1. Introduction

The context of the term 'geophysics' has changed considerably during the second half of this century. Well into the fifties the key interest of geophysics was the interior of our planet, i.e., solid Earth geophysics covering seismology, rock physics, magnetic and electric properties of crust and mantle, etc. With the advent of the spaceflight era, the interests of geophysicists broadened and extended into the external neighborhood of our planet. It was realized that the extraterrestrial matter is in an ionized state, very different from the state of known matter near the ground of the Earth.

Matter of this kind behaves unexpected because of its sensitivity to electric and magnetic fields and its ability to carry electric currents. Within this context, the concept of a plasma became introduced and space plasma physics became a new and important branch of geophysics. Nowadays, methods of plasma physics are not only used in external geophysics, but are essential to understand the dynamics of the Earth's fluid core and the generation of the terrestrial magnetic field.

1.1. Definition of a Plasma

A *plasma* is a gas of charged particles, which consists of equal numbers of free positive and negative charge carriers. Having roughly the same number of charges with different signs in the same volume element guarantees that the plasma behaves *quasineutral* in the stationary state. On average a plasma looks electrically neutral to the outside, since the randomly distributed particle electric charge fields mutually cancel.

For a particle to be considered a free particle, its typical potential energy due to its nearest neighbor must be much smaller than its random kinetic (thermal) energy. Only then the particle's motion is practically free from the influence by other charged particles in its neighborhood as long as no direct collisions take place.

Since the particles in a plasma have to overcome the coupling with their neighbors, they must have thermal energies above some electronvolts. Thus a typical plasma is a hot and highly ionized gas. While only a few natural plasmas, such as flames or lightning strokes, can be found near the Earth's surface, plasmas are abundant in the universe. More than 99% of all known matter is in the plasma state.

Debye Shielding

For the plasma to behave quasineutral in the stationary state, it is necessary to have about equal numbers of positive and negative charges per volume element. Such a volume element must be large enough to contain a sufficient number of particles, yet small enough compared with the characteristic lengths for variations of macroscopic parameters such as density and temperature. In each volume element the microscopic space charge fields of the individual charge carriers must cancel each other to provide macroscopic charge neutrality.

To let the plasma appear electrically neutral, the electric *Coulomb potential* field of every charge, q

$$\phi_C = \frac{q}{4\pi\epsilon_0 r} \tag{1.1}$$

with ϵ_0 being the free space permittivity, is shielded by other charges in the plasma and assumes the *Debye potential* form

$$\phi_D = \frac{q}{4\pi\epsilon_0 r} \exp\left(-\frac{r}{\lambda_D}\right) \tag{1.2}$$

in which the exponential function cuts off the potential at distances $r > \lambda_D$. The characteristic length scale, λ_D, is called *Debye length* and is the distance, over which a balance is obtained between the thermal particle energy, which tends to perturb the electrical neutrality, and the electrostatic potential energy resulting from any charge separation, which tends to restore charge neutrality. Figure 1.1 shows the shielding effect.

In Sec. 9.1 we will show that the Debye length is a function of the electron and ion temperatures, T_e and T_i, and the plasma density, $n_e \simeq n_i$ (assuming singly charged ions)

$$\boxed{\lambda_D = \left(\frac{\epsilon_0 k_B T_e}{n_e e^2}\right)^{1/2}} \tag{1.3}$$

where we have assumed $T_e \simeq T_i$ and where k_B the Boltzmann constant and e the electron charge. We will give the exact definition for the temperature in Sec. 6.5. Until then we will use the terms temperature and average energy, $\langle W \rangle = k_B T$, as synonyms.

In order for a plasma to be quasineutral, the physical dimension of the system, L, must be large compared to λ_D

$$\lambda_D \ll L \tag{1.4}$$

Otherwise there is not enough space for the collective shielding effect to occur, and we have a simple ionized gas. This requirement is often called the first plasma criterion.

