Description of the fortran code kinetic_sw

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1 Overview

In this document, we briefly recall the philosophy behind exospheric models of the solar wind and we describe the structure of the fortran code **kinetic_sw.f**. This code is an exospheric model of the solar wind with only protons and electrons (we defer the inclusion of heavy ions to upcoming versions of the code), with a non-monotonic total potential for the protons and with a Lorentzian (kappa) velocity distribution function (VDF) for the electrons. This code is developed for the coronal holes.

2 Basics of exospheric models

In exospheric models of the solar wind, we assume that electrons and protons move collisionless above a radial distance r_{exo} called the exobase. For given VDFs at the exobase for electrons and protons, we can calculate the moments of these VDFs (densities n, fluxes F, parallel and perpendicular pressures, $P_{\|}$ and $P_{\perp}$, heat fluxes, ϵ) at every radial distance above r_{exo} if we know the radial distribution of the electrostatic potential, $V\left(r\right)$. This latter quantity is determined by imposing the quasi-neutrality, $n_p\left(r\right) = n_e\left(r\right)$, at every radial distance r, while the zero-current equation, $F_p\left(r\right) = F_e\left(r\right)$, allows us to calculate the electrostatic potential difference, V_0, between r_{exo} and ∞ in order to avoid accumulation of negative charges at large distance and positive charges in the solar corona. When the exobase is located close to the Sun (typically $r_{\mathrm{exo}} < 5\,\mathrm{R_s}$), there is an additional complication : the total potential of the protons (given by the sum of their attractive gravitational potential and their repulsive electrostatic potential) has a maximum located at a radial distance $r_{\max}$. Therefore, for given conditions at the exobase, the moments of the VDFs of the protons not only depend on $V\left(r\right)$ but they also depend on three additional unknowns, namely V_0, the electrostatic potential at the exobase, V_m, the electrostatic potential at $r_{\max}$ and $r_{\max}$ itself. The search of $r_{\max}$ is the crucial and difficult point of this exospheric model since we do not know a priori the distribution of $V\left(r\right)$ (recall that $r_{\max}$ is the distance where the attractive gravitational and the repulsive electrostatic force acting on a proton exactly cancel).

3 Search of the $r_{\max}$ value

To find the correct value of $r_{\max}$, we follow a method described by Jockers (1970). Let us assume a given value for $r_{\max}$: $r^{\star}_{\mathrm{m}}$. We are left with two unknowns, V_0 and $V_{\max}$, which can be determined by simultaneously solving the quasi-neutrality equation and the zero-current equation, expressed at $r = r^{\star}_{\mathrm{m}}$. Therefore, for this given set of parameters, we can solve the quasi-neutrality equation, $n_p\left(r\right) = n_e\left(r\right)$, for all radial distances above $r^{\star}_{\mathrm{m}}$. For most values of $r^{\star}_{\mathrm{m}}$, there is a small range of radial distances for which the quasi-neutrality equation has not a single solution but instead there are

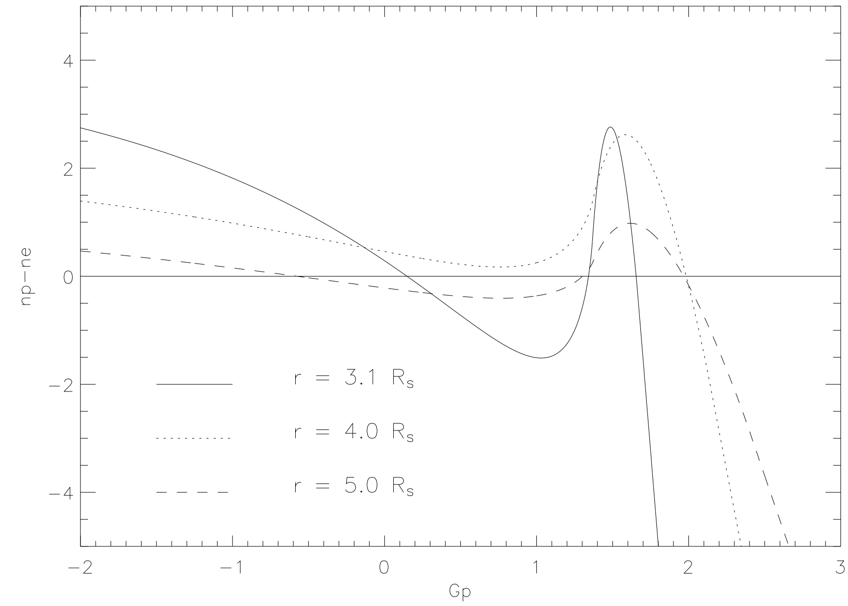

Figure 1: The difference between the protons and electrons densities, $n_p - n_e$, is plotted versus G_p, the normalized total potential of protons in the case of $r^\star_{\mathrm{m}} = 2.77\,\mathrm{R_s}$. The values of $n_p - n_e$ are expressed in arbitrary units. Three different radial distances above $r^\star_{\mathrm{m}}$ are considered : 3.1, 4.0 and 5.0 $\mathrm{R_s}$, illustrating that for some radial distances, the solution of the quasi-neutrality equation, G_p, is not unique.

