

CONTENTS

PREFACE	xv
CHAPTER 1. INTRODUCTION	1
1.1. The Solar Corona	2
1.1.1. Brief Overview of the Sun	2
1.1.2. Optical Observations of the Corona	4
1.1.3. Soft X-Rays	4
1.1.4. Thermal Radio Emissions	5
1.2. Dynamic Processes	7
1.2.1. Processes in the Upper Corona	7
1.2.2. Processes in the Lower Corona	7
1.2.3. Solar Flares	8
1.2.4. Other Dynamic Processes	9
1.3. Stellar Coronae	11
1.3.1. Soft X-Ray Emission	11
1.3.2. Stellar Flares	12
1.3.3. Quiescent Radio Emission	14
1.4. Fundamental Equations	15
1.4.1. Magnetohydrodynamic Approach	17
1.4.2. Kinetic Approach	18
Further Reading and References	21
CHAPTER 2. BASIC CONCEPTS	22
2.1. Single Particle Orbit	22
2.1.1. Homogeneous Magnetic Field	22
2.1.2. Inhomogeneous Magnetic Field	25
2.1.3. Conservation of the Magnetic Moment	26
2.1.4. Particle Drifts	27
A. Electric Field	29
B. Gravitational Field	29
C. Curved Field Lines	29
2.2. Particle Trapping in Magnetic Fields	30
2.3. Generation of Beams	32
2.4. Debye Shielding	35
2.5. Charge Oscillations and the Plasma Frequency	38
2.6. Collisions	40

2.6.1. Particle Encounters in a Plasma	40
2.6.2. Fokker-Planck Method	42
2.6.3. Collision Times	43
A. Angular Deflection	43
B. Energy Loss	45
C. Momentum Loss	46
D. Discussion	46
E. Thermal Collision Times	48
Exercises	49
Further Reading and References	50
 CHAPTER 3. MAGNETOHYDRODYNAMICS	51
3.1. Basic Statistics	51
3.1.1. Boltzmann Equation	51
3.1.2. Velocity Moments of the Boltzmann Equation	52
A. Conservation of Particles	53
B. Conservation of Momentum	53
C. Conservation of Energy	54
3.1.3. Elementary Magnetohydrodynamics (MHD)	55
A. MHD Equations and Approximations	56
B. Electric Fields	58
C. MHD Properties	58
3.2. MHD Waves	61
3.2.1. Linearization	61
3.2.2. Dispersion Relation and Polarization (Parallel Propagation)	62
3.2.3. Perpendicular Propagation	65
3.2.4. General Case	66
Exercises	67
Further Reading and References	68
 CHAPTER 4. WAVES IN A COLD, COLLISIONLESS PLASMA	69
4.1. Approximations and Assumptions	69
4.2. Cold Plasma Modes	71
4.2.1. Linearization	71
4.2.2. Ohm's Law	73
4.2.3. Dielectric Tensor	74
4.2.4. Dispersion Relation	75
4.3. Parallel Waves	76
4.3.1. Electrostatic Waves	76
4.3.2. Electromagnetic Waves	77
4.3.3. Dispersion Relations of the L and R Waves	78
4.3.4. Resonances at the Gyrofrequencies	79
4.3.5. Cutoffs Near ω_p	80

4.4. Perpendicular Propagation	81
4.4.1. Electrostatic Waves	81
4.4.2. Electromagnetic Waves	82
4.5. Oblique Propagation and Overview	83
4.6. Beam Mode	85
Exercises	87
Further Reading and References	88
 CHAPTER 5. KINETIC PLASMA AND PARTICLE BEAMS	89
5.1. Radio Observations of Solar Electron Beams	89
5.1.1. Radio Instruments	92
5.1.2. Type III Radio Bursts	93
5.2. Waves and Instability in Kinetic Plasmas	94
5.2.1. Singularities	98
5.2.2. Dispersion Relation	100
A. Principal Part	100
B. Singular Point	100
5.2.3. Landau Damping	101
5.2.4. Bump-on-Tail Instability	102
5.2.5. Čerenkov Resonance	103
5.2.6. Ion Acoustic Waves	104
5.2.7. Thermal Level of Waves	106
5.3. Plasma Waves in the Solar Corona	107
5.3.1. Plasma Density	107
5.3.2. Drift	108
5.3.3. Field Geometry	109
A. U-Bursts	109
B. Magnetic Field Configuration Near Acceleration	111
C. Interplanetary Space	111
5.3.4. Decay Time	112
5.3.5. Other Radio Wave Emitting Beams	113
Exercises	113
Further Reading and References	114
 CHAPTER 6. ASTROPHYSICAL ELECTRON BEAMS	115
6.1. The Beam-Plasma System	115
6.1.1. Magnetically Driven Return Current	116
6.1.2. Electrostatic Return Current	119
6.2. Non-Linear Evolution and Saturation	120
6.2.1. Quasi-Linear Diffusion	122
6.2.2. Strong Turbulence	124
6.2.3. Deflection of Electrostatic Waves	126
6.2.4. Summary	127

