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Kappa Distributions: Theory and Applications in Space Plasmas

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Abstract The plasma particle velocity distributions observed in the solar wind generally show enhanced (non-Maxwellian) suprathermal tails, decreasing as a power law of the velocity and well described by the family of Kappa distribution functions. The presence of non-thermal populations at different altitudes in space plasmas suggests a universal mechanism for their creation and important consequences concerning plasma fluctuations, the resonant and nonresonant wave – particle acceleration and plasma heating. These effects are well described by the kinetic approaches where no closure requires the distributions to be nearly Maxwellian. This paper summarizes and analyzes the various theories proposed for the Kappa distributions and their valuable applications in coronal and space plasmas.

Keywords (Sun:) Corona · Solar wind · Plasmas · Kappa distributions · Kinetic models · Turbulence · Instabilities

1. Introduction

Non-thermal particle distributions are ubiquitous in the solar-wind and near-Earth space plasma, their presence having frequently been confirmed by interplanetary missions (Mont-

This article is an invited review.

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gomery, Bame, and Hundhause, 1968; Feldman *et al.*, 1975; Pilipp *et al.*, 1987; Maksimovic, Pierrard, and Riley, 1997; Zouganelis, 2008). Such distributions represent suprathermal deviations from the Maxwellian equilibrium and are expected to exist in any low-density plasma in the Universe, where binary collisions of charges are sufficiently rare.

The suprathermal populations are well parameterized by the so-called Kappa (κ) or the generalized Lorentzian velocity-distribution functions (VDFs), as shown for the first time by Vasyliunas (1968). Kappa-distribution functions have high-energy tails deviating from a Maxwellian and decreasing as a power law in particle speed:

$$f_i^\kappa(r,v) = \frac{n_i}{2\pi(\kappa w_{\kappa i}^2)^{3/2}} \frac{\Gamma(\kappa+1)}{\Gamma(\kappa-1/2)\Gamma(3/2)} \left(1+\frac{v^2}{\kappa w_{\kappa i}^2}\right)^{-(\kappa+1)}, \tag{1}$$

where $w_{\kappa i} = \sqrt{(2\kappa-3)kT_i/\kappa m_i}$ is the thermal velocity, m_i the mass of the particles of species i, n_i their number density, T_i their equivalent temperature, v the velocity of the particles, and $\Gamma(x)$ is the Gamma function. The spectral index [κ] must take sufficiently large values $\kappa > 3/2$ to avoid the critical value $\kappa_c = 3/2$, where the distribution function (1) collapses and the equivalent temperature is not defined. The value of the index κ determines the slope of the energy spectrum of the suprathermal particles forming the tail of the VDF, as illustrated in Figure 1. In the limit $\kappa \to \infty$, the Kappa function degenerates into a Maxwellian. Note also that different mathematical definitions of Kappa distributions are commonly used and various authors characterize the power-law nature of suprathermal tails in different ways.

Here some comments are necessary because the conventional Kappa-distribution function (1) used to fit and describe high-energy tails incorporates macroscopic parameters defined by the lowest moments of the distribution function. We follow some suggestive explanations from Hellberg *et al.* (2009), and first recall that $w_{\kappa i}$ in Equation (1) was originally stated by Vasyliunas (1968) to be the most probable particle speed. Thus, a characteristic (nonrelativistic) kinetic energy [$W = mw_{\kappa i}^2/2$] can be associated with the most probable speed, and by considering the second moment of the distribution function $U = \int d\mathbf{v} f_i^\kappa mv^2/2$, the mean energy per particle reads $W_m \equiv U/N = W(3\kappa/2)/(\kappa - 3/2)$. Later, Formisano *et al.* (1973) have introduced a plasma temperature related to the mean energy per particle [$k_B T = (2/3)W_m = mw_{\kappa i}^2\kappa/(2\kappa-3)$], which is exactly the equivalent temperature proposed by Leubner (1982) and Chateau and Meyer-Vernet (1991) by relation to the average energy $k_B T = m\langle v^2\rangle/3$. On this basis, it was also shown that, in a Kappa-distributed plasma, the Debye length is less than in a Maxwellian plasma: $\lambda_\kappa = \lambda(2\kappa-3)/(2\kappa-1)$. Such a temperature definition, making use of equipartition of energy, although appropriate for an equilibrium Maxwellian distribution, is not strictly valid for a Kappa distribution, but there are practical advantages to using such an equivalent kinetic temperature, which can be a useful concept already accepted in practice for non-Maxwellian distributions (see Hellberg *et al.*, 2009 and references therein).

