CORE, HALO AND STRAHL ELECTRONS IN THE SOLAR WIND

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Abstract. Electron velocity distribution functions (VDF) observed in the low speed solar wind flow are generally characterized by 'core' and 'halo' electrons. In the high speed solar wind, a third population of 'strahl' electrons is generally observed. New collisional models based on the solution of the Fokker-Planck equation can be used to determine the importance of the different electron populations as a function of the radial distance. Typical electron velocity distribution functions observed at 1 AU from the Sun are used as boundary conditions for the high speed solar wind and for the low speed solar wind. Taking into account the effects of external forces and Coulomb collisions with a background plasma, suprathermal tails are found to be present in the electron VDF at low altitudes in the corona when they exist at large radial distances.

1. Introduction

It is now established that the observed velocity distribution functions (VDFs) of the electrons in the solar wind exhibit three different components: a thermal core and a suprathermal halo which are both present at all pitch angles, and a sharply field aligned 'strahl', which is observed mostly in the fast solar wind (Feldman *et al.*, 1975; Pilipp *et al.*, 1987; Hammond *et al.*, 1996).

What are the origins of such velocity distribution functions? The classical hydrodynamic approach is inadequate to answer this question since it assumes that the particles VDFs are very close to a Maxwellian. A kinetic approach can be expected to answer this question.

In a collisionless approximation (Lemaire and Scherer, 1971; Schulz and Eviatar, 1972), the core corresponds to the relatively cool population which is trapped within the ambipolar thermo-electric potential well of the heliosphere (ϕ_E), whereas the halo and strahl are composed of electrons energetic enough to escape this potential barrier. The strongly anisotropic strahl component can be understood as the result of focussing along the magnetic field due to conservation of the magnetic moment. However, the isotropy of the halo component is not well understood. Indeed in the collisionless exospheric models, the electron VDF is truncated for local velocities larger than $\sqrt{2e\phi_E/m_e}$ and there should be a halo component in the parallel anti-sunward direction for velocities larger than the local escape velocity.

Kinetic models for the heat conduction in the solar wind acceleration regions and attempts to describe the origin of typical 1 AU electron VDFs have been pro-

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posed (Scudder and Olbert, 1979a and b). Scudder (1992a and b) has also shown that the 'velocity filtration' effect can explain the temperature increase when halo electrons are present at low radial distances. Super-diffusion processes have been proposed to explain the suprathermal tails observed in many space plasmas (Treumann, 1997). Nevertheless, up to now, nobody has comprehensively explained the origin and isotropy of electron suprathermal halo component. Do the halo electrons have their origin in the corona or are they due to other processes like wave-particle interactions or reflections at large scale interplanetary CIR-shocks?

In order to trace the origin of the shape of the electron VDF observed at 1 AU, it is useful to study its change from deep inside the corona, where the plasma is dominated by collisions, up to large heliocentric distances, where the solar wind is expected to become almost collisionless. The evolution of the VDFs with the radial distance contains information about the physical processes in the acceleration region. One of the options is to solve the Fokker-Planck equation, which is well suited to this situation. We present here one strategy to solve this equation. However there are other alternative strategies to study the solar wind transition between collision dominated to collisionless regimes. Some of them are described in the present issue, e.g. the simulations developed by Pantellini and Landi (2001) and the generalized multi-moments model developed by Hubert and Leblanc (2001).

2. Kinetic Collisional Model

The kinetic equation for the evolution of the velocity distribution function $f(\mathbf{r}, \mathbf{v}, t)$ of the electrons in the solar wind is:

$$\frac{\partial f(\mathbf{r}, \mathbf{v}, t)}{\partial t} + (\mathbf{v}.\nabla_{\mathbf{r}}) f(\mathbf{r}, \mathbf{v}, t) + (\mathbf{a}.\nabla_{\mathbf{v}}) f(\mathbf{r}, \mathbf{v}, t) = \left(\frac{df}{dt}\right)_c \tag{1}$$

where $\mathbf{r}$ and $\mathbf{v}$ are respectively the position and velocity vectors of the particles, $\mathbf{a}$ is the acceleration due to external forces and t is the time. The forces are the gravitational force (negligible for the electrons), the electric force, and the Lorentz force resulting from the magnetic field.