three mathematical solutions. This is illustrated in Figure 1 which gives the values of $n_p\,(r) - n_e\,(r)$ as a function of G_p, the total normalized potential of protons (which is a function of well defined quantities and $V\,(r)$ only). As we will show below, only one of these three solutions has a physical meaning. The important concept to note is that the form of these solutions is different depending on $r^\star_{\mathrm{m}}$ is smaller or larger than $r_{\max}$. The code makes use of this property to iteratively converge to $r_{\max}$.

In Figures 2 and 3, we illustrate the search of $r_{\max}$. We consider the following parameters at the exobase : $r_{\mathrm{exo}} = 2\,\mathrm{R_s}$, $T^p_0 = T^e_O = 1.5 \times 10^6\,\mathrm{K}$ (the temperature at the exobase, here assumed identical for electrons and protons) and $\kappa_e = 2.5$ (the kappa index of the electrons VDF : the lower kappa, the larger the amount of suprathermal electrons). In these Figures, we represent all the values of G_p, the normalized total potential of the protons, that are solutions of the quasi-neutrality equation, $n_p - n_e$, for radial distances $r > r^\star_{\mathrm{m}}$. Above a radial distance we call **altmax**, there is only one solution for G_p. The region of interest to determine if $r^\star_{\mathrm{m}}$ is smaller or larger than $r_{\max}$ is the region between $r^\star_{\mathrm{m}}$ and **altmax**.

In Figure 2, the value of $r^\star_{\mathrm{m}}$ is lower than the correct value of $r_{\max}$. The radial distance $r^\star_{\mathrm{m}}$ is located at the origin of the x-axis. $G^m_p = G_p\,(r^\star_{\mathrm{m}})$ is the point located at [2.77, 1.35] $\mathrm{R_s}$. **altmax** is $\sim 5.95\,\mathrm{R_S}$. The three G_p solutions of the quasi-neutrality equation are respectively the upper curve (with $G_p > G^m_p$ at every radial distance, hereafter called **sol 1**), the upper parts of the left and right loops (hereafter called **sol 2**) and the lower parts of the same left and right loops (hereafter called **sol 3**). Obviously, **Sol 1** is only a mathematical solution and has no physical meaning since it is always larger than G^m_p. The physically correct solution starts from G^m_p and

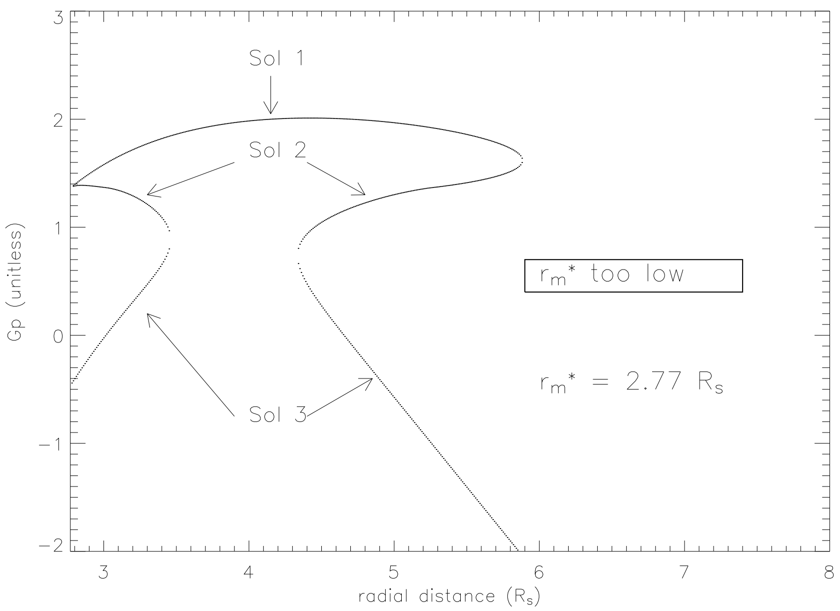

Figure 2: An example with $r^\star_{\rm m} < r_{\rm max}$.

decreases continuously with increasing radial distance. Therefore, it must start with the left part of **sol 2** and continue further with the right part of **sol 3**. The fact that $r^\star_{\rm m} < r_{\rm max}$ translates into a range of radial distances ($\sim$ [3.45, 4.25] $\mathrm{R_s}$ in this example) with only one solution (**sol 1**), the left part of **sol 2** and the right part of **sol 3** being disjoined.

