



# Contents

Preface .....	v
1. Cosmic Plasma Fundamentals .....	1
1.1 Plasma .....	1
1.2 The Physical Sizes and Characteristics of Plasmas in the Universe .....	2
1.2.1 Plasmas on Earth .....	2
1.2.2 Near-Earth Plasmas .....	4
1.2.3 Plasmas in the Solar System .....	8
1.2.4 Transition Regions in the Solar System .....	10
1.2.5 Solar, Stellar, and Interstellar Plasmas .....	10
1.2.6 Galactic and Extragalactic Plasmas .....	16
1.3 Regions of Applicability of Plasma Physics .....	17
1.4 Power Generation and Transmission .....	20
1.5 Electrical Discharges in Cosmic Plasma .....	22
1.6 Particle Acceleration in Cosmic Plasma .....	23
1.6.1 Acceleration of Electric Charges .....	23
1.6.2 Collective Ion Acceleration .....	23
1.7 Plasma Pinches and Instabilities .....	26
1.7.1 The Bennett Pinch .....	26
1.7.2 The Force-Free Configuration .....	28
1.7.3 The Diocotron Instability .....	29
1.7.4 Critical Ionization Velocity .....	30
1.8 Diagnosing Cosmic Plasmas .....	33
1.8.1 The Electromagnetic Spectrum .....	33
1.8.2 In Situ Space Probes .....	39
2. Birkeland Currents in Cosmic Plasma .....	43
2.1 History of Birkeland Currents .....	43
2.2 Field-Aligned Currents in Laboratory Plasma .....	47
2.3 Field-Aligned Currents in Astrophysical Plasmas .....	48
2.4 Basic Equations of Magnetohydrodynamics .....	49
2.4.1 General Plasma Fluid Equations .....	49
2.4.2 Magnetic Reynolds and Lundquist Numbers .....	51
2.5 The Generalized Bennett Relation .....	52
2.5.1 The Bennett Relation .....	55
2.5.2 Alfvén Limiting Current .....	55

2.5.3	Charge Neutralized Beam Propagation .....	56
2.5.4	Current Neutralized Beam Propagation .....	57
2.5.5	Discussion .....	57
2.5.6	Beam Propagation Along an External Magnetic Field .....	58
2.5.7	Schönherr Whirl Stabilization .....	58
2.5.8	The Carlqvist Relation .....	58
2.5.9	The Cylindrical Pinch .....	59
2.5.10	The Sheet Pinch .....	61
2.6	Application of the Carlqvist Relation .....	62
2.6.1	Birkeland Currents in Earth's Magnetosphere .....	62
2.6.2	Currents in the Solar Atmosphere .....	63
2.6.3	Heliospheric Currents .....	64
2.6.4	Currents in the Interstellar Medium .....	65
2.6.5	Currents in the Galactic Medium .....	66
2.6.6	Currents in the Intergalactic Medium .....	66
2.7	Basic Fluid and Beam Instabilities .....	67
2.7.1	Jeans Condition for Gravitational Instability .....	67
2.7.2	Two-Stream (Buneman) Instability .....	68
2.7.3	Sausage and Kink Instabilities .....	70
2.8	Laboratory Simulation of Cosmic Plasma Processes .....	71
2.8.1	High-Current Plasma Pinches .....	72
2.8.2	Laboratory Aurora Simulations .....	74
2.9	The Particle-in-Cell Simulation of Beams and Birkeland Currents .....	76
2.9.1	Charge and Current Neutralized Beam Propagation in Plasma .....	77
2.9.2	Relativistic and Mildly Relativistic Beam Propagation in Plasma .....	78
2.9.3	Propagation of a Relativistic Beam Bunch Through Plasma .....	79
2.9.4	Beam Filamentation .....	79
2.9.5	Dynamical Evolution of a Narrow Birkeland Filament .....	80
2.9.6	Vortex Formation in Thin Cylindrical Electron Beams Propagating Along a Magnetic Field .....	84
2.9.7	Charge-Neutralized Relativistic Electron Beam Propagation Along a Magnetic Field .....	87
2.9.8	Numerical Aurora Simulations .....	89
3.	Biot-Savart Law in Cosmic Plasma .....	93
3.1	History of Magnetism .....	93
3.2	The Magnetic Interaction of Steady Line Currents .....	94
3.3	The Magnetic Induction Field .....	95
3.3.1	Field from an Infinite Conductor of Finite Radius .....	96
3.3.2	Force Between Two Infinite Conductors .....	97
3.4	The Vector Potential .....	99
3.4.1	Field from a Circular Loop and Force Between Two Circular Loops .....	99
3.4.2	Force Between Two Circular Loops Lying in a Plane .....	101
3.5	Quasi-Stationary Magnetic Fields .....	101
3.5.1	Faraday's Law .....	102
3.5.2	Motion Induced Electric Fields .....	103
3.5.3	Faraday Disk Dynamo .....	104

