1. GENERAL PROPERTIES OF PLASMAS

1.1 Definition of a Plasma

The word plasma is used to describe a wide variety of macroscopically neutral substances containing many interacting free electrons and ionized atoms or molecules. Not all media containing charged particles, however, can be classified as plasmas. For a collection of interacting charged and neutral particles to exhibit plasma behavior it must satisfy certain conditions, or criteria, for plasma existence. These criteria will be discussed in some detail in the next section. The word plasma comes from the Greek and means something molded. It was applied for the first time by Tonks and Langmuir, in 1929, to describe the inner region, remote from the boundaries, of a glowing ionized gas produced by electric discharge in a tube, the ionized gas as a whole remaining electrically neutral.

1.2 Plasma as the Fourth State of Matter

From a scientific point of view, matter in the known universe is often classified in terms of four states: solid, liquid, gaseous, and plasma. The basic distinction among solids, liquids, and gases lies in the difference between the strength of the bonds that hold their constituent particles together. These binding forces are relatively strong in a solid, weak in a liquid, and essentially almost absent in the gaseous state. Whether a given substance is found in one of these states depends on the random kinetic energy (thermal energy) of its atoms or molecules, i.e., on its temperature. The equilibrium between this particle thermal energy and the interparticle binding forces determines the state.

By heating a solid or liquid substance, the atoms or molecules acquire more thermal kinetic energy until they are able to overcome the binding potential energy. This

leads to phase transitions, which occur at a constant temperature for a given pressure. The amount of energy required for the phase transition is called the latent heat.
If sufficient energy is provided, a molecular gas will gradually dissociate into an atomic gas as a result of collisions between those particles whose thermal kinetic energy exceeds the molecular binding energy. At sufficiently elevated temperatures an increasing fraction of the atoms will possess enough kinetic energy to overcome, by collisions, the binding energy of the outermost orbital electrons, and an ionized gas or plasma results. However, this transition from a gas to a plasma is not a phase transition in the thermodynamic sense, since it occurs gradually with increasing temperature.

1.3 Plasma Production

A plasma can be produced by raising the temperature of a substance until a reasonably high fractional ionization is obtained. Under thermodynamic equilibrium conditions, the degree of ionization and the electron temperature are closely related. This relation is given by the Saha equation. Although plasmas in local thermodynamic equilibrium are found in many places in nature, as is the case for many astrophysical plasmas, they are not very common in the laboratory.

Plasmas can also be generated by ionization processes that raise the degree of ionization much above its thermal equilibrium value. There are many different methods of creating plasmas in the laboratory and, depending on the method, the plasma may have a high or low density, high or low temperature, it may be steady or transient, stable or unstable, and so on. In what follows, a brief description is presented of the most commonly known processes of photoionization and electric discharge in gases.

In a gas discharge, an electric field is applied across the ionized gas, which accelerates the free electrons to energies sufficiently high to ionize other atoms by collisions. One characteristic of this process is that the applied electric field transfers energy much more efficiently to the light electrons than to the relatively heavy ions. The electron temperature in gas discharges is therefore usually higher than the ion temperature, since the transfer of thermal energy from the electrons to the heavier particles is very slow.

When the ionizing source is turned off, the ionization decreases gradually because of recombination until it reaches an equilibrium value consistent with the temperature of the medium. In the laboratory the recombination usually occurs so fast that the plasma completely disappears in a small fraction of a second.

1.4 **Particle Interactions and Collective Effects**

The properties of a plasma are markedly dependent upon the particle interactions. One of the basic features that distinguish the behavior of plasmas from that of ordinary fluids and solids is the existence of collective effects. Due to the long range of electromagnetic forces, each charged particle in the plasma interacts simultaneously with a consider- able number of other charged particles, resulting in important collective effects that are responsible for the wealth of physical phenomena that take place in a plasma.