Furthermore, generalizations of thermodynamics based on the Tsallis nonextensive entropy formalism (Tsallis, 1995) have been used for several decades (see Livadiotis and McComas, 2009 and references therein). The family of Kappa distributions result from a new generalized Lorentzian statistical mechanics formulated for a collisionless plasma far from thermal (Boltzmann–Maxwell) equilibrium but containing fully developed turbulence in quasistationary equilibrium (Treumann, 1999a, 1999b; Leubner, 2002; Fisk and Gloeckler, 2006; Gloeckler and Fisk, 2006; Treumann and Jaroschek, 2008). Thus, in phase space, the Kappa-type power-law distributions describe marginally stable Gibbsian equilibria, and the parameter κ controls the strength of the plasma particle correlation in the turbulent-field fluctuations (Hasegawa, Mima, and Duong-van, 1985;

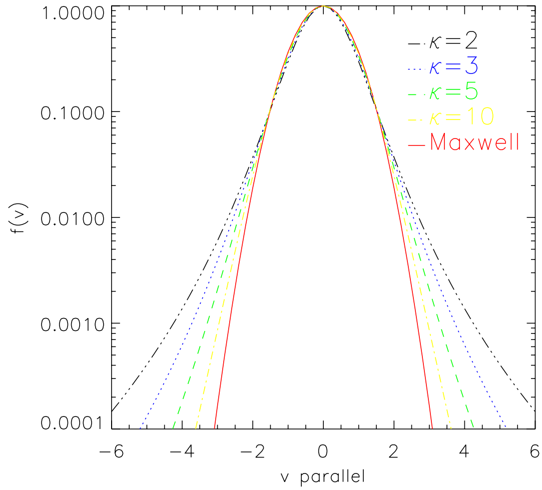

Figure 1 The Kappa velocity-distribution function for different values of the κ parameter.

Table 1 Comparison of different analytical expressions for a Maxwellian and a Kappa VDF.

Parameter	Maxwellian	Kappa
Number density	$n(r) = n_0 \exp(-\frac{R(r)}{w^2})$	$n(r) = n_0(1 + \frac{R(r)}{\kappa w^2})^{-\kappa+1/2}$
Temperature	$T(r) = T_0$	$T(r) = T_0 \frac{\kappa}{\kappa-3/2}(1 + \frac{R(r)}{\kappa w^2})$
Escaping flux	$F(r) = \frac{n_0 w(1+v_e^2/w^2)}{2\pi^{1/2}} \exp(-\frac{v_e^2}{w^2})$	$F(r) = \frac{n_0 A_k w(1+v_e^2/w^2)}{4(\kappa-1)\kappa^{1/2}[1+v_e^2/(\kappa w^2)]^\kappa}$

Treumann and Jaroschek, 2008). In such systems, the temperature is redefined on the basis of a superadditive (superextensive) entropy, because the interdependence of subsystems contributes an extra amount to entropy (Treumann and Jaroschek, 2008).

Such Kappa functions give the best fit to the observed velocity-distribution functions, using only three parameters (the number density n, the temperature T, and the parameter κ characterizing the suprathermal tails). A sum of two Maxwellians can also represent distributions with enhanced suprathermal tails, but they need four parameters (n_1, T_1 and n_2, T_2 representing the number density and temperatures of the two populations) and generally give less good fits than Kappa functions (Zouganelis *et al.*, 2004).

Considering the suprathermal particles has important consequences for space plasmas. For instance, an isotropic Kappa distribution (instead of a Maxwellian) in a planetary or stellar exosphere leads to a number density $[n(r)]$ decreasing as a power law (instead of exponentially) with the radial distance $[r]$ and a temperature $[T]$ increasing with the radial distance (instead of being constant), as shown by the expressions given in Table 1. $R(r)$ is the potential energy containing the effects of the gravitation, the electrostatic and centrifugal force. v_e is the escape velocity and A_k is the fraction of Gamma functions appearing in the Kappa VDF. Considering particles escaping as planetary or stellar wind, the Kappa distribution yields a higher flux than a Maxwellian, since more suprathermal particles are able to escape.

This review is organized in the following fashion. Reports of measurements or indirect detections of Kappa distributions in our interplanetary space are reviewed in the next section. In Section 3, we identify the mechanisms made responsible for the occurrence of non-thermal populations in different environments. Representative theories and scenarios developed for Kappa-distributed plasmas are discussed in Section 4. In Section 5 we present a short overview of the dynamics and dispersion properties of Kappa distributions including the recent results on the stability of anisotropic plasmas and kinetic instabilities. The impact and favorable perspectives for these distributions are discussed in Section 6.

2. Detection of Kappa Distributions

Distributions with suprathermal tails have been observed in various space plasmas. Kappa distributions with $2 < \kappa < 6$ have been found to fit the observations and satellite data in the solar wind (Gloeckler *et al.*, 1992; Maksimovic, Pierrard, and Riley, 1997), the terrestrial magnetosphere (Gloeckler and Hamilton, 1987), the terrestrial plasmasheet (Bame *et al.*, 1967; Christon *et al.*, 1988, 1989; Kletzing, 2003), the magnetosheath (Formisano *et al.*, 1973), the radiation belts (Pierrard and Lemaire, 1996b; Xiao *et al.*, 2008b), the magnetosphere of other planets such as Mercury (Christon, 1987), the plasmasheet of Jupiter (Collier and Hamilton, 1995), the magnetosphere of Jupiter (Krimigis *et al.*, 1981; Mauk *et al.*, 2004), of Saturn (Krimigis *et al.*, 1983; Schippers *et al.*, 2008; Dialynas *et al.*, 2009), Uranus (Krimigis *et al.*, 1986), Neptune (Mauk *et al.*, 1991), and even on Titan (De la Haye *et al.*, 2007) and in the Io plasma torus as observed by *Ulysses* (Meyer-Vernet, Moncuquet, and Hoang, 1995), *Cassini* (Steffl, Bagenal, and Stewart, 2004), and the *Hubble Space Telescope* (Retherford, Moos, and Strobel, 2003).

