 Bouncing EMIC Waves Versus Unidirectional Propagation	445
9.3.1 Poynting Flux Analysis: No Reflection	446
9.3.2 Poynting Flux Analysis: With Reflection	448
9.3.3 EMIC Wave Ellipticity Argument	454
9.3.4 Convective Instability Argument	456
9.4 Governing Equations	458

9.4.1 Wave Kinetic Equation	458
9.4.2 Ring Current Particle Transport	462
9.4.3 Coupling with the Magnetospheric Electric Field	463
9.4.4 Simulation Scenarios	465
9.5 The EMIC Wave Normal Angle Distribution	471
9.5.1 Prediction from Theory	471
9.5.2 Comparison with Observations	476
9.6 The Effect of Ring Current H ⁺ Density	479
References	482
10 Kinetic Theory of Ring Current and Electromagnetic Ion Cyclotron Waves: Applications	491
10.1 Wave-Induced Precipitated RC Fluxes	491
10.2 Heating of Thermal Plasmaspheric Electrons and Subauroral Ionospheric Temperature Enhancement	494
10.2.1 EMIC Wave and Coulomb Heating of Thermal Plasmaspheric Electrons	494
10.2.2 Electron Heating Events in Subauroral Tropside Ionosphere: Qualitative Comparison with Observations ...	498
10.2.3 Relationship of Wave Heating to SAR Arcs	501
10.3 Associated Global Inner Magnetosphere Environment	502
10.3.1 Magnetospheric Electric Field	502
10.3.2 Plasmasphere	505
10.4 Relativistic Electrons Scattering by EMIC Waves	507
10.4.1 Introduction	507
10.4.2 Pitch-Angle Diffusion Coefficients: Model Calculations ...	509
10.4.3 Bounce-Averaged Diffusion Coefficient: Self-Consistent Calculations	513
10.4.4 CRRES-Based Calculations	515
10.5 The Nonlinear Coupling of Electromagnetic Ion Cyclotron and Lower Hybrid Waves in the Ring Current Region	521
10.5.1 Lower Hybrid Waves	521
10.5.2 Generation of Lower Hybrid Waves	523
10.5.3 Results and Discussion	531
References	535
Concluding Remarks	541
Appendix A	545
Appendix B	549
Appendix C	553
Appendix D	557

Appendix E	561
Appendix F	563
Appendix G	565
Appendix H: Other Possible Potential Energies	567
H.1 The Ponderomotive Potential of Alfvén Waves	567
H.2 Centrifugal Acceleration	568
Appendix I	571
I.1 Coulomb Collisions	571
I.2 Elastic Collisions	571
I.3 Inelastic Collisions	572
References	575
Index	577

Abbreviations

AMIE	Assimilative Mapping of Ionospheric Electrodynamics
AMPTE	Active Magnetospheric Particle Tracer Explorers
AMPTE/CCE	Active Magnetospheric Particle Tracer Explorers/Charge Composition Explorer
BGK	Bhatnagar-Gross-Krook
CGL	Chew-Goldberger-Low
CPCP	Cross Polar Cap Potential
CRRES	Combined Release and Radiation Effects Satellite
DE	Dynamics Explorer
DMSP	Defense Meteorological Satellites Program
ELF	Extremely Low Frequency
EMIC-waves	ElectroMagnetic Ion Cyclotron waves
EUV	Extreme UltraViolet
FAC	Field-Aligned Current
FFT	Fast Fourier Transform
FLIP	Field Line Interhemispheric Plasma
FMS	Fast MagnetoSonic
FWHM	Full Width at Half Maximum
GPS	Global Positioning System
HENA	High-Energy Neutral Atom
ICME	Interplanetary Coronal Mass Ejection
IM/S	Inner Magnetosphere/Storm
IMAGE	Imager for Magnetopause-to-Aurora Global Exploration
IMF	Interplanetary Magnetic Field
IRI	International Reference Ionosphere
IRM	Ion Release Module
ISEE	International Sun–Earth Explorer
ISIS	International Satellites for Ionospheric Studies
LANL	Los Alamos National Lab
LCB	Loss Cone Boundary