Book Review

“*Introduction to Plasma Physics. With Space, Laboratory and Astrophysical Applications*”, 2nd Edition, by D. A. Gurnett and A. Bhattacharjee, Cambridge University Press, 2017. ISBN 978-1-107-02737-4.

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The term *plasma* was first used in physics by Irving Langmuir in a paper in 1928 [Proc. Natl. Acad. Sci. USA, 14 (8), 627–637] to describe “a macroscopically electrically neutral substance containing many interacting free electrons and ions which exhibit collective behaviour due to the long-range Coulomb forces” (Goossens M., *An Introduction to Plasma Astrophysics and Magnetohydrodynamics*. Springer Science+Business Media Dordrecht, 2003, p. 2). It is often referred to as the fourth state of matter.

The book consists of 12 chapters and 4 appendices. Problems, references and suggested additional bibliography are provided at the end of each chapter, which illustrate further applications of the theory and supplement the textual material.

Chapter 1, *Introduction*, contains a very brief invitation to plasma physics, at a descriptive level, intended to give the reader a terse overview of the subject.

Chapter 2, *Characteristic Parameters of a Plasma*, presents a short discussion of some key plasma characteristics like particle densities, Debye shielding length, electron plasma oscillations, and the number of electrons per Debye cube. The differences and similarities between the classical and quantum plasma are also briefly stressed.

Chapter 3, *Single-Particle Motions*, treats plasma from the point of view of the behaviour of charged particles under the influence of specified electric and magnetic fields. It analyses the simplest problems of motion in static and uniform electric and magnetic

fields, and examines some rudimentary applications. The expressions for the gradient drift and curvature drift, together with several examples, are presented and discussed. The simple self-consistent plasma-magnetic field configuration that involves some of the drift motions mentioned earlier is described. Also, the motions of particles in a magnetic mirror and the non-stationary magnetic fields are analysed. A detailed discussion of the concept of adiabatic invariance with the aim of demonstrating that this crucial concept is an important property of all nearly periodic Hamiltonian systems, is presented. The chapter is concluded by the motion of a particle within the Hamiltonian approach, and the description of plasma complexity in the frame of the chaos paradigm.

Chapter 4, *Waves in a Cold Plasma*, contains the basic knowledge concerning the propagation of small-amplitude waves in a homogeneous plasma for which temperature effects are unimportant. The essence of the Fourier transformation method used for solving linearized wave problems is presented first. Next, the basic dielectric tensor formalism is introduced and the special cases of waves propagating in a cold, uniform, unmagnetized plasma as well as the waves in a cold plasma with an externally imposed static uniform magnetic field are considered. Because of the many kinds of waves which may propagate in different regions of parameter space, the problem of identification and classification of the miscellaneous wave types is of great importance. A particularly beneficial tool for this purpose is a graphical representation of the various types of wave modes, specified as the Clemmow–Mullaly–Allis (CMA) diagram. It is illustrated in the subsequent section. Finally, the elements of the ray-tracing

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theory applied to the inhomogeneous plasma treated as the slowly varying medium are outlined.

In the next two chapters, the fundamental equations necessary for deeper description of plasma phenomena are presented.

Chapter 5, *Kinetic Theory and the Moment Equations*, introduces the concepts of phase space and distribution function, and derives the basic differential equation that governs the evolution of the distribution function in phase space (the Boltzmann equation, and the Vlasov equation, i.e., the collisionless Boltzmann equation). A general form of the solution to the Vlasov equation based on constants of the motion is obtained. Next, the derivations of the moment equations based on the Boltzmann equation are presented, and their physical interpretation are discussed (continuity, momentum, and energy equations). The closure problem is outlined and, in this context, the three types of state equations are considered. As the example of the use of the adiabatic equation of state, the propagation of small-amplitude waves in a plasma with a finite pressure is studied, with a special emphasis on Langmuir and ion acoustic modes. Also, the effect of collisions is briefly exposed using the relatively simple “Lorentz gas” approximation, i.e., a plasma model in which the electrons are supposed to collide only with fixed ions and not with other electrons.

Chapter 6, *Magnetohydrodynamics*, concentrates on the simplest theory of plasma dynamics [magnetohydrodynamics (MHD)], which can be specified as the mathematical model for the low-frequency interaction between electrically conducting fluids and electromagnetic fields. The derivation of the mass continuity and momentum equations from the kinetic (Boltzmann) equation is performed. Then, the generalized Ohm’s law is obtained, and the equation of state is suggested (in power law form). Subsequently, the complete set of resistive MHD equations is formulated, and discussed in many contexts. Some remarks on conservation relations in ideal MHD is also presented. The MHD waves—or Alfvén waves as they are called in appropriate respect of their discoverer—are discussed in terms of relatively simple mathematical, physical, and observational pictures. An analysis of the validity conditions for resistive MHD equations is also given briefly.

Chapter 7, *MHD Equilibria and Stability*, discusses magnetostatic and MHD equilibria, and the basic concepts of plasma instabilities. The virial theorem which says that a magnetic fluid cannot be in MHD equilibrium under forces generated by its own internal currents is formulated and proved first. Then, some generic examples of MHD equilibrium conditions, namely the cases of force-free fields and the more complicated force-balanced equilibrium states in cylindrical geometries, are considered. An MHD equilibrium with a sheared flow in the context of studying accretion disks in the cylindrical limit is also briefly analysed. The particular techniques developed to study the stability of ideal MHD equilibria including the normal mode method and the energy method are demonstrated to test whether an arbitrary MHD equilibrium is stable or not. Subsequently, a brief outline of the linear approach to the simplified magnetorotational instability in the context of the formation, dynamics, and evolution of accretion disks is presented. The instabilities produced by small but non-zero resistivity effects in a plasma are elucidated, and the specified type of plasma transport in 2D, called magnetic reconnection or field line merging, together with the Sweet–Parker model of magnetic reconnection and qualitative mechanism for the transition from slow to fast reconnection are finally discussed.