6.3. Plasma Emission	127
6.3.1. Harmonics	127
6.3.2. Phonons and Their Scattering (Wave Conversion)	129
A. Spontaneous Scattering off Ions	130
B. Induced Scattering	131
C. Scattering off Other Waves	132
6.3.3. Plasma Radiation Emissivities	135
A. Emission at the Harmonic	135
B. Emission at the Fundamental: Scattering off Ions	136
C. Emission at the Fundamental: Decay	137
6.3.4. Sense of Polarization	139
6.3.5. Magnetic Field Strength in the Corona	140
6.4. Hard X-Ray Emission of Beams	142
6.4.1. Emission Process	142
6.4.2. Observations	144
6.4.3. X-Rays from Beams	145
6.4.4. Radio – Hard X-Ray Association	147
6.4.5. Diagnostics of the Accelerator	147
A. Energy of Flare Electrons	148
B. Fragmentation of Flares	150
Exercises	151
Further Reading and References	152
 CHAPTER 7. ION BEAMS AND ELECTROMAGNETIC INSTABILITIES	 154
7.1. Observations of Energetic Ions	154
7.1.1. Solar Ion Beams	154
7.1.2. Cosmic Rays	156
7.1.3. Ion Beams Near Earth	158
7.2. Electromagnetic Instabilities of Velocity Space Anisotropy	158
7.2.1. Fire-Hose Instability	159
7.2.2. Kinetic Instability	160
A. Dispersion Relation of Transverse Waves in Kinetic Plasma	160
B. Resonance Condition	163
C. Wave-Particle Interaction	164
D. Growth Rate	166
7.3. Applications to Ion Beams	168
7.3.1. Instability Threshold	168
7.3.2. Wave Growth	169
7.3.3. Ion Beam Propagation	170
A. Deflection Time	171
B. Diffusive Propagation	172
7.4. Electrostatic Ion Beam Instabilities	174
7.4.1. Low-Frequency Waves	174
7.4.2. High-Frequency Waves	175

Exercises	175
Further Reading and References	176
CHAPTER 8. ELECTRONS TRAPPED IN MAGNETIC FIELDS 177	
8.1. Observational Motivation	178
8.1.1. Incoherent Solar Emissions	178
8.1.2. Synchrotron Emission	179
8.1.3. Narrowband Spikes	182
8.2. Loss-Cone Instabilities	184
8.2.1. Low-Frequency Electromagnetic Instability	184
8.2.2. High-Frequency Waves and Cyclotron Masers	186
A. Linear Growth Rates	186
B. Particles in Resonance	188
C. Resonance Curve	190
D. Loss-Cone Instabilities	191
8.3. Precipitation by Trapped Electrons	194
8.3.1. Weak and Strong Diffusion	194
8.3.2. Diffusion Time	195
A. Collisions	195
B. Quasi-Linear Diffusion	195
8.3.3. Equilibrium of Quasi-Linear Diffusion	196
8.3.4. Dominant Waves	197
8.4. Observations of Trapped Electrons	198
8.4.1. Injection Dominated	198
8.4.2. Trapping and Resupply	198
A. Moving Type IV Bursts	199
B. Stationary Metric Type IV Bursts	202
C. Decimetric Bursts	202
8.4.3. Depletion Dominated	203
8.4.4. Stellar Emissions by Trapped Electrons	205
A. Quiescent Radio Emission	205
B. Stellar Flares	207
Exercises	209
Further Reading and References	210
CHAPTER 9. ELECTRIC CURRENTS 212	
9.1. Origin of Currents in Coronae	212
9.1.1. MHD Generator	213
9.1.2. Current Sheet	214
9.2. Classical Conductivity and Particle Acceleration in Stable Currents	215
9.2.1. Conductivity	216
9.2.2. Runaway Electrons	217
9.3. Instabilities of Electric Currents	220

9.3.1. Parallel Currents	220
A. Ion Cyclotron Instability	220
B. Buneman Instability	220
C. Ion Acoustic Instability	221
9.3.2. Perpendicular Currents	222
9.4. Anomalous Conductivity, Heating, and Acceleration	223
9.4.1. Anomalous Conductivity	223
9.4.2. Ohmic Heating	224
9.4.3. Particle Acceleration	225
A. Runaway Particles	225
B. Resonance Acceleration	226
9.5. Observing Currents	227
9.5.1. Currents in the Photosphere	227
9.5.2. Noise Storms	228
9.5.3. Radio Emission of Low-Frequency Turbulence	230
Exercises	232
Further Reading and References	233
 CHAPTER 10. COLLISIONLESS SHOCK WAVES	234
10.1. Elementary Concepts	235
10.1.1. Types of Shocks	235
10.1.2. Conservation Equations (MHD Shocks)	238
10.2. Collisionless Shocks in the Solar System	241
10.2.1. Planetary and Cometary Bow Shocks	241
A. Non-Thermal Particles	242
B. Upstream Waves	243
10.2.2. Interplanetary Shocks	245
10.2.3. Coronal Shocks	246
A. Coronal Mass Ejection	246
B. Type II Radio Bursts	247
10.3. Particle Acceleration and Heating	249
10.3.1. Electron Acceleration at Quasi-Perpendicular Shocks	249
A. De Hoffmann-Teller Frame	250
B. Electron Acceleration	251
10.3.2. Ion Acceleration at Quasi-Parallel Shocks	253
10.3.3. Resonant Acceleration and Heating	254
Exercises	255
Further Reading and References	257
 CHAPTER 11. PROPAGATION OF RADIATION	258
11.1. Transfer Equation	259
11.2. Collisional Absorption	262
11.3. Dispersion Effects	264

11.3.1. Geometric Optics	264
11.3.2. Plasma Dispersion	266
11.3.3. Faraday Rotation	267
11.3.4. Quasi-Transverse Region	269
A. Mode Coupling in Quasi-Transverse Regions	270
B. Confrontation with Observations	272
C. Depolarization	273
11.4. Scattering at Plasma Inhomogeneities	273
11.5. Propagation in a Fibrous Medium	276
11.5.1. Ducting	277
11.5.2. Anisotropic Scattering	279
Exercises	280
Further Reading and References	281
APPENDIX A. Mathematical Expressions	282
APPENDIX B. Units	284
APPENDIX C. Frequently Used Expressions	285
APPENDIX D. Notation	287
AUTHOR INDEX	290
SUBJECT INDEX	293