Kinetics of Electrons in the Corona and Solar Wind

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Abstract. The velocity distribution functions (VDFs) of electrons as measured in the solar wind show pronounced deviations from a Maxwellian. They seem to be composed of a thermal core and energetic tails, called halo. These VDFs can be fitted very well by kappa distributions. The formation of the energetic tails in the corona or in the solar wind is investigated. The relaxation of a kappa distribution under the influence of Coulomb collisions in the coronal plasma is calculated. This allows an estimation if the energetic tails of the VDFs can be formed in the corona. Resonant interaction between the electrons and electron cyclotron waves is suggested as a mechanism for the generation of the energetic tails. A kinetic model for electrons is presented. Coulomb collisions and wave-particle interactions are considered. With this model, electron VDFs can be calculated from the transition region up into the solar wind.

INTRODUCTION

Observations of solar wind electron velocity distribution functions (VDFs) reveal non-Maxwellian high-energy tails [1]. The VDFs are often described as core, halo and superhalo populations. They can also be fitted by $\kappa$-distributions, especially at higher energies of several keV [2]. Thus, at higher energies much more electrons are present than expected from a simple Maxwellian setup.

The question arises how these high-energy tails of the electron VDFs are formed. In [3] exospheric model results are presented that show a core and halo population, but no tails at higher energies. However, these models do not include an energy source for the formation of high-energy tails.

In this paper, resonant interaction between electrons and plasma waves is discussed as a possible candidate for the generation of the high-energy tails.

CORONAL ORIGIN OF HIGH-ENERGY TAILS?

The high-energy tails of the electron VDFs are measured in-situ in the solar wind. The question arises whether a coronal origin of these energetic electrons is possible, or if they have to be accelerated in the interplanetary space.

A coronal origin of the high-energy tails requires that these electrons have relaxation times due to Coulomb collisions in the corona, that are larger than the time for the passage through a characteristic length like the coronal pressure scale height of $5 \times 10^4$ km.

FIGURE 1. Electron VDF in $v_{||}$ (solid line) and $v_{\perp}$ (dotted line) after a simulation time of 5 s. Shown are also a Maxwellian (dashed line) and the initial $\kappa$ distribution (dash-dotted line) with $\kappa = 10$.

Numerical simulation of relaxation process

To assess the relaxation process due to Coulomb collisions in the corona, a numerical simulation of a homogeneous, force-free proton-electron plasma is performed. With a particle density $N = 10^{14}$ m$^{-3}$ and a temperature $T = 10^6$ K, typical coronal conditions are chosen. The model includes no heating process. The proton distribution is set to a Maxwellian one. The initial condition for the electrons is an isotropic $\kappa$-distribution with $\kappa = 10$. 


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Figure 1 shows the model electron VDF after a simulation time of 5 s. For low speeds, \( v < 5v_{th} \), the distribution function has already relaxed to a Maxwellian. But at higher speeds, \( v > 5v_{th} \), the high-energy tails of the original \( \kappa \) - distribution are still present.

This result is due to the \( v^{-3} \) dependence of the Coulomb collision frequency. Consequently, for low speeds the relaxation process is much faster than for higher speeds.

At a coronal temperature of \( T = 10^6 \) K, the electron thermal velocity is \( v_{th} = 3893 \) km/s, thus for \( v = 5v_{th} \) the transit time through one pressure scale height \((5 \cdot 10^4 \) km\) is 2.6 s. This is just half of the simulation time needed for the results displayed in figure 1.

**Conclusions from the simulation**

Since electrons with higher speeds, \( v > 5v_{th} \), can leave the corona on a time scale that is smaller than the time needed to deform their VDF significantly due to Coulomb collisions, it is concluded that they can preserve non-Maxwellian VDFs while they are propagating from the corona towards the solar wind.

Thus, it is possible that high-energy tails of the electron VDFs as they are measured in the interplanetary space can be formed already in the solar corona.

**QUASILINEAR WAVE-ELECTRON INTERACTION**

In this paper, resonant interaction between electrons and electron cyclotron waves is discussed as a possible mechanism for the generation of high-energy tails of the electron VDF in the corona.

