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Solar Wind Electron Transport: Interplanetary Electric Field and Heat Conduction

Viviane Pierrard

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Abstract The presence of suprathermal electrons has important consequences on the acceleration process of the solar wind: they increase the electrostatic potential between the corona and the interplanetary space and accelerate of the solar wind to high bulk velocities. Moreover, they modify the heat conduction and can explain the sharp increase of the temperature in the solar corona. These consequences are well evidenced in the kinetic approach where no closure requires the distributions to be nearly Maxwellians.

Keywords Solar wind · Kinetic model · Kappa functions · Acceleration

1 Introduction: the Kinetic and the MHD Approaches

Many sophisticated models of the solar wind have been developed based on the magnetohydrodynamic (MHD) and on the kinetic theory. These two approaches are complementary, but it is clear that kinetic processes prevail in the corona and the solar wind because they are low density non uniform plasmas (Marsch 2006). The difference between these two approaches comes from the approximations that are made to solve the basic equations. Kinetic models provide the velocity distribution functions (VDF) f of the particles as a solution of the evolution equation:

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

where the first term represents the time dependence of the VDF, the second term corresponds to the spatial diffusion ($\mathbf{r}$ is the position and $\mathbf{v}$ the velocity vector of the particles), the

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V. Pierrard (✉)
Belgian Institute for Space Aeronomy, 3 avenue circulaire, 1180 Brussels, Belgium
e-mail: viviane.pierrard@oma.be

V. Pierrard
Center for Space Radiations, Institute of Research in Mathematics and Physics, Université Catholique de Louvain, 2 chemin du cyclotron, 1348 Louvain-La-Neuve, Belgium

third term takes into account the effects of the external forces $\mathbf{F}$ ($\mathbf{a} = \mathbf{F}/m$ where $\mathbf{a}$ is the acceleration and m is the mass of the particles), and the term in the right hand side of the equation represents the effects of collisions and other interactions.

The calculation of the VDF moments gives the macroscopic quantities such as

$$\text{the number density:} \qquad n(\mathbf{r}) = \int_{-\infty}^{\infty} f(\mathbf{r}, \mathbf{v}) d\mathbf{v} \tag{2}$$

$$\text{the particle flux:} \qquad \mathbf{F}(\mathbf{r}) = \int_{-\infty}^{\infty} f(\mathbf{r}, \mathbf{v}) \mathbf{v} d\mathbf{v} \tag{3}$$

$$\text{the bulk velocity:} \qquad \mathbf{u}(\mathbf{r}) = \frac{\mathbf{F}(\mathbf{r})}{n(\mathbf{r})} \tag{4}$$

$$\text{the pressure:} \qquad \vec{P}(\mathbf{r}) = m \int_{-\infty}^{\infty} f(\mathbf{r}, \mathbf{v})(\mathbf{v} - \mathbf{u})(\mathbf{v} - \mathbf{u}) d\mathbf{v} \tag{5}$$

$$\text{the temperature:} \qquad T(\mathbf{r}) = \frac{m}{3kn(\mathbf{r})} \int_{-\infty}^{\infty} f(\mathbf{r}, \mathbf{v}) |v - u|^2 d\mathbf{v} \tag{6}$$

$$\text{the energy flux:} \qquad \mathbf{E}(\mathbf{r}) = \frac{m}{2} \int_{-\infty}^{\infty} f(\mathbf{r}, \mathbf{v}) |v - u|^2 (\mathbf{v} - \mathbf{u}) d\mathbf{v} \tag{7}$$

The MHD transport equations are obtained by integrating (1) in velocity space:

$$\int_{-\infty}^{\infty} (1) d\mathbf{v} \rightarrow \text{Continuity eq.} \tag{8}$$

$$\int_{-\infty}^{\infty} (1) m\mathbf{v} d\mathbf{v} \rightarrow \text{Momentum eq.} \tag{9}$$

$$\int_{-\infty}^{\infty} (1) \frac{mv^2}{2} d\mathbf{v} \rightarrow \text{Energy eq.} \tag{10}$$

In each equation of order n appears the moment of order $n + 1$, so that there are more unknowns than equations: assumptions need to be used to close the MHD system.

These approximations generally concern the highest moments such as the heat flux and assume that the VDF of the particles is close to a Maxwellian, i.e. that the plasma is dominated by collisions. But in low-density plasmas like the solar wind and the solar corona, the mean free path of the particles becomes larger than the density scale height at low radial distances. A kinetic approach is then more appropriate to describe the characteristics of the plasma (Lemaire and Pierrard 2001).