The term on the right hand side $(df/dt)_c$ corresponds to the effects of the binary Coulomb collisions. We ignore here the effects of wave-particle interactions as well as scattering due to large or small scale magnetic field inhomogeneities since the gyroradius of thermal solar wind electrons (as well as protons) is much smaller than the MHD wavelengths and interplanetary magnetic field inhomogeneities. We adopt the Fokker-Planck collision operator appropriate when large-angle deflections due to binary collisions are unimportant (Spitzer, 1956; Hinton, 1983). The detailed mathematical expression of the Fokker-Planck Coulomb collision operator, together with the numerical method used to solve Equation (1) are fully described in Pierrard *et al.* (1999) (hereafter quoted as P99). We only discuss here the main results of this work.

2.1. THE STRATEGY FOR SOLVING THE FOKKER-PLANCK EQUATION

The numerical method used to solve the Fokker-Planck equation is adapted from the models developed for the polar wind (Lie-Svendsen and Rees, 1996; Pierrard, 1997; Pierrard and Lemaire, 1998). This strategy has been first applied to the solar wind by Lie-Svendsen *et al.* (1997) (hereafter quoted as L-S97) whose model has been compared with the work reported in P99 and discussed below. The steady state diffusion of a population of test electrons undergoing Coulomb collisions with a background solar wind plasma has been studied. The VDF of the background particles is assumed to be known and given by a Maxwellian characterized by a given density $n_e(r)$ and an electron temperature distribution $T(r)$, or more generally by a Lorentzian VDF with a given or fitted index κ (which is the index characterizing the power law decrease of the Lorentzian VDFs at large velocities, $f(v) \propto v^{-\kappa}$). Different numerical methods of solution have been used: a finite difference method is used in L-S97 and a specific spectral method is applied in P99.

2.2. TWO BOUNDARY CONDITIONS AND RESULTS

The solutions of the Fokker-Planck equation depend greatly on the boundary conditions. Generally, one assumes two boundary conditions which can be justified theoretically. At low altitude, one usually argues that the collisions maintain a nearly isotropic and Maxwellian VDF, and that the outward moving particles are distributed accordingly (see Equation (19) in P99). This Maxwellian character of the upward moving particles is an assumption which has not been observationally tested. At high altitude, the VDF can be assumed truncated as in exospheric models: the particles with energies high enough to escape never return back. In other words, the effect of distant collisions is ignored. Only trapped and ballistic particles which have not enough energy to escape, have an isotropic pitch angle distribution (see Equation (19) in P99). In that case, the medium is assumed to be completely collisionless above the high altitude boundary.

Figure 1 shows the isocontours of the VDF found by P99 at three different radial distances. The VDFs found at intermediate radial distances and at boundary levels are asymmetric in the direction parallel to the magnetic field lines: this can be interpreted as being the strahl population.

However, we do not obtain suprathermal tails at large radial distances corresponding to the observed isotropic halo electrons when Maxwellian VDFs are imposed at the low altitude boundary. Note that L-S97 obtain similar results (see Figures 1 and 5 in L-S97). In particular, no halo population is found in the perpendicular direction.