The wave-particle interaction is described within the framework of quasilinear theory [4]. Only waves propagating anti-sunward and parallel to the background magnetic field are considered.

Since electron cyclotron waves are restricted to frequencies \( \omega \) less than the electron cyclotron frequency, \( \Omega_e \), if follows from the resonance condition

\[
\omega - kv_{\parallel} - \Omega_e = 0
\]

that only sunward moving electrons, \( v_{\parallel} < 0 \), can interact resonantly with the outward propagating waves.

**Maximum effect of the waves**

The resonant interaction of the electrons with the waves leads to pitch-angle diffusion in the reference frame of the waves. If the wave-particle interaction is the dominant process in the plasma, this leads to the formation of “shells” with no pitch angle gradients of the VDF [5].

Figure 2 displays the shells calculated under consideration of the dispersive relation of the electron cyclotron waves [6]. The ratio between the plasma frequency, \( \omega_p \), and the electron cyclotron frequency, \( \Omega_e \), is set to a value of 2, that is typical for the lower corona.

These shells indicate a strong temperature anisotropy with \( T_{\perp} \gg T_{\parallel} \). This is characteristic for a heating process due to resonant interaction with cyclotron waves.

**Generation of high energetic electrons**

As an example, we consider an electron with \( v_{\perp} = 0 \) and \( v_{\parallel} = 0.08c \), i.e. 6.16 \( v_{th} \) at \( T = 10^6 \) K. According to figure 2, it can reach the position \((v_{\perp} = 0, v_{\parallel} = 0.2c)\) due to quasilinear diffusion along its resonance shell. This corresponds to an energy of 10 keV.

Of course, the production of high-energy electrons due to quasilinear wave-particle interaction can work only if a sufficient supply of wave energy is present.

Resonant interaction between ions and ion cyclotron waves is discussed as a heating mechanism for the solar corona ([7], [8], [9]), and ion distributions measured in the solar wind show signatures of interaction with cyclotron waves ([10]).
So wave energy is likely to be present at ion cyclotron frequencies. Since the electron cyclotron frequency is considerably higher, much less spectral wave energy is expected to be found there. For a power law spectrum with \( \omega^{-1} \), the ratio of spectral wave energies at the electron and proton cyclotron frequency would correspond to the mass ratio, \( m_e/m_p \).

However, the bulk of the electrons is not to be heated as the ions are in the corona. From the resonance condition, eq. (1), it follows that electrons with higher energies interact with waves with lower frequencies. As the waves propagate away from the sun, their frequencies increase in units of the local electron cyclotron frequency. Thus, at a certain height a wave will interact with the most energetic electrons. At larger heights, it can interact with less energetic electrons, if it hasn’t been absorbed at lower heights. Thus, the most energetic electrons experience a preferred acceleration due to electron cyclotron resonance.

The above example deals with electrons with an initial speed of 6 thermal speeds. In comparison to the total number density of both ions and electrons, only a minor number of the electrons has such an initial speed. Thus, it is reasonable to assume that the wave energy is fully sufficient to have a significant effect on them.

Figure 3 shows the resonance shells for a plasma with \( \omega_p/\Omega_e = 20 \). This higher ratio is typical for the solar wind. The shells hardly differ from the isocontours of a Maxwellian distribution, thus indicating only a weak energetization of electrons.

From the results in this section it is concluded that resonant wave-electron interaction as described by quasilinear theory is a possible mechanism of accelerating electrons to energies of the order 10 keV. This mechanism is restricted to the corona, since the parameter \( \omega_p/\Omega_e \) increases towards the solar wind, thus leading to a less efficient acceleration of the electrons. The numerical simulation in the previous section shows that the energetic electrons produced in the corona can leave the corona towards the interplanetary space without being relaxed by Coulomb collisions with ions or other electrons.

**KINETIC MODEL OF ELECTRON-WAVE INTERACTION**

To study the evolution of the electron VDF from the corona into the solar wind a kinetic model has to be developed. The model is based on the kinetic model for ions in the solar corona of [11], but here two velocity coordinates \((v_\parallel, v_\perp)\) are considered. Gyrotropy is still assumed. This reduces the number of spatial coordinates to one, \( s \), along the background magnetic field.

