CONTENTS

18352

此为试读，需要完整PDF请访问：www.ertongbook.com

1

INTRODUCTION TO PLASMA PHYSICS

Plasma physics is the study of charged particles collected in sufficient number so that the long-range Coulomb force is a factor in determining their statistical properties, yet low enough in density so that the force due to a near-neighbor particle is much less than the long-range Coulomb force exerted by the many distant particles. It is the study of low-density ionized gases. The term "plasma" was first used to describe a collection of charged particles by Tonks and Langmuir,[1] in 1929, in their studies of oscillations in electric discharges. However, the most characteristic aspect of the plasma state, the fact that because of the long range of the Coulomb force the charged particles exhibit a collective behavior, was known much earlier, and was probably first described by Lord Rayleigh,[2] in 1906, in his analysis of electron oscillations in the Thomson model of the atom.

The term "fourth state of matter," often used to describe the plasma state, was coined by W. Crookes[3] in 1879 to describe the ionized medium created in a gas discharge. The term fourth state of matter follows from the idea that as heat is added to a solid, it undergoes a phase transition to a new state, usually liquid.

[1] L. Tonks and I. Langmuir, Oscillations in Ionized Gases, *Phys. Rev.*, **33**:195 (1929).
[2] Lord Rayleigh, *Phil. Mag.*, **11**:117 (1906).
[3] W. Crookes, *Phil. Trans.*, **1**:135 (1879).

If heat is added to a liquid, it undergoes a phase transition to the gaseous state. The addition of still more energy to the gas results in the ionization of some of the atoms. At a temperature above 100,000°K most matter exists in an ionized state; this ionized state of matter is called the *fourth state*. A plasma state can exist at temperatures lower than 100,000°K provided there is a mechanism for ionizing the gas, and if the density is low enough so that recombination is not rapid.

Although 99.9 percent of the apparent universe exists in a plasma state, there is very little in the way of natural plasma here on earth because the low temperature and high density of the earth and its near atmosphere preclude the existence of plasma. This means that plasma must be created by experimental means to study its properties. However, in the upper atmosphere (ionosphere), plasma does exist, created by photoionization of the tenuous atmosphere. Farther out from the earth, plasma is trapped in the earth's magnetic field in the near vacuum of space. Plasma streams toward the earth from the sun (the solar wind), and fills many regions of interstellar space, forming the medium through which outer space is viewed.

Plasma physics generally involves the well-known physics of classical mechanics, electromagnetism, and nonrelativistic statistical mechanics. The challenge of plasma physics comes from the fact that many plasma properties result from the long-range Coulomb interaction, and therefore are collective properties that involve many particles interacting simultaneously.

In its simplest form, a plasma is a collection of protons and electrons at sufficiently low density so that binary (short-range) interactions are negligible. Many-body theory, or the many-body problem, is the study of the properties of such a medium. When a collection of protons and electrons coexist in an equilibrium state, the properties of this state are described by equilibrium statistical mechanics with the appropriate Gibbs ensemble. However, most of the interesting features of plasmas occur for nonequilibrium situations.

Revived interest in plasma physics in the United States began in 1952 with the attempts of a program, then classified, known as Project Sherwood,[1] to develop a controlled thermonuclear fusion reactor. Similar programs were started in England, France, and the U.S.S.R. at about the same time. These programs have grown substantially since that time, and now there are many nations with major research programs in this field. Although the development of a controlled fusion reactor is one of the more challenging practical applications of plasma physics, it is only one of the many areas in which plasma physics plays a role. Plasma physics has played a major role in the development of much

[1] A. S. Bishop, "Project Sherwood," Addison-Wesley, Reading, Mass., 1958.

of contemporary physics, and it is important in the study of problems in such areas as astrophysics, atomic physics, chemistry, life sciences, molecular physics, magnetohydrodynamic power generation, and atmospheric physics.

Plasma physics has its own vocabulary and set of ideas. The main purpose of this chapter is to review plasma physics on an elementary level, provide a background sketch of the familiar concepts of the field, identify many of the terms used repeatedly in discussing the plasma state, review some of the schemes by which plasma is produced in the laboratory, and review some of the methods by which plasma properties are measured.

PART ONE: PLASMA CONCEPTS AND TERMINOLOGY

1.1 EQUILIBRIUM AND METAEQUILIBRIUM

The term "equilibrium" is often loosely used in plasma physics to describe a quasi-steady-state condition that persists only until the plasma particles collide with each other. Frequently, plasma studies are made by investigating small perturbations about such a *metaequilibrium* state.

