Part I

Fundamental Processes in Plasmas

A general definition of a plasma is: *plasma is an ionized gas or other medium in which charged particle interactions are predominantly collective.* By an "ionized" gas we mean that there are significant numbers of "free" (unbound) electrons and electrically charged ions in addition to the neutral atoms and molecules normally present in a gas. In a neutral gas the particle interactions are dominated by isolated, distinct two-particle (binary) collisions. In contrast, in a plasma the charged particles interact simultaneously and hence collectively with many other nearby charged particles in the plasma. However, the typical particle interaction energies are small compared to the thermal energies of the particles. Thus, a plasma's behavior is determined by the collective but weak interactions between large numbers of nearby charged particles in it.

Charged particles interact collectively in most plasmas through their electromagnetic fields. In collective interactions many charged particles interact simultaneously — because the Coulomb electric field force induced by each charged particle is a "long range force" that decreases as only the reciprocal of the square of the distance from the charged particle. Thus, a "test" charged particle experiences the sum of the electric field forces from many nearby charged particles. The interaction is collective because the nearby particles also experience and respond to the electric field forces from all the other nearby charged particles, as well as that of the test particle. Hence, a plasma is a highly polarizable medium. These collective rather than binary charged particle interactions in a plasma lead to a wide variety of interesting phenomena — collective (Debye) shielding of individual charges, oscillations at the "plasma" frequency, dielectric medium responses to perturbations, and wave propagation. Chapter 1 develops descriptions of these fundamental collective phenomena and their consequences.

Collisions of charged particles in plasmas are quite different from normal neutral particle collisions. Neutral particles move independently along straight-line trajectories between distinct collision events, which are typically "strong," inelastic events that cause the neutral to be scattered in an approximately random direction. In contrast, a charged test particle moving through a plasma simultaneously experiences (and is deflected by) the weak Coulomb electric field forces around all the nearby charged particles as it passes by each of them. Since the electric fields around the individual charged particles are quite weak and Coulomb collisions are elastic (energy-conserving), they individually lead to typically only very small deflections in the direction of motion of the initial test particle. Thus, the trajectory of a charged test particle is influenced by many simultaneous, small angle deflections in its direction of motion, with occasional larger deflections when it passes close to another charged particle. Because charged particles in an ionized gas are usually essentially randomly distributed in space, the deflections produced by Coulomb collisions are random and lead to a diffusive or random walk (Brownian motion) process in the direction of motion (or velocity vector) of a charged particle. The properties of the cumulative effects of many Coulomb collisions on a single charged test particle, including the effective collision frequency for 90° deflection of its velocity vector, and the net collisional effects on a near Maxwellian distribution of such particles are developed in Chapter 2.

In some of the most important applications of plasma physics a quasi-stationary magnetic field permeates the plasma — e.g., in magnetic confinement devices for fusion, the solar corona, and in the earth's magnetosphere. These magnetic fields can have quite complicated behavior (e.g., curvature, shear) and structures (e.g., magnetic islands). Since we will want to investigate the properties of plasmas imbedded in such magnetic fields, in Chapter 3 we discuss the general structure (kinematics) of magnetic fields and the mathematical models (local and global) used to describe them.

Charged particles in plasmas move along trajectories governed by a combination of inertia ($m\,d\mathbf{v}/dt = \mathbf{0} \implies \mathbf{x} = \mathbf{x}_0 + \mathbf{v}t$ — "straight-line" trajectories) and the acceleration induced by the Lorentz force on the charged particle. The Lorentz force in turn depends on the electromagnetic fields in the plasma. The Lorentz force due to an electric field accelerates positively charged particles in the electric field direction, and can trap charged particles in an electric field's potential well. A quasi-stationary magnetic field causes a charged particle to execute a cyclotron or Larmor orbit about a magnetic field line. If the magnetic field is inhomogeneous or an electric field is present, there are, in addition, charged particle drifts in directions perpendicular to the magnetic field direction. Since the overall behavior of a plasma is governed by the sum of what all its constituent charged particles are doing, in Chapter 4 we investigate the trajectories of charged particles moving in various types of electromagnetic fields.

