Solar wind kinetic exospheric models with typical coronal holes exobase conditions

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Abstract. In coronal holes where densities are lower than in equatorial streamers, the exobase, which is the radial distance where collisions between solar wind particles become negligible, is located closer to the basis of the corona where the downward gravitationnal force exceeds the upward electrostatic force acting on the protons. Therefore, the total potential of the protons is a non-monotonic function of the radial distance with a maximum value at a distance r_{max}. A new kinetic model with an exobase located at low radial distances is presented and compared to previous kinetic models where the exobase was located at larger radial distance. With such a low exobase, the electric field that ensures the quasi-neutrality of the plasma is strongly enhanced which has for consequence to accelerate the solar wind to values comparable to the velocities observed in the fast solar wind. We show that the lower the radial distance of the exobase, the larger the bulk velocity of the solar wind at large distance.

INTRODUCTION

The mechanisms accelerating the solar wind to supersonic speeds have been intensively studied either by hydrodynamic/fluid models assuming a collision-dominated plasma, or by kinetic theories in a collisionless plasma. Early in situ observations by space probes revealed that the bulk velocities are drastically different in the slow solar wind ($\sim 300-400\,\mathrm{km\,s^{-1}}$) and in the fast solar wind ($\sim 700-800\,\mathrm{km\,s^{-1}}$). The fast solar wind originates from the high latitude coronal holes where at least the electron temperature is lower than in the equatorial streamers. Since in current models the velocities of the particles are related to their temperatures in the corona, these observations represent a severe constraint that yet no solar wind models, either hydrodynamic or kinetic, have been able to explain without postulating too large coronal temperatures or an additional ad-hoc deposition of heat/momentum. In this paper, we review the basic concepts of the kinetic models and show their evolution since the early models of [6]. We will emphasize on our most recent kinetic model taking into account a non-monotonic potential for the protons and accelerating the solar wind to velocities similar to those observed in the fast solar wind [5].

THE BASICS OF KINETIC EXOSPHERIC MODELS

Exospheric kinetic models assume that above a sharp level called the exobase, the particles are collisionless and 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 their energy and of their magnetic moment, assuming that the guiding center approximation is valid. Depending on their energies and their pitch angles, four classes of particles can populate the region above the exobase : the escaping particles,which have sufficiently large kinetic energy to escape from the Sun's gravitationnal potentiel well, the ballistic particles that do not have enough energy to escape and fall back into the corona, the trapped particles which are continuously bouncing up and down the magnetic field lines between a magnetic mirror point and a gravitational mirror point, and the incoming particles arriving from the interplanetary regions. In kinetic models these latter particles are usually assumed to be negligible [6]. For simplicity, the interplanetary magnetic field is assumed to be radial since a spiral structure does not significantly change the bulk speed of the solar wind in these kinetic models [10]

Since electrons are more lighter than protons, their gravitational binding is smaller and so they tend to slightly separate from the protons. A polarisation electric field parallel to the magnetic field lines appears and adjusts itself in order to maintain the electrical neutrality

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of the plasma. This is the Pannekoek- Rosseland electric field which appears in a plasma of electrons and protons in hydrostatic equilibrium. However, the solar wind is an expanding medium with no particles coming from infinity. The fluxes of electrons and protons escaping from the corona are proportional to their thermal velocities which vary as the inverse square root of their masses. Therefore, to prevent the accumulation of negative charges at large distance from the Sun and of positive charges at the basis of the corona, a larger electrostatic potential difference between the exobase and infinity must establish in order to decelerate the electrons and accelerate the protons outwards. This larger electrostatic field accelerates the solar wind particles to supersonic velocities.

EXOSPHERIC MODELS WITH MONOTONIC ENERGY POTENTIAL FOR THE PROTONS

The exobase level, r_0, is defined as the radial distance where the mean free path of the particles is equal to the density scale height and is usually located at a distance of $\sim 6-10$ solar radii (R_s) according to typical coronal parameters in the equatorial regions [6]. In this case, the total potential for the electrons, essentially due to the electrostatic potential, is attractive from the exobase to infinity and increases monotonically. Only the electrons with enough kinetic energy can overcome the potential barrier and escape. The situation is different for the protons since their total potential energy, given by the sum of their gravitational and electrostatic potentials, is repulsive and monotonically decreasing. All protons are moving outwards and can escape, in contrast with the electrons for which only high speed particles contribute to the escape flux. The first exospheric models with an exobase located at these radial distances predicted values for the solar wind bulk velocities around $300\,\mathrm{km\,s^{-1}}$ at Earth's orbit in satisfactory agreement with the average observations of the slow solar wind but were unable to reproduce the velocities observed in the fast solar wind.

Later on, these models were modified in order to use electrons velocity distribution functions (VDF) with an excess of high energy particles compared to a Maxwellian distribution [9], as is actually observed in the fast solar wind at large distance [7]. These suprathermal electrons increase the number of particles with a kinetic energy sufficient to overcome the potential well and escape to infinity. The electric field that warrants the electrical neutrality of the plasma increases in order to accelerate the solar wind protons to larger values. Therefore, the solar wind bulk speed increases as well.