In the solar wind, electron velocity distributions are characterized by a thermal core and a halo suprathermal population present in all directions (Pierrard, Maksimovic, and Lemaire, 2001b), as illustrated on Figure 2. These electron VDFs are also characterized by a strahl component aligned with the interplanetary magnetic field. Electron VDFs measured by *Ulysses* have been fitted with Kappa functions by Maksimovic, Pierrard, and Riley (1997). They show a global anticorrelation between the solar-wind bulk speed and the value of the parameter κ, which supports the kinetic theoretical result that the suprathermal electrons influence the solar-wind acceleration (Maksimovic, Pierrard, and Lemaire, 1997). The solar-wind particle VDFs observed by *Cluster* have also been fitted by the generalized Kappa function (Qureshi *et al.*, 2003). Radial evolution of non-thermal electron populations in the low-latitude solar wind with *Helios*, *Cluster*, and *Ulysses* observations shows that the relative number of strahl electrons is decreasing with radial distance, whereas the relative number of halo electrons is increasing (Stverak *et al.*, 2009). Observations of electron suprathermal tails in the solar wind suggest their existence in the solar corona, since the electron mean free path in the solar wind is around 1 AU. The ion-charge measurements found by *Ulysses* were found to be consistent with coronal Kappa VDFs of electrons with kappa index ranging between 5 and 10 (Ko *et al.*, 1996). Non-Maxwellian electron energy distributions were even suggested in the solar transition region from Si III line ratio from SUMER by Pinfield *et al.* (1999).

To be able to measure the suprathermal electron parameters in space plasmas, the quasi-thermal noise spectroscopy was implemented with Kappa distributions using *in-situ Ulysses*/URAP radio measurements in the solar wind (Zouganelis, 2008). This noise is produced by the quasi-thermal fluctuations of the electrons and by the Doppler-shifted thermal fluctuations of the ions. A sum of two Maxwellians has been used extensively, but the observations have shown that the electrons are better fitted by a Kappa-distribution function (Le Chat *et al.*, 2009).

Solar-wind ion (^{20}Ne, ^{16}O, and ^{4}He) distribution functions measured by *Wind* and averaged over several days have also been fitted by Kappa functions (Collier *et al.*, 1996). Low

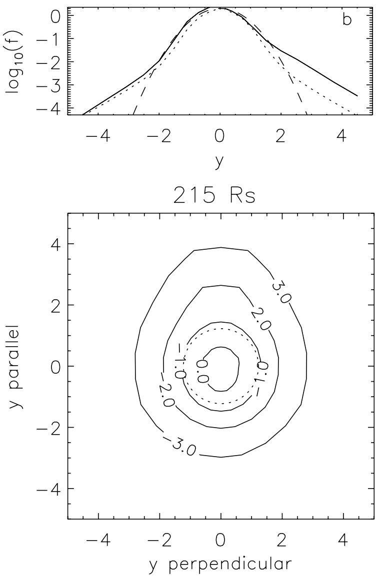

Figure 2 Electron velocity-distribution function observed by the *Wind* spacecraft at 1 AU ($215R_S$) in the high-speed solar wind. Bottom panel: Isocontours in the plane of velocities (normalized to the thermal velocity) parallel and perpendicluar to the interplanetary magnetic field. Top panel: Parallel (solid line) and perpendicular (dotted line) cross section of the observed VDF. The dashed line represents the Maxwellian distribution that fits well the core of the observed VDF (Pierrard, Maksimovic, and Lemaire, 1999).

values of κ (between 2.4 and 4.7) are obtained due to the presence of high suprathermal tails. Suprathermal solar-wind particles were also measured in H^+, He^{++}, and He^+ distribution functions during corotating interaction region (CIR) events observed by *Wind* at 1 AU (Chotoo *et al.*, 2000).

3. Generation of Kappa Distributions in Space Plasmas

Various mechanisms have been proposed to explain the origin of the suprathermal tails of the VDFs and occurrence of Kappa-like distributions in the solar wind, the corona, and other space plasmas. The first one was suggested by Scudder and Olbert (1979) who showed that the inhomogeneity due to the solar-wind expansion combined with the reduced Coulomb collisions undergone by the suprathermal ($E > 7k_BT$) electrons naturally give rise to non-thermal distributions.

Another mechanism was proposed by Hasegawa, Mima, and Duong-van (1985) who showed that a plasma immersed in a suprathermal radiation field suffers velocity-space diffusion which is enhanced by the photon-induced Coulomb-field fluctuations. This enhanced diffusion universally produces a power-law distribution.