In a plasma we must distinguish between charge-charge and charge- neutral interactions. A charged particle is surrounded by an electric field and interacts with the other charged particles according to the coulomb force law, with its dependence on the inverse of the square of the separation distance. Furthermore, a magnetic field is associated with a moving charged particle, which also produces a force on other moving charges.

A distinction can be made between weakly ionized and strongly ionized plasmas in terms of the nature of the particle interactions. In a weakly ionized plasma, the charge-neutral interactions dominate over the multiple coulomb interactions. When the degree of ionization is such that the multiple coulomb interactions become dominant, the plasma is considered strongly ionized. As the degree of ionization increases, the coulomb interactions become increasingly important so that in a fully ionized plasma all particles are subjected to the multiple coulomb interactions.

2. The occurrence of Plasma in nature

With the progress made in astrophysics and in theoretical physics during the last century, it was realized that most of the matter in the known universe, with a few exceptions such as the surface of cold planets (the Earth, for example) exists as a plasma.

The *sun,* which is our nearest star and upon which the existence of life on Earth fundamentally depends, is a plasma phenomenon. Its energy output is derived from thermonuclear fusion reactions of protons forming helium ions deep in its interior, where temperatures exceed 1.2×10^7 K.

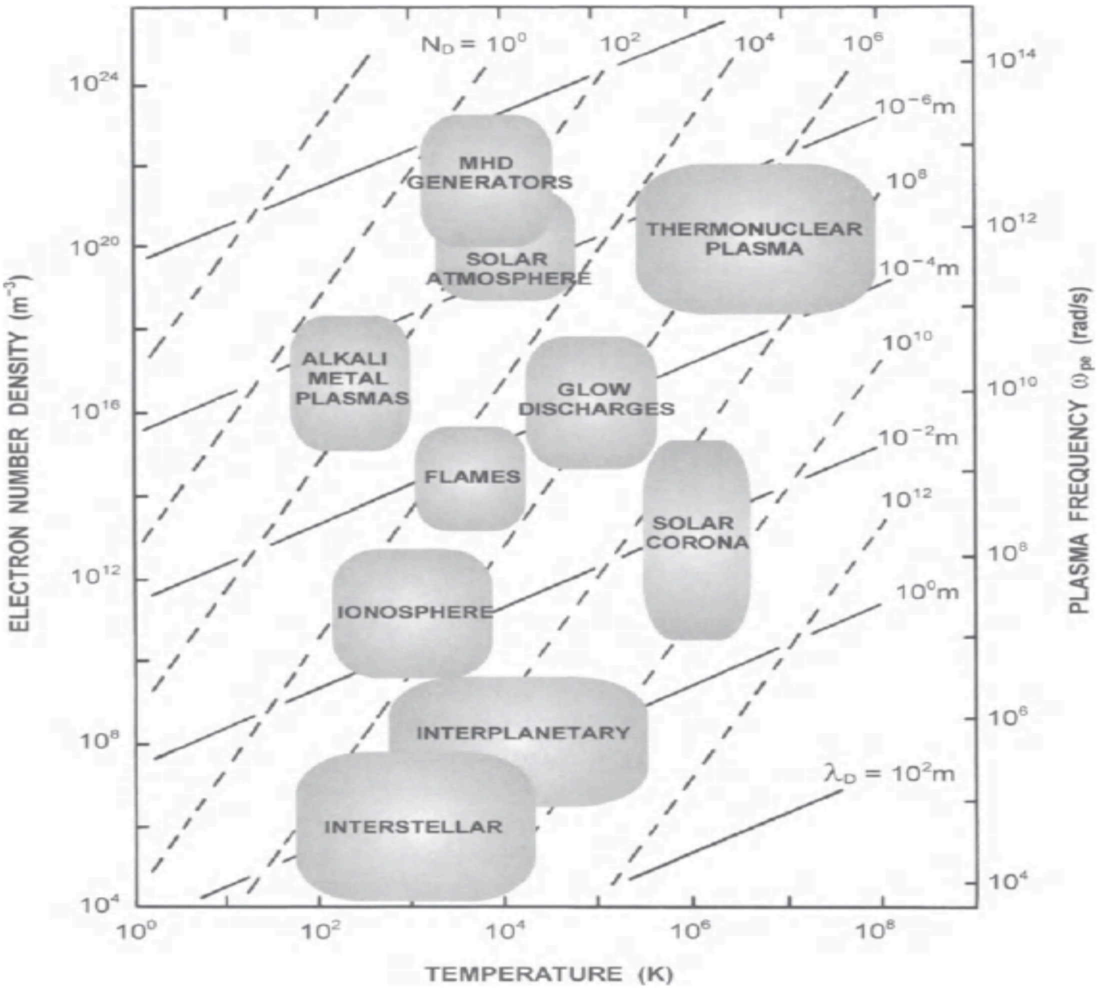


Fig.1 Ranges of temperature and electron density for several laboratory and cosmic plasmas and their characteristic physical parameters: Debye length λ_D, plasma frequency ω_{pe}, and number of electrons N_D in a Debye sphere. MHD, magnetohydrodynamic.