The pioneer solar wind MHD model of Parker (1958) reproduced bulk velocities reaching 400 km/s at 1 AU when assuming a temperature of the electrons of 10^6 K in the solar corona. This velocity corresponds to what is observed on average in the slow speed solar wind. To reach higher bulk velocities as observed in the high speed solar wind, it is necessary to assume a higher temperature in the solar corona, while it is well known that the high speed solar wind originates in fact from the coronal holes where the temperature is observed to be lower than in the other regions of the corona. This paradox led the solar scientists to propose other mechanisms to accelerate the high speed solar wind, such as Alfvén or cyclotron waves (Cranmer 2002).

2 The Role of the Interplanetary Electric Field

Lemaire and Scherer (1971) developed a kinetic exospheric model where only the effects of the external forces are taken into account. Assuming Maxwellian VDFs for the solar particles in the corona, this model gave a bulk velocity increasing with the radial distance, with a profile quite similar to that of Parker's model (Lemaire and Pierrard 2001). These kinetic results are illustrated by the blue lines on Fig. 1.

The bottom left panel of Fig. 1 (blue line) illustrates the bulk speed of the solar wind electrons and protons that increases and reaches 320 km/s at 1 AU, assuming a temperature of 10^6 K and a density of 3×10^{10} m^{-3} at the exobase radial distance $r_0 = 6\ R_s$. Like in MHD models, higher bulk velocities can be obtained by assuming higher temperatures in the corona, but that seems unrealistic especially in the coronal holes where the observations of SoHo show a maximum of less than 1 MK at 1.15 R_s (David et al. 1998).

This simple exospheric model shows directly the physical processes implicated in the solar wind acceleration and especially the importance of the internal electric field in the acceleration of the solar wind. In such exospheric models, it becomes clear that the solar wind is accelerated outwards by an electrostatic potential difference established between the exobase r_0 and infinity. This electrostatic potential ensures that the flux of the protons

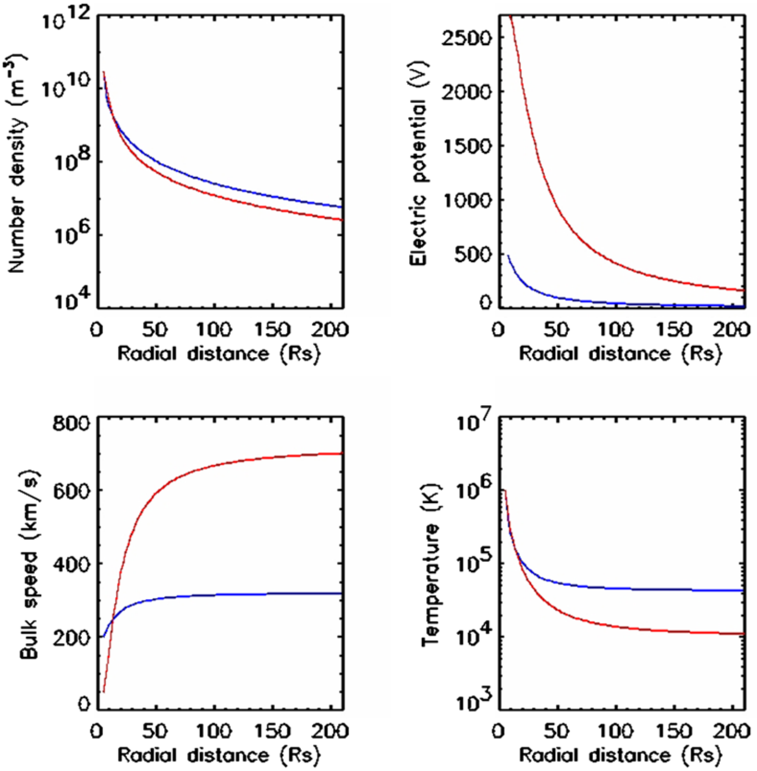


Fig. 1 Profiles of the number density, electrostatic potential, bulk speed and electron temperature for a Maxwellian VDF (*blue line*) and for a kappa VDF with $\kappa = 2$ (*red line*), with a coronal temperature of 10^6 K and a density of 3×10^{10} m^{-3} at $r_0 = 6\ R_s$. This figure is obtained with the Lorentzian model adapted for the solar wind (Pierrard and Lemaire 1996)

is everywhere equal to the electron flux, so that no net current is transported by the wind. The electrostatic potential difference is illustrated in the top right panel of Fig. 1 and reaches 500 V in this example (blue line).

