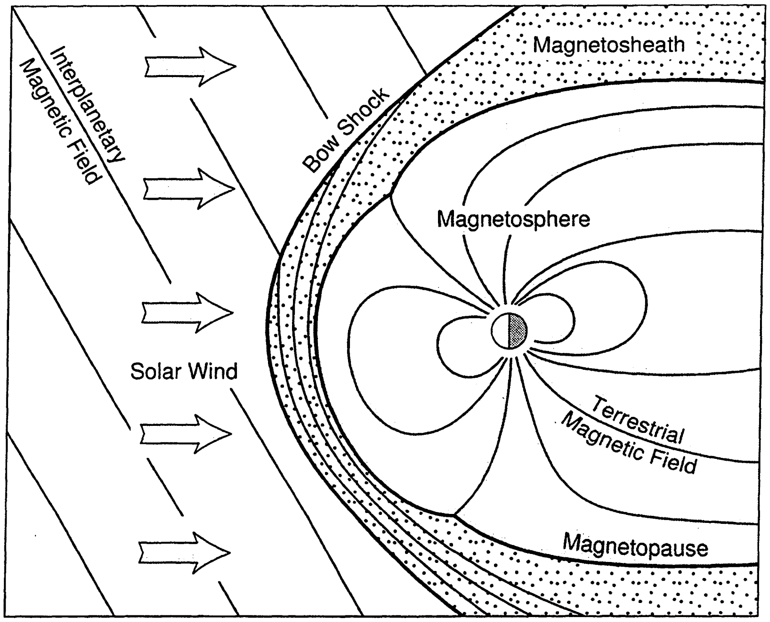

Fig. 1.3. Topography of the solar-terrestrial environment.

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.

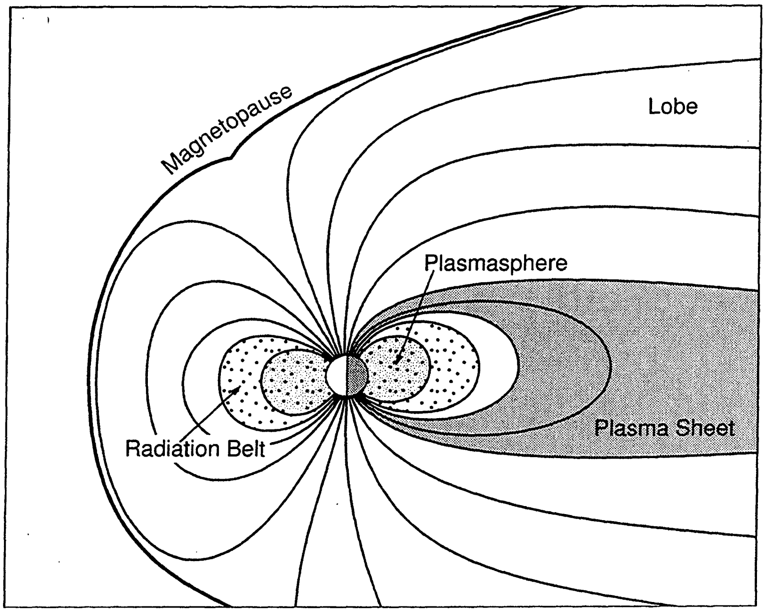

Fig. 1.4. Plasma structure of the Earth's magnetosphere.

When the solar wind hits on the Earth's dipolar magnetic field, it cannot simply penetrate it but rather is slowed down and, to a large extent, deflected around it. Since the solar wind hits the obstacle with supersonic speed, a *bow shock* wave is generated (see Fig. 1.3), where the plasma is slowed down and a substantial fraction of the particles' kinetic energy is converted into thermal energy. The region of thermalized subsonic plasma behind the bow shock is called the *magnetosheath* (see Fig. 1.3). Its plasma is denser and hotter than the solar wind plasma and the magnetic field strength has higher values in this region.

Magnetosphere

The shocked solar wind plasma in the magnetosheath cannot easily penetrate the terrestrial magnetic field but is mostly deflected around it. This is a consequence of the fact that the interplanetary magnetic field lines cannot penetrate the terrestrial field lines and that the solar wind particles cannot leave the interplanetary field lines due to the aforementioned frozen-in characteristic of a highly conducting plasma.

The boundary separating the two different regions is called *magnetopause* and the cavity generated by the terrestrial field has been named *magnetosphere* (see Figs. 1.3 and

1.4). The kinetic pressure of the solar wind plasma distorts the outer part of the terrestrial dipolar field. At the frontside it compresses the field, while the nightside magnetic field is stretched out into a long *magnetotail* which reaches far beyond lunar orbit.

The plasma in the magnetosphere consists mainly of electrons and protons. The sources of these particles are the solar wind and the terrestrial ionosphere. In addition there are small fractions of He^+ and O^+ ions of ionospheric origin and some He^{++} ions originating from the solar wind. However, the plasma inside the magnetosphere is not evenly distributed, but is grouped into different regions with quite different densities and temperatures. Figure 1.4 depicts the topography of some of these regions.