Thermodynamic equilibrium means that the ions and the electrons are each described by a maxwellian distribution characterized by the same single parameter, the temperature. In this situation, the medium is in equilibrium with its surroundings, and it radiates and absorbs energy at the same rate. The spectrum of emitted radiation is *blackbody*.

In many of the theoretical and experimental situations of interest in plasma physics, the ions and electrons are neither at the same temperature nor in thermodynamic equilibrium with their surroundings. The term metaequilibrium is used to describe situations that eventually will be altered by binary collisions.

1.2 DEBYE LENGTH

The electrostatic potential of an isolated particle of charge q is

$$\phi = \frac{q}{r} \qquad (1.2.1)$$

In a plasma, electrons are attracted to the vicinity of an ion and shield its electrostatic field from the rest of the plasma. Similarly, an electron at rest repels other electrons and attracts ions. This effect alters the potential in the vicinity of a charged particle. The potential of a charge at rest in a plasma is given by

$$\phi = \frac{q}{r} e^{-r/\lambda_D} \qquad (1.2.2)$$

where λ_D is the Debye length originally defined in the Debye-Hückel theory of electrolytes. For an electron-proton plasma

$$\lambda_D = \left(\frac{\kappa T}{8\pi n e^2}\right)^{1/2} = 4.9\left(\frac{T}{n}\right)^{1/2} \tag{1.2.3}$$

where n = density of electrons (or ions), cm^{-3}
T = temperature, °K
κ = Boltzmann's constant ($= 1.38 \times 10^{-16}$ ergs/°K)

The Debye length is a measure of the sphere of influence of a given test charge in a plasma. In general, the Debye length depends on the speed of the test charge with respect to the plasma.

1.3 PLASMA PARAMETER

The plasma parameter g indicates the number of plasma particles in a Debye sphere, and is defined by

$$g = \frac{1}{n\lambda_D^3} \tag{1.3.1}$$

For Debye shielding to occur, and for the description of a plasma to be statistically meaningful, the number of particles in a Debye sphere must be large; that is, $g \ll 1$. The assumption $g \ll 1$ is called the *plasma approximation*. The plasma parameter is also a measure of the ratio of the mean interparticle potential energy to the mean plasma kinetic energy. An ideal gas corresponds to *zero* potential energy between the particles. In many situations the plasma parameter is small and the plasma is treated as an ideal gas of charged particles, that is, a gas that can have a charge density and electric field but in which no two *discrete* particles interact.

To ensure that $n\lambda_D^3$ be large, the density must be *low*, since

$$g = \frac{1}{n\lambda_D^3} \propto \frac{n^{1/2}}{T^{3/2}}$$

Because the collision frequency decreases with density n, and also decreases with increasing temperature T, the condition $g \to 0$ corresponds to a decreasing collision frequency.

Problem 1.3.1 Show that, if ratio of mean kinetic energy to mean interparticle potential energy is much greater than 1, that is, if

$$\frac{\langle KE \rangle}{\langle PE \rangle} \gg 1$$

the number of particles per Debye sphere $n\lambda_D{}^3$ must also be much larger than 1. ////

The plasma parameter g is one of the more important dimensionless parameters associated with a plasma, and may be interpreted as a measure of the degree to which plasma or collective effects dominate over single-particle behavior. The plasma state is described by equations obtained from an expansion of the exact many-body equations in powers of g.

A distinctive constrast between the statistical mechanics of a plasma and that of a neutral gas is that in a plasma the expansion parameter g is small when *many* particles interact at the same time, since $\lambda_D{}^3$ is essentially the volume of the interaction region; for a neutral gas, the atomic radius R is a measure of the interaction region and nR^3 ($\ll 1$) is the expansion parameter. The plasma behaves as a nearly ideal gas *in spite of* the presence of many interacting particles; the reason is that the strength of the interaction between individual particles is so weak, as shown in Prob. 1.3.1.

1.4 DISTRIBUTION FUNCTION

The most detailed description of a plasma gives the location and velocity of each plasma particle as a function of time. It is impossible to obtain such a description of a real plasma, except in some recent "experiments" which involve the use of digital computers to follow the position and velocity of a large number of ions and electrons. Therefore it is customary to use the distribution function f to describe a plasma. The distribution function is the number of particles per unit volume in six-dimensional velocity-configuration phase space. From the Boltzmann H theorem[1] it is known that under the action of binary collisions an ideal gas relaxes to a maxwellian distribution of velocities.

$$\bar{n}f(v) = \bar{n}\left(\frac{m}{2\pi\kappa T}\right)^{3/2} e^{-mv^2/2\kappa T} \qquad (1.4.1)$$

where $\bar{n} = N/V$, with N the number of particles of a certain type (e.g., ions or electrons) in the system and V the volume of the system. Although laboratory plasmas probably never achieve exactly a maxwellian distribution, they may approach it closely, and it is useful in many theoretical treatments to assume that the plasma is described by a maxwellian velocity distribution.