The high temperature of its interior and the consequent thermonuclear reactions keep the entire sun gaseous. Due to its large mass (2 x 10^{30} kg), the sun's gravitational force is sufficient to prevent the escape of all but the most energetic particles and, of course, radiation from the hot solar plasma. There is no sharp boundary surface to the sun. Its visible part is known as the solar atmosphere, which is divided into three general regions or layers. The ***photosphere***, with a temperature of about 6,000 K, comprises the visible disk, the layer in which the gases become opaque, and is a few hundred kilometers thick. Surrounding the photosphere there is a reddish ring called the ***chromosphere***, approximately 10,000 km thick, above which flame-like prominences rise with temperatures of the order of 100,000 K. Surrounding the chromosphere there is a tenuous hot plasma, extending millions of kilometers into space, known as the ***corona***. A steep temperature gradient extends from the chromosphere to the hotter corona, where the temperature exceeds 10^6 K. The sun possesses a variable magnetic field, which at its surface is typically of the order of 10^{-4} tesla, but in the regions of ***sunspots*** (regions of relatively cooler gases) the solar magnetic field rises to about 0.1 tesla.

2.1 The Solar Wind

A highly conducting tenuous plasma called the ***solar wind***, composed mainly of protons and electrons, is continuously emitted by the sun at very high speeds into interplanetary space, as a result of the supersonic expansion of the hot solar corona. Because of solar rotation, the field lines are carried into ***Archimedean*** spirals by the radial motion of the solar wind (see Fig. 2). Most of the particles are steered round the Earth without getting too close (see Fig. 3). When there is a ***flare*** on the Sun, charged particles can get through the magnetic and interact with the upper atmosphere, giving rise to aurora displays (see Fig. 4). It the solar wind is further increased by, say, a ***coronal mass ejection***, the Earth's magnetic field can be severely overcome, and the charged particles get much closer to the ground and cause parasitic currents to flow in long conductors such as power lines. This can cause destructive failures of the power system costing millions of dollars and months of time to repair.

