SPACE PHYSICS – COURSE INTRODUCTION

(course web page   http://www.sp.ph.ic.ac.uk/~mkd/)

This handout describes the aims and objectives of the Space Physics course as well as a brief introduction to the different topics and concepts that will be covered in the course.

1. Aims of the Space Physics course

- to acquaint the students with

    - the Sun and its atmosphere
    - the heliosphere and the heliospheric medium
    - the interaction of the solar wind with the planetary magnetic field of the Earth and other magnetised planets and the formation and properties of the magnetosphere
    - the formation and properties of the Earth's ionosphere
    - the basic concepts of solar-terrestrial physics

- to introduce the students to the application of the quantitative concepts and analysis methods of plasma physics applied to the space environment in the solar system

2. Objectives of the Space Physics course

- The acquisition of a descriptive knowledge of the space environment in the solar system, in particular the main properties of the solar corona, the solar wind, the heliospheric magnetic field, the solar wind's interaction with the Earth's magnetic field, the formation of the magnetosphere, the formation of the ionosphere, magnetospheric structure and convection for open and closed configurations, the effects of solar-variability on solar-terrestrial relations.

- The acquisition of a quantitative knowledge of:

    - charged particle motion (in particular, drift motion, for e.g. the ring current) in electric and magnetic fields
    - the conservation of the first adiabatic invariant and its application for particle motion in the Earth's trapped radiation belts
    - the derivation and interpretation of the conservation equations in space plasmas
    - the basic concepts of magnetohydrostatics and magnetohydrodynamics, applied to the solar corona, solar wind and the Earth's magnetosphere
    - the calculation of simple magnetic field configurations
    - the heliospheric magnetic field configuration
    - the magnetic field of a dipole applied to the Earth's magnetic field
    - the derivation of the current density vector in the presence of collisions in a magnetised plasma, applied in the ionosphere

3. The domains of Space Physics

Space Physics is interested in the natural plasma environments that are close enough to the Earth to be studied by in situ measurements made by instruments onboard spacecraft. Today these measurements cover most of the heliosphere including the Sun, its extension the solar wind; all planetary bodies with plasma environments, including the Earth; and cosmic rays.

This section gives a brief introduction to the main Space Physics domains.

The Sun*: Its sources of energy and variability, its influence on Earth, and its role as the dominant source of energy in the solar system.*

The Sun, is the star of the solar system, and is the source of virtually all energy in our solar system, including the Earth. Solar radiation heats our atmosphere and provides the light needed to sustain life on the planet. It is also the source of space plasmas throughout the solar system. The energy from the Sun is provided mainly in the form of electromagnetic radiation over a very wide frequency range (from gamma rays to long-wavelength radio waves). However energy is also emitted in the form of particles emitted in the solar wind and at higher energies as a result of transient outbursts and solar flares.

There are both short-term and long-term temporal variations in solar phenomena (solar activity) and this variability is controlled by magnetic flux emerging from the Sun's surface. The complex magnetic cycle of the Sun has approximately a 22-year period. Twice in each magnetic period, solar activity has a maximum and minimum – resulting in an approximately 11-year solar activity cycle. At solar maximum the energy output of the Sun is at its highest and during solar minimum the energy output is relatively quieter.

Solar-Terrestrial and Solar-Planetary relations*: The influence of energetic solar radiation and the solar wind on the magnetospheres and upper atmospheres of the Earth and other planets.*

Planetary bodies in the solar system present an obstacle to the solar wind. The solar wind is a continuous outstreaming of plasma from the solar atmosphere which becomes supersonic above a few solar radii. For planets that have magnetic fields, like our Earth, the magnetic field acts as an obstacle to the solar wind (which cannot easily penetrate through it) and a magnetic bubble forms as a result of the flow of the solar wind around magnetised planets. This bubble is known as a magnetosphere and the physical processes which occur within it are dependent on the solar wind behaviour which is very variable. Some responses on the ground to solar effects are for e.g., the northern and southern lights (aurorae) and magnetic storms. Lately it has been recognised that phenomena studied in space physics can have important practical consequences for e.g. strong solar flares can cause damage to communications satellites, pose a threat to space missions and even disrupt power grids. These effects are studied within solar-terrestrial relations.

Similar solar-induced phenomena occur near other magnetised planets such as Mercury, Jupiter, Saturn, Uranus and Neptune, although as we shall see each of the resulting magnetospheres is unique. The interaction of the solar wind with planets that are unmagnetised is different, with the ionosphere (ionised upper atmosphere) acting as the obstacle to solar wind flow. Here again solar wind variability leads to important changes within the different ionospheres.