These suprathermal electrons are well fitted by Lorentzian (or Kappa) distributions characterized by the value of a κ index

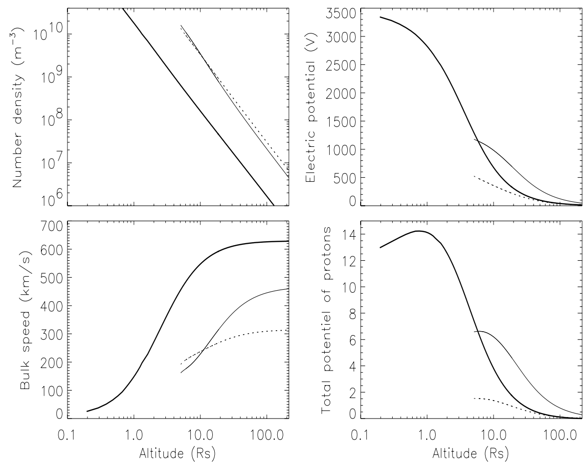

FIGURE 1. Comparison of the various exospheric kinetic models of the solar wind. For each model, we present the number density, the electrostatic potential and the bulk speed of the solar wind as well as the total (gravitational+electrostatic) potential of the protons. The dotted line corresponds to a model with a monotonically decreasing potential for the protons (r_0 located at $6\mathrm{R_s}$) and a Maxwellian VDF for the electrons. The solid line represents a model with a monotically decreasing potential for the protons (r_0 located at $6\,\mathrm{R_s}$) and a Kappa distribution for the electrons ($\kappa = 3$). The thick line is our generalized model with r_0 located at $1.1\,\mathrm{R_s}$ and $\kappa = 3$. The temperature at the exobase is $1,5\,10^6\,\mathrm{K}$ and is assumed identical for electrons and protons for simplicity.

$$f\kappa = \frac{n_0}{(\pi\kappa v_{th}^2)^{3/2}}\frac{\Gamma(\kappa+1)}{\Gamma(\kappa-1/2)}\left(1+\frac{v^2}{\kappa v_{th}^2}\right)^{-(\kappa+1)} \qquad (1)$$

where $v_{th} = \left(\frac{2\kappa-3}{\kappa}\frac{k_B T_0}{m_e}\right)^{1/2}$ is the thermal speed of electrons, n_0 and T_0 are respectively the electronic density and temperature at the exobase. These VDF decrease as a power law of the electrons velocity instead of exponentially for a Maxwellian. As $\kappa \to \infty$, the kappa function approaches a Maxwellian distribution.

Although the kinetic models based on these electrons VDF were able to accelerate the solar wind to larger bulk velocities [8] (see Figure 1), they were still unable to reach the velocities observed in the fast solar wind without assuming exobase temperatures of the order of $2\times10^6\,\mathrm{K}$, in disagreement with current observations of the coronal holes (electron temperatures $\sim 10^6\,\mathrm{K}$) [7].

CORONAL HOLES EXOBASE CONDITIONS AND NON-MONOTONIC ENERGY POTENTIAL FOR THE PROTONS

In coronal holes, the densities are lower than in equatorial streamers. As a consequence, the mean free path of the particles is larger and the altitude of the exobase is located deeper in the corona, at distances of only $1.1-3\,\mathrm{R_s}$. At these low radial distances, the gravitational force acting on the protons becomes larger than the outward repulsive electrostatic force. Above the exobase, the gravitational force decreases as $1/\mathrm{r}^2$ and the repulsive electric force decreases as $\sim 1/\mathrm{r}$, so that there is a radial distance, $\mathrm{r_{max}}$, for which the two forces balance each other. Therefore, the protons are first located in an attractive potential, from the exobase to $\mathrm{r_{max}}$ and then, in a repulsive potential, from $\mathrm{r_{max}}$ to infinity.

Below $\mathrm{r_{max}}$, the protons now can also be ballistic or trapped, so that the flux of escaping protons is reduced. The situation is not changed for electrons since their attractive electrostatic potential is still much larger than their gravitational potential. Therefore, in order to guarantee equal fluxes of escaping protons and electrons, a larger electric field than in the case with the exobase located above r_{max} is needed to increase the number of protons with an energy allowing them to overcome the potential barrier. This mechanism simply explains how the solar wind emerging from the coronal holes can be accelerated to larger velocities even with lower electron temperatures at the exobase.

In Figure 1, the different kinetic models are compared. The electrostatic potential difference between the exobase and infinity strongly increases either when we add suprathermal electrons or when the radial distance of the exobase is decreased. As a consequence, the solar wind is accelerated to large values.