Collier (1993) uses random-walk jumps in velocity space whose path lengths are governed by a power or Lévy flight-probability distribution to generate Kappa-like distribution functions. The adiabatic transport of suprathermal distributions modeled by Kappa functions is studied by Collier (1995). The same author shows that space plasmas are dynamic systems where the energy is not fixed, so that the maximum entropy should not be considered (Collier, 2004).

Treumann (2001) developed a kinetic theory to show that Kappa-like VDFs correspond to a particular thermodynamic equilibrium state (Treumann, 1999b; Treumann, Jaroschek, and Scholer, 2004). A new kinetic-theory Boltzmann-like collision term including correlations was proposed. In equilibrium (turbulent but stable state far from thermal equilibrium), it yields the one-particle distribution function in the form of a generalized Lorentzian resembling, but not being identical with, the Kappa distribution (Treumann, 1999a).

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 and Voros, 2005; Treumann and Jaroschek, 2008). The Kappa distribution is equivalent to the q distribution function obtained from the maximization of the Tsallis entropy. Systems subject to long-range interactions and correlations are fundamentally related to non-Maxwellian distributions (Leubner, 2008). Core – halo distribution functions are a natural equilibrium state in generalized thermostatistics (Leubner, 2004b). Fundamental issues concerning Kappa distributions in space plasmas and interplanetary proton distributions are emphasized in Leubner (2004a). Livadiotis and McComas (2009) also examined how Kappa distributions arise naturally from Tsallis statistical mechanics and provide a solid theoretical basis for describing complex systems.

The generation of suprathermal electrons by resonant interaction with whistler waves in the solar corona and wind was suggested by Vocks and Mann (2003) and Vocks, Mann, and Rausche (2008). Introducing antisunward-propagating whistler waves into a kinetic model in order to provide diffusion, their results show 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 (Vocks *et al.*, 2005).

In an ambient quasi-static magnetic field, plasma charges gain energy through the cyclotron resonance and the transit-time damping (magnetic Landau resonance) of the linear waves. This is the case of a high-frequency whistler mode that enhances the energy of electrons in the Earth’s foreshock (Ma and Summers, 1998), or that of MHD waves, which can accelerate both the electrons and the protons in solar flares (Miller, 1991, 1997), and in the inner magnetosphere (Summers and Ma, 2000).

When large-amplitude waves are present, nonlinear Landau damping may be responsible for the energization of plasma particles (Miller, 1991; Leubner, 2000; Shizgal, 2007). Stochastic acceleration of plasma particles in compressional turbulence seems to be consistent with the power-law spectra that occurred throughout the heliosheath downstream from the termination shock of the solar wind (Fisk and Gloeckler, 2006, 2007). A mechanism for the generation of an electron-distribution function with suprathermal tails in the upper regions of the solar atmosphere in the presence of collisional damping was suggested by Viñas, Wong, and Klimas (2000) as due to finite-amplitude, low-frequency, obliquely propagating electromagnetic waves. The non-thermal features of the VDFs can also result from superdiffusion processes (Treumann, 1997), and may be due to heat flows or the presence of the temperature anisotropies (Leubner and Viñas, 1986).

In the same spirit, Ma and Summers (1999) considered the steady-state solution of the Fokker – Planck (FP) equation and obtained a Kappa distribution for a quasi-linear wave – particle diffusion coefficient that varies inversely with the particle speed for velocities larger than the thermal speed. Shizgal (2007) used the same FP equation to study the relative strengths of the wave – particle interactions and Coulomb collisions. The formation of high-energy tails in the electron VDFs was also investigated with a FP model by Lie-Svendsen, Hansteen, and Leer (1997).

Note that a one-dimensional, electrostatic Vlasov model has been proposed for the generation of suprathermal electron tails in solar-wind conditions (Califano and Mangeney, 2008). The possible development of a Kappa velocity distribution was also illustrated by Hau and Fu (2007) for the problem of low-frequency waves and instabilities in uniform magnetized plasmas with a bi-Maxwellian distribution.

Very different mechanisms have thus been invoked to explain the physical origin of the Kappa distributions. Whatever the mechanisms of the formation of suprathermal tails, the Kappa function is a useful mathematical tool to generalize the velocity distributions to the observed power-law functions, the particular Maxwellian VDF corresponding to the specific value of $\kappa \to \infty$.

4. Theories Based on the Existence of Kappa Distributions

4.1. Stellar Coronae

Scudder (1992a, 1992b) showed the consequences of a postulated non-thermal distribution in stellar atmospheres and especially the effect of the velocity filtration: the ratio of suprathermal particles over thermal ones increases as a function of altitude in an attraction field. The anticorrelation between the temperature and the density of the plasma leads to this natural explanation of velocity filtration for the heating of the corona, without depositing wave or magnetic-field energy. Scudder (1992b) determined also the value of the kappa parameter for different groups of stars. Scudder (1994) showed that the excess Doppler line widths may also be a consequence of non-thermal distributions of absorbers and emitters. The excess brightness of the hotter lines can satisfactorily be accounted for by a two-Maxwellian electron-distribution function (Ralchenko, Feldman, and Doschek, 2007) and should also maybe accounted for by a Kappa distribution. Note that many solar observations implicitly assume that the velocity distributions are Maxwellian in their proper frame, so that the presence of suprathermal tails should lead to the reinterpretation of many observations. The influence of the Kappa distribution on the ionization equilibrium, excitation equilibrium, or line intensities of the ions observed in the transition and coronal spectrum has been studied by Anderson, Raymond, and van Ballegooijen (1996) and Dzifcakova (2006). These authors show that the line intensities can differ significantly from those obtained under the assumption of Maxwellian distributions. EUV-filter responses to plasma emission of TRACE for the non-thermal Kappa distributions have been analyzed by Dudik *et al.* (2009): they are more broadly dependent on the temperature, and their maxima are flatter than for Maxwellians. The positions of the maxima may also be shifted.