Of course, this electric field **E** also exists in MHD models: it appears in the equations of momentum conservation:

For the ions, the steady state equation is:

$$n_i m_i u_i \frac{\partial u_i}{\partial r} + \frac{\partial p_i}{\partial r} = -n_i m_i g + Z_i n_i e E \tag{11}$$

and for the electrons:

$$n_e m_e u_e \frac{\partial u_e}{\partial r} + \frac{\partial p_e}{\partial r} = -n_e m_e g - n_e e E \tag{12}$$

where g is the gravitational acceleration and $Z_i e$ the charge of the ion species i.

Considering protons and electrons and adding these two equations to obtain the global equation of the plasma, this electric field disappears from the equation due to the opposite charges:

$$nmu \frac{\partial u}{\partial r} + \frac{\partial p}{\partial r} = -nmg \tag{13}$$

but the electric field is not equal to zero and ensures the equality of the bulk speed of the electrons and protons. Note that the E field can be obtained using these (11) and (12) and imposing same scale heights for electrons and protons.

3 The Effects of Suprathermal Electrons in the Solar Wind Acceleration

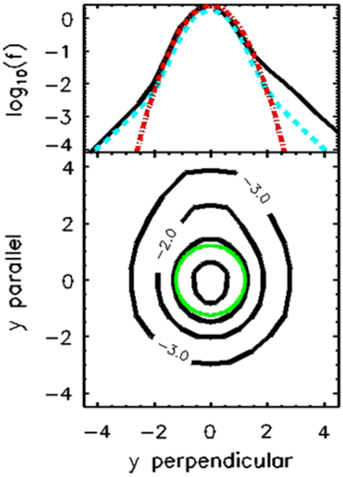
The observed velocity distribution functions of the particles contain useful information on the solar wind processes. Especially, particle velocity distribution functions of the solar wind particles show non-Maxwellian features that have to be taken into account in models.

The solar protons VDFs are characterized by an anisotropic core and a proton beam aligned with the magnetic field direction (Marsch et al. 1982). The solar wind electron VDFs are observed to possess non Maxwellian suprathermal tails decreasing as a power law of the velocity. A typical VDF observed by WIND at 1 AU is illustrated on Fig. 2. Such electron VDFs are characterized by a thermal core and a halo suprathermal population (Pierrard et al. 2001) that exists in the directions parallel and perpendicular to the magnetic field. They are also characterized by a strahl component aligned with the interplanetary magnetic field.

Such distributions with suprathermal tails are well fitted by the so-called kappa distributions (Pierrard and Lemaire 1996). The value of the index kappa determines the slope of the energy spectrum of the suprathermal electrons forming the tail of the VDF. In the limit $\kappa \to \infty$, the kappa function degenerates into a Maxwellian.

Electron VDFs measured by Ulysses have been fitted by kappa functions with small values of κ (Maksimovic et al. 1997a). These fits show a global anticorrelation between the solar wind bulk speed and the value of the parameter κ that supports the kinetic theoretical result that the suprathermal electrons influence the solar wind acceleration (Maksimovic et al. 1997b). Indeed, using the ion-exosphere model developed by Pierrard and Lemaire (1996), these authors showed that the presence of suprathermal electrons increases the electrostatic potential difference between the solar corona and the interplanetary space and thus increases the solar wind velocity.

Fig. 2 Typical velocity distribution function observed by the WIND satellite at 1 AU (215 R_S) for high speed solar wind electrons. *Bottom panel*: Isocontours in the plane of velocities (normalized to the thermal velocity) parallel and perpendicular to the interplanetary magnetic field. *Top panel*: Parallel (*solid black line*) and perpendicular (*dashed blue line*) cross section of the observed VDF. The *dashed-dotted red line* represents the Maxwellian distribution that well fits the core of observed VDF. (Adapted from Pierrard et al. 1999)



The importance of suprathermal electrons in the acceleration mechanism of the solar wind is illustrated on Fig. 1 by the red lines corresponding to the results obtained for a kappa VDF with $\kappa = 2$, using the same values for T_0, n_0 and r_0 as for the Maxwellian case illustrated by the blue lines. The electrostatic potential difference reaches more than 3000 V in this example and pushes the particles outside with large bulk velocities (700 km/s in this example), in good agreement with what is observed in the high speed solar wind. With larger values of κ as observed in the slow speed solar wind, the acceleration is moderated and leads to bulk velocities around 350–450 km/s for $\kappa > 5$.