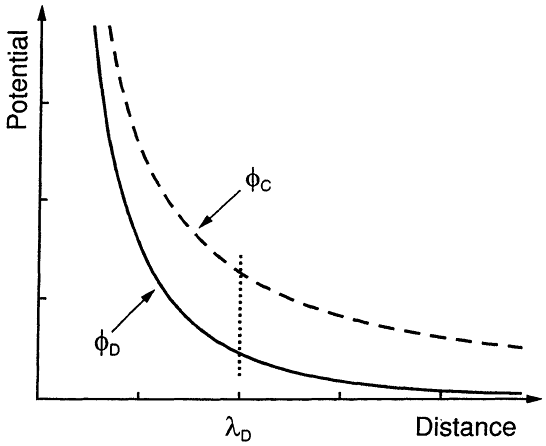

Fig. 1.1. Comparison of Debye and Coulomb potential.

Plasma Parameter

Since the shielding effect is the result of the collective behavior inside a Debye sphere of radius λ_D, it is necessary that this sphere contains enough particles. The number of particles inside a Debye sphere is $\frac{4\pi}{3}n_e\lambda_D^3$. The term $n_e\lambda_D^3$ is often called the *plasma parameter*, Λ, and the second criterion for a plasma reads

$$\Lambda = n_e\lambda_D^3 \gg 1 \tag{1.5}$$

By substituting λ_D by the expression given in Eq. (1.3) and raising each side of Eq. (1.5) to the 2/3 power, it becomes apparent that the second criterion quantifies what is meant by free particles. The mean potential energy of a particle due to its nearest neighbor, which is inversely proportional to the mean interparticle distance and thus proportional to $n_e^{1/3}$, must be much smaller than its mean energy, $k_B T_e$.

Plasma Frequency

The typical oscillation frequency in a fully ionized plasma is the electron *plasma frequency*, ω_{pe}. If the quasineutrality of the plasma is disturbed by some external force, the electrons, being more mobile than the much heavier ions, are accelerated in an attempt to restore the charge neutrality. Due to their inertia they will move back and forth around the equilibrium position, resulting in fast collective oscillations around the more massive ions. In Sec. 9.1 it will be shown that the plasma frequency depends on the

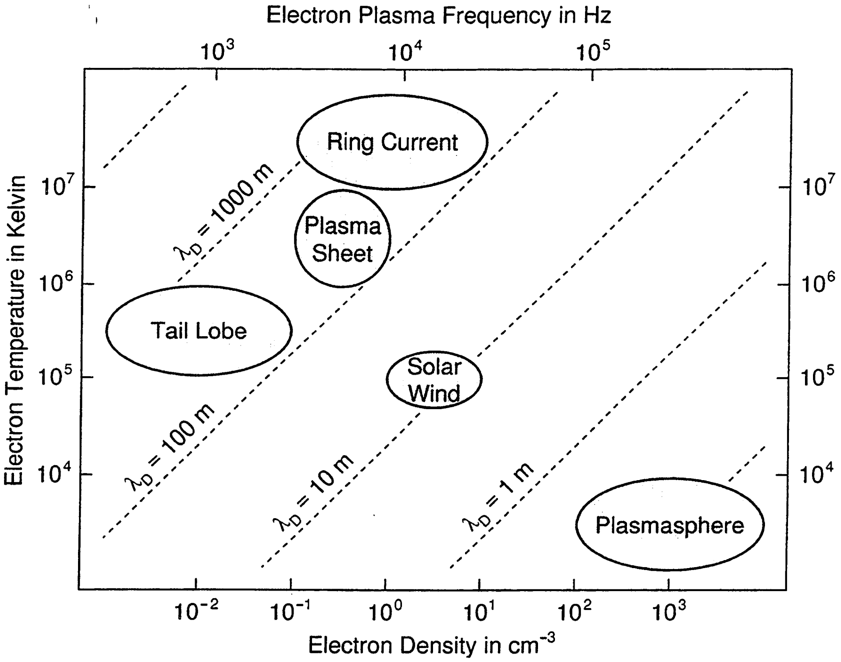

Fig. 1.2. Ranges of typical parameters for several geophysical plasmas.