In Figure 3, the value of $r^\star_{\rm m}$ is larger than the correct value of $r_{\rm max}$. Now, **sol2** and **sol3** are continuous from $r^\star_{\rm m}$ until the radial distance **altmax** but there is no solution starting with **sol2** and decreasing continuously through **sol3**.

These different behaviours, depending on $r^\star_{\rm m}$ is $<$ or $>$ $r_{\rm max}$, are used in the code by the subroutine called **dicho_rmax** to iteratively converge to $r_{\rm max}$. At the beginning of the program, we start with an initial range of values for $r^\star_{\rm m}$ supposed to contain the true $r_{\rm max}$. Theoretically, any value of $r^\star_{\rm m}$ belonging to $]r_{\rm exo}, \infty[$ could be used. In practical, $r^\star_{\rm m}$ cannot be much smaller or much larger than $r_{\rm max}$. Normally, the code takes these possibilities into account but the convergence will be very low. However, estimate the approximate value of $r_{\rm max}$ is not an easy task since the radial distance $r_{\rm max}$ varies in a complicated way with the kappa index of the electrons VDF, with the temperatures chosen at the exobase and with the position of the exobase itself. To help users choose an adequate range of $r^\star_{\rm m}$, we give in Table 1 values of $r_{\rm max}$ obtained for a few typical cases.

The program indicates to the user if $r_{\rm max}$ belongs or not to the $r^\star_{\rm m}$ range initially chosen. If $r_{\rm max}$ is outside this range, the user has to start the program again with appropriate changes. Otherwise, the program uses a dichotomy method to converge to $r_{\rm max}$ with a desired precision. The IDL program **rmax.pro** allows the user to check that the value of $r_{\rm max}$ given by the program is actually correct. The Figure 4 is an example of what can be visualized with this procedure.

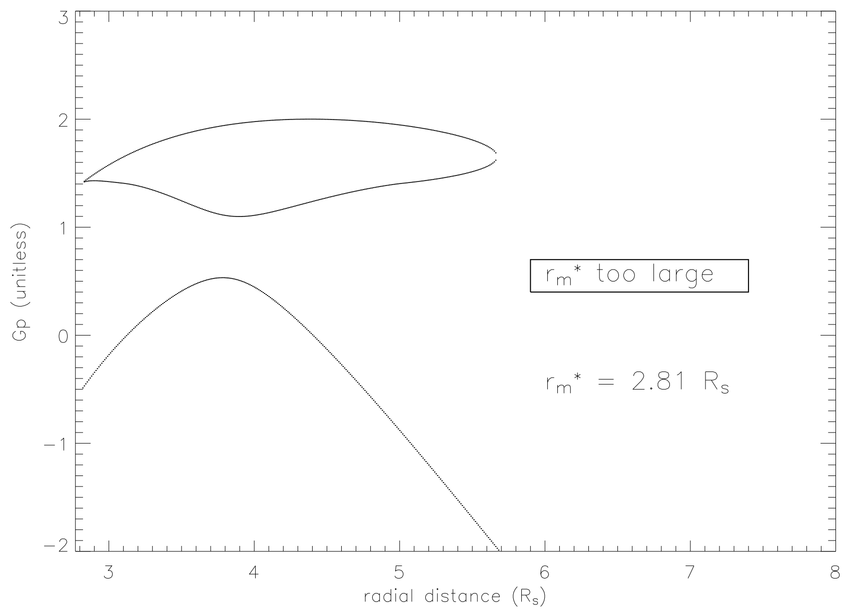

Figure 3: An example with $r_{\mathrm{m}}^{\star} > r_{\max}$.

Table 1: Values of $r_{\max}$ for typical values of r_{exo} and κ_e. The temperatures at the exobase for electrons and protons are assumed to be 1.0×10^6 K in this example.