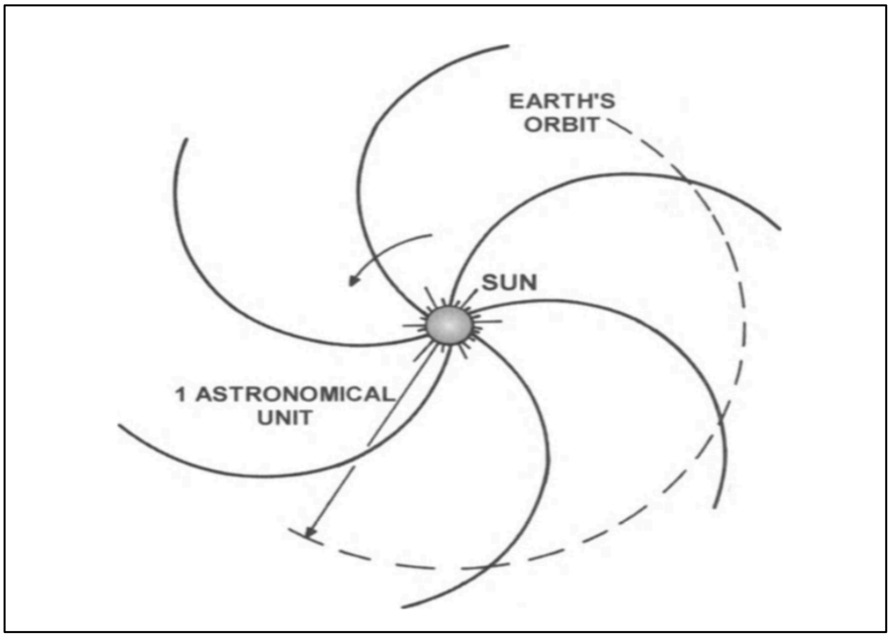
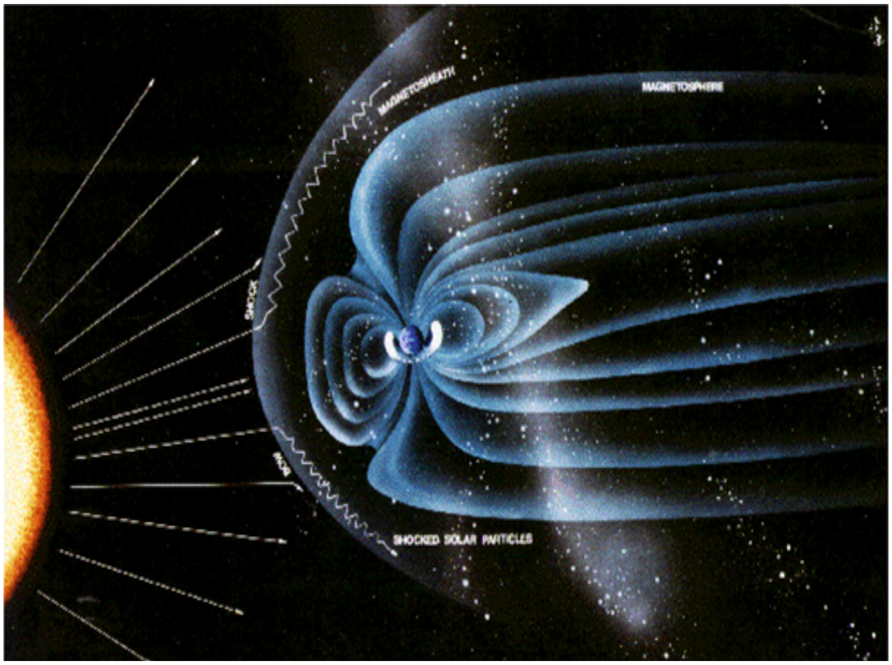


