Computer Session
“Conceptual Introduction to Kinetic Theory”

1. Objectives

1. get aquainted with a self-consistent model of the solar wind based on the kinetic theory.
2. use the Linux GNU FORTRAN compiler to run the model and carry on a parametric study of various input conditions in the solar corona and the corresponding characteristics of the solar wind
3. prepare plots of results with data analysis software (MATLAB or IDL)
4. relate the results with the information provided in the lecture, in particular the acceleration of protons to observed solar wind velocities.

2. Introduction

Understanding how nature “works” is one of the main goals of scientific investigation. Modeling of physical processes in space aims to give a quantitative description based on physical insight. Most of the modelers start with a set of mathematical equations whose solutions describe the spatial and/or temporal evolution of the system. This exercise will introduce to you a kinetic model of the solar wind that describes the spatial distribution of plasma microscopic and macroscopic parameters from the exobase to a solar distance arbitrarily chosen by the user. Using the Liouville theorem the velocity distribution function is found at each altitude. The program solves the quasineutrality equation in order to derive the electrostatic potential. The magnetic field is given.

The exospheric kinetic model of the solar wind is included in one of the collections of models available on-line, http://ccmc.gsfc.nas.gov/models/models_at_glance.php. The Community Coordinated Modeling Center is hosted by NASA and is freely available to the community. The main service offered by CCMC is to run the models by request, for various input parameters chosen by the user.

3. Description of the model

(more details in Lamy, Pierrard, Maksimovic and Lemaire, A Kinetic Exospheric Model Of the Solar Wind With a Nonmonotonic Potential Energy For the Protons, J. Geophys. Res., 108, 1047, 2003)

The exospheric model of the solar wind considers only protons and electrons, with a non-monotonic total potential for the protons and with a Lorentzian (kappa) velocity distribution function (VDF) for the electrons at the exobase. The code is developed for the coronal holes. Exospheric kinetic models assume that there is a sharp level called the exobase, separating a collision dominated region (where a fluid approximation is valid) from a region fully collisionless. In fact, there is a transition region where collisions between particles become less and less numerous when the distance to the Sun increases.

The radial distance of the exobase, ***r0***, is usually defined as the distance from the Sun where the Coulomb mean free path becomes equal to the local density scale height ***H*** or, equivalently, i.e. when the Knudsen number, ***Kn***, is equal to 1.

In the collisionless region (also called *the exosphere*), particles move freely under the influence of the Sun's gravitational field and of the interplanetary electrostatic and magnetic fields. Their trajectories solely depend on the conservation of the total energy (sum of their kinetic energy + gravitational potential energy, m$\boldsymbol{\Phi_g(r)}$ + electrostatic potential energy, e$\boldsymbol{\Phi_E(r)}$) and of their magnetic moment, μ.

The correct determination of the radial profile of the electrostatic potential, $\boldsymbol{\Phi_E(r)}$, is the key-point in the exospheric kinetic models of the solar wind . Because of their lower mass, the electrons tend to escape more easily from the Sun's gravitational field than the protons (ions). To avoid charge separations and currents on large scales in the exosphere, the electrostatic potential gives rise to a force which attracts the electrons towards the Sun and repels the protons.

For the **electrons**, the gravitational potential is negligible at all radial distances in the exosphere. Therefore the total potential for an electron is given by the electrostatic potential and the force acting on an electron is always towards the Sun whatever the radial distance to the Sun *r*. The electrons moving along a magnetic field line may then belong to different classes of orbits:

- **the escaping electrons** : these electrons have a kinetic energy larger than the escape energy and can reach infinity

- **the ballistic electrons** : their kinetic energy is too low to escape and they fall back into the corona

- **the trapped particles** : these electrons have a magnetic mirror point and a turning point in the exosphere such that they bounce continuously up and down along a magnetic field line above the exobase altitude

- **the incoming particles** : these electrons come from the interplanetary medium. It is usually assumed that their velocity distribution function is empty.

