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978-0-521-70524-0 - Advanced Magnetohydrodynamics: With Applications to Laboratory and Astrophysical Plasmas
J. P. (Hans) Goedbloed, Rony Keppens and Stefaan Poedts
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ADVANCED MAGNETOHYDRODYNAMICS

With Applications to Laboratory and Astrophysical Plasmas

Following on from the companion volume *Principles of Magnetohydrodynamics*, this textbook analyzes the applications of plasma physics to thermonuclear fusion and plasma astrophysics from the single viewpoint of MHD. This approach turns out to be ever more powerful when applied to streaming plasmas (the vast majority of visible matter in the Universe), toroidal plasmas (the most promising approach to fusion energy), and nonlinear dynamics (where it all comes together with modern computational techniques and extreme transonic and relativistic plasma flows).

The textbook interweaves theory and explicit calculations of waves and instabilities of streaming plasmas in complex magnetic geometries. It is ideally suited to advanced undergraduate and graduate courses in plasma physics and astrophysics.

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To Antonia, 陆蓉 (Rong Lu), and Micheline

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J. P. (Hans) Goedbloed, Rony Keppens and Stefaan Poedts
Frontmatter
More information

Contents

Preface *page* xiii

Part III Flow and dissipation 1

12 Waves and instabilities of stationary plasmas 3
- 12.1 Laboratory and astrophysical plasmas 3
  - 12.1.1 Grand vision: magnetized plasma on all scales 3
  - 12.1.2 Differences between laboratory and astrophysical plasmas 6
  - 12.1.3 Plasmas with background flow 12
- 12.2 Spectral theory of stationary plasmas 13
  - 12.2.1 Basic equations 13
  - 12.2.2 Frieman–Rotenberg formulation 16
  - 12.2.3 Self-adjointness of the generalized force operator⋆ 22
  - 12.2.4 Energy conservation and stability 27
- 12.3 Solution paths in the complex ω plane 35
  - 12.3.1 Opening up the boundaries 35
  - 12.3.2 Approach to eigenvalues 40
- 12.4 Literature and exercises 47

13 Shear flow and rotation 49
- 13.1 Spectral theory of plane plasmas with shear flow 49
  - 13.1.1 Gravito-MHD wave equation for plane plasma flow 49
  - 13.1.2 Kelvin–Helmholtz instabilities in interface plasmas 55
  - 13.1.3 Continua and oscillation theorem $\mathcal{R}$ for real eigenvalues 59
  - 13.1.4 Complex eigenvalues and the alternator 65
- 13.2 Case study: flow-driven instabilities in diffuse plasmas 71
  - 13.2.1 Rayleigh–Taylor instabilities of magnetized plasmas 73
  - 13.2.2 Kelvin–Helmholtz instabilities of ordinary fluids 76
  - 13.2.3 Gravito-MHD instabilities of stationary plasmas 85

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Cambridge University Press
978-0-521-70524-0 - Advanced Magnetohydrodynamics: With Applications to Laboratory and Astrophysical Plasmas
J. P. (Hans) Goedbloed, Rony Keppens and Stefaan Poedts
Frontmatter
More information

13.2.4 Oscillation theorem $\mathcal{C}$ for complex eigenvalues 91
13.3 Spectral theory of rotating plasmas 93
13.3.1 MHD wave equation for cylindrical flow 93
13.3.2 Local stability* 98
13.3.3 WKB approximation 102
13.4 Rotational instabilities 104
13.4.1 Rigid rotation of incompressible plasmas 104
13.4.2 Magneto-rotational instability: local analysis 112
13.4.3 Magneto-rotational instability: numerical solutions 118
13.5 Literature and exercises 123

14 Resistive plasma dynamics 127
14.1 Plasmas with dissipation 127
14.1.1 Conservative versus dissipative dynamical systems 127
14.1.2 Stability of force-free magnetic fields: a trap 128
14.2 Resistive instabilities 135
14.2.1 Basic equations 135
14.2.2 Tearing modes 138
14.2.3 Resistive interchange modes 149
14.3 Resistive spectrum 150
14.3.1 Resistive wall mode 150
14.3.2 Spectrum of homogeneous plasma 155
14.3.3 Spectrum of inhomogeneous plasma 158
14.4 Reconnection 162
14.4.1 Reconnection in 2D Harris sheet 162
14.4.2 Petschek reconnection 168
14.4.3 Kelvin–Helmholtz induced tearing instabilities 169
14.4.4 Extended MHD and reconnection 171
14.5 Literature and exercises 175