The acceleration is especially large when it takes place at low radial distances, which explains why the high speed solar wind originates from the coronal holes where the number density (and thus the exobase) is lower than in other regions of the corona (Lamy et al. 2003). Zouganelis et al. (2004) demonstrated with a parametric study that this acceleration is a robust result produced by the presence of a sufficient number of suprathermal electrons and is valid also for other VDF with suprathermal tails than kappa functions.

There are no in-situ observations of the particles VDF at radial distances lower than the orbit of Mercury, so that it is not sure that these suprathermal electrons are present in the solar corona. But observations of electron suprathermal tails in the solar wind suggest their existence in the corona, since the electron mean free path in the solar wind is around 1 AU (Meyer-Vernet 2006). Moreover, the ion charge measurements stated by Ulysses were found to be consistent with coronal kappa VDF of electrons with kappa index ranging between 5 and 10 (Ko et al. 1996). Scudder (1994) showed that the excess of Doppler line widths can also be a consequence of non thermal distributions of absorbers and emitters. A kappa distribution is also consistent with mean electron spectra producing hard X-ray emission in some coronal sources (Kasparova and Karlicky 2009). The low coronal electron temperatures and high ion charge states can be reconciled if the coronal electron distribution function starts to develop a significant suprathermal halo already below 3 R_s (Esser and Edgar 2000).

Note that the presence of nonthermal kappa distributions would lead to the reinterpretation of solar observations implicitly assuming Maxwellian distributions. For instance, the influence of nonthermal kappa distributions on diagnostics of temperature obtained from the observations in EUV filters is investigated by Dudik et al. (2009). The equilibrium ionization fractions of N, O, Ne, Mg, S, Si, Ar, Ca, Fe and Ni were also calculated for Maxwellian and kappa VDF based on a balance of ionization and recombination processes for typical temperatures in astrophysical plasmas (Wannawichian et al. 2003). Low kappa values lead generally to a higher mean charge.

We have shown that the acceleration of the solar wind can be due to the presence of suprathermal electrons in the corona, but it remains to explain the reason of this presence (Pierrard and Lazar 2010 for a review). Resonant interaction with whistler waves in the solar corona and the solar wind was suggested by Vocks and Mann (2003) and Vocks et al. (2008) to explain the generation of suprathermal electrons. Introducing antisunward-propagating whistler waves into a kinetic model in order to provide diffusion, Vocks et al. (2005) have shown that the whistler waves are capable of influencing the solar wind electron VDFs significantly, leading to the formation of both the halo and strahl populations and a more isotropic distribution at higher energies.

Nevertheless, the presence of similar power law distributions in many different space plasmas suggests a universal mechanism for the creation of such suprathermal tails. Leubner (2002) shows that kappa-like distributions can result as a consequence of the entropy generalization in nonextensive Tsallis statistics (Tsallis 1995), physically related to the long range nature of the Coulomb potential, turbulence and intermittency (Leubner 2004; Treumann and Jaroschek 2008). The presence of suprathermal particles as observed in the VDF of magnetospheric particles has also interesting consequences concerning for instance the acceleration of the polar wind escaping from the planets (Pierrard 2009).

4 Electron Heat Flux

The expression of the heat flux for kappa VDF was calculated in Pierrard and Lemaire (1998). The heat flux increases when kappa is small, due to the presence of the suprathermal particles. This is illustrated in Fig. 3 showing in the last panel the heat flux profile obtained for different values of kappa. The other panels illustrate the profiles obtained for the other moments of the VDF.

Studying the heat flow carried by kappa distributions in the solar corona, Dorelli and Scudder (1999) demonstrated that a weak power law tail in the electron VDF can allow heat to flow up a radially directed temperature gradient. They generalized the Spitzer and Härm (1953) heat law to distributions with power laws and showed that the density gradient and gradients of the higher moments can also support a heat flux in this case. The heat flux reduces to the Spitzer-Härm expression depending on the temperature gradient only for local Maxwellian distributions.

This result was also confirmed for collisional regions by Landi and Pantellini (2001) who obtained the heat flux versus kappa in a slab of the solar corona from a kinetic simulation taking collisions into account. For kappa >5, the flux is close to the Spitzer-Harm classical collisional values while for smaller values of kappa, the heat flux strongly increases and changes of sign. If kappa is small enough, the fast wind can be suprathermally driven (Zouganelis et al. 2005). This shows the inadequacy of the classical heat conduction law in space plasmas and the importance to deal with non-Maxwellian velocity distribution such as kappa VDF in the kinetic theory (Meyer-Vernet 1999). The classical heat flow only holds in plasmas highly dominated by collisions.