[1] S. Chapman and T. G. Cowling, "The Mathematical Theory of Non-uniform Gases," Cambridge, London, 1952.

此为试读,需要完整PDF请访问: www.ertongbook.com

Because ions and electrons behave rather differently on a time scale less than ion-electron relaxation times (a binary collision process), it is usually necessary to define a separate distribution function for each charge species α, so that

$$\bar{n}_\alpha f_\alpha(\mathbf{x}, \mathbf{v})\, d\mathbf{x}\, d\mathbf{v} = \text{number of particles of type } \alpha \text{ in a volume element } d\mathbf{x}\, d\mathbf{v} \text{ centered about } \mathbf{x}, \mathbf{v}$$

with the normalization

$$\int \bar{n}_\alpha f_\alpha\, d\mathbf{x}\, d\mathbf{v} = N_\alpha = \text{total number of particles of type } \alpha \text{ in the system}$$

1.5 TEMPERATURE AND OTHER MOMENTS OF THE DISTRIBUTION FUNCTION

In the maxwellian distribution, the parameter T, which defines the distribution function, is the temperature of the plasma.

$$\tfrac{3}{2} n\kappa T = \frac{1}{2}\int \bar{n} m \mathbf{v}^2 f\, d\mathbf{v} \qquad (1.5.1)$$

Even in cases where laboratory plasmas are not accurately described by a maxwellian, it is customary to relate the experimental distribution function to the maxwellian distribution which best fits the data, by describing the system as a plasma at temperature T, with T *defined* by (1.5.1). If the distribution function has no relation to a maxwellian distribution, it is poorly described by merely specifying the temperature. Instead, a complete description must either specify the distribution function itself or specify *all* the moments of the distribution.

$$n_\alpha = \bar{n}_\alpha \int f_\alpha\, d\mathbf{v} \qquad \text{density} \qquad (1.5.2)$$

$$\mathbf{V}_\alpha = \frac{\int \mathbf{v} f_\alpha\, d\mathbf{v}}{\int f_\alpha\, d\mathbf{v}} \qquad \text{mean velocity} \qquad (1.5.3)$$

$$\mathsf{P}_\alpha = \frac{n_\alpha m_\alpha \int (\mathbf{v} - \mathbf{V}_\alpha)(\mathbf{v} - \mathbf{V}_\alpha) f_\alpha\, d\mathbf{v}}{\int f_\alpha\, d\mathbf{v}} \qquad \text{pressure tensor} \qquad (1.5.4.)$$

$$\vdots$$

These moments are associated with the macroscopic parameters of the system such as the density, mean velocity, pressure, etc. Note that for an isotropic system at rest, the pressure tensor reduces to a scalar,

$$\mathsf{P}_\alpha = \begin{bmatrix} p & 0 & 0 \\ 0 & p & 0 \\ 0 & 0 & p \end{bmatrix}$$

where $p = n_\alpha \kappa T_\alpha$.

1.6 MAGNETIC PRESSURE

Frequently plasma is imbedded in, or surrounded by, a magnetic field. In a static magnetic field there is a pressure force $B^2/8\pi$ dynes/cm^2 across a surface tangent to the magnetic flux surface, at a point. Characteristically, a plasma is diamagnetic, and thus it excludes a magnetic field suddenly applied to its boundary. This means that a magnetic pressure force $B^2/8\pi$ can balance the kinetic pressure $p = n\kappa T$ of the plasma at a boundary between plasma and magnetic field. If $B^2/8\pi > p$, the plasma may be compressed to a higher density and temperature.

In situations where plasma and magnetic field coexist, a frequently used parameter is the local ratio of plasma pressure to magnetic pressure, given the name *plasma beta*; i.e.,

$$\beta = \frac{n_i \kappa T_i + n_e \kappa T_e}{B^2/8\pi} \tag{1.6.1}$$

This β should not be confused with the relativistic $\beta = v/c$. At a plane plasma magnetic field interface in equilibrium, pressure balance requires

$$\nabla\left(n\kappa T + \frac{B^2}{8\pi}\right) = 0 \tag{1.6.2}$$

Problem 1.6.1 What is the magnetic pressure in atmospheres of a 100,000-G magnetic field? What magnetic field strength is required to confine a plasma of density $n = 10^{12}$ cm^{-3} at a kinetic temperature of 100 keV, if $\beta = 1.0$ percent? ////