15 Computational linear MHD 177
15.1 Spatial discretization techniques 178
15.1.1 Basic concepts for discrete representations 180
15.1.2 Finite difference methods 182
15.1.3 Finite element method 186
15.1.4 Spectral methods 196
15.1.5 Mixed representations 201
15.2 Linear MHD: boundary value problems 204
15.2.1 Linearized MHD equations 204
15.2.2 Steady solutions to linearly driven problems 206
15.2.3 MHD eigenvalue problems 209

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CAMBRIDGE

Cambridge University Press
978-0-521-70524-0 - Advanced Magnetohydrodynamics: With Applications to Laboratory and Astrophysical Plasmas
J. P. (Hans) Goedbloed, Rony Keppens and Stefaan Poedts
Frontmatter
More information

15.2.4 Extended MHD examples 211
15.3 Linear algebraic methods 217
15.3.1 Direct and iterative linear system solvers 217
15.3.2 Eigenvalue solvers: the QR algorithm 220
15.3.3 Inverse iteration for eigenvalues and eigenvectors 221
15.3.4 Jacobi–Davidson method 222
15.4 Linear MHD: initial value problems 225
15.4.1 Temporal discretizations: explicit methods 225
15.4.2 Disparateness of MHD time scales 233
15.4.3 Temporal discretizations: implicit methods 234
15.4.4 Applications: linear MHD evolutions 236
15.5 Concluding remarks 240
15.6 Literature and exercises 241

Part IV Toroidal plasmas 245

16 Static equilibrium of toroidal plasmas 247
16.1 Axi-symmetric equilibrium 247
16.1.1 Equilibrium in tokamaks 247
16.1.2 Magnetic field geometry 252
16.1.3 Cylindrical limits 256
16.1.4 Global confinement and parameters 260
16.2 Grad–Shafranov equation 269
16.2.1 Derivation of the Grad–Shafranov equation 269
16.2.2 Large aspect ratio expansion: internal solution 271
16.2.3 Large aspect ratio expansion: external solution 277
16.3 Exact equilibrium solutions 284
16.3.1 Poloidal flux scaling 284
16.3.2 Soloviev equilibrium 289
16.3.3 Numerical equilibria⋆ 293
16.4 Extensions 299
16.4.1 Toroidal rotation 299
16.4.2 Gravitating plasma equilibria⋆ 301
16.4.3 Challenges 302
16.5 Literature and exercises 304

17 Linear dynamics of static toroidal plasmas 307
17.1 “Ad more geometrico” 307
17.1.1 Alfvén wave dynamics in toroidal geometry 307
17.1.2 Coordinates and mapping 308
17.1.3 Geometrical–physical characteristics 309

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CAMBRIDGE

Cambridge University Press
978-0-521-70524-0 - Advanced Magnetohydrodynamics: With Applications to Laboratory and Astrophysical Plasmas
J. P. (Hans) Goedbloed, Rony Keppens and Stefaan Poedts
Frontmatter
More information

17.2 Analysis of waves and instabilities in toroidal geometry 315
17.2.1 Spectral wave equation 315
17.2.2 Spectral variational principle 318
17.2.3 Alfvén and slow continuum modes 319
17.2.4 Poloidal mode coupling 322
17.2.5 Alfvén and slow ballooning modes 326
17.3 Computation of waves and instabilities in tokamaks 334
17.3.1 Ideal MHD versus resistive MHD in computations 334
17.3.2 Edge localized modes 340
17.3.3 Internal modes 344
17.3.4 Toroidal Alfvén eigenmodes and MHD spectroscopy 347
17.4 Literature and exercises 352

18 Linear dynamics of stationary toroidal plasmas⋆ 355
18.1 Transonic toroidal plasmas 355
18.2 Axi-symmetric equilibrium of transonic stationary states⋆ 357
18.2.1 General equations and toroidal rescalings⋆ 357
18.2.2 Elliptic and hyperbolic flow regimes⋆ 365
18.2.3 Expansion of the equilibrium in small toroidicity⋆ 366
18.3 Equations for the continuous spectrum⋆ 374
18.3.1 Reduction for straight-field-line coordinates⋆ 374
18.3.2 Continua of poloidally and toroidally rotating plasmas⋆ 378
18.3.3 Analysis of trans-slow continua for small toroidicity⋆ 385
18.4 Trans-slow continua in tokamaks and accretion disks⋆ 392
18.4.1 Tokamaks and magnetically dominated accretion disks⋆ 393
18.4.2 Gravity dominated accretion disks⋆ 396
18.4.3 A new class of transonic instabilities 397
18.5 Literature and exercises⋆ 402