The Coulomb collisions are calculated using the Landau collision integral (e.g. [12]). For the wave-particle interaction, the quasilinear theory is employed. The Boltzmann-Vlasov equation for the VDF \( f(s, v_\parallel, v_\perp) \) reads:

\[
\frac{\partial f}{\partial t} + \frac{\partial f}{\partial v_\parallel} + \left( v_\parallel \cdot \frac{\partial f}{\partial s} \right) = \left( \frac{\partial f}{\partial s} \right)_{\text{Coul.}} + \left( \frac{\partial f}{\partial s} \right)_{w,p}. 
\]

(2)

Here, \( v_\parallel \) and \( E_\parallel \) are the components of the gravitational and electric field parallel to the background magnetic field, and \( A(s) \) is the cross sectional area of the magnetic flux tube under consideration.

A simple fluid model yields densities, drift velocities and temperatures for a proton-electron plasma as background conditions. This background is constant in time, and the electron VDF represents a test particle population. The background is also used to provide Maxwellians as initial condition for the electron VDFs. From this initial condition, the temporal evolution of the VDF is calculated using the Boltzmann-Vlasov equation (2).

The simulation box extends from the low corona up to 0.67 AU into the interplanetary space. The velocity coordinates cover electron energies up to 100 keV. In the corona, the magnetic field decreases with height according to the geometry of a coronal funnel as modelled by [13]. At larger heights, it decreases radially.
The plasma waves are assumed to be emitted from the sun, i.e. only outward propagating waves are considered. They enter the simulation box at the lower boundary with a given power law spectrum proportional to $\omega^{-1}$. The evolution of the spectrum within the simulation box is within the scope of the model, and energy conservation between waves and electrons is guaranteed.

Kinetic results

Figure 4 shows the electron VDF after a simulation time of 100 s. The initial Maxwellian distribution has developed an asymmetry between $v_{\parallel} < 0$ and $v_{\parallel} > 0$ and a temperature anisotropy with $T_{\perp} > T_{\parallel}$. It follows from the resonance condition, eq. (1), that only electrons with $v_{\parallel} < 0$ can interact with the waves propagating away from the sun. Indeed, the isolines of the electron VDF show the same deformation and anisotropy as in figure 2. Thus, they are in coincidence with the theoretical expectations for a plasma in which quasilinear wave-particle interaction plays a major role.

The mirror force in the opening magnetic field geometry of the coronal funnel and in the solar wind has the tendency to bring particles with high $v_{\parallel}$ towards high positive $v_{\perp}$. Since it scales with $v_{\perp}^2$, see eq. (2), electrons with higher energies are pushed more strongly towards the anti-sunward side.

This explains the deformation of the electron VDF on the anti-sunward side in figure 4. Electrons accelerated on the sunward side due to wave-particle interaction cross the line $v_{\parallel} = 0$ and are just being focused towards high $v_{\parallel}$ and low $v_{\perp}$ by the mirror force.

CONCLUSIONS

In this paper, a mechanism for generating high-energetic electrons in the solar corona with resonant wave-particle interaction is presented. It is demonstrated that the waves are capable of accelerating electrons from a few thermal speeds up to energies of the order 10 keV. The demand on wave energy is not too high, since it is not necessary to heat the bulk of the electron VDF. So sufficient wave energy is likely to be present in the corona.

This process is restricted to the corona due to the increase of $\omega_p/\Omega_e$ from the corona towards interplanetary space. However, the assessment in the first section shows that electrons with only 5 thermal speeds can leave the corona towards the solar wind without significant changes of their VDFs. Electrons with higher energies will even more easily propagate from the corona into the interplanetary space.

The numerical results presented in the last section show that the electron VDF is influenced by the waves in the way expected from quasilinear theory.

Thus, it is concluded that interaction between electrons and plasma waves in the solar corona is a promising candidate for the generation of the high-energy tails of the electron VDFs that are observed in the solar wind.

REFERENCES