1.7 PARTICLE DRIFTS

Most of the interesting plasma properties result from collective effects, as previously mentioned. However, some plasma properties can be obtained by considering the motion of individual charged particles in various combinations of electric, magnetic, and gravitational fields, which may be time-varying and inhomogeneous. In a uniform magnetic field in the absence of collisions, a charged particle moves on a helical trajectory. The particle rotates at the cyclotron frequency $\omega_c = eB/mc$ perpendicular to the magnetic field with a radius of rotation $a_L = v_\perp/\omega_c$, called the *Larmor*[1] *radius*, or the *gyro radius*. Its motion along the magnetic field is unimpeded. The cyclotron frequency is given in radians per second. For example,

$$\omega_c = \frac{eB}{mc} = 1.76 \times 10^7 B \text{ (Gauss)} \qquad \text{rad/s, for electrons} \qquad (1.7.1)$$

Problem 1.7.1 Find the orbit of a particle of charge q and mass m started from rest in a crossed electric and magnetic field. Write the orbit in terms of a cyclotron orbit and a drift, and show that the drift is $V_{DE} = cE/B$. Show that one half of this particle's kinetic energy is in drift motion and one half is orbital energy. ////

This cyclotron rotation is the basic motion of a charged particle perpendicular to a magnetic field, but there are departures from this motion when other fields are involved. For instance, an $\mathbf{E} \times \mathbf{B}$ drift occurs when a steady electric and magnetic field both act on a charged particle. The combined action of these two fields causes, in addition to the cyclotron rotation, a drift motion perpendicular to both the electric and magnetic fields, at a velocity given by

$$\mathbf{V}_{DE} = c\frac{\mathbf{E} \times \mathbf{B}}{B^2} \qquad (1.7.2)$$

This drift motion is independent of either the mass or charge of the particle involved, and is superposed on the cyclotron rotation. Frequently the cyclotron motion is much more rapid than the drift motion, and the motion is well described by specifying the orbit of the *guiding center*,[2] defined as the center of the particle's circular orbit. Thus $\mathbf{V}_{DE}$ is referred to as a drift velocity of the guiding center.

If instead of an electric field acting on the particle there is a gravitational field, the drift velocity is

$$\mathbf{V}_{DG} = \frac{mc}{q}\frac{\mathbf{g} \times \mathbf{B}}{B^2} \qquad (1.7.3)$$

Another drift motion that is important in plasma problems is the gradient B drift that occurs when the magnetic field is inhomogeneous. The gradient drift is

[1] This radius of gyration should be called the "cyclotron radius," to be consistent with conventional terminology; however, it is referred to as the Larmor radius in most of the contemporary plasma physics literature.

[2] The concept of a guiding center for charged-particle motions was introduced in 1940 by H. Alfvén, who used the guiding-center motions in a theory of magnetic storms and aurora. He collected his works and ideas in "Cosmical Electrodynamics," Oxford, New York, 1950, and in 1970 he was awarded the Nobel prize in physics for his pioneering work in plasma physics.

also superposed on the cyclotron rotation. For weak gradients ($\nabla B/B < 1/a_L$), the drift speed of the guiding center (perpendicular to **B** and to ∇B) is

$$V_{D,\mathrm{grad}} = \frac{w_\perp c}{qB^2} \nabla_\perp B \qquad (1.7.4)$$

where $w_\perp$ ($=\frac{1}{2} m v_\perp^2$) is the kinetic energy perpendicular to **B**. The details of particle-orbit theory are given in Appendix I, where curvature drift and other drift motions are treated.

1.8 PLASMA FREQUENCY

Because of the long-range forces between plasma particles, a plasma behaves in some situations as a system of coupled oscillators. One basic characteristic oscillator frequency of the plasma state is the plasma frequency ω_p, defined as

$$\omega_p = 2\pi f_p = \left(\frac{4\pi n e^2}{m}\right)^{1/2} \quad \text{rad/s}$$

$$f_p \approx 10^4 \sqrt{n} \quad \text{Hz, for electrons} \qquad (1.8.1)$$

where n is the number of particles per cubic centimeter, and m is the electron mass. It is customary to call ω_p the plasma "frequency," even though it has units of radians per second.

The plasma frequency is often used as a means of specifying the electron density in a plasma. It is also a measure of the length of time required for an electron or ion moving with thermal speed to travel a Debye length.

If a group of electrons in a two-component plasma are displaced slightly from their equilibrium position $\mathbf{x}_0$, they will experience a force that seeks to return them to $\mathbf{x}_0$. When they arrive at the equilibrium position, they will have a kinetic energy equal to the potential energy of their initial displacement, and will continue past $\mathbf{x}_0$ until they have reconverted their kinetic energy back to potential energy. The frequency of this simple period harmonic motion will be at ω_p, the plasma frequency. This phenomenon is known as a *plasma oscillation*.