	$\kappa_e = 2.2$	$\kappa_e = 2.5$	$\kappa_e = 3.0$	$\kappa_e = 10.0$
$r_{\mathrm{exo}} = 1.1\,\mathrm{R_s}$	1.4343	1.5102	1.6504	3.8690
$r_{\mathrm{exo}} = 1.5\,\mathrm{R_s}$	1.9942	2.0895	2.2655	4.6650
$r_{\mathrm{exo}} = 2.5\,\mathrm{R_s}$	3.3699	3.4751	3.6763	5.8385
$r_{\mathrm{exo}} = 5.0\,\mathrm{R_s}$	6.4572	6.4443	6.5117	7.5320

4 Calculation of the moments of the electrons and protons VDFs

Once $r_{\max}$ has been determined, we search for the radial distribution of the electrostatic potential, $V(r)$, by solving the quasi-neutrality equation at 200 (default value) equally spaced radial distances between r_{exo} and a radial distance called r_{end}. The choice of r_{end} depends on what the user is interested in : if you want the properties of the solar wind at 1 AU, then you have to enter $r_{\mathrm{end}} = 215\,\mathrm{R_s}$. However, if you want to look in more details at the acceleration region of the solar wind, then a value of $r_{\mathrm{end}} \sim 10 - 20\,\mathrm{R_s}$ should be more appropriate. The determination of the radial distribution of the electrostatic potential is performed in the subroutine **solarwind**.

With $V(r)$, we can now calculate all the moments of the electrons and protons VDFs. For the Kappa VDF of electrons, we make use of the formulae given in Pierrard & Lemaire, JGR, 101, 7923-7934, 1996. For the Maxwellian VDF of protons, we make use of the formulae described in Lamy, Pierrard, Maksimovic and Lemaire, JGR, 108, 1047-1057, 2003. Note that in this last article, there are some misprints in the formulae giving the parallel and perpendicular pressures.

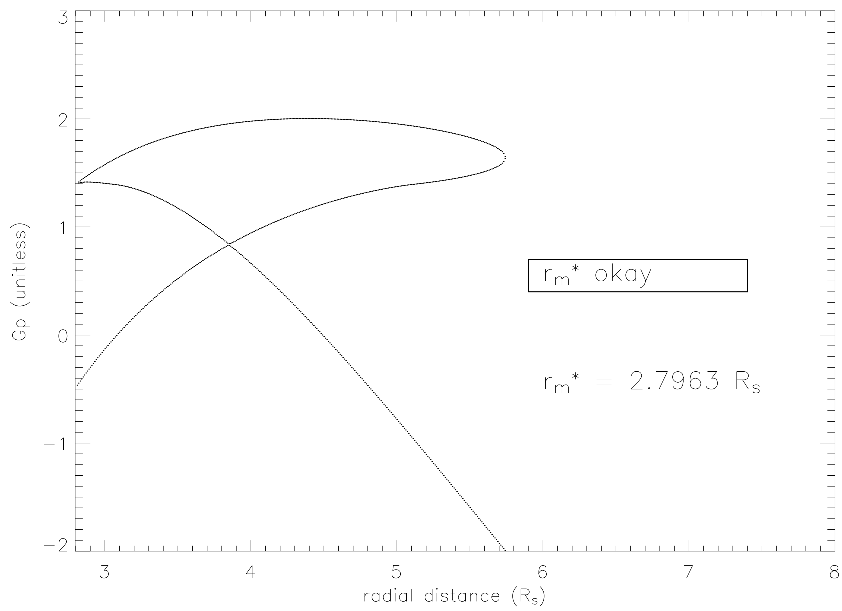

Figure 4: An example with $r_{\rm m}^{\star} \cong r_{\rm max}$.

The correct version of these formulae has been included in this fortran code and will be published soon in a forthcoming paper.

5 In practice

5.1 The fortran code

The determination of $r_{\rm max}$ and the calculation of the radial distributions of the electrostatic potential and of the moments of the electrons and protons VDFs have been combined in a single fortran code named **kinetic_sw.f**. It does not require any specific option for compilation. All subroutines have been put inside the code. Many comments have been added throughout the code itself in order to explain the different steps.

5.2 Input data

The input data are read from the ascii file **input.dat**. This file must contain the following data :

1. $r_{\rm exo}$: the radial distance of the exobase (in solar radii).It must be located **between 1.1 and 5** $\rm R_s$ because the model has been developed for the coronal holes where the number densities are lower than in equatorial streamers. In equatorial streamers, the exobase level is located at larger distance from the Sun and the total potential of the protons is a monotonically decreasing function of the radial distance (which means that the repulsive electrostatic force is larger than the attractive gravitational force at every radial distance above the exobase).

2. T_0^e : temperature of the electrons at the exobase (in K). This temperature is usually observed to be **between 800 000 K and** $2 \times 10^6\,$K. Other values can probably be used but have not

been tested.