Having established in Chapters 1–4 the fundamental processes in plasmas (collective phenomena, Coulomb collisions, magnetic structure, charged particle motion), in Chapters 5 and 6 we present the most commonly used descriptions of plasmas — kinetic, two-fluid, and (one-fluid) magnetohydrodynamics (MHD) — and use them to discuss the most fundamental plasma responses to perturbations. Chapter 5 discusses how to obtain the plasma kinetic equation starting from a microscopic description. Then, various levels of simplified fluid moment descriptions and approximate plasma responses are deduced — e.g., inertial (fluidlike) for rapid processes and adiabatic for slow processes. Also, general conditions for stability against growing collective perturbations of the plasma are noted there. Chapter 6 discusses the main properties of the MHD model of plasmas — equations, equilibrium, Alfvén waves and magnetic reconnection via the small electrical resistivity in a plasma. This chapter also introduces the important magnetized plasma parameter β, which is the ratio of plasma pressure to magnetic energy density, and discusses some of its effects. Finally, both these chapters conclude with discussions of the types of plasma models that are used to describe the behavior of both stable and unstable plasmas on various time and length scales.

REFERENCES AND SUGGESTED READING

The standard introductory level textbook for plasma physics is

Chen, *Introduction to Plasma Physics and Controlled Fusion* (1974, 84) [**?**].

Some recently published plasma physics textbooks that are useful complements or supplements to this standard introductory textbook and this book are

Bittencourt, *Fundamentals of Plasma Physics* (1986) [?].

Chakraboty, *Principles of Plasma Mechanics* (1978, 90) [?].

Dendy, *Plasma Dynamics* (1990) [?].

Golant, Zhilinsky and Sakharov, *Fundamentals of Plasma Physics* (1980) [?].

Goldston and Rutherford, *Introduction to Plasma Physics* (1995) [?].

Hazeltine and Waelbroeck, *The Framework of Plasma Physics* (1998) [?].

Nicholson, *Introduction to Plasma Theory* (1983) [?].

Nishikawa and Wakatani, *Plasma Physics, Basic Theory with Fusion Applications* (1990) [?].

Schmidt, *Physics of High Temperature Plasmas* (1966, 79) [?].

Some of the early, influentual textbooks on plasma physics were

Spitzer, *Physics of Fully Ionized Gases* (1956, 62) [?].

Chandrasekhar, *Plasma Physics* (1960) [?].

Thompson, *An Introduction to Plasma Physics* (1962) [?].

Krall and Trivelpiece, *Principles Of Plasma Physics* (1973) [?].

Longmire, *Elementary Plasma Physics* (1963) [?].

Arzimovich, *Elementary Plasma Physics* (1965) [?].

Other textbooks that contain introductory-level discussions of plasma physics include

Boyd and Sanderson, *Plasma Dynamics* (1969) [?].

Clemmow and Dougherty, *Electrodynamics of Particles and Plasmas* (1969) [?].

Hellund, *The Plasma State* (1961) [?].

Holt and Haskell, *Plasma Dynamics* (1965) [?].

Ichimaru, *Basic Principles of Plasma Physics, A Statistical Approach* (1973) [?].

Rosenbluth and Sagdeev, eds., *Handbook of Plasma Physics* (1983) [?].

Shohet, *The Plasma State* (1971) [?].

Seshadri, *Fundamentals of Plasma Physics* (1973) [?].

Tannenbaum, *Plasma Physics* (1967) [?].

. Useful compendia of plasma physics formulas include:

Book, *NRL Plasma Formulary* (1977, 1990) [?].

Anders, *A Formulary for Plasma Physics* (1990) [?].

