Study of the Electron Velocity Distribution Functions in the Solar Wind

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ABSTRACT

Electron velocity distribution functions (VDF) observed by ULYSSES and WIND in the solar wind have an enhanced tail of high energy electrons compared to a Maxwellian. To take into account the effects of these suprathermal electrons, an exospheric kinetic model based on a Lorentzian VDF has been developed. The results obtained with this new model of the solar wind fit better than earlier models many major observed features, e.g. large bulk velocities emitted out of the coronal holes and the low speed solar wind originating from the hotter regions of the solar corona.
In order to determine the importance of the Coulomb collision cross section on the origin of the suprathermal electrons, a new collisional model based on the solution of the Fokker-Planck equation has been developed.
Typical electron velocity distribution functions observed by WIND at 1 AU from the Sun are used as boundary conditions to obtain the velocity distribution functions of the electrons at any radial distance.

KEY WORDS

Solar wind, electrons, acceleration, Kappa functions, Fokker-Planck equation.

INTRODUCTION

The solar wind is constituted mainly by electrons and protons, which escape continuously from the solar corona to the interplanetary space. The solar wind has different characteristics following the region of the corona it originates from. The high-speed solar wind is characterized by an average velocity around 800 km/s and originates from the coronal holes, where the temperature is lower than in the other regions of the corona. The slow speed solar wind has an average velocity around 350 km/s, with large variability. It originates from equatorial streamers, which correspond to regions below 20 degrees of heliographic latitudes during minimum solar activity.

To model the solar wind and to find the velocity distribution functions of the electrons and the protons at any radial distances, the Fokker-Planck equation has to be solved. Two different approaches are generally used to simplify the problem: the classical hydrodynamic approach and the exospheric approach. These approaches correspond to two extreme regimes of the Knudsen number, which is defined as the ratio of the particle mean free path and the density scale height.

The approximations made to close the system of hydrodynamic equations are applicable under the assumption that the Knudsen number is smaller than unity. But already above 7 solar radii (in fact between 2 and 10 R_s), the mean free path of the particles becomes larger than the density scale height. Coulomb collisions become very scarce above this level, called the exobase. That is why exospheric models have been developed where Coulomb collisions between particles are completely neglected above the exobase. Earlier exospheric models were applied with the assumption of a maxwellian VDF for protons and electrons [Lemaire and Scherer, 1970, 1973]. The authors calculated the electric potential difference between the exobase level and infinity that is necessary to warrant the equality of outward fluxes for the electrons and protons, i.e. zero net electric current. Local quasi-neutrality was used to determine the distribution of the electrostatic potential at all altitudes above the exobase.

With a truncated maxwellian distribution at the exobase, they found that the zero electric current condition requires a large electrostatic potential difference. Considering realistic conditions at the exobase taken at 6.6 Rs for the protons and the electrons, Lemaire and Scherer's kinetic models predicted radial profiles for the number density, bulk velocity, temperature and heat flux of the solar wind electrons and protons. Speeds around 300 km/s are obtained at 1 AU in their exospheric model.

Satisfactory agreement is obtained between the results of the model and the average slow solar wind observations, except for the predicted temperature anisotropies, which are too large in the theoretical model. The excessive temperature anisotropies are the consequence of the simplifying assumption that the particles are completely collisionless.

But the exospheric models described above were unable to account for the fast solar wind, which is characterized by velocities higher than 500 km/s at 1 AU. In order to reach such velocities, exobase temperatures larger than 2 10^6 K would have to be postulated in these exospheric models, as it is the case also for hydrodynamic models [Lemaire and Pierrard, 2000]. Moreover, it was found that fast speed streams originate from coronal holes at high heliospheric latitudes where the electron coronal temperature is lower than in the equatorial source region of the slow wind. The slow and fast solar winds seem to be two different flow regimes driven by different physical mechanisms.

In 1992, Scudder suggested a new physical mechanism to explain the high temperature observed in the corona without invoking dissipation of energy or momentum by wave-particle interactions in the inner corona. He called this mechanism "velocity filtration effect". It implies the assumption that the velocity distribution function of the electrons has an enhanced population of suprathermal electron at the base of the corona. Observations by ULYSSES at large radial distances show that electron VDFs are non-Maxwellian and have suprathermal tails which decrease as a power law of the energy. We have fitted electron VDFs measured by ULYSSES by Lorentzian functions to establish the importance of the suprathermal tails. Then we have developed a new kinetic model of the solar wind based on the exospheric approximations and have shown that such suprathermal tails have a very important role in the acceleration mechanism of the high speed solar wind.