square root of the plasma density. With m_e as electron mass, ω_{pe} can be written as

$$\boxed{\omega_{pe} = \left(\frac{n_e e^2}{m_e \epsilon_0}\right)^{1/2}} \tag{1.6}$$

Some plasmas, like the Earth's ionosphere, are not fully ionized. Here we have a substantial number of neutral particles and if the charged particles collide too often with neutrals, the electrons will be forced into equilibrium with the neutrals, and the medium does not behave as a plasma anymore, but simply like a neutral gas. For the electrons to remain unaffected by collisions with neutrals, the average time between two electron-neutral collisions, τ_n, must be larger than the reciprocal of the plasma frequency

$$\omega_{pe}\tau_n \gg 1 \tag{1.7}$$

This is the third criterion for an ionized medium to behave as a plasma.

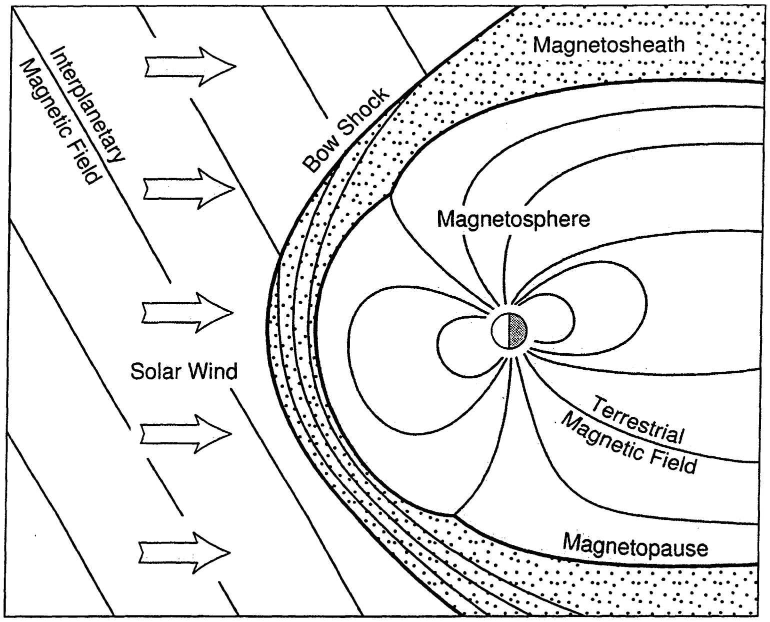

Fig. 1.3. Topography of the solar-terrestrial environment.

1.2. Geophysical Plasmas

Plasmas are not only abundant in the universe, but also in our solar system. Even in the immediate neighborhood of the Earth, all matter above about 100 km altitude, within and above the ionosphere, has to be treated using plasmaphysical methods. There are quite a number of different geophysical plasmas, with a wide spread in their characteristic parameters like density and temperature (see Fig. 1.2).

Solar Wind

The sun emits a highly conducting plasma at supersonic speeds of about 500 km/s into the interplanetary space as a result of the supersonic expansion of the solar corona. This plasma is called the *solar wind* and consists mainly of electrons and protons, with an admixture of 5% Helium ions. Because of the high conductivity, the solar magnetic field is frozen in the plasma (like in a superconductor, see Sec. 5.1) and drawn outward by the expanding solar wind. Typical values for the electron density and temperature in the solar wind near the Earth are $n_e \approx 5\,\mathrm{cm}^{-3}$ and $T_e \approx 10^5\,\mathrm{K}$ (1 eV = 11,600 K; see App. A.2). The *interplanetary magnetic field* is of the order of 5 nT.