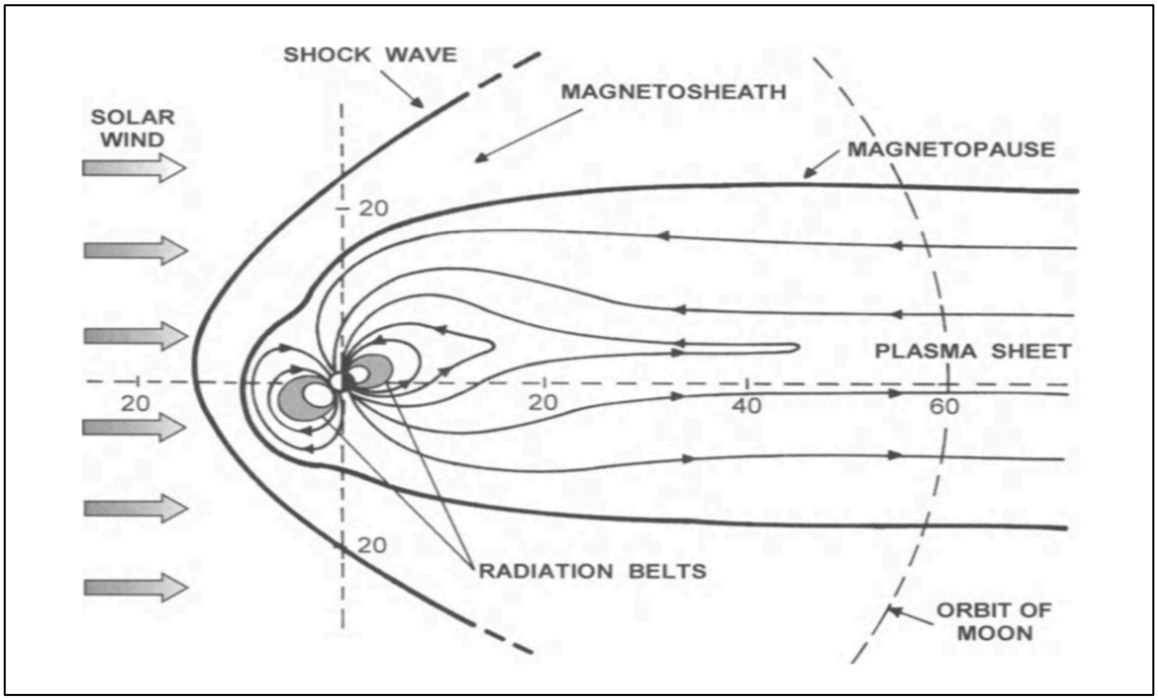
Fig. 2 Schematic representation of the Archimedes spiral structure of the interplanetary magnetic field in the ecliptic plane.



2.2 The Magnetosphere and the Van Allen Radiation Belts

When the highly conducting solar wind impinges on the Earth's magnetic field, it compresses the field on the sunward side and flows around it at supersonic speeds. This creates a boundary, called the magnetopause, which is roughly spherical on the sunward side and roughly cylindrical in the anti-sun direction (see Fig. 5). The inner region, from which the solar wind is excluded and which contains the compressed Earth's magnetic field, is called the ***magnetosphere***.

Inside the magnetosphere we find the Van Allen radiation belts, in which energetic charged particles (mainly electrons and protons) are trapped into regions where they execute complicated trajectories that spiral along the geomagnetic field lines and, at the same time, drift slowly around the Earth. The origin of the inner belt is ascribed to cosmic rays, which penetrate into the atmosphere and form proton-electron pairs that are then trapped by the Earth's magnetic field. The outer belt is considered to be due to and maintained by streams of plasma consisting mainly of protons and electrons that are ejected from time to time by the sun. Depending on solar activity, particularly violent solar eruptions may occur with the projection of hot streams of plasma material into space. The separation into inner and outer belts reflects only an altitude-dependent energy spectrum, rather than two separate trapping regions.



2.3 The Ionosphere

The large natural blanket of plasma in the atmosphere, which envelopes the Earth from an altitude of approximately 60 km to several thousands of kilometers, is called the ionosphere. The ionized particles in the ionosphere are produced during the daytime through absorption of solar extreme ultraviolet and x-ray radiation by the atmospheric species. As the ionizing radiation from the sun penetrates deeper and deeper into the Earth's atmosphere, it encounters a larger and larger density of gas particles, producing more and more electrons per unit volume. However, since radiation is absorbed in this process, there is a height where the rate of electron production reaches a maximum. Below this height the rate of electron production decreases, in spite of the increase in atmospheric density, since most of the ionizing radiation was already absorbed at the higher altitudes.