3.6	Inductance .....	104
3.7	Storage of Magnetic Energy .....	106
3.7.1	Energy in a System of Current Loops .....	106
3.7.2	In Situ Storage in Force Free Magnetic Field Configurations .....	107
3.8	Forces as Derivatives of Coefficients of Inductance .....	108
3.9	Measurement of Magnetic Fields in Laboratory Plasmas .....	108
3.10	Particle-in-Cell Simulation of Interacting Currents .....	110
3.10.1	Simulation Setup .....	111
3.10.2	Initial Motion of Current Filaments .....	111
3.10.3	Polarization Forces .....	113
3.10.4	Magnetic Energy Distribution and Magnetic Isobars .....	113
3.10.5	Net Motion .....	119
3.10.6	“Doubleness” in Current-Conducting Plasmas .....	119
3.11	Magnetic Fields in Cosmic Dimensioned Plasma .....	119
3.11.1	Measurement of Galactic Magnetic Fields .....	119
3.11.2	Milky Way Galaxy .....	122
3.11.3	Spiral Galaxies .....	126
3.11.4	Rotational Velocities of Spiral Galaxies .....	128
3.11.5	Elliptical Galaxies .....	131
3.11.6	Intergalactic Magnetic Fields .....	135
4.	Electric Fields in Cosmic Plasma .....	137
4.1	Electric Fields .....	137
4.2	Measurement of Electric Fields .....	138
4.3	Magnetic Field Aligned Electric Fields .....	143
4.3.1	Collisionless Thermoelectric Effect .....	143
4.3.2	Magnetic Mirror Effect .....	144
4.3.3	Electrostatic Shocks .....	145
4.3.4	Electric Double Layers .....	146
4.4	Magnetospheric Electric Fields .....	146
4.4.1	The Plasmasphere .....	146
4.4.2	The Plasmasheet .....	147
4.4.3	The Neutral Sheet .....	149
4.4.4	The Magnetotail .....	149
4.4.5	The Magnetopause .....	149
4.4.6	The Auroral Acceleration Region .....	149
4.4.7	Global Distributions of Auroral Electric Fields .....	153
4.5	Outstanding Questions .....	154
4.6	Phenomena Associated with Electric Fields .....	156
4.6.1	Surface Discharges .....	156
4.6.2	Plasma Gun Arc Discharges .....	156
4.6.3	Marklund Convection and Separation of Elements .....	165
4.6.4	Particle Acceleration and Runaway .....	168
4.6.5	Field-Aligned Electric Fields as the Source of Cosmic Rays .....	170
5.	Double Layers in Astrophysics .....	171
5.1	General Description of Double Layers .....	171

5.2	The Time-Independent Double Layer	173
5.2.1	One-Dimensional Model	173
5.2.2	Ratio of the Current Densities	175
5.2.3	The Potential Drop	176
5.2.4	Structure of the Double Layer	176
5.2.5	Kinetic Description	176
5.3	Particle-in-Cell Simulation of Double Layers	179
5.3.1	Simulations of the Two-Stream Instability	180
5.3.2	Simulations of Double Layers	182
5.4	Double Layers in Current Filaments	183
5.5	Basic Properties of Double Layers	185
5.5.1	Double Layers as a Surface Phenomena	185
5.5.2	Noise and Fluctuations in Double Layers	186
5.5.3	Exploding Double Layers	186
5.5.4	Oblique Double Layers	188
5.6	Examples of Cosmic Double Layers	188
5.6.1	Double Layers in the Auroral Circuit	188
5.6.2	Solar Flares	191
5.6.3	Double Radio Galaxies and Quasars	194
5.6.4	Double Layers as a Source of Cosmic Radiation	195
6.	Synchrotron Radiation	197
6.1	Theory of Radiation from an Accelerated Charge	198
6.1.1	The Induction Fields	199
6.1.2	The Radiation Fields	201
6.2	Radiation of an Accelerated Electron in a Magnetic Field	207
6.2.1	Angular Distribution of the Radiation	211
6.2.2	Frequency Distribution of the Radiation	213
6.3	Field Polarization	219
6.3.1	Polarization in the Plane of Rotation	219
6.3.2	Polarization for Arbitrary Angles of Observation	220
6.4	Radiation from an Ensemble of Electrons	222
6.4.1	Velocity-Averaged Emissivity	222
6.4.2	Emission from an Ensemble of Electrons	227
6.5	Synchrotron Radiation from Z Pinches	229
6.5.1	X Ray Emission	229
6.5.2	X Ray Spectroscopy	230
6.5.3	Morphology of the Thermal X Ray Source	230
6.6	Particle-in-Cell Simulation of Synchrotron Processes	233
6.6.1	Simulated Z Pinches	233
6.6.2	Synchrotron Bursts from Simulated Z Pinches	234
6.6.3	Synchrotron Source Radiation Patterns	236
6.7	Synchrotron Radiation from Cosmic Sources	236
6.7.1	Gross Radio Properties of Galaxies	236
6.7.2	Double Radio Galaxies	240
6.7.3	“Jets” and Superluminosity	244
6.7.4	Quasars and Active Galaxy Nuclei	248
6.7.5	X Ray and Gamma-Ray Sources	251