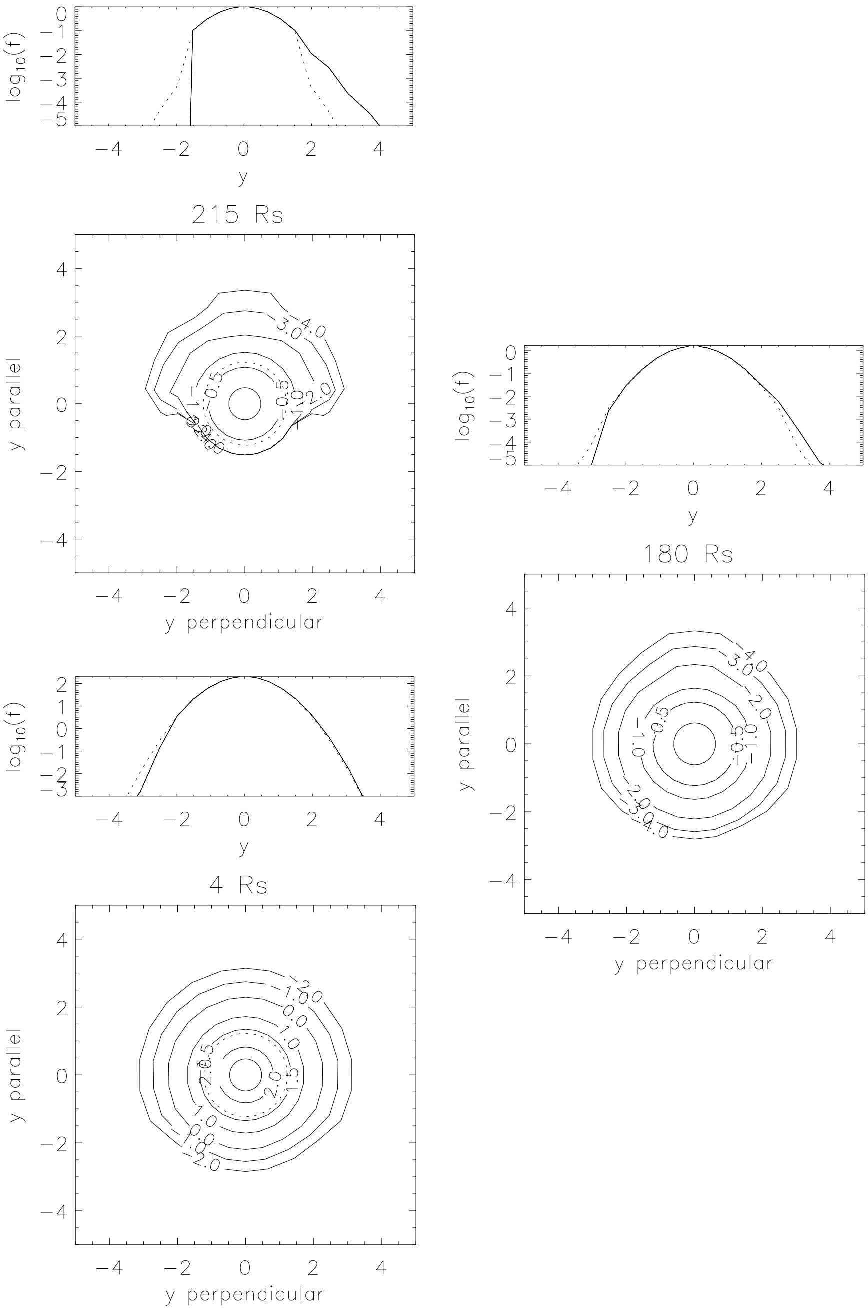

Figure 1. Velocity distribution function of electrons at three different radial distances in a collisional model with two boundary conditions. The parallel and perpendicular velocities y are normalized to the thermal speed of the electrons. The dotted circle corresponds to the thermal speed of the electrons.

2.3. BOUNDARY CONDITION AT 1 AU AND RESULTS

As already mentioned, isotropic suprathermal tails are observed at large radial distances. In P99, we have developed a model where a VDF measured at 1 AU is used as a unique boundary condition for the Fokker-Planck equation. The VDF obtained at low altitude (4 solar radii) is determined in order to match the VDF of electrons observed at 1 AU. It is important to note here that, when an observed VDF is used as boundary condition at 1 AU, it is assumed that the region beyond 1 AU is still collisional and that this collisionality is responsible for the isotropic halo component in the anti-sunward direction.

The VDF obtained at 4 solar radii by solving the Fokker-Planck equation, and taking into account the external forces and Coulomb collisions, demonstrates that suprathermal tails already exist in the corona at 4 R_S. The suprathermal tails of the electron VDF are less asymmetric deep in the corona than at 1 AU. The index κ is found to be between 4 and 10 in the corona, depending if we model the slow or fast solar wind. Finally, note that there are additional indications that suprathermal tails exist in the corona (for instance Ko *et al.*, 1996).

3. Conclusions

To study the solar wind from very low altitudes, where the plasma is dominated by collisions, to very large radial distances, where the solar wind becomes almost collisionless, it is necessary to solve the Fokker-Planck equation. We have developed a kinetic model based on the solution of this equation. The strategy is to study the diffusion of a population of test electrons undergoing Coulomb collisions with a background solar wind plasma (Pierrard *et al.*, 1999). Our results show that, in order to match the observed velocity distributions at 1 AU, suprathermal tails must already exist in the corona at 4 solar radii, but they are much less developed at these altitudes than at larger distances.

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