3. T_0^p : temperature of the protons at the exobase (in K). This temperature is usually observed to be **between** $1 \times 10^6\,\mathrm{K}$ **and** $2 \times 10^6\,\mathrm{K}$. Other values can probably be used but have not been tested.

4. κ_e : value of the kappa index of the electrons VDF at the exobase. This value ranges from 2 to 1000 ($\sim \infty$, Maxwellian case). However, as will be shown in a forthcoming paper, when the exobase is located low in the solar corona, a certain amount of suprathermal electrons is necessary in order to accelerate the solar wind to large velocities ($> 500\,\mathrm{km\,s^{-1}}$). The characteristics of the fast solar wind originating from the coronal holes are obtained with κ_e **between 2.5 and 3.0**, also corresponding to 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).

5. $r_{\mathrm{m}}^{\mathrm{inf}}$ and $r_{\mathrm{m}}^{\mathrm{sup}}$: the limits (in solar radii) of the interval where r_{max} has to be found. The closer to r_{max} these limits, the faster the fortran code will converge (see Table 1 to help to choose reasonable values for these two parameters). Of course, $r_{\mathrm{m}}^{\mathrm{inf}}$ must be chosen such that $r_{\mathrm{exo}} < r_{\mathrm{m}}^{\mathrm{inf}} < r_{\mathrm{max}}$. If r_{max} is not located in the considered interval, a message appears on screen. In practical cases, do not choose $r_{\mathrm{m}}^{\mathrm{sup}}$ too large (see Table 1) nor $r_{\mathrm{m}}^{\mathrm{inf}}$ too small (usually take $r_{\mathrm{m}}^{\mathrm{inf}} > r_{\mathrm{exo}} + 0.3\,\mathrm{R_s}$).

6. 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.

5.3 Output data

The results given by the fortran code are written in the following ascii files : **idl.dat**, **gp_res.dat**, **moments1.dat** and **moments2.dat**.

The file **idl.dat** contains values of three parameters used by the IDL procedure rmax.pro. The file **gp_res.dat** contains all the solutions of the quasi-neutrality equation for $r > r_{\mathrm{max}}$ until a radial distance equal to altmax + $0.5\,\mathrm{R_s}$. These data are also used by the IDL procedure rmax.pro. The file **moments1.dat** and **moments2.dat** contain the moments of the electrons and protons VDFs for the 200 radial distances considered between r_{exo} and r_{end}. More specifically, the file **moments1.dat** contain (by order of columns) :

1. r : the radial distance (in solar radii)

2. G_p : the total normalized potential of the protons (unitless)

3. V : the electrostatic potential (in Volts)

4. n : the number density (in $10^6\,\mathrm{m^{-3}}$)

5. F : the flux of particles (in $10^{12}\,\mathrm{m^{-2}\,s^{-1}}$)

6. v_{bulk} : the bulk velocity of the solar wind (in $\mathrm{km\,s^{-1}}$)

The file **moments2.dat** contain (by order of columns) :

1. r : the radial distance (in solar radii)
2. $T_e^{\|}$: the parallel temperature of the electrons (in K)
3. $T_e^{\perp}$: the perpendicular temperature of the electrons (in K)
4. T_e : the total temperature of the electrons (in K)
5. $T_e^{\|}/T_e^{\perp}$: anisotropy of the electron temperature (unitless)
6. $T_p^{\|}$: the parallel temperature of the protons (in K)
7. $T_p^{\perp}$: the perpendicular temperature of the protons (in K)
8. T_p : the total temperature of the protons (in K)
9. $T_p^{\|}/T_p^{\perp}$: anisotropy of the proton temperature (unitless)
10. ϵ_e : the heat flux of the electrons (in $\mathrm{J\,m^{-2}\,s^{-1}}$)
11. ϵ_p : the heat flux of the protons (in $\mathrm{J\,m^{-2}\,s^{-1}}$)

5.4 Visualization tools

We give two IDL procedures named **rmax.pro** and **moments.pro**. The first procedure is meant to check that the $r_{\max}$ value found by the fortran code is indeed correct. It happens sometimes that the fortran code has not been able to converge to a value of $r_{\max}$ with the required precision. In these rare cases, usually, the precision on $r_{\max}$ is however good enough in order to calculate the moments of the electrons and protons VDFs at large distance. The correct solution of G_p is drawn with a thicker line.

The second IDL procedure gives respectively (from left to right and from top to bottom) the density, the electrostatic potential, the flux, the bulk velocity, the electron parallel and perpendicular temperatures, the proton parallel and perpendicular temperatures, the normalized total potential of the protons and the electrons and protons heat fluxes, as functions of the radial distance from r_{exo} to r_{end}.