# 1. Introduction

Space physics is to a large part plasma physics. This was realized already in the first half of this century, when plasma physics started as an own field of research and when one began to understand geomagnetic phenomena as effects caused by processes in the uppermost atmosphere, the ionosphere and the interplanetary space. Magnetic storms, bay disturbances, substorms, pulsations and so on were found to have their sources in the ionized matter surrounding the Earth.

In our companion volume, *Basic Space Plasma Physics*, we have presented its concepts, the basic processes and the basic observations. The present volume builds on the level achieved therein and proceeds into the domain of instabilities and nonlinear effects in collisionless space plasmas. In this introduction we review some of the very basics from the companion volume.

## 1.1. Plasma Properties

Classical non-relativistic plasmas are defined as quasineutral, i.e., in a global sense non-charged mixtures of gases of negatively charged electrons and positive ions, containing very large numbers of particles such that it is possible to define quantities like number densities, $n_s$, thermal velocities, $v_{\mathrm{th}s}$, bulk velocities, $\mathbf{v}_s$, pressures, $p_s$, temperatures, $T_s$, and so on. Viewed from kinetic theory, it must be possible to define a distribution function, $f_s(\mathbf{x}, \mathbf{v}, t)$, for each species $s = e, i$ (electrons, ions) in the plasma such that it gives the probability of finding a certain number of particles in the phase space interval $[\mathbf{x}, \mathbf{v}; \mathbf{x} + d\mathbf{x}, \mathbf{v} + d\mathbf{v}]$. If this is the case, any microscopic electric fields of a test charge in the plasma, i.e., of every point charge or every particle in the plasma, will be screened out by the Coulomb fields of the many other charges over the distance of a *Debye length* given in Eq. (I.1.3) of our companion book (equation numbers from that volume are prefixed by the roman numeral). Here it is written for the particle species $s$

$$\lambda_{Ds} = \left( \frac{\epsilon_0 k_B T_s}{n_e e^2} \right)^{1/2} \tag{1.1}$$

where $k_B$ is the Boltzmann constant. The Debye length of electrons is abbreviated as $\Lambda_D = \Lambda_{De}$ throughout this book. The condition for considering a group of particles to constitute a plasma is then that the number of particles in the Debye sphere is large, or after Eq. (I.1.5) that the *plasma parameter*

$$\Lambda = n_e \lambda_D^3 \gg 1 \tag{1.2}$$

In this book we deal mainly with collisionless plasmas. These are plasmas where the Coulomb collision time, $\tau_c = 1/\nu_c$, is much longer than any other characteristic time of variation in the plasma. The quantity $\nu_c$ is the collision frequency between the particles. For Coulomb collisions between electrons and ions it has been derived in Eq. (I.4.9) of our companion volume, *Basic Space Plasma Physics*. Plasmas are collisional if

$$\omega \gg \nu_c \tag{1.3}$$

where $\omega$ is the frequency of the variation under consideration.

Plasmas, in general, have a number of such characteristic frequencies. The most fundamental one is the *plasma frequency* of a species $s$

$$\omega_{ps} = \left(\frac{n_s q_s^2}{m_s \epsilon_0}\right)^{1/2} \tag{1.4}$$

It increases with charge, $q_s$, and density, $n_s$, but decreases with increasing mass, $m_s$, of the particle species. It gives the frequency of oscillation of a column of particles of species $s$ against the background plasma consisting of all other plasma populations. Thus it is the characteristic frequency by which quasineutrality in a plasma can be violated if no external electric field is applied to the plasma. The *electron plasma frequency* is the highest plasma frequency, since the electron mass is small and, furthermore, quasineutrality requires $n_e = \sum_i n_i$. Between the plasma frequency and the thermal velocity of a species there is the simple relation

$$v_{\text{th}s} = \omega_{ps} \lambda_{Ds} \tag{1.5}$$

Magnetized plasmas have another fundamental frequency, the *cyclotron frequency* given in Eq. (I.2.12). For a magnetic field of strength $B$ this frequency is

$$\omega_{gs} = \frac{q_s B}{m_s} \tag{1.6}$$

The cyclotron frequency increases with magnetic field and charge, but, as in the case of the plasma frequency, heavier particles have a lower cyclotron frequency. Physically the cyclotron frequency counts the rotations of the charge around a magnetic field line in its gyromotion (see Sec. 2.2 of *Basic Space Plasma Physics*). A given plasma particle population can be considered to be magnetized if its cyclotron frequency is larger than the frequency of any variation applied to the plasma, $\omega_{gs} \gg \omega$. In the opposite case, when its cyclotron frequency is low, this particular species behaves as if the plasma would not contain a magnetic field. Because of the different particle masses, different plasma components may have a different magnetization behavior for a given variation frequency, $\omega$.

As with the plasma frequency, there is a relation between the thermal velocity of a species and the cyclotron frequency of its particles

$$v_{\mathrm{th}s} = \omega_{gs} r_{gs} \tag{1.7}$$

This equation defines the *gyroradius*, $r_{gs}$, of species $s$. This particular length is the radius of the circular orbit a particle performs in its motion around the magnetic field.

The gyroradius given above is actually the thermal gyroradius, because it is defined through the thermal velocity of the species. It is the average gyroradius of the particles of the particular species. Of course, each particle has its own gyroradius, depending on its velocity component perpendicular to the magnetic field. The gyroradius increases with velocity and also with mass or, better, it increases with particle energy. Energetic particles thus have large gyroradii.

Finally, we introduce one particular important quantity used in plasma physics, i.e., the ratio of thermal-to-magnetic energy density in the plasma, the so-called *plasma beta*

$$\beta = \frac{nk_B T}{B^2/2\mu_0} \tag{1.8}$$

This ratio tells us whether the plasma is dominated by the thermal pressure in the plasma or if the magnetic field dominates the dynamics of the plasma. Clearly, for $\beta > 1$ the former case is realized, and the magnetic field plays a relatively subordinate role, while in the opposite case, when $\beta < 1$, the magnetic field governs the dynamics of the plasma. The dynamics of the magnetospheric plasma is controlled by the geomagnetic field, while in the solar wind beta is large, and the dynamics of the solar wind plasma is dominated by the solar wind flow.

## 1.2. Particle Motions

Single particle motion in a plasma is naturally strongly distorted by the presence of all the other particles, the propagation of disturbances across a plasma, and a number of other effects. However, due to the Debye screening, the particles move approximately freely in a dilute collisionless and hot plasma for distances larger than one Debye length. One can assume that the small distortions of the particles caused by their participation in the *Debye screening* of the Coulomb fields of the other particles they pass along in their motion will in the average be small and will constitute only negligible wiggles around their collisionless orbits. This kind of wiggling in a more precise theory can be described by the *thermal fluctuations* of the particle density and velocity.