7. Transport of Cosmic Radiation .....	253
7.1 Energy Transport in Plasma .....	254
7.1.1 Group Velocity .....	256
7.1.2 Time Rate of Decay of Wave Oscillations .....	262
7.2 Applications of Geometrical Optics .....	262
7.2.1 Basic Principle and Limitations of Geometrical Optics .....	262
7.2.2 Equation of Transfer .....	267
7.3 Black Body Radiation .....	270
7.4 The Source Function and Kirchoff's Law .....	272
7.4.1 Classical Limit of the Emission, Absorption, and Source Functions ...	273
7.5 Self Absorption by Plasma Filaments .....	275
7.6 Large-Scale, Random Magnetic Field Approximation .....	277
7.6.1 Plasma Effects .....	279
7.6.2 Monoenergetic Electrons .....	280
7.7 Anisotropic Distribution of Velocities .....	281
8. Particle-in-Cell Simulation of Cosmic Plasma .....	285
8.1 "In-Situ" Observation of Cosmic Plasmas via Computer Simulation .....	285
8.2 The History of Electromagnetic Particle-in-Cell Simulation .....	286
8.3 The Laws of Plasma Physics .....	287
8.4 Multidimensional Particle-in-Cell Simulation .....	288
8.4.1 Sampling Constraints in Multidimensional Particle Codes .....	288
8.4.2 Discretization in Time and Space .....	289
8.4.3 Spectral Methods and Interpolation .....	291
8.5 Techniques for Solution .....	292
8.5.1 Leap-Frogging Particles Against Fields .....	293
8.5.2 Particle Advance Algorithm .....	294
8.5.3 Field Advance Algorithm .....	295
8.6 Issues in Simulating Cosmic Phenomena .....	296
8.6.1 Boundary Conditions .....	296
8.6.2 Relativity .....	296
8.6.3 Compression of Time Scales .....	297
8.6.4 Collisions .....	297
8.7 Gravitation .....	299
8.8 Scaling Laws .....	300
8.9 Data Management .....	301
8.10 Further Developments in Plasma Simulation .....	302
Appendix A. Transmission Line Fundamentals in Space and Cosmic Plasmas .....	305
A.1 Transmission Lines .....	305
A.2 Definition of the State of the Line at a Point .....	305
A.3 Primary Parameters .....	306
A.4 General Equations .....	307
A.4.1 The General Case .....	307
A.4.2 The Special Case of the Lossless Line .....	308

- A.5 Heaviside’s Operational Calculus (The Lapace Transform) ..... 309
  - A.5.1 The Propagation Function ..... 309
  - A.5.2 Characteristic Impedance ..... 311
  - A.5.3 Reflection Coefficients ..... 312
- A.6 Time-Domain Reflectometry ..... 314
- Appendix B. Polarization of Electromagnetic Waves in Plasma ..... 317
- Appendix C. Dusty and Grain Plasmas ..... 325
  - C.1 Dusty Plasma ..... 325
  - C.2 Grain Plasma ..... 326
- Appendix D. Some Useful Units and Constants ..... 331
- Appendix E. TRISTAN ..... 335
- References ..... 345
- Index ..... 363