For the **protons**, gravity cannot be neglected and their total potential energy is the sum of their gravitational and electrostatic potentials. At large radial distances, the electrostatic potential dominates the gravitational potential: all the protons experience an outward directed total force. However, closer to the Sun, the gravitational potential dominates the electrostatic potential : the total force acting on the protons is therefore oriencted towards th Sun.

In coronal holes, the density is lower than in the other regions of the solar corona resulting in larger mean free paths for the particles. the exobase is then located deeper into the solar corona (between 1.1 and ~ 5 solar radii). Therefore, the protons in the coronal holes experience a non-monotonic total potential energy which is first attractive from the exobase r_0 to a radial distance called r_{max} (where the two forces balance each other) and then repulsive beyond r_{max}. Below r_{max}, the protons can also be ballistic or trapped. The situation is unchanged for electrons since their electrostatic potential is attractive. Therefore, in order to keep the flux of escaping electrons equal to that of escaping protons, a significant electrostatic potential difference between infinity and the exobase is required. This electrostatic potential is found by iterating this potential difference until the fluxes of electrons and protons are equal within a certain approximation. The solar wind ions emerging from the coronal holes can thus be accelerated to large velocities even if the temperatures are lower than in other parts of the solar corona.

4. Input Parameters of the Model:

- **Radial Distance of the Exobase, r_0:** The radial distance of the exobase in solar radii. It must be located **between 1.1 and 5** because the model has been developed only for the coronal holes where the exobase is at low altitude since the number densities are lower than in equatorial streamers. In equatorial streamers, the exobase level is located at a larger distance from the Sun; the total potential of the protons is then a monotonically decreasing function of radial distance (which means that the repulsive electrostatic force is larger than the attractive gravitational force at every radial distance above the exobase). This latter situation cannot be handled by the current situation.
- **Electron Temperature at Exobase, T_e:** The temperature of the electrons at the exobase in K. This temperature is usually observed to be **between 800000 K and 2000000 K**.
- **Proton Temperature at Exobase, T_p:** The temperature of the protons at the exobase in K. This temperature is usually observed to be **between 1000000 K and 2000000 K**. It can be related to Te by $Tp=Te(1.8/0.75)^{1/2}$ as a consequence of the different meand free path (mfp) of the two species.
- **Kappa Index Value, k:** The value of the kappa index of the electron VDF at the exobase determines the population of suprathermal particles forming the tail of the VDF. This value ranges from 2 to 1000 (~ infinity, the Maxwellian case). However, when the exobase is located deep in the solar corona, a larger amount of suprathermal electrons is necessary in order to obtain a larger total potential difference and therefore to accelerate the solar wind ions to large velocities (> 500 km/s). The characteristics of the fast solar wind originating from the coronal holes are obtained with kappa **between 2.5 and 3.0.** These are typical values obtained by fitting the electrons VDF of the solar wind with Kappa distributions (see Maksimovic, Pierrard & Riley, Geophys. Res. Let., 24, 9, 1151-1154, 1997).
- **Domain of r_{max}:** $[r_{max\_inf}, r_{max\_sup}]$ inside which the iterative procedure determines the appropriate value of r_{max}

- **Max Radial Distance, r_{end}:** The last radial distance (in solar radii) where the program calculates the moments of the electrons and of the protons VDFs of the solar wind.

The plotting program displays a the radial distributions of a set of moments between r_0 and r_{max}.