The mechanism of velocity filtration in the solar corona has been proposed to explain the high-energy electrons at higher altitudes in the solar wind (Scudder, 1992a, 1992b). Velocity filtration was also applied to heavy ions in the corona to explain their temperatures being more than proportional to their mass observed in the high-speed solar wind (Pierrard and Lamy, 2003).

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. This result was also confirmed by Landi and Pantellini (2001) who obtained the heat flux *versus* κ 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 κ, the heat flux strongly increases and changes of sign! If κ 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 a non-Maxwellian velocity distribution such as a Kappa VDF (Meyer-Vernet, 1999, 2007).

Note that the Kappa distribution is also consistent with mean electron spectra producing hard X-ray emission in some coronal sources (Kasparova and Karlicky, 2009). Moreover, 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 $3R_s$ (Esser and Edgar, 2000). Effects of a Kappa-distribution function of electrons on incoherent scatter spectra were studied by Saito *et al.* (2000). The equilibrium ionization fractions of N, O, Ne, Mg, S, Si, Ar, Ca, Fe, and Ni were calculated for Maxwellian and Kappa VDFs based on a balance of ionization and recombination processes (Wannawichian, Ruffolo, and Kartavykh, 2003) for typical temperatures in astrophysical plasmas. Low κ values lead generally to a higher mean charge.

The Coulomb-focusing effects on the bremsstrahlung spectrum are investigated in anisotropic bi-Lorentzian distribution plasmas in Kim, Song, and Jung (2004). Plasma-screening effects on elastic electron–ion collision processes in a Lorentzian (Kappa)-distribution plasma were analyzed in Jung and Hong (2000).

4.2. Solar Wind

Pierrard and Lemaire (1996a) developed a kinetic model of the ion-exospheres based on the Kappa VDF. The heat flux was specified in Pierrard and Lemaire (1998). Their model has been applied to the solar wind by Maksimovic, Pierrard, and Lemaire (1997) and predicts the high-speed solar-wind velocities with reasonable temperatures in the corona and without additional acceleration mechanism. Indeed, the presence of suprathermal electrons increases the electrostatic potential difference between the solar corona and interplanetary space and accelerates the solar wind. The collisionless or weakly collisional models in the corona (Scudder, 1992b; Maksimovic, Pierrard, and Lemaire, 1997; Zouganelis *et al.*, 2005), all using VDFs with a suprathermal tail, are able to reproduce the high-speed streams of the fast solar wind emitted out of coronal regions where the plasma temperature is smaller, as well as the low-speed solar wind originating in the hotter equatorial regions of the solar corona.

The exospheric Lorentzian (or Kappa) model was extended to non-monotonic potential energy for the protons (Lamy *et al.*, 2003a) and shows that the acceleration is especially large when it takes place at low radial distances in the coronal holes where the number density is lower than in other regions of the corona, as illustrated on Figure 3. In a parametric study Zouganelis *et al.* (2004) have shown that this acceleration is a robust result produced by the presence of a sufficient number of suprathermal electrons and is valid also for other VDFs with suprathermal tails than Kappa.

The acceleration of the solar-wind heavy ions is investigated in Pierrard, Lamy, and Lemaire (2004): due to their different masses and charges, the minor ions reach different velocities. Even if their mass-to-charge ratio is always larger than that of the protons, they can be accelerated to velocities larger than that of the protons if their temperatures are sufficiently high in the corona.

Adding the effects of the Coulomb collisions, a kinetic solar-wind model based on the solution of the Fokker–Planck equation was developed (Pierrard, Maksimovic, and Lemaire, 1999, 2001a). Typical electron VDFs measured at 1 AU by *Wind* have been used as a boundary condition to determine the VDFs at lower altitudes and it was proved that, for several solar radii, the suprathermal populations must be present in the corona as well (Pierrard, Maksimovic, and Lemaire, 1999). Indeed, since the particle free path increases as v^4 in a plasma due to the properties of Coulomb collisions, the suprathermal particles are non-collisional even when thermal particles are subjected to collisions. High-energy tails can develop for Knudsen numbers (*i.e.* ratio of mean free path to scale height) as low as 10^{-3} (Shoub, 1983). Marsch and Livi (1985) have studied the collisional relaxation process and