The *radiation belt* lies on dipolar field lines between about 2 and 6 R_E (1 Earth radius = 6371 km). It consists of energetic electrons and ions which move along the field lines and oscillate back and forth between the two hemispheres (see Sec. 3.2). Typical electron densities and temperatures in the radiation belt are $n_e \approx 1\,\mathrm{cm}^{-3}$ and $T_e \approx 5 \cdot 10^7\,\mathrm{K}$. The magnetic field strength ranges between about 100 and 1000 nT.

Most of the magnetotail plasma is concentrated around the tail midplane in an about 10 R_E thick *plasma sheet.* Near the Earth, it reaches down to the high-latitude *auroral ionosphere* along the field lines. Average electron densities and temperatures in the plasma sheet are $n_e \approx 0.5\,\mathrm{cm}^{-3}$ and $T_e \approx 5 \cdot 10^6\,\mathrm{K}$, with $B \approx 10\,\mathrm{nT}$.

The outer part of the magnetotail is called the *magnetotail lobe.* It contains a highly rarified plasma with typical values for the electron density and temperature and the magnetic field strength of $n_e \approx 10^{-2}\,\mathrm{cm}^{-3}$, $T_e \approx 5 \cdot 10^5\,\mathrm{K}$, and $B \approx 30\,\mathrm{nT}$, respectively.

Ionosphere

The solar ultraviolet light impinging on the Earth's atmosphere ionizes a fraction of the neutral atmosphere. At altitudes above 80 km collisions are too infrequent to result in rapid recombination and a permanent ionized population called the *ionosphere* is formed. Typical electron densities and temperatures in the mid-latitude ionosphere are $n_e \approx 10^5\,\mathrm{cm}^{-3}$ and $T_e \approx 10^3\,\mathrm{K}$. The magnetic field strength is of the order of 10^4 nT.

The ionosphere extends to rather high altitudes and, at low- and mid-latitudes, gradually merges into the *plasmasphere.* As depicted in Fig. 1.4, the plasmasphere is a torus-shaped volume inside the radiation belt. It contains a cool but dense plasma of ionospheric origin ($n_e \approx 5 \cdot 10^2\,\mathrm{cm}^{-3}$, $T_e \approx 5 \cdot 10^3\,\mathrm{K}$), which corotates with the Earth. In the equatorial plane, the plasmasphere extends out to about 4 R_E, where the density drops down sharply to about $1\,\mathrm{cm}^{-3}$. This boundary is called the *plasmapause.*

At high latitudes plasma sheet electrons can precipitate along magnetic field lines down to ionospheric altitudes, where they collide with and ionize neutral atmosphere particles. As a by-product, photons emitted by this process create the polar light, the *aurora.* These auroras are typically observed inside the *auroral oval* (see Fig. 1.5), which contains the footprints of those field lines which thread the plasma sheet. Inside of the auroral oval lies the *polar cap*, which is threaded by field lines connected to the tail lobe.

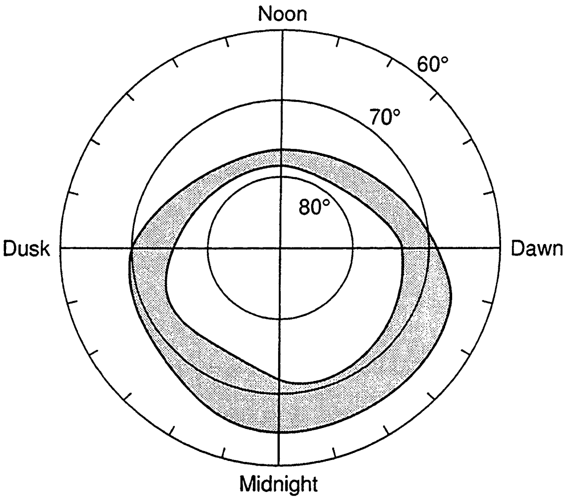

Fig. 1.5. Average auroral oval and polar cap.

1.3. Magnetospheric Currents

The plasmas discussed in the last section are usually not stationary but move under the influence of external forces. Sometimes ions and electrons move together, like in the solar wind. But at other occasions and in other plasma regions, ions and electrons move into different directions, creating an electric current. Such currents are very important for the dynamics of the Earth's plasma environment. They transport charge, mass, momentum and energy. Moreover, the currents create magnetic fields, which may severely alter or distort any pre-existing fields.

Actually, the distortion of the terrestrial dipole field into the typical shape of the magnetosphere is accompanied by electrical currents. As schematically shown in Fig. 1.6, the compression of the terrestrial magnetic field on the dayside is associated with current flow across the magnetopause surface, the *magnetopause current*. The tail-like field of the nightside magnetosphere is accompanied by the *tail current* flowing on the tail surface and the *neutral sheet current* in the central plasma sheet, both of which are connected and form a Θ-like current system, if seen from along the Earth-Sun line.

Another large-scale current system, which influences the configuration of the inner magnetosphere, is the *ring current*. The ring current flows around the Earth in a westward direction at radial distances of several Earth radii and is carried by the radiation belt particles mentioned above. In addition to their bounce motion, these particles drift slowly around the Earth. Since the protons drift westward while the electrons move in the eastward direction, this constitutes a net charge transport.