Part V Nonlinear dynamics 405

19 Computational nonlinear MHD 407
19.1 General considerations for nonlinear conservation laws 408
19.1.1 Conservative versus primitive variable formulations 408
19.1.2 Scalar conservation law and the Riemann problem 415
19.1.3 Numerical discretizations for a scalar conservation law 420
19.1.4 Finite volume treatments 430
19.2 Upwind-like finite volume treatments for 1D MHD 433
19.2.1 The Godunov method 434
19.2.2 A robust shock-capturing method: TVDLF 440
19.2.3 Approximate Riemann solver type schemes 446

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CAMBRIDGE

Cambridge University Press
978-0-521-70524-0 - Advanced Magnetohydrodynamics: With Applications to Laboratory and Astrophysical Plasmas
J. P. (Hans) Goedbloed, Rony Keppens and Stefaan Poedts
Frontmatter
More information

19.2.4 Simulating 1D MHD Riemann problems 451
19.3 Multi-dimensional MHD computations 454
19.3.1 $\nabla \cdot \mathbf{B} = 0$ condition for shock-capturing schemes 455
19.3.2 Example nonlinear MHD scenarios 461
19.3.3 Alternative numerical methods 466
19.4 Implicit approaches for extended MHD simulations 473
19.4.1 Alternating direction implicit strategies 474
19.4.2 Semi-implicit methods 475
19.4.3 Simulating ideal and resistive instability developments 481
19.4.4 Global simulations for tokamak plasmas 482
19.5 Literature and exercises 484

20 Transonic MHD flows and shocks 487
20.1 Transonic MHD flows 487
20.1.1 Flow in laboratory and astrophysical plasmas 487
20.1.2 Characteristics in space and time 488
20.2 Shock conditions 490
20.2.1 Special case: gas dynamic shocks 492
20.2.2 MHD discontinuities without mass flow 498
20.2.3 MHD discontinuities with mass flow 500
20.2.4 Slow, intermediate and fast shocks 505
20.3 Classification of MHD shocks 507
20.3.1 Distilled shock conditions 507
20.3.2 Time reversal duality 513
20.3.3 Angular dependence of MHD shocks 520
20.3.4 Observational considerations of MHD shocks 527
20.4 Stationary transonic flows 529
20.4.1 Modeling the solar wind–magnetosphere boundary 530
20.4.2 Modeling the solar wind by itself 531
20.4.3 Example astrophysical transonic flows 534
20.5 Literature and exercises 540

21 Ideal MHD in special relativity 543
21.1 Four-dimensional space-time: special relativistic concepts 544
21.1.1 Space-time coordinates and Lorentz transformations 544
21.1.2 Four-vectors in flat space-time and invariants 547
21.1.3 Relativistic gas dynamics and stress–energy tensor 551
21.1.4 Sound waves and shock relations in relativistic gases 556
21.2 Electromagnetism and special relativistic MHD 564
21.2.1 Electromagnetic field tensor and Maxwell's equations 564
21.2.2 Stress–energy tensor for electromagnetic fields 569

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CAMBRIDGE

Cambridge University Press
978-0-521-70524-0 - Advanced Magnetohydrodynamics: With Applications to Laboratory and Astrophysical Plasmas
J. P. (Hans) Goedbloed, Rony Keppens and Stefaan Poedts
Frontmatter
More information

21.2.3 Ideal MHD in special relativity 570
21.2.4 Wave dynamics in a homogeneous plasma 572
21.2.5 Shock conditions in relativistic MHD 577
21.3 Computing relativistic magnetized plasma dynamics 580
21.3.1 Numerical challenges from relativistic MHD 583
21.3.2 Example astrophysical applications 584
21.4 Literature and exercises 588

Appendices 591

A Vectors and coordinates 591
A.1 Vector identities 591
A.2 Vector expressions in orthogonal coordinates 592
A.3 Vector expressions in non-orthogonal coordinates 600

References 604
Index 629

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Preface

This book, together with the preceding *Principles of Magnetohydrodynamics* (to be referred to as Volume [1]), describes the two main applications of plasma physics, laboratory research on thermonuclear fusion energy and plasma-astrophysics of the solar system, stars, accretion disks, etc., from the single viewpoint of magnetohydrodynamics (MHD). This provides effective methods and insights for the interpretation of plasma phenomena on virtually all scales, ranging from the laboratory to the Universe. The key issue is understanding the complexities of plasma dynamics in extended magnetic structures. In Volume [1], the classical MHD model was developed in great detail without omitting steps in the derivations. This necessitated restriction to ideal dissipationless plasmas, in static equilibrium and with inhomogeneity in one direction. In the present volume on *Advanced Magnetohydrodynamics* [2], these restrictions are relaxed one by one: introducing stationary background flows, resistivity and reconnection, two-dimensional toroidal geometry, linear and nonlinear computational techniques and transonic flows and shocks. These topics transform the subject into a vital new area with many applications in laboratory, space and astrophysical plasmas.