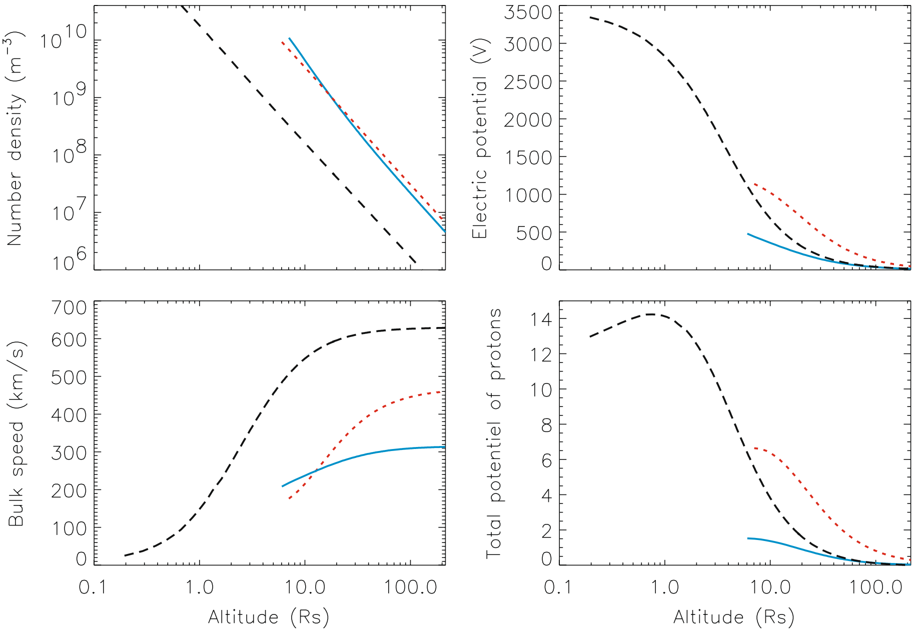

Figure 3 Number density, electrostatic potential, bulk speed, and potential of protons for different solutions of the Kappa kinetic model of the solar wind. The lowest blue velocity curve ($u = 320$ km s^{-1} at $215R_\mathrm{S}$) in the bottom left panel corresponds to a Maxwellian model with a starting radial distance (called exobase) at $r_0 = 6R_\mathrm{S}$. The middle red line ($u = 460$ km s^{-1} at $215R_\mathrm{S}$) corresponds to a Kappa VDF with $\kappa = 3$ and $r_0 = 6R_\mathrm{S}$. The upper black line ($u = 640$ km s^{-1} at $215R_\mathrm{S}$) corresponds to a Kappa VDF for $\kappa = 3$ with an exobase at $r_0 = 1.2R_\mathrm{S}$. [Adapted from Lamy *et al.* (2003b).]

the associated rates (diffusion and friction) for a non-thermal solar wind with Kappa VDFs. The Fokker – Planck model (Pierrard, Maksimovic, and Lemaire, 2001a) also illustrated the transformation of the VDF of the electrons in the transition region between the collision-dominated region in the corona and the collisionless region at larger radial distances. The VDFs became more and more anisotropic in the transition region. Contrary to exospheric models that are analytic, these collisional kinetic models are solved numerically using a spectral method of expansion of the solution in orthogonal polynomials. This expansion converges faster for suprathermal plasmas by using polynomials based on the Kappa function weight developed by Magnus and Pierrard (2008).

As a result of the low collision rates in the interplanetary plasma, the electrons and the ions develop temperature anisotropies and their VDFs become skewed and develop tails and heat fluxes along the ambient magnetic field (Marsch *et al.*, 1982; Pilipp *et al.*, 1987; Salem *et al.*, 2003; Stverak *et al.*, 2008). Moreover, field-aligned fluxes of (suprathermal) particles can be encountered at any altitude in the solar wind (Pilipp *et al.*, 1990), but they become prominent in energetic shocks, like the coronal mass ejections or the fast solar wind at the planetary bow shock, giving rise to counterstreaming plasma events (Feldman *et al.*, 1974; Gosling *et al.*, 1993; Steinberg *et al.*, 2005; Gloeckler and Fisk, 2006). The same mechanisms mentioned above can induce anisotropic non-thermal VDFs in counterstreaming plasmas, and such complex plasmas can hold an important amount of free energy that makes them unstable to the excitation of waves and instabilities.

Fainberg *et al.* (1996) suggested that the non-thermal electrons can contribute as much as 50% of the total electron pressure within magnetic clouds. Using this hypothesis, Nieves-Chinchilla and Viñas (2008) have assumed two populations of electrons in magnetic clouds: a core Maxwellian and a halo Kappa-like distribution. They found that κ values exhibit either minor differences or, for some events, may be greater inside than outside the magnetic clouds.

Observations from *Voyager* indicate that ions in the outer heliosphere are well described by Kappa functions (Decker *et al.*, 2005). The effects of a Kappa distribution in the heliosheath on the global heliosphere and energetic neutral atoms (ENA) flux have been studied in Heerikhuisen *et al.* (2008). The use of a Kappa, as opposed to a Maxwellian, gives rise to greatly increased ENA fluxes above 1 keV, while medium-energy fluxes are somewhat reduced. The effect of a Kappa distribution on the global interaction between the solar wind and the local interstellar medium (LISM) is generally an increase in energy transport from the heliosphere into the LISM, due to the modified profile of the ENA's energies. This results in a motion of the termination shock (by 4 AU), of the heliopause (by 9 AU) and of the bow shock (25 AU) farther out, in the nose direction.