Chapter 8, *Discontinuities and Shock Waves*, contains the background information concerning the basic shock physics in plasma. The possible types of discontinuities that can occur in an ideal MHD fluid together with the MHD jump conditions are enumerated first. Then, the terse survey of the theory of plasma shock waves is presented in the de Hoffmann–Teller frame of reference in which the flow is aligned with the upstream magnetic field on the both upstream and downstream sides. Observational aspects of MHD shocks in geophysical, laboratory, and astrophysical contexts are also mentioned. Because the shocks are believed to be the primary accelerator of charged particles, the mechanisms by which collisionless shocks can accelerate such particles are described and discussed. Some remarks on diffusive shock acceleration are also included briefly.

Two chapters deal with various types of waves in both hot unmagnetized and magnetized plasmas.

Chapter 9, *Electrostatic Waves in a Hot Unmagnetized Plasma*, concerns the propagation of small-amplitude waves in such a medium. A terse review of two alternative descriptions of the problem, namely, the Vlasov approach and the Landau approach, is presented. The various dispersion relations are derived in context of Vlasov's equation, and the use of Landau's method to describe the system is motivated and explained. The mathematical aspects of the Laplace transform are described briefly, and the illustration of the Landau approach by considering the small-amplitude waves that can occur in a plasma of hot electrons and immobile ions is presented. The tools needed for the study of the Landau damping are introduced and the physical interpretation of the Landau damping phenomenon is performed. It should be recalled that the Landau damping is referred to as the damping of a collective mode of oscillations in plasmas without collisions of charged particles. The well-known plasma dispersion function with extensions from Maxwellian distribution to another distribution functions is introduced and analysed. Finally, the general condition for stability together with some representative instabilities for various types of potentially unstable distribution functions are surveyed. In the next chapter, *Waves in a Hot Magnetized Plasma*, a differential equation for small-amplitude wave propagation is obtained from the Vlasov equation by a perturbation expansion to derive a general dispersion relation for the propagation of such waves in a hot magnetized plasma. The Harris dispersion relation for electrostatic waves is derived and discussed first, and the special case of an isotropic Maxwellian velocity distribution which leads to the Bernstein dispersion relation is analysed. As an illustration of various types of electrostatic instabilities that can occur in a hot magnetized plasma, two representative classes of instabilities are considered: the anisotropy-driven instabilities, and the current-driven instabilities. The final section deals with the dispersion relation of electromagnetic waves. However, except for some particular cases, the dispersion relations are usually too complicated to be solved either analytically or even numerically; therefore, the special case is described in some detail, when the wave vector is parallel to the magnetic field.

Chapter 11, *Nonlinear Effects*, gives some ideas and methodologies for exploring nonlinear phenomena associated with plasma, including quasi-linear approximation, wave-wave interactions, Langmuir wave solitons, and time-stationary electrostatic potentials. The basic features of the quasi-linear approach are illustrated first and the quasi-linear diffusion equation for spectral density of the electric field is derived. Next, the time evolution of the electron bump-on-tail instability is analysed, and the chaotic particle motions using the standard map (or Chirikov map) are discussed. Complexity in plasmas is also outlined in the nonlinear wave-wave interaction paradigm, which is the theme of the subsequent section. Soliton-like excitations forming intense isolated Langmuir wave packets, i.e., the Langmuir solitons are investigated and the collapse mechanism of the solitons is studied, using the Zakharov equations and the nonlinear Schrödinger equation. Finally, one-dimensional stationary solutions of the Vlasov-Poisson system are obtained, known as the BGK solutions (after Bernstein, Greene, and Kruskal 1957). Some observational aspects of BGK electrostatic potentials in the Earth's magnetosphere are also mentioned briefly.

Chapter 12, *Collisional Processes*, concentrates on the kinetic theory of collisional processes in a fully ionized plasma. The kinematics of binary Coulomb collisions which are the basic form of interactions in such a medium is analysed first from the point of view of classical mechanics. Next, the Fokker-Planck equation which plays a key role in the statistical description of many-body problems, is derived in the context of plasma physics. To obtain this equation in a closed form, the functional relationships for the dynamical friction vector and the diffusion tensor are calculated, assuming that the collisional processes are dominated by binary Coulomb interactions. The strength of the Fokker-Planck formalism is shown through the two examples: computation of the conductivity of a plasma using the Lorentz gas approximation, and the generalization to the case when the electrons and ions both have Maxwellian distributions (with finite mass of the ions).

In addition to main text, there are a set of four appendices containing useful information for

clarifications of the subjects treated in the chapter. Appendix A contains all of the mathematical symbols used in the book; Appendix B gives the useful trigonometric identities, while Appendices C and D include expressions for the relevant differential operators in various coordinate systems, and the vector calculus identities that are used.

In sum, this textbook should be useful primarily for advanced undergraduate and first-year graduate students meeting the subject of plasma physics for the first time. It can be used also for teaching the essentials of plasma physics and its applications to low-temperature laboratory, space environment, and astrophysical contexts. Students of physics, astronomy, geophysics, engineering, and applied mathematics will find a lucid and understandable explanation of the fundamental properties of plasmas with the use of basic physical and mathematical apparatus. The reader should be prepared in electro-

magnetic theory, including Maxwell's equations, and also have some knowledge of thermodynamics and statistical mechanics. The mathematical prerequisites include field theory, some elements of complex analysis (e.g., the Cauchy integral theorem, and the residue theorem), and the basic knowledge of the integral transforms.

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