In order to understand the origin of the suprathermal electrons, we have developed a more complete model based on the solution of the Fokker-Planck equation taking into account the effects of Coulomb collisions of the particles. This model calculates the velocity distribution function of the particles and its moments (number density, flux, temperatures of the particles, ...) as a function of the radial distance. Electron VDFs measured by the instrument 3DP on WIND at 1 AU were used as boundary conditions and radial profiles are compared with our theoretical results. The development of these models is explained in next sections.

EXPERIMENT: FIT OF ULYSSES VDF MEASUREMENTS

The electron plasma instrument on board Ulysses has measured three dimensional electron velocity distribution functions in the solar wind. The data set contained 15,887 electron VDF spectra obtained during periods covering a large range of velocities, from 300 km/s near the ecliptic to 800 km/s at high latitudes.

As mentioned above, the observed velocity distribution functions of electrons are not well fitted by maxwellians because they have suprathermal tails. But they can be fitted by lorentzian (also called kappa) functions. Lorentzian distributions are characterized by enhanced suprathermal tails with a phase space density decreasing as a power law of v^2 instead of $\exp(-a\ v^2)$ when v tends to infinity. The slope of the tail is determined by the value of an index kappa: when kappa is small, there are many high energy electrons in the distribution; when kappa tends to infinity, the Kappa function tends to become identically maxwellian. By fitting the observations with lorentzian functions, we find that the electrons have an index kappa between 1.7 and 6. In the fast solar wind, the electron VDFs have well defined high velocity tails while they are closer to a maxwellian in the slow solar wind [Maksimovic et al., 1997b]. The characteristic suprathermal electron tails are known as the halo population.

Other measurements of electron VDFs have been provided by the electrostatic analyzer of the 3DP experiment on WIND at 1AU. Typical electron velocity distribution functions are represented on Figure 1. In the top panel, two cross sections of the phase space density are shown as a function of the normalized velocity parallel (solid lines) and perpendicular (dotted lines) to the magnetic field direction. The maxwellian velocity distribution with the same thermal speed is shown by a dashed line. In the bottom panel, the velocity distribution functions are represented by isocontours of constant phase space density in the (y parallel, y perpendicular) plane. The dotted circle corresponds to the maxwellian thermal velocity $y=(3/2)^{1/2}$. The distribution on the left-hand side (a) is typical of the low-speed solar wind. It has been measured on 24 01 1997 at 18:34. The distribution on the right-hand side (b) is typical of the high-speed solar wind and has been measured on the 28 01 1997 at 13:36. Halo population is also clearly visible. These typical electron VDFs measured by the instrument 3-DP on WIND have been used as boundary conditions in the models we have developed.

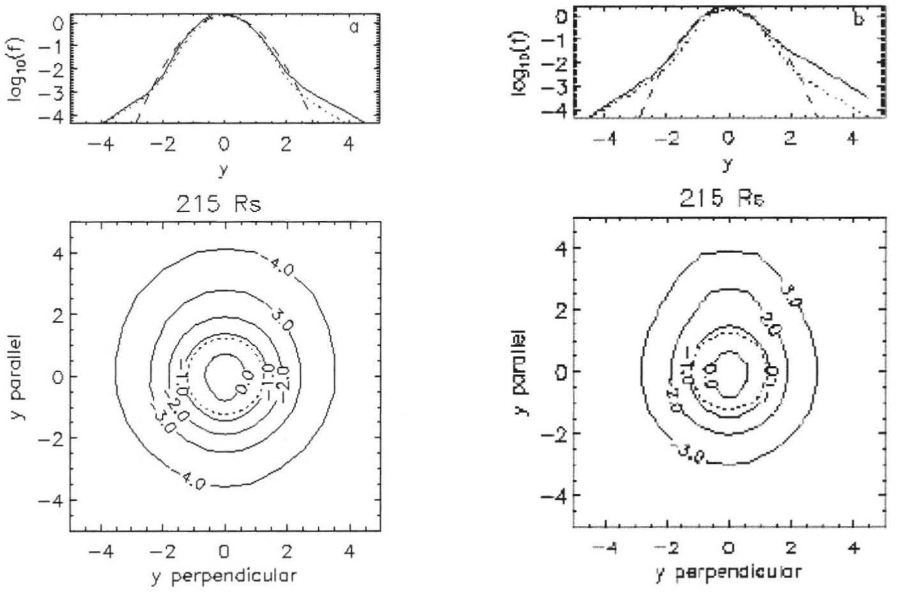

Figure 1: electron velocity distribution functions of low-speed solar wind (left) and high-speed solar wind (right)

