Contents

Preface XI References XII Books for Plasma Physics XII

1 General Concepts in Physics of Excited and Ionized Gases 1

۱v

- 1.1 Ideal Plasma 1
- 1.1.1 Plasma as a State of Matter 1
- 1.1.2 The History of the Study of Electricity 5
- 1.1.3 Methods of Plasma Generation 7
- 1.1.4 Charged Particles in a Gas 9
- 1.1.5 Definition of a Plasma 12
- 1.1.6 Oscillations of Plasma Electrons 13
- 1.1.7 Interaction of Charged Particles in an Ideal Plasma 14
- 1.1.8 Microfields in an Ideal Plasma 15
- 1.1.9 Beam Plasma 19
- 1.2 Statistics of Atomic Particles in Excited and Weakly Ionized Gases 22
- 1.2.1 Distribution Function of a System of Identical Particles 22
- 1.2.2 The Boltzmann Distribution 23
- 1.2.3 Statistical Weight of a State and Distributions of Particles in Gases 25
- 1.2.4 The Maxwell Distribution 27
- 1.2.5 The Saha Distribution 28
- 1.2.6 Dissociative Equilibrium in Molecular Gases 29
- 1.2.7 Laws of Blackbody Radiation 29
- 1.2.8 Ionization Equilibrium in a Plasma with Particles 31
- 1.2.9 Thermoemission of Electrons 33
- 1.2.10 The Treanor Effect 34
- 1.2.11 Normal Distribution 36
- 1.3 Rarefied and Dense Plasmas 38
- 1.3.1 Criteria for an Ideal Plasma 38
- 1.3.2 Conditions for Ideal Equilibrium Plasmas 39
- 1.3.3 Instability of Two-Component Strongly Coupled Plasmas 41
- 1.3.4 Special Features of Strongly Coupled Plasmas 42
- 1.3.5 Quantum Plasmas 44

VI Contents

1.3.6 1.3.7	Ideal Electron–Gas and Ion–Gas Systems 46 Decrease of the Atomic Ionization Potential in Plasmas 47
1.3.8	Spectrum of Atoms in a Plasma 49 References 51
2	Elementary Processes in Excited and Ionized Gases 53
2.1	Elastic Collision of Atomic Particles 53
2.1.1	Elementary Act of Collisions of Particles in a Plasma 53
2.1.2	Model of Hard Spheres 57
2.1.3	Collision Processes Involving Clusters 60
2.1.4	Cross Section of Capture 62
2.1.5	Total Cross Section of Scattering 63
2.1.6	Gaseous State Criterion 64
2.1.7	Elastic Collisions of Electrons with Atoms 65
2.1.8	Elastic Scattering of Charged Particles in a Plasma 68
2.1.9	Elastic Ion–Atom Collision and Resonant Charge Exchange 70
2.2	Inelastic Processes Involving Electrons 77
2.2.1	Excitation and Quenching of Atoms by Electron Impact 77
2.2.2	Atom Ionization by Electron Impact 81
2.2.3	Three Body Recombination of Electrons and Ions 84
2.2.4	Autoionizing and Autodetaching States in Collision Processes 86
2.2.5	Dissociative Recombination 90
2.2.6	Dielectronic Recombination 92
2.2.7	Attachment of Electrons to Molecules 93
2.3	Elementary Processes Involving Ions and Atoms 96
2.3.1	Slow Inelastic Collisions of Heavy Atomic Particles 96
2.3.2	Three Body Collision Processes Involving Ions 98
2.3.3	Three Body Processes Involving Excited Atoms 100
2.3.4	Associative Ionization and the Penning Process 103
2.3.5	Pairwise Recombination of Positive and Negative Ions 107
2.3.6	Processes Involving Formation of a Long-Lived Complex 108
2.3.7	Types of Elementary Processes 112
2.4	Radiative Processes in Excited and Ionized Gases 112
2.4.1	Interaction of Radiation with Atomic Systems 112
2.4.2	Spontaneous and Stimulated Emission 113
2.4.3	Radiative Transitions in Atoms 115
2.4.4	Photoionization and Photorecombination Processes 117
2.4.5	Bremsstrahlung in Ionized Gases Involving Electrons 120
2.4.6	Broadening of Spectral Lines 123
2.4.7	Cross Section and Absorption Coefficient for Resonant Photons 126 References 129
3	Physical Kinetics of Ionized Gases 133
3.1	Kinetics of Atomic Particles in Gases and Plasmas 133
3.1.1	The Boltzmann Kinetic Equation 133
3.1.2	Collision Integral for Gas Atoms 134

