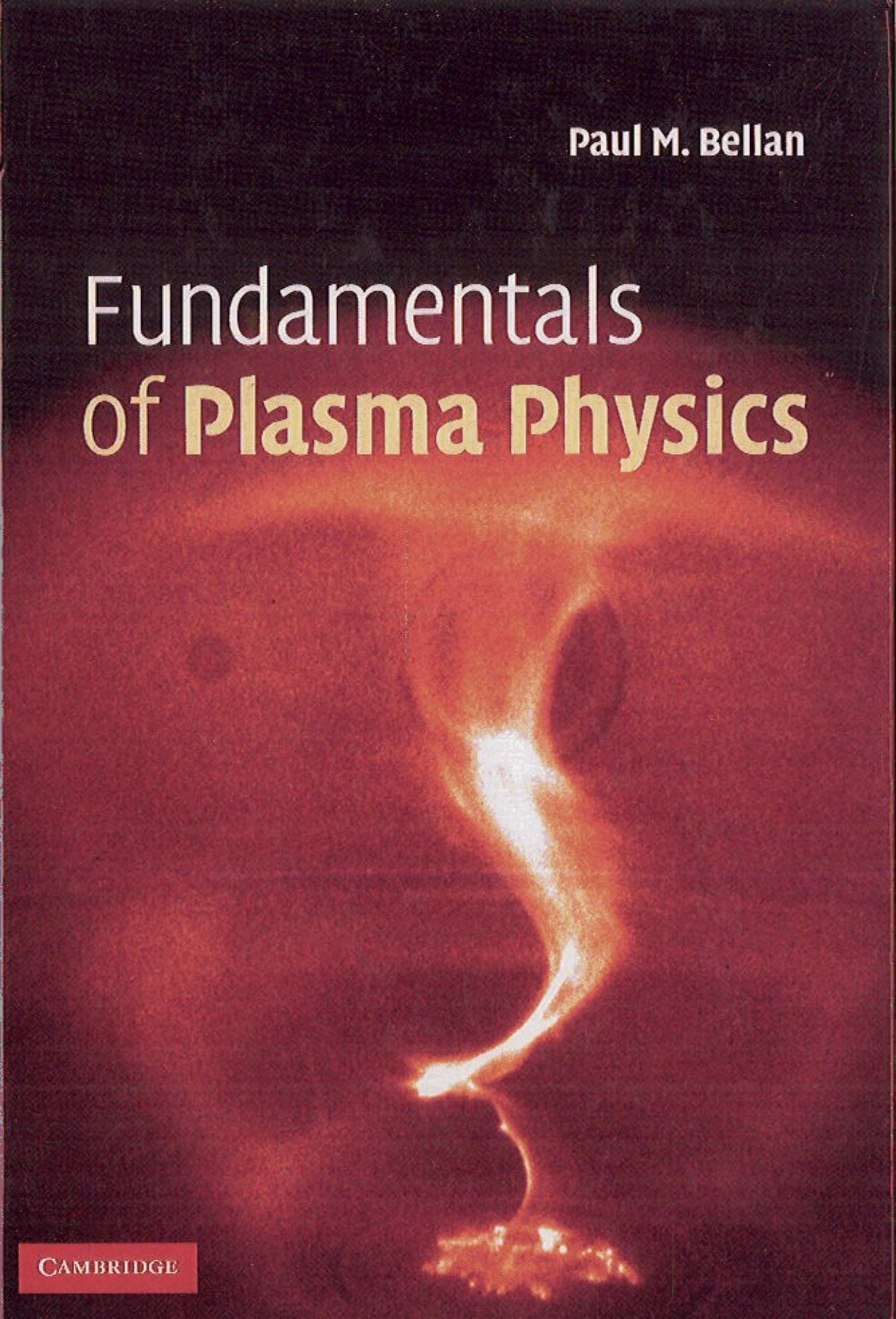


Paul M. Bellan

Fundamentals of **Plasma Physics**



CAMBRIDGE

Contents

<i>Preface</i>	<i>page xiii</i>
1 Basic concepts	1
1.1 History of the term “plasma”	1
1.2 Brief history of plasma physics	1
1.3 Plasma parameters	3
1.4 Examples of plasmas	4
1.5 Logical framework of plasma physics	4
1.6 Debye shielding	7
1.7 Quasi-neutrality	11
1.8 Small- vs. large-angle collisions in plasmas	12
1.9 Electron and ion collision frequencies	16
1.10 Collisions with neutrals	19
1.11 Simple transport phenomena	20
1.12 A quantitative perspective	23
1.13 Assignments	25
2 The Vlasov, two-fluid, and MHD models of plasma dynamics	34
2.1 Overview	34
2.2 Phase-space	34
2.3 Distribution function and Vlasov equation	35
2.4 Moments of the distribution function	38
2.5 Two-fluid equations	41
2.6 Magnetohydrodynamic equations	52
2.7 Summary of MHD equations	61
2.8 Classical transport	62
2.9 Sheath physics and Langmuir probe theory	64
2.10 Assignments	69