4.3. Earth's Exosphere

The Kappa model of the ion-exosphere (Pierrard and Lemaire, 1996b) has been used to study different plasma regions in the magnetosphere of the Earth. Pierrard (1996) and Pierrard, Khazanov, and Lemaire (2007) obtained new current – voltage relationships in auroral regions when suprathermal particles were assumed to be present with Lorentzian and bi-Lorentzian distributions. Field-aligned conductance values were also estimated from Maxwellian and Kappa distributions in quiet and disturbed events using Freja electron data (Olsson and Janhunen, 1998).

Introducing a Kappa model appears to resolve the discrepancy between calculations and observations of resonant plasma echoes and emissions used for *in-situ* measuring the local electron density and the magnetic-field strength in the magnetospheric environments (Viñas, Mace, and Benson, 2005; Decker *et al.*, 1995).

The three-dimensional plasmasphere has been modeled using Kappa velocity-distribution functions for the particles (Pierrard and Stegen, 2008): this physical dynamic model of the plasmasphere gives the position of the plasmapause and the number density of the particles inside and outside of the plasma sphere. The effects of suprathermal particles on the temperature in the terrestrial plasmasphere were illustrated using Kappa functions by Pierrard and Lemaire (2001).

The terrestrial polar wind is, in some way, similar to the escape of the solar wind: similar effects of suprathermal particles appear and lead to an increase of the escaping flux (Lemaire and Pierrard, 2001; Tam, Chang, and Pierrard, 2007). Along open magnetic-field lines, the wind speed is increased by the presence of suprathermal particles. A Monte Carlo simulation developed by Barghouthi *et al.* (2001) shows the transformation of the H^+ polar-wind velocity distributions with Kappa suprathermal tails in the collisional transition region.

4.4. Planetary Exospheres

Meyer-Vernet (2001) emphasized the importance of not being Maxwellian for the large-scale structure of planetary environments. For bound structures shaped along magnetic-field lines, the temperature increases with the distance, in contrast to classical isothermal equilibrium (see Table 1). The rise in temperature as the density falls is a generic property of distributions with suprathermal tails, as shown in Meyer-Vernet, Moncuquet, and Hoang (1995) and Moncuquet, Bagenal, and Meyer-Vernet (2002) to explain the temperature inversion in the Io torus.

The ion-exosphere Kappa model (Pierrard and Lemaire, 1996a) has been adapted to the Saturnian plasmasphere (Moore and Mendillo, 2005). The κ index gives an additional parameter to fit observations from *Cassini*. The polar wind and plasmasphere of Jupiter and Saturn were also recently modeled with Kappa functions (Pierrard, 2009): the suprathermal particles significantly increase the escape flux from these giant planets, so that the ionosphere may become an important source for their inner magnetosphere.

Spacecraft-charging environments at the Earth, Jupiter, and Saturn were also obtained by Garrett and Hoffman (2000) using Kappa distributions for the warm electrons and protons.

5. Dispersion Properties and Stability of Kappa Distributions

In many circumstances, the wave – particle interactions can be responsible for establishing non-Maxwellian particle distribution functions with an enhanced high-energy tail and shoulder in the profile of the distribution function. In turn, the general plasma dynamics and dispersion properties are also altered by the presence of non-thermal populations. Thus, the waves and instabilities in Kappa-distributed plasmas, where collisions are sufficiently rare, are investigated using kinetic approaches based on the Vlasov – Maxwell equations.

5.1. Vlasov – Maxwell Kinetics. Dielectric Tensor

Using a kinetic approach, Summers, Xue, and Thorne (1994) have calculated the dielectric tensor for the linear waves propagating at an arbitrary angle to a uniform magnetic field in a hot plasma with particles modeled by a Kappa-distribution function. Despite the fact that the elements of this tensor take complicated integral forms, this paper is of reference for the theory of waves in Kappa-distributed plasmas. This dielectric tensor can be applied for analyzing the plasma modes as well as the kinetic instabilities in a very general context, limited only by the assumptions of linear plasma theory. The analytical dispersion relations derived previously (Thorne and Summers, 1986) in terms of the modified Bessel functions of the lowest order I_0, I_1, K_0, and K_1 (which are tabulated) were restricted to weak damping or growth of plasma waves by resonant interactions with plasma particles.

The approach developed by Summers, Xue, and Thorne (1994) is also restricted to the distributions functions which are even functions of the parallel velocity of particles [$v_\parallel$ (where parallel or perpendicular directions are taken with respect to the stationary magnetic field)], and this is what the authors called a usual condition in practice. This condition fails only in some extreme situations (Summers, Xue, and Thorne, 1994) such as, for instance, the asymmetric-beam plasma structures developing in astrophysical jets or more violent shocks. These cases can however be approached distinctively in the limits of waves propagating along or perpendicular to the ambient magnetic field (Lazar *et al.*, 2008, 2009; Lazar and Poedts, 2009).