I

- 3.1.3 Equilibrium Distribution of Gas Atoms 136
- 3.1.4 Collision Integral for Electrons in a Gas 137
- 3.1.5 Collision Integral for Fast Electrons in an Electron Gas 140
- 3.1.6 The Landau Collision Integral 142
- 3.2 Kinetics of Electrons in a Gas in an External Electric Field 145
- 3.2.1 Kinetics of Electrons in a Gas Resulting from Elastic Collisions with Atoms 145
- 3.2.2 Evolution of Electrons in an Atomic Gas in an Electric Field 149
- 3.2.3 Electrons in a Gas in the Regime of High Electron Number Density 151
- 3.2.4 Conductivity of an Ionized Gas and a Plasma 155
- 3.2.5 Electrons in a Gas in an Alternating Electromagnetic Field 158
- 3.2.6 Kinetics of Atom Excitation in Ionized Gases in an Electric Field 159
- 3.3 Radiation Transfer and Kinetics of Excitations in a Plasma 168
- 3.3.1 Equilibrium of Resonantly Excited Atoms in a Plasma 168
- 3.3.2 Stepwise Ionization of Atoms 169
- 3.3.3 Excited Atoms in a Helium Plasma 170
- 3.3.4 Emission from a Flat Plasma Layer 173
- 3.3.5 Propagation of Resonant Radiation in a Dense Plasma 175
- 3.3.6 Resonant Emission from a Nonuniform Plasma and Self-Reversal of Spectral Lines 178
- 3.3.7 Radiation from the Solar Photosphere 181
- 3.3.8 Excitations in a Photoresonant Plasma 184
- 3.3.9 Kinetics of Electrons and Ionization Processes in Photoresonant Plasma 188 References 192

4 Transport Phenomena in Ionized Gases 195

- 4.1 Hydrodynamics of Ionized Gases 195
- 4.1.1 Macroscopic Gas Equations 195
- 4.1.2 Equation of State for a Gas 198
- 4.1.3 The Navier–Stokes Equation 199
- 4.1.4 Macroscopic Equation for Ion Motion in a Gas 200
- 4.1.5 The Chapman–Enskog Approximation for Ion Mobility in Gas 201
- 4.1.6 Excitation of an Ionized Gas in an Electric Field 202
- 4.2 Transport Phenomena in Neutral Gases 204
- 4.2.1 Transport of Particles in Gases 204
- 4.2.2 Diffusive Motion of Particles in Gases 206
- 4.2.3 The Einstein Relation 207
- 4.2.4 Heat Transport 208
- 4.2.5 Thermal Conductivity Due to Internal Degrees of Freedom 209
- 4.2.6 Thermal Capacity of Molecules 211
- 4.2.7 Momentum Transport and Gas Viscosity 212
- 4.2.8 The Chapman–Enskog Approximation for Kinetic Coefficients of Gases 213
- 4.3 Transport of Electrons in Gases 218

- 4.3.1 Diffusion and Mobility of Electrons in Gases in Electric Field 218
- 4.3.2 Diffusion of Electrons in a Gas in a Magnetic Field 222
- 4.3.3 Thermal Conductivity of Electrons in an Ionized Gas 223
- 4.3.4 Thermal Diffusion of Electrons 225
- 4.3.5 Cross-Fluxes in Electron Thermal Conductivity 226
- 4.3.6 Townsend Energy Coefficient 227
- 4.4 Transport of Atomic ions and Clusters in Plasma 230
- 4.4.1 Zero-Field Mobility of Ions in Gases 230
- 4.4.2 Mobility of Ions at High and Intermediate Field Strengths 235
- 4.4.3 Diffusion of Atomic Ions in Gases in External Fields 238
- 4.4.4 Conversion of Ions During Drift in an Electric Field 241
- 4.4.5 Mobility and Diffusion of Large Clusters in a Gas 249
- 4.4.6 Ambipolar Diffusion 253
- 4.4.7 Double Layer 256
- 4.4.8 Electrophoresis 258
- 4.4.9 Recombination of Positive and Negative Ions in Gases 258
- 4.5 Plasma in a Magnetic Field 261
- 4.5.1 Electron Hydrodynamics in a Gas in an External Field 261
- 4.5.2 Hall Effect 262
- 4.5.3 Cyclotron Resonance 265
- 4.5.4 Motion of Charged Particles in a Nonuniform Magnetic Field 266
- 4.5.5 Magnetic Traps 269
- 4.5.6 Charge Particles in the Earth's Magnetic Field 272
- 4.5.7 High-Conductivity Plasma in a Magnetic Field 275
- 4.5.8 Pinch Effect 277
- 4.5.9 Reconnection of Magnetic Lines of Force 277 References 279
- 5 Waves, Instabilities, and Structures in Excited and Ionized Gases 283
- 5.1 Instabilities of Excited Gases 283
- 5.1.1 Convective Instability of Gases 283
- 5.1.2 Rayleigh Problem 284
- 5.1.3 Convective Movement of Gases 286
- 5.1.4 Convective Heat Transport 287
- 5.1.5 Instability of Convective Motion 289
- 5.1.6 Thermal Explosion 291
- 5.1.7 Thermal Waves 293
- 5.1.8 Thermal Waves of Vibrational Relaxation 298
- 5.1.9 Ozone Decomposition Through Thermal Waves 301
- 5.2 Waves in Ionized Gases 304
- 5.2.1 Acoustic Oscillations 304
- 5.2.2 Plasma Oscillations 306
- 5.2.3 Ion Sound 308
- 5.2.4 Magnetohydrodynamic Waves 309
- 5.2.5 Propagation of Electromagnetic Waves in a Plasma 310