3	Motion of a single plasma particle	75
3.1	Motivation	75
3.2	Hamilton–Lagrange formalism vs. Lorentz equation	76
3.3	Adiabatic invariant of a pendulum	80
3.4	Extension of WKB method to general adiabatic invariant	83
3.5	Drift equations	88
3.6	Relation of drift equations to the double adiabatic MHD equations	108
3.7	Non-adiabatic motion in symmetric geometry	115
3.8	Particle motion in small-amplitude oscillatory fields	129
3.9	Wave–particle energy transfer	131
3.10	Assignments	142
4	Elementary plasma waves	146
4.1	General method for analyzing small-amplitude waves	146
4.2	Two-fluid theory of unmagnetized plasma waves	147
4.3	Low-frequency magnetized plasma: Alfvén waves	155
4.4	Two-fluid model of Alfvén modes	164
4.5	Assignments	172
5	Streaming instabilities and the Landau problem	174
5.1	Overview	174
5.2	Streaming instabilities	174
5.3	The Landau problem	180
5.4	The Penrose criterion	200
5.5	Assignments	203
6	Cold plasma waves in a magnetized plasma	206
6.1	Overview	206
6.2	Redundancy of Poisson’s equation in electromagnetic mode analysis	206
6.3	Dielectric tensor	208
6.4	Dispersion relation expressed as a relation between n_x^2 and n_z^2	223
6.5	A journey through parameter space	225
6.6	High-frequency waves: Altar–Appleton–Hartree dispersion relation	228
6.7	Group velocity	233
6.8	Quasi-electrostatic cold plasma waves	234
6.9	Resonance cones	236
6.10	Assignments	240

7	Waves in inhomogeneous plasmas and wave-energy relations	242
7.1	Wave propagation in inhomogeneous plasmas	242
7.2	Geometric optics	245
7.3	Surface waves – the plasma-filled waveguide	247
7.4	Plasma wave-energy equation	253
7.5	Cold plasma wave-energy equation	255
7.6	Finite-temperature plasma wave-energy equation	259
7.7	Negative energy waves	260
7.8	Assignments	263
8	Vlasov theory of warm electrostatic waves in a magnetized plasma	265
8.1	Solving the Vlasov equation by tracking each particle's history	265
8.2	Analysis of the warm plasma electrostatic dispersion relation	272
8.3	Bernstein waves	273
8.4	Finite $k_{\parallel}$ dispersion: linear mode conversion	276
8.5	Analysis of linear mode conversion	279
8.6	Drift waves	289
8.7	Assignments	304
9	MHD equilibria	305
9.1	Why use MHD?	305
9.2	Vacuum magnetic fields	306
9.3	Force-free fields	309
9.4	Magnetic pressure and tension	310
9.5	Magnetic stress tensor	312
9.6	Flux preservation, energy minimization, and inductance	314
9.7	Static versus dynamic equilibria	316
9.8	Static equilibria	316
9.9	Dynamic equilibria: flows	328
9.10	Assignments	338
10	Stability of static MHD equilibria	342
10.1	Introduction	342
10.2	The Rayleigh–Taylor instability of hydrodynamics	343
10.3	MHD Rayleigh–Taylor instability	346
10.4	The MHD energy principle	351
10.5	Discussion of the energy principle	365
10.6	Current-driven instabilities and helicity	366
10.7	Magnetic helicity	367
10.8	Characterization of free-boundary instabilities	370

10.9	Analysis of free-boundary instabilities	374
10.10	Assignments	383
11	Magnetic helicity interpreted and Woltjer–Taylor relaxation	385
11.1	Introduction	385
11.2	Topological interpretation of magnetic helicity	385
11.3	Woltjer–Taylor relaxation	392
11.4	Kinking and magnetic helicity	394
11.5	Assignments	407
12	Magnetic reconnection	410
12.1	Introduction	410
12.2	Water-beading: an analogy to magnetic reconnection	412
12.3	Qualitative description of sheet current instability	413
12.4	Semi-quantitative estimate of the tearing process	416
12.5	Generalization of tearing to sheared magnetic fields	424
12.6	Magnetic islands	430
12.7	Assignments	432
13	Fokker–Planck theory of collisions	436
13.1	Introduction	436
13.2	Statistical argument for the development of the Fokker–Planck equation	438
13.3	Electrical resistivity	450
13.4	Runaway electric field	451
13.5	Assignments	453
14	Wave–particle nonlinearities	456
14.1	Introduction	456
14.2	Vlasov nonlinearity and quasi-linear velocity space diffusion	458
14.3	Echoes	473
14.4	Assignments	489
15	Wave–wave nonlinearities	491
15.1	Introduction	491
15.2	Manley–Rowe relations	493
15.3	Application to waves	499
15.4	Instability onset via nonlinear dispersion method	511
15.5	Digging a density hole via ponderomotive force	517
15.6	Ion acoustic wave soliton	523
15.7	Assignments	527

16 Non-neutral plasmas	530
16.1 Introduction	530
16.2 Brillouin flow	530
16.3 Isomorphism to incompressible 2-D hydrodynamics	533
16.4 Near-perfect confinement	535
16.5 Diocotron modes	537
16.6 Assignments	550
17 Dusty plasmas	556
17.1 Introduction	556
17.2 Electron and ion current flow to a dust grain	557
17.3 Dust charge	559
17.4 Dusty plasma parameter space	563
17.5 Large P limit: dust acoustic waves	564
17.6 Dust ion acoustic waves	568
17.7 The strongly coupled regime: crystallization of a dusty plasma	569
17.8 Assignments	579
Appendices	
A Intuitive method for vector calculus identities	582
B Vector calculus in orthogonal curvilinear coordinates	586
C Frequently used physical constants and formulae	593
<i>Bibliography and suggested reading</i>	597
<i>References</i>	599
<i>Index</i>	604