

Contents

Preface	xi
Introduction	1
1 Charged Particles in the Electromagnetic Field	5
1.1 Initial equations and their properties	5
1.2 Liouville's theorem and the exact distribution function	9
2 The Motion of a Charged Particle in Given Fields	15
2.1 A particle in constant homogeneous fields	15
2.2 Weakly inhomogeneous slowly changing fields	20
2.3 Adiabatic invariants	29
2.4 Reconnection and particle acceleration	36
2.4.1 Neutral points of a magnetic field	36
2.4.2 Reconnecting current sheets	39
2.4.3 Acceleration in current sheets	41
3 Coulomb Collisions of Particles	47
3.1 Close and distant collisions	47
3.2 Debye shielding	51
3.3 Times of collisional relaxations	53
4 Statistical Description of a Plasma	59
4.1 The averaging of Liouville's equation	59
4.2 Collisional integral and correlation functions	66
4.3 Equations for correlation functions	70
4.4 Approximations for binary collisions	72
4.5 Correlation function and Debye shielding	76

5	Hydrodynamic Description of a Plasma	81
5.1	Transition to macroscopic transfer equations	81
5.2	Hydrodynamic equations for plasma	88
5.3	Generalized Ohm's law	92
5.3.1	Basic equations	92
5.3.2	Conductivity of magnetized plasma	96
5.3.3	Volume charge and quasi-neutrality	99
6	Magnetohydrodynamics	101
6.1	Basic assumptions and the MHD equations	101
6.2	Magnetic flux conservation. Ideal MHD	106
6.3	The main approximations in ideal MHD	110
7	Plasma Flows in a Strong Magnetic Field	117
7.1	General formulation of the problem	117
7.2	The formalism of two-dimensional problems	119
7.2.1	First type of problems	119
7.2.2	Second type of problems	121
7.3	On the existence of continuous flows	126
7.4	Plasma flows in the field of a time-dependent magnetic dipole	128
8	Waves and Discontinuous Flows in a MHD Medium	135
8.1	Small-amplitude waves	135
8.1.1	Entropy waves	138
8.1.2	Alfvén waves	139
8.1.3	Magnetoacoustic waves	140
8.1.4	Phase velocity diagram	142
8.2	Discontinuity surfaces in hydrodynamics	143
8.3	Magnetohydrodynamic discontinuities	146
8.3.1	Boundary condition at a discontinuity surface	146
8.3.2	Discontinuities without matter flows across them	150
8.3.3	Perpendicular shock wave	152
8.3.4	Oblique shock waves	154
8.3.5	Alfvén discontinuity	161
8.4	Continuous transitions between discontinuous solutions	163
9	Evolutionarity of MHD discontinuities	167
9.1	Conditions for evolutionarity	167
9.1.1	Physical meaning and definition	167

9.1.2	Linearized boundary conditions	169
9.1.3	Number of small-amplitude waves	171
9.1.4	Domains of evolutionarity	173
9.2	Consequences of evolutionarity conditions	175
9.2.1	The order of wave propagation	175
9.2.2	Evolutionarity and transitions between discontinuities	177
10	Plasma Equilibrium in a Magnetic Field	179
10.1	The virial theorem in MHD	179
10.1.1	Deduction of the scalar virial theorem	179
10.1.2	Some astrophysical applications	183
10.2	Force-free fields and Shafranov's theorem	185
10.3	Properties of equilibrium configurations	188
10.4	Archimedean force in MHD	194
11	Stationary Plasma Flows in a Magnetic Field	197
11.1	Ideal plasma flows	197
11.2	Flows at small magnetic Reynolds numbers	202
11.3	Expulsion force and vortex flows	207
11.4	Expulsion force for large magnetic Reynolds numbers	214
11.4.1	Formula for the expulsion force	215
11.4.2	Observable characteristics of prominences	217
12	Magnetic Reconnection in Current Sheets	221
12.1	Small perturbations near a neutral line	221
12.1.1	Historical comment	221
12.1.2	Linearized problem in ideal MHD	222
12.1.3	Converging wave and cumulative effect	225
12.2	Field line deformation due to current displacement	226
12.3	Dynamic dissipation of a magnetic field	231
12.4	Particle acceleration into current sheets	234
12.4.1	Introduction in the problem	234
12.4.2	Dimensionless parameters and equations	235
12.4.3	Iterative solution	237
12.4.4	Maximum energy	239
12.4.5	Non-adiabatic thickness of current sheet	241
12.5	Regular Versus Chaotic Acceleration	241
12.5.1	Reasons for Chaos	242
12.5.2	Stabilizing influence of the longitudinal field	244

12.5.3	Particle dynamics in current sheets on the Sun	246
13	Evolutionarity of current sheets	249
13.1	Properties of reconnecting current sheets	249
13.2	Small perturbations outside the RCS	253
13.2.1	Basic assumptions	253
13.2.2	Propagation of perturbations normal to the RCS . . .	254
13.2.3	Inclined propagation	255
13.3	Small perturbations inside the RCS	258
13.3.1	Linearized MHD equations	258
13.3.2	Solution of the linearized equations	263
13.4	Solution on the boundary of the RCS	266
13.5	Criterion of evolutionarity	268
13.5.1	Boundary conditions	268
13.5.2	Evolutionarity of reconnecting current sheets	269
14	Tearing Instability of the Reconnecting Current Sheet	273
14.1	Origin of tearing instability	273
14.2	Formulation of the problem and its analytic solution	276
14.2.1	The model and equations for small disturbances . . .	276
14.2.2	External non-dissipative region	278
14.2.3	Internal dissipative region	279
14.2.4	Matching of the solutions and dispersion relation . . .	281
14.3	Physical interpretation of the instability	282
14.4	Stabilizing effect of the transverse field	286
14.5	Compressibility and a longitudinal field	289
14.5.1	Neutral current sheet	289
14.5.2	Non-neutral current sheet	290
14.6	Kinetic approach	291
14.6.1	Kinetic tearing instability	291
14.6.2	Stabilization by the transverse field	294
15	Selected Trends in Cosmic Electrodynamics	297
15.1	Reconnection and magnetic helicity	297
15.2	Reconnection in low-temperature plasma	300
15.2.1	Observations and models	300
15.2.2	Balance equations and their solution	301
15.2.3	Characteristics of the reconnecting current sheet . . .	303
15.2.4	Summary	306

16 Reconnection of Electric Currents	307
16.1 Models for flare energy storage and release	307
16.1.1 From early models to future investigations	307
16.1.2 Some new trends in the flare theory	309
16.1.3 Current sheets at separatrices	311
16.2 Current sheet formation mechanisms	312
16.2.1 Magnetic footpoints and their displacements	312
16.2.2 Classical 2D reconnection	313
16.2.3 Creation of current sheets by shearing motions	314
16.2.4 Antisymmetrical shearing motions	317
16.2.5 Third class displacements	319
16.3 Shear and reconnection of currents	320
16.3.1 Physical processes related to shear and reconnection	320
16.3.2 Topological interruption of electric currents	322
16.3.3 Conclusion	323
 Appendix 1. Notation	 325
 Appendix 2. Useful Expressions	 333
 Appendix 3. Constants	 335
 Bibliography	 337
 Index	 355