5 The Role of the Coulomb Collisions

A neutral gas is dominated by collisions where the density scale height is larger than the mean free path (see for instance Pierrard 2003). Considering the same definition for the

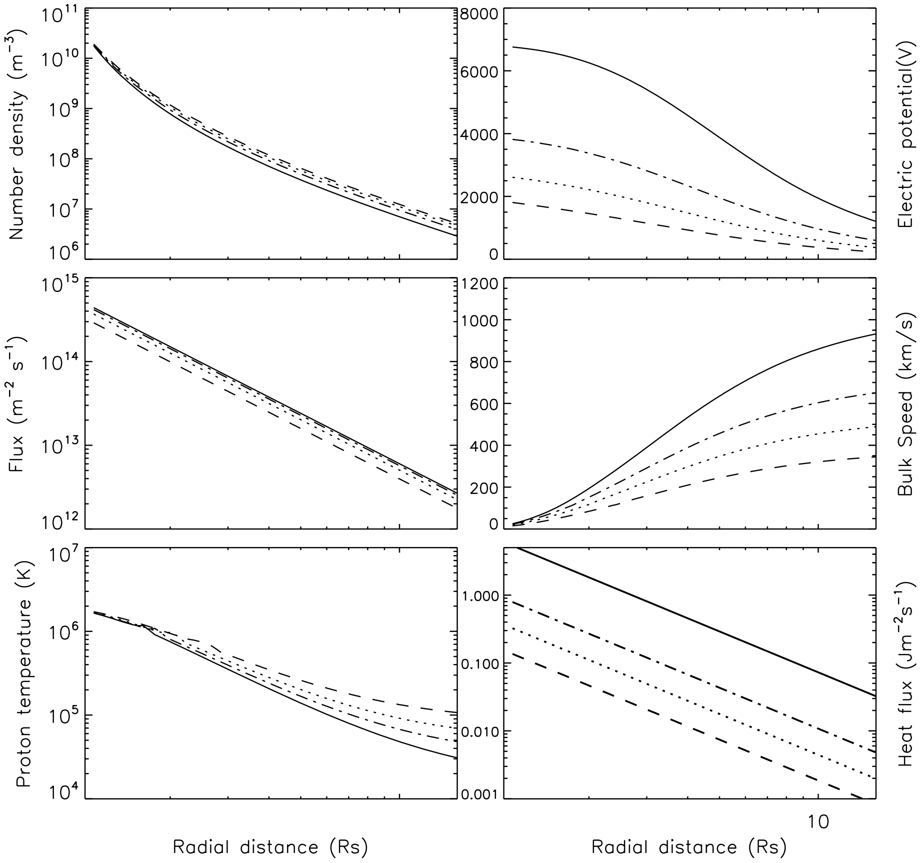


Fig. 3 Profiles of number density, electric potential, flux, bulk speed, proton temperature and electron heat flux from $r_0 = 1.1\ R_s$ up to 15 R_s obtained with an kinetic exospheric model of the solar wind with $T_e = 1.2 \times 10^6$ K and $T_p = 2 \times 10^6$ K for $\kappa = 2.1$ (*solid line*), $\kappa = 2.5$ (*dashed-dotted line*), $\kappa = 3$ (*dotted line*) and $\kappa = 4$ (*dashed line*). This figure is obtained with the model of Lamy et al. (2003)

exobase in plasmas, the solar wind and the corona are not dominated by collisions, since the mean free path is already larger than the density scale height at low radial distances (Pierrard and Lamy 2003; Meyer-Vernet 2006).

Even at very low altitudes, the plasma can not be considered as dominated by collisions, due to the long range properties of the Coulomb interaction. Indeed, since the particle free path increases as v^4 in a plasma, the suprathermal particles are non collisional even when thermal particles are submitted to many collisions. In the solar transition region, the corona and the wind, the heat flux is not classical (Shoub 1983). The VDF of the particles is not well represented by a Maxwellian VDF in such regions where strong gradients of temperature and of density are observed. The presence of nonthermal electrons in the solar transition of active regions was evidenced observationally by Si III line rations from SUMER (Pinfield et al. 1999).