The two volumes now consist of five parts:

I *Plasma physics preliminaries* (Volume [1], Chapters 1–3),
II *Basic magnetohydrodynamics* (Volume [1], Chapters 4–11),
III *Flow and dissipation* (Volume [2], Chapters 12–15),
IV *Toroidal plasmas* (Volume [2], Chapters 16–18),
V *Nonlinear dynamics* (Volume [2], Chapters 19–21).

Inevitably, with the chosen distinction of topics for Volume [1] (mostly ideal linear phenomena described by self-adjoint linear operators) and topics for Volume [2] (mostly non-ideal, toroidal and nonlinear phenomena), the difference between "basic" and "advanced" levels of magnetohydrodynamics could not be strictly maintained. The logical order required inclusion of some advanced topics in Volume [1],

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Frontmatter
More information

whereas some topics that now appear in Volume [2] (like stationary flows and toroidal effects) really belong to the "principles" of MHD. Difficult parts or asides with tedious derivations, that may be skipped on first reading, are again indicated by a star (*) or put in small print in between triangles ($\triangleright \cdots \triangleleft$).

An overview of the subject matter of the different chapters of the two volumes may help the reader to find his way.

Contents of Volume [1]:

- Chapter 1 gives an introduction to laboratory fusion and astrophysical plasmas, and formulates provisional microscopic and macroscopic definitions of the plasma state.
- Chapter 2 discusses the three complementary points of view of single particle motion, kinetic theory, and fluid description. The corresponding theoretical models provide the opportunity to introduce some of the basic concepts of plasma physics.
- Chapter 3 gives the "derivation" of the macroscopic equations from the kinetic (Boltzmann) equation. Quotation marks because a fully satisfactory derivation can not be given at present in view of the largely unknown contribution of turbulent transport processes. The presentation given is meant to provide some idea on the limitations of the macroscopic view point.
- Chapter 4 defines the MHD model and introduces the concept of scale independence. The central importance of the conservation laws is discussed at length. Based on this, the similarities and differences of laboratory and astrophysical plasmas are articulated in terms of a number of generic boundary value problems.
- Chapter 5 derives the basic MHD waves and describes their properties, with an eye on their role in spectral analysis and computational MHD. The theory of characteristics is introduced as a way to describe the propagation of nonlinear disturbances.
- Chapter 6 treats the subject of waves and instabilities from the unifying point of view of spectral theory. The force operator formulation and the energy principle are extensively discussed. The analogy with quantum mechanics is pointed out and exploited. The difficult extension to interface systems is treated in detail.
- Chapter 7 applies the spectral analysis developed in Chapter 6 to inhomogeneous plasmas in a plane slab. The wave equation for gravito-MHD waves is derived and solved in various limits. Here, all the intricacies of the subject enter: continuous spectra, damping of Alfvén waves, local instabilities, etc. The analogy between helioseismology and MHD spectroscopy in tokamaks is shown to hold great promise for the investigation of plasma dynamics.
- Chapter 8 introduces the enormous variety of magnetic phenomena in astrophysics, in particular for the solar system (dynamo, solar wind, magnetospheres, etc.), and provides basic examples of plasma dynamics worked out in later chapters.
- Chapter 9 is the cylindrical counterpart of Chapter 7, with a wave equation describing the various waves and instabilities. It presents the stability analysis of diffuse cylindrical plasmas (classical pinches and present tokamaks) from the spectral perspective.

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Frontmatter
More information

– Chapter 10 solves the initial value problem for one-dimensional inhomogeneous MHD and the associated damping due to the continuous spectrum.
– Chapter 11 discusses resonant absorption and phase mixing in the context of heating mechanisms of solar and stellar coronae. Sunspot seismology is introduced as another example of MHD spectroscopy.