***The Heliosphere**: Its nature, dynamics and contents, extending from the Sun to the outer frontiers of the solar system.*

The heliosphere is the region of space that is influenced by the Sun and the solar wind. In some respects the heliosphere encompasses the true extent of the solar system. This volume expands out to distances where the dynamic pressure of the solar wind drops below that of the pressure exerted outside of the solar system by the Local Interstellar Medium. We are still not aware of how big the heliosphere is since no spacecraft has yet reached it, however it is thought to be about 200 AU in diameter (1AU ≡ 1 Astronomical Unit ≡ distance between the Sun and the Earth, 1.5 x 10^8 km). The solar wind carries with it solar coronal magnetic field lines which go on to form the IMF (interplanetary magnetic field). The speed of the solar wind is variable and different solar wind streams interact in the heliosphere to form complex dynamic patterns with compressive and rarefied regions. As a result of compression, when slower solar wind is caught up by faster solar wind, large shock waves can form which will accelerate and energise charged particles. The heliosphere is filled with solar wind and magnetic structures that evolve as they travel out through the solar system.

***Cosmic rays**: The origin, acceleration and propagation of solar and galactic cosmic rays in the heliosphere and galaxy.*

Cosmic rays are not really rays at all but energetic charged particles. A significant portion of our present knowledge of the global structure of the heliosphere comes from energetic particle observations. These particles travel through space at velocities higher than that of the local plasma population. Since the propagation of the energetic particles is greatly affected by various physical properties of the medium through which it passes, energetic particles sample regions of the heliosphere and the galaxy that are currently inaccessible to spacecraft. High energy particles observed in the heliosphere (outside of planetary magnetospheres) can be divided into 3 broad categories; galactic cosmic rays coming from outside the solar system, solar energetic particles produced by the Sun, and heliospheric particles accelerated in the heliosphere by processes such as shock acceleration or ion pickup. The intensity of galactic cosmic rays varies as a function of the solar activity cycle, their intensity is largest near solar minimum and smallest near solar maximum. It was this 11-year modulation of the cosmic ray intensity that first indicated the existence of the heliosphere and led to estimates of its size.

4. Space Plasma Physics

The space environment consists almost exclusively of plasma of different origins, densities, composition and temperature, threaded by magnetic fields. Plasma is an electrically neutral gas composed predominantly of charged particles, hence the roles of electrical and magnetic fields are critical to understanding the behaviour of the plasma. The space plasma environment we are interested in is very rarefied, its particle density is much lower than that of an extremely good laboratory vacuum. As a result of this, in most instances collisions between particles in space plasmas can be ignored and we in effect examine collisionless plasmas.

Plasmas are generated by heating a collection of atoms to high temperatures, causing the atoms to move at high speeds, so that when they collide electrons are stripped off the colliding atoms. Once a plasma has been created it can be maintained either by keeping the temperature very high, or by reducing the density. Most of the universe is made up of either very hot and dense plasma (in the interior of stars) or cooler, rarefied plasma in interstellar and interplanetary space. While only a few natural plasmas, such as flames or lightning strokes can be found near the Earth's surface, more than 99% of all known matter in the universe is in the plasma state.

The plasma state is different from other states of matter because its constituents are electrically charged. This means they interact through electric forces (Coulomb force) and this force acts over long distances. Hence each particle is subjected to forces from a large number of particles surrounding it – making the plasma behave very differently to other states of matter. The dynamics of a plasma is governed by the interaction of the charge carriers with the electric and magnetic fields. If all the fields were of external origin that would make it a relatively simple problem, however as the particles move around they create electric and magnetic fields. These internally generated fields and their feedback into the motion of the plasma particles make plasma physics rather complicated.

There are a number of different ways of describing a plasma, each of the approaches makes different approximations and are therefore suitable to different types of problems:

1) single particle motion description – describes the motion of a particle under the influence of external electric and magnetic fields. This description neglects the collective behaviour of a plasma and is useful for studying very low density plasma, such as the Earth's ring current.
2) the Magnetohydrodynamic approach (MHD) is at the other extreme and neglects all single particle aspects. Here the plasma is treated as a single conducting fluid with macroscopic variables like average density, temperature and velocity. This is applicable when the plasma has very high electrical conductivity.
3) multi-fluid approach – similar to the MHD approach but it accounts for different particle species (electrons, protons and possibly heavier ions) and treats each species as a separate fluid.
4) kinetic theory is the most developed plasma theory and takes a statistical approach.

Waves play a very important role in plasmas. They provide the means for particles to interact with each other and also provide the means for the plasma to act as a fluid. Many different kinds of waves only exist in plasmas. The rich variety of plasma waves control the interaction of particles which make up the plasma. Interactions between the different waves and particles form the heart of the physics of plasmas.