5. Model Output:

- **G_p:** the total normalized potential of the protons (unitless)
- **PHI:** the electrostatic potential (in Volts)
- **N_e:** the number density of electrons (in 10^6 m^{-3})
- **N_p:** the number density of protons (in 10^6 m^{-3})
- **F_e:** the flux of electrons (in $10^{12} m^{-2} s^{-1}$)
- **F_p:** the flux of protons (in $10^{12} m^{-2} s^{-1}$)
- **V_e:** the bulk velocity of the solar wind electrons (in kms^{-1})
- **V_p:** the bulk velocity of the solar wind protons (in kms^{-1})
- **ALT:** radial distance from the Sun **(**altitude), in Solar radii
- **T_e_par:** parallel temperature of electrons, in Kelvin
- **T_e_perp**: perpendicular temperature of electrons, in Kelvin
- **T_e**: temperature of electrons averaged over 4π, in Kelvin
- **A_e:** electron temperature anisotropy
- **T_p_par:** parallel temperature of protons, in Kelvin
- **T_p_perp**: perpendicular temperature of protons, in Kelvin
- **T_p**: temperature of protons, in Kelvin
- **A_p:** proton temperature anisotropy
- **h_e**: electron heat flux
- **h_p**: proton heat flux

6. Computer session.

T a s k 1.

6.1 Compile the FORTRAN programme/code "*Exospheric Solar Wind Model*" developed by H. Lamy & V. Pierrard (IASB).

a) make a local copy of the directory */mnt/share/SW_model* and make it your local directory:

cp –r /mnt/share/SW_model
cd SW_model

b) use open source GNU FORTRAN compiler to compile the source code of the model and produce the executable binary:

g77 –o SW_model.exe kinetic_sw_1.22.f

c) check the binary (executable) file is produced (*ls*).

6.2. Run the kinetic model:

a) check default values of the input parameters, use any editor, e.g. :

emacs input.dat &

the format of the input file:
line 1: r_0 (in solar radii) T_e (in Kelvin) T_p (in Kelvin) kappa
line 2: r_{max_inf} (in solar radii) r_{max_sup} (in solar radii)
line 3: r_{end} (in solar radii)

b) run the model for the default values of the input parameters:

./SW_model.exe

c) check the output files, '*moments1.dat*' and '*moments2.dat*'.
Format of output files, columns from the left:
moments1.dat: ALT G_P PHI G_e N_e N_p F_e F_p V_p
moments2.dat: ALT T_e_par T_e_perp T_e A_e T_p_par T_p_perp T_p A_p h_e h_p

6.3. Plot the results of the first run:

a) open interactive session of IDL:
idlde
b) open and compile the following IDL programs *moments_V2.pro* and *rmax.pro*, that read and plot the results produced by the FORTRAN code
c) open an IDL window with size 800 x 800 (*window*)
d) run MOMENTS_V2 in idl environment

6.4. do a parametric study of the model and run it for slightly different conditions and plot the results in three separate IDL windows (*window*):
a) compute the solution for r_{end} = 1 A.U.
b) compute the solution for a kappa index equal to 5, r_0=1.5, T_e=2.0x10^6, T_p=2.0x10^6, r_{max_inf}=2.5, r_{max_sup}=5, r_{end}=215 and assess the change of the potential at the exobase
c) compute the solution for a decrease of the electron temperature at the exobase to Te=1.5x106, all the other input parameters being unchanged.

T a s k 2.

7.1. Use the output density, pressure, temperature distributions to calculate the density scale height (1) , the mean free paths of the electrons (2), of the protons (3) at $r = 2\ R_S$; 5 R_S; 10 R_S ; 100 Rs ; 215 R_S.

7.2. Use the electrostatic potential distribution given in the output file to calculate the polarization electric field (4)

h =altitude above photosphere ;

$R_s = 6.9598\ 10^5$ km = $7\ 10^5$ km

7.3. plot the mean free path as a function of the radial distance.

Mfp electrons : $l_{D,e} = 0.75\ T_e^2 / n_e \ln \Lambda$ (km) ; $\ln \Lambda = 23$

Mfp protons : $l_{D,p} = 1.8\ T_p^2 / n_e \ln \Lambda$ (km)

$$l_{D,ee} : l_{D,ei} : l_{D,ie} : l_{D,ii} = 1 : 2^{1/2} / Z_i : (2\ m_e / m_i)^{1/2} / Z_i^{\ 2} : 1 / Z_i^{\ 3}$$

when $T_e = T_i$