The presence of suprathermal electrons in the corona has been confirmed theoretically in Pierrard et al. (1999) and Pierrard et al. (2001) by using a kinetic solar wind model based on the solution of the Fokker-Planck equation and including the effects of the Coulomb collisions. The Fokker-Planck equation was solved using a spectral method of expansion of the solution in orthogonal polynomials. This method was recently improved by the generation of polynomials based on the kappa function (Magnus and Pierrard 2008). Typical electron VDFs measured at 1 AU by WIND were used as boundary condition to determine the VDFs at lower altitudes. It was obtained that the suprathermal populations has to be present in the corona to exist at larger radial distances. The Coulomb collisions play an important role in the overall shaping of the distributions, as clearly established by comparison with purely exospheric distributions (Lemaire and Pierrard 2003). Nevertheless, the electron VDF obtained with the Fokker-Planck model is different from a simple local Maxwellian even in the solar corona. Even when Coulomb collisions are included, the solar wind electron VDF remains characterized by suprathermal tails that are so important for the acceleration mechanism described in this paper.

6 The Minor Ions

Due to their different masses and charges, the minor ions of the Sun can reveal very interesting processes playing a role in the heating of the corona and in the solar wind acceleration (von Steiger et al. 1995). It is interesting to note that solar wind ion VDF are also observed to be characterized by power law suprathermal tails. For instance, ^{20}Ne, ^{16}O and ^{4}He distribution functions measured by WIND at 1 AU and averaged over several days have been fitted by kappa functions with low values of kappa (between 2.4 and 4.7) (Collier et al. 1996). Moreover, in the high speed solar wind, it is observed that the ion temperatures are higher than the temperature of the protons and more than proportional to their mass (Cranmer 2002).

To assume that the suprathermal ions exist at low radial distances in the solar transition region leads again to interesting results concerning the coronal heating (Scudder 1992a, 1992b). Indeed, by the mechanism of velocity filtration, the temperature of the ions increases more than proportionally to their mass to reach high values in the solar corona, in good agreement with SoHo observations (Pierrard et al. 2004). The acceleration of the solar wind heavy ions, investigated in Pierrard and Lamy (2003), shows that light ions with a high degree of ionization can reach velocities larger than that of the protons if their temperatures are sufficiently high in the corona. The Helium ions are often observed to have bulk velocities larger than that of the protons by a few percent (Ogilvie et al. 1982).

7 Conclusion

The kinetic approach has to be used in the solar wind where the VDF of the particles departs from simple Maxwellians. In the kinetic approach the solar wind particles are accelerated by the interplanetary electric field ensuring the equality of the electron and proton fluxes (Lemaire and Scherer 1971; Parker 2010). This electric field is increased by the simple presence of suprathermal electrons in the solar corona, leading to solar wind acceleration to high bulk velocities as observed in the high speed solar wind (Maksimovic et al. 1997b). The presence of these suprathermal electrons modifies also the heat flux expression that is then not well represented by Spitzer-Härm in the solar corona (Dorelli and Scudder 1999). The solar atmosphere is not dominated by collisions so that the particle VDFs are not Maxwellians and the heat transport is not given by the classical theory.

The presence of suprathermal electrons is ubiquitous in the solar wind at 1 AU and suggested in the solar corona by several observational features related to the ions charge states and the solar wind acceleration. Future in-situ observations closer to the Sun should verify their presence at low radial distances.

To reproduce the heating of the corona and the high speed solar wind, numerous theories have been developed that require Alfven or cyclotron waves. A simpler alternative is the presence of suprathermal electrons in the low corona. The presence of these suprathermal electrons can be explained by waves as well (Vocks et al. 2005), but their generalized presence in many space plasmas like the magnetospheres of the planets suggests a universal mechanism related to the long range properties of the Coulomb collision term (Leubner 2002; Treumann and Jaroschek 2008).

Waves are present in the sea, but they are not the cause of the tides. Waves are also not the main cause of solar wind acceleration (Parker 1958), but they can play a role to explain some VDF characteristics (Cranmer 2002; Pierrard and Voitenko 2010). The high speed solar wind and the heating of the corona can be suprathermally driven and this simple assumption would explain many observations made in the solar corona, in the solar wind and in stellar winds. Of course, the presence of the suprathermal electrons can be due to waves as it was shown from the whistler wave turbulence properties (Vocks et al. 2005, 2008; Pierrard et al. 2010). The properties of the statistical system leading to kappa distributions rely indeed on properties of fluctuations such as turbulence and intermittency. Note nevertheless that other mechanisms have also been invoked to generate such suprathermal particles universally observed in space plasmas, as recently reviewed in Pierrard and Lazar (2010).

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