- The Faraday Effect in a Plasma 312 5.2.6
- 5.2.7 Whistlers 314
- 53 Plasma Instabilities 316
- 5.3.1 Damping of Plasma Oscillations in Ionized Gases 316
- Interaction Between Plasma Oscillations and Electrons 317 5.3.2
- Attenuation Factor for Waves in Plasmas 320 5.3.3
- 534 Beam-Plasma Instability 321
- 5.3.5 Buneman Instability 323
- 5.3.6 Hvdrodvnamic Instabilities 324
- 5.4 Nonlinear Phenomena in Plasmas 325
- The Lighthill Criterion 325 5.4.1
- 5.4.2 The Korteweg–de Vries Equation 326
- 5.4.3 Solitons 327
- 5.4.4 Langmuir Solitons 328
- 5.4.5 Nonlinear Ion Sound 329
- 5.4.6 Parametric Instability 332
- 5.5 Ionization Instabilities and Plasma Structures 335
- Drift Waves 335 5.5.1
- Ionization Instability from Thermal Effects 336 5.5.2
- 5.5.3 Ionization Wave in a Photoresonant Plasma 337
- 5.5.4Ionization Instability of a Plasma in a Magnetic Field 339
- 5.5.5 Attachment Instability of a Molecular Gas 341
- 5.5.6 Current Convective Instability 343
- 5.5.7 Electric Domain 345
- 5.5.8 Striations as Ionization Waves 347
- Self-Consistent Structure of Striations 351 5.5.9 References 355

6 **Complex Plasmas, Including Atmospheric Plasmas** 3.59

- 6.1 Single Cluster or Particle in an Ionized Gas 359
- Characteristics of a Complex Plasma 359 6.1.1
- Transport Parameters of Clusters 360 6.1.2
- 6.1.3 Charging of Particles in a Dense Ionized Gas 362
- 6.1.4 The Charge Distribution Function for Clusters 365
- Charging of Clusters or Particles in a Rare Ionized Gas 6.1.5 367
- 6.1.6 Ionization Equilibrium for Large Dielectric Clusters 370
- 6.2 Particle Fields in an Ionized Gas 372
- Self-Consistent Particle Field in a Rare Ionized Gas 372 6.2.1
- 6.2.2 Trapped Ions of Low-Density Plasma in a Particle Field 377
- 6.2.3 Interaction of Dust Particles with the Solar Wind 383
- 6.2.4 Screening of the Particle Field in a Dense Ionized Gas 385
- 6.2.5 Influence of Particles on the Properties of Ionized Gases 388
- 6.2.6 Particle Structures in Dusty Plasma 390
- 6.3 Cluster Plasma 395
- 6.3.1 Ionization Equilibrium for Metal Clusters in a Cluster Plasma 395

- X | Contents
 - 6.3.2 Conversion of an Atomic Vapor into a Gas of Clusters 397
 - 6.3.3 Cluster Growth in Coagulation and Coalescence 401
 - 6.3.4 Cluster Growth in a Hot Gas with Metal-Containing Molecules 406
 - 6.3.5 Passage of Cluster Plasma Flow through an Orifice 411
 - 6.4 Plasma Processes in the Earth's Atmosphere 412
 - 6.4.1 Processes in Atmospheric Plasmas 412
 - 642 Aerosol Plasma 417
 - 6.4.3 The Ionosphere as a Mirror for Electromagnetic Waves 418
 - 6.4.4 Atomic Oxygen in the Upper Atmosphere 421
 - 6.4.5 Ions in the Upper Atmosphere 423
 - 6.5 Electric Machine of the Earth's Atmosphere 425
 - 6.5.1 The Earth as an Electric System 425
 - 6.5.2 Lightning 428
 - 6.5.3 Electric Processes in Clouds 430
 - 6.5.4 Characteristics of Earth Charging 433
 - 6.5.5 Charged Particles in an Aerosol Plasma 438
 - Prebreakdown Phenomena in the Atmosphere 439 6.5.6 References 441
 - Conclusion Plasmas in Nature and the Laboratory 447 7 References 457
 - Appendix A Physical Constants and Units 459

References 466

Appendix B Parameters of Atoms and Ions 467

Index 469