Fig. 6 provides some information on the relative concentration and altitude distribution of the electrons and of the principal positive ions, typical of the daytime ionosphere, for average solar conditions. The Earth's magnetic field exerts a great influence on the dynamic behavior of the ionospheric plasma. An interesting phenomenon that occurs in the ionospheric polar regions is the aurora. It consists of electromagnetic radiation emitted by the atmospheric species and induced by energetic particles of solar and cosmic origin that penetrate into the atmosphere along the geomagnetic field lines near the poles.

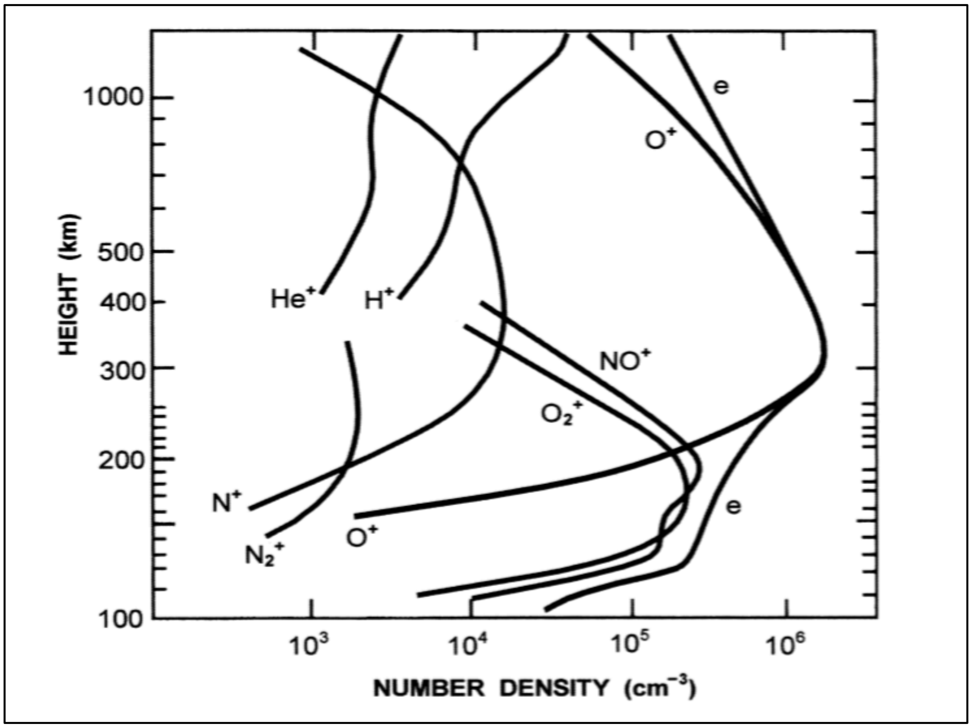


Fig. 6 Height distribution of the electrons and of the principal positive ions, typical of the daytime ionosphere, for average solar conditions.

2.4 Plasmas Beyond the Solar System

Beyond the solar system we find a great variety of natural plasmas in ***stars, interstellar space, galaxies, intergalactic space,*** and far beyond to systems quite unknown before the start of astronomy from space vehicles. There we find a variety of phenomena of great cosmological and astrophysical significance, including interstellar shock waves from remote ***supernova*** explosions, rapid variations of x-ray fluxes from ***neutron stars*** with densities like that of atomic nuclei, pulsating radio stars or ***pulsars*** (which are theoretically pictured as rapidly rotating neutron stars with plasmas emitting synchrotron radiation from the surface), and the plasma phenomena around the remarkable ***black holes*** (which are considered to be singular regions of space into which matter has collapsed, possessing such a powerful gravitational field that nothing, whether material objects or even light itself, can escape from them).

The behavior of plasmas in the universe involves the interaction between plasmas and magnetic fields. The crab nebula, for example, is a rich source of plasma phenomena because it contains a magnetic field. The widespread existence of magnetic fields in the universe has been demonstrated by independent measurements, and a wide range of field magnitudes has been found, varying from 10^{-9} tesla in interstellar space to 1 tesla on the surface of magnetic variable stars.