Contents of Volume [2]:

– Chapter 12 initiates the most urgent extension of the theory presented in Volume [1]: waves and instabilities in plasmas with stationary background flows, a theme of common interest for laboratory fusion and astrophysical plasma research. The old problem of how to find the complex eigenvalues of stationary plasmas is solved by means of a new method of constructing solution paths in the complex plane.
– Chapter 13 applies the new theory of Chapter 12 to the two classical topics of shear flow in plane plasma slabs, including the Kelvin–Helmholtz instability, and to rotation in cylindrical plasmas, including the magneto-rotational instability.
– Chapter 14 treats the considerable modification of plasma dynamics when resistivity is introduced in the MHD description, both in the linear domain of spectral theory and in the nonlinear domain of reconnection.
– Chapter 15 introduces the basic techniques of computational MHD, the discretization techniques, the methods of time stepping, etc. It thus provides the modern techniques needed to solve for the dynamics of plasmas in complicated magnetic geometries.
– Chapter 16 presents the classical theory of static equilibrium of toroidal plasmas, a topic of central interest in fusion research of tokamaks. Both analytical theory and numerical solutions are presented.
– Chapter 17 concerns the spectral theory of waves and instabilities in toroidal equilibria, again a central topic in tokamak research. Because of this important application, this part of MHD spectral theory is the most developed one, also with respect to comparison with experimental data. This activity is rightly called *MHD spectroscopy*.
– Chapter 18 introduces the theory of transonic equilibria and spectral theory of those equilibria, a subject of huge interest, but still in its infancy.
– Chapter 19 presents the counterpart of Chapter 15 by introducing the numerical methods for nonlinear MHD, in particular for plasmas with large background flows, applied in the last two chapters.
– Chapter 20 discusses the MHD shock conditions from a new perspective, scale independence leading to time reversal duality, and it introduces some of the important areas of application of nonlinear MHD, viz. astrophysical winds and transonic flows.
– Chapter 21 introduces special relativistic MHD, in particular the linear waves and nonlinear shocks that occur at relativistic speeds. The books ends with applications to astrophysical phenomena, like relativistic jets, and thus completes the panorama of the tremendously exciting field of magnetohydrodynamics dominated by flows.

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Frontmatter
More information

It is impossible to include all topics that actually belong to the field of advanced MHD. Fortunately, books or chapters of books exist on most of those topics, like *dynamos* (Moffatt [337], Ortolani & Schnack [357], Ferriz-Mas & Núñez [133], Rüdiger & Hollerbach [397]); *chaos* (White [483]); *stellarators* (Freidberg [141]); *spheromaks* (Bellan [31]); *anomalous transport* (Balescu [21], Yoshizawa, Itoh & Itoh [492]); *MHD turbulence* (Biskamp [47]).

We wish to acknowledge Guido Huysmans, Jelle Kaastra, Giovanni Lapenta, Sasha Lifschitz, Zakaria Meliani, Gábor Tóth, Ronald Van der Linden and Henk van der Vorst for constructive comments on selected chapters, Jan Willem Blokland for his input on the exercises of various chapters, and Bram Achterberg, Hubert Baty, Sander Beliën, Nicolas Bessolaz, Tom Bogdan, Fabien Casse, Paul Charbonneau, Peter Delmont, Dan D'Ippolito, Jeff Freidberg, Ricardo Galvão, Marcel Goossens, Giel Halberstadt, Tony Hearn, Bart van der Holst, Hanno Holties, Wolfgang Kerner, Rob Kleibergen, Max Kuperus, Keith MacGregor, Daniel Mueller, Valery Nakariakov, Ronald Nijboer, Eric Priest, Jan Rem, Ilia Roussev, Paulo Sakanaka and Karel Schrijver for fruitful collaborations and exchange of ideas. We also thank our copy-editor, Frances Nex, for very careful and efficient editing of our text.

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Circle theorem: The actual time to complete a project is precisely π times the best estimate of the time that one foresees at the beginning of it.
Proof: Standing at the disk of the unknown, the best estimate is based on how long it takes to reach the other side, the actual time spent involves encircling it so as to really enclose it from all sides. That path is precisely π times longer; QED.

Finally, a frequently asked question is: "Will there be a third volume?" Yes, there will be, and you, the serious students of these two volumes who realized that these are just introductions to an enormous field of largely unexplored territory, are going to write it. Remember, with plasmas making up 90% of all (so far visible) matter of the Universe, and plasma physics under-represented in the physics curriculum of the universities, there is no doubt that there will be completely unexpected discoveries for you in store. Nature is on your side!

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