The details of this generalized exospheric kinetic model are given elsewhere [5]. A description of this model in the formalism developed by [4] is also given in [12]. Here, we briefly describe the characteristics of this new model. The main difficulty of all kinetic models is to determine the radial distribution of the electrostatic potential, $V(\mathrm{r})$ in order to compute densities, fluxes and temperatures for the different classes of electrons and protons. For that purpose, we solve at every radial distance above the exobase a quasi-neutrality equation,

$$n_p\,(\mathrm{r}) = n_e\,(\mathrm{r}) \tag{2}$$

where $n_p\,(\mathrm{r})$ and $n_e\,(\mathrm{r})$ are respectively the protons and electrons densities at the radial distance r above the exobase. In previous exospheric models with monotonically decreasing potential for the protons, the only additional unknown in this equation was V_0, the electrostatic potential at the exobase which determines the potential barrier the electrons have to overcome in order to escape to infinity. In this new model with a non-monotonic potential for the protons, the situation is a bit more complicated : in addition to $V(\mathrm{r})$ and V_0, the densities n_p and n_e also depend on two additional parameters : $r_{\max}$, the altitude of the maximum of the total potential of the protons and $V_{\max}$, the electrostatic potential at $r_{\max}$ which determines the potential barrier for the protons. All these parameters depend on the values chosen for the model which are essentially the radial distance of the exobase, r_0, the kappa index of the electrons VDF, κ, and the protons and electrons temperatures at the exobase, T_0.

In order to determine these unknowns, we followed a method developed by Jockers [3] for Maxwellian electrons VDF and generalized it to the case of a Kappa VDF. Practically, the value of $r_{\max}$ is fixed and V_0 and $V_{\max}$ are found by simultaneously resolving a zero-current equation and a quasi-neutrality equation at $r = r_{\max}$,

$$F_p(r_{\max}) = F_e(r_{\max}) \tag{3}$$

$$n_p(r_{\max}) = n_e(r_{\max}) \tag{4}$$

where F_e and F_p are respectively the electrons and protons fluxes. Once these parameters are known, the radial distribution of $V(\mathrm{r})$ can be calculated from the exobase to infinity. There is only one value of $r_{\max}$ for which this distribution is continuous [5] [3]. The bulk velocity of the solar wind is then simply the ratio between the fluxes and the densities.

In Figure 2, we illustrate the influence of the radial distance of the exobase on the bulk velocity of the solar wind at large distance with realistic temperatures ($T_0 = 10^6\,\mathrm{K}$ for electrons and $T_0 = 2.10^6\,\mathrm{K}$ for protons) and kappa value of the electrons VDF at the exobase. In that particular case where the exobase is located very low ($r_0 = 1.1\,\mathrm{R_S}$), the bulk speed at 1 AU is $\sim 700\,\mathrm{km\,s^{-1}}$, of the order of the velocities observed in the fast solar wind. The densities required in order to have the exobase located at 1.1 $\mathrm{R_s}$ can be derived by equalizing the mean free path of the particles to the scale height. For that purpose, we use equations (11) and (12) of [6] and find that, for a proton temperature $T_0 = 2.10^6\,\mathrm{K}$ at the exobase, the densities are $n_0 \sim 2,5.10^6\,\mathrm{cm^{-3}}$, in good agreement with current observations [1] [2].

CONCLUSION

We have presented a new kinetic model of the solar wind with an exobase located very close to the basis of the corona, a situation which adequately describes the coronal holes where the densities are lower. With the use of suprathermal tails in the electrons VDF, these new kinetic models are able to reproduce the large velocities

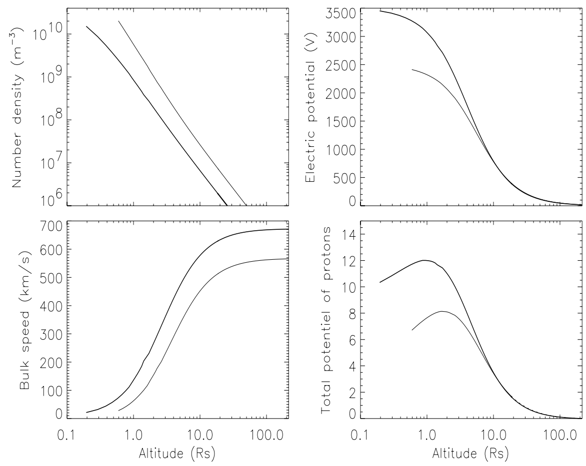

FIGURE 2. Influence of a change of the radial distance of the exobase on the number density, the electrostatic potential and the bulk speed of the solar wind for the case of $\kappa = 3$ and of electron and proton temperatures at the exobase respectively of 10^6 K and 2.10^6 K. The total potential of the protons is given in the lower right panel. The thicker line corresponds to the case of an exobase located at a radial distance $r_0 = 1.1\,\mathrm{R_s}$ while the other line corresponds to $r_0 = 1.5\mathrm{R_s}$.

observed in the fast solar wind without the need of additional ad-hoc heat/momentum deposition and even if the electron temperatures are lower than in other parts of the corona. The problem with models using Kappa distributions for the electrons is that they predict an increase of electron temperatures (as a consequence of the velocity filtration effect described by Scudder [11]) within a few solar radii, in disagreement with observations [12]. Although this problem has to be more carefully studied, it may suggest the use of a more appropriate method to describe the electrons suprathermal tails observed in the corona.

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