1.9 WAVES IN PLASMAS

There are a large number of possible oscillations in a system of coupled oscillators with as many degrees of freedom as a plasma, and wavelike disturbances, e.g., electric fields $\mathbf{E} = \mathbf{E}_0 \exp[i(\mathbf{k} \cdot \mathbf{x} - \omega t)]$, will propagate in a plasma. The frequency ω and the wave number k are functionally related to one another by a dispersion relation obtained from the plasma equations. A knowledge of the dispersion characteristics $\omega(k)$ for the propagating waves is certainly necessary for an understanding of the plasma state. The phase velocity of a wave is $v_p = \omega/k$, and the group velocity of a wave is $v_g = \partial\omega/\partial k$.

A plasma can propagate both linear and nonlinear waves. *Linear* refers to the simplifying approximations that are possible for small-amplitude waves, and *nonlinear* refers to shock waves and large-amplitude phenomena not predicted by linear models.

Four examples of linear waves (ion-sound waves, electromagnetic waves, drift waves, and plasma waves) are discussed below.

1.9.1 Ion-sound Waves

Sound waves in an ideal gas are dispersionless longitudinal waves that propagate below the gas collision frequency with speed $V_s = (\gamma\kappa T/m)^{1/2}$. A plasma also propagates a low-frequency acoustic, or *ion-sound wave* by a mechanism in which the perturbation charge-separation electric field provides the coupling between the electrons and the ions. These waves propagate with speed

$$C_s = \left(\frac{Z\gamma_e \kappa T_e + \gamma_i \kappa T_i}{m_i}\right)^{1/2} \tag{1.9.1}$$

The symbols γ_e and γ_i denote the usual ratio of specific heats, and Z is the ionic charge expressed in electron units. These waves are strongly damped (unlike sound waves in an ordinary gas) unless the electron temperature is much higher than the ion temperature and the wave frequency is much higher than the collision frequency. In this latter case these longitudinal waves propagate as acoustic waves. The electron pressure provides the restoring force, and the ion mass provides the inertial effect.

1.9.2 Electromagnetic Waves

Homogeneous plane electromagnetic waves propagate through a dielectric medium with dispersion given by

$$k^2 = \frac{\omega^2 \varepsilon}{c^2} \tag{1.9.2}$$

For a cold homogeneous isotropic plasma of mobile electrons and immobile ions, the high-frequency dielectric constant is

$$\varepsilon = 1 - \frac{\omega_p^{\ 2}}{\omega^2} \tag{1.9.3}$$

Problem 1.9.1 Derive the dielectric constant as given in (1.9.3) for a plasma of cold electrons and stationary ions by computing the field arising from a displacement of electrons. ////

The corresponding dispersion relation for electromagnetic waves in a plasma is

$$k^2 = \frac{\omega^2 - \omega_p{}^2}{c^2} \qquad (1.9.4)$$

If the wave frequency ω is less than the plasma frequency ω_p, the wave number is imaginary and the waves are evanescent. Above the plasma frequency ($\omega > \omega_p$), waves propagate, and at very high frequencies, the free electrons of the plasma only slightly influence the electromagnetic wave. Effects such as finite size, a steady magnetic field, or plasma inhomogeneities modify this picture considerably.

1.9.3 Waves in Magnetized or Nonuniform Plasmas

In a homogeneous steady magnetic field many additional wave motions are possible. For example, a slow dispersionless electromagnetic wave or magnethydrodynamic wave, called an *Alfvén wave*, propagates through the plasma at frequencies below the ion-cyclotron frequency with speed

$$V_A = \frac{B}{\sqrt{4\pi\rho_m}} \qquad (1.9.5)$$

where $\rho_m = nm_i$ is the mass density.

As a second example, drift waves propagate in inhomogeneous plasmas as a result of particle drifts and plasma currents associated with plasma density gradients. This extra freedom introduced by the density gradient allows a new wave motion in which

$$\omega \approx \frac{\kappa T}{m} \frac{1}{\omega_c} \frac{\nabla n_0}{n_0} k \qquad (1.9.6)$$

where κ is the Boltzmann constant, and T is the temperature.

1.9.4 Plasma Waves

These waves are also known as *space-charge waves*, *electrostatic waves*, or *Langmuir waves*. They propagate only if there is a distribution of electron velocities or if the electrons have an average velocity in the observer's frame.

此为试读，需要完整PDF请访问：www.ertongbook.com