Analysis

Starting from the observation that the VDFs of the electrons are non-maxwellian in the solar wind and in many space plasmas, we have developed a new kinetic model based on kappa VDFs for the electrons in the exosphere [Pierrard and Lemaire, 1996, 1998]. High energy tails have important consequences concerning the positive temperature gradients in the plasmasphere [Pierrard, 1997] and the current-voltage relationship (Pierrard, 1996). Applied to the solar wind [Maksimovic et al., 1997a], we have shown that important high velocity tails can accelerate the wind and create the high speed solar wind streams. Suprathermal tails increase the electric potential difference between the exobase and infinity and thus larger bulk velocities are obtained at 1 AU by reducing the value of kappa without unreasonably large coronal temperatures and without additional heating process in the inner or outer region of the corona. The evaporation of the electrons is very sensitive to the value of the index kappa.

We have also included the effects of the spiral magnetic field lines [Pierrard et al., 2000b] in the model. The characteristic electron temperature profile were compared to the observations of $T_e(r)$ as determined from the plasma wave experiment onboard of Ulysses at different heliographic latitudes [Issautier et al., 2000].

Origin of the suprathermal tails

In analytic exospheric models, we assume that the plasma of the solar wind is completely collisionless above the exobase. Nevertheless, Coulomb collisions still have some effects above this level. Since the Coulomb cross section is inversely proportional to the fourth power of the relative velocity between the colliding particles, the exobase for a given particle decreases with its energy. Therefore, no unique exobase corresponding to the mean thermal velocity of particles should possibly be used. Particles with velocities larger than the mean thermal velocity become collisionless even at lower altitudes. On the other hand, the assumption that the plasma is collision-dominated, as implicitly assumed in fluid models, is also difficult to justify since the mean free path of the particles becomes larger than the scale height above 7 R_s.

In the Fokker-Planck equation, the effects of external forces (gravitational, electric and Lorentz forces) are taken into account, as well as the Coulomb collisions between the particles. In order to solve this equation, we have developed a spectral method based on the expansion of the solution in orthogonal polynomials. To avoid singular (unphysical) solutions, we imposed regularity conditions to the electron VDF at the boundaries of the integration domain. Typical electron velocity distribution functions observed at 1 AU by the instrument 3DP on WIND (see Figure 1) are used as boundary conditions to determine the velocity distribution function of the electrons at 4 solar radii in the corona [Pierrard et al., 1999, 2000; Maksimovic et al., 1999, 2000]. We found that suprathermal tails should be present in the velocity distribution function of the electrons already at low altitude in the corona in order to match the observed distributions at 1 AU. Of course deeper into the solar corona, the relative number density of these halo electrons forming the non-maxwellian tails becomes negligibly small compared to that of the low energy core electrons.

CONCLUSIONS

Solar wind electrons VDFs observed in the inner heliosphere by ULYSSES and WIND exhibit large suprathermal tails. Analyzing data from ULYSSES, we have shown that this halo population is particularly important in the high speed solar wind and that it can play an important role in the acceleration mechanism of the solar wind, by increasing the electrostatic potential difference between the exobase and the infinity. Assuming that the VDF of the electrons is a lorentzian distribution with small value of kappa, the particles can reach high velocities with realistic values of temperature in the corona.

Furthermore, the effects of Coulomb collisions on the electron velocity distribution functions have recently been taken into account by solving the Fokker-Planck equation for the electrons in the solar wind plasma [Pierrard et al., 1999]. Typical electron velocity distribution functions observed at 1 AU by the instrument 3DP aboard of WIND were used as boundary conditions. The velocity distribution function of the electrons at other radial distances has been determined by solving numerically the Fokker-Planck equation using a spectral method and a new polynomial expansion of the solution developed in Pierrard and Lemaire [1998] for the polar wind. The fraction of suprathermal versus thermal electrons has been determined to fit the observations [Pierrard et al., 1999].

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