5.2. The Modified Plasma Dispersion Function

Early dispersion studies have indeed described the simple unmagnetized plasma modes and the field-aligned waves in the presence of an ambient magnetic field (Leubner, 1983; Summers and Thorne, 1991). Let us first recall the most important analytical changes introduced by the power-law distributions of plasma particles.

Kinetic theory of an equilibrium Maxwellian plasma naturally produces a dispersion approach based upon the well-known Fried and Conte plasma dispersion function (Fried and Conte, 1961),

$$Z(f) = \frac{1}{\pi^{1/2}} \int_{-\infty}^{\infty} \mathrm{d}x \frac{\exp(-x^2)}{x - f}, \qquad f = \frac{\omega}{k}\sqrt{\frac{m}{2k_{\mathrm{B}}T}}, \quad \mathrm{Im}(f) > 0. \tag{2}$$

For a non-Maxwellian plasma characterized by the Kappa-distribution function (1), Summers and Thorne (1991) have derived a modified plasma dispersion function

$$Z_\kappa(f) = \frac{1}{\pi^{1/2}\kappa^{1/2}} \frac{\Gamma(\kappa)}{\Gamma(\kappa - \frac{1}{2})} \int_{-\infty}^{+\infty} \mathrm{d}x \frac{(1 + x^2/\kappa)^{-(\kappa+1)}}{x - f}, \quad \mathrm{Im}(f) > 0, \tag{3}$$

where the spectral index [κ] was first restricted to positive integers $\kappa > 1.5$. This new dispersion function has been ingenuously generalized to arbitrary real $\kappa > 1.5$ by Mace and Hellberg (1995) also showing that it is proportional to the Gauss hypergeometric function, ${}_2F_1$. Extensive characterizations for this Kappa dispersion function have been made by Summers and Thorne (1991), Mace and Hellberg (1995), Mace (2003), Valentini and D'Agosta (2007), and Mace and Hellberg (2009). Furthermore, for a (space) plasma immersed in a stationary magnetic field, which determines a preferred direction for the acceleration and motion of electrons and ions, Hellberg and Mace (2002) have introduced a hybrid Kappa–Maxwellian distribution function, a one-dimensional Kappa along the magnetic-field lines and a Maxwellian perpendicular to this direction. The new dispersion function [$Z_{\kappa\mathrm{M}}$] obtained for this anisotropic plasma differs from Z_κ in (3) in the power to which the term $(1 + x^2/k)^{-1}$ is raised: in the isotropic case it is $\kappa + 1$, while in the one-dimensional case it is κ. The relation between these two integral functions takes two forms (Hellberg and Mace, 2002; Lazar, Schlickeiser, and Shukla, 2008):

$$\begin{aligned} Z_{\kappa\mathrm{M}}(f) &= \frac{(\kappa - 1)^{3/2}}{(\kappa - 3/2)\kappa^{1/2}} Z_{\kappa-1}\left[\left(\frac{\kappa - 1}{\kappa}\right)^{1/2} f\right] \\ &= \left(1 + \frac{f^2}{\kappa}\right) Z_\kappa(f) + \frac{f}{\kappa}\left(1 - \frac{1}{2\kappa}\right), \end{aligned} \tag{4}$$

and both the $Z_{\kappa\mathrm{M}}(f)$ and $Z_\kappa(f)$ function approaches the Maxwellian dispersion function $Z(f)$ from (2) in the limit of $\kappa \to \infty$.

5.3. Isotropic Kappa Distributions

The effect of an isotropic Kappa population on plasma modes has been described by the first dispersion studies already reviewed by Hellberg, Mace, and Verheest (2000, 2005).

5.3.1. Unmagnetized Plasma

The fluctuations are, in general, enhanced in low-κ plasmas, and the electromagnetic and electrostatic dispersion relations show a significant dependence on the spectral index κ (Thorne and Summers, 1991; Summers and Thorne, 1992; Mace and Hellberg, 1995; Mace, Hellberg, and Treumann, 1998).

For Langmuir oscillations, Landau damping in a hot, isotropic, unmagnetized plasma is controlled by the spectral index, while for ion-acoustic waves Landau damping is more sensitive to the ion temperature than the spectral index (Qureshi, Shi, and Ma, 2006). Thus, Landau-damping growth rates of long wavelengths Langmuir modes become much larger for a Lorentzian (Kappa) plasma (Thorne and Summers, 1991), limiting the existence of the (weakly damped) Langmuir waves in space plasmas with Kappa distributions to a narrow band just above the electron plasma frequency. The significant increase of spatial Landau damping by small-κ electrons is also demonstrated for spatially damped plasma waves generated by a planar grid electrode with an applied time harmonic potential (Podesta, 2005). Hybrid models of Maxwellian plasmas partially populated by hot κ components can provide better fits to the observations and experiments than the simple uniform Maxwellian (Hellberg *et al.*, 2000; Mace, Amery, and Hellberg, 1999).

The relativistic effects on dispersion and Landau damping of Langmuir waves in a relativistic Kappa-distributed plasma have been studied by Podesta (2008). The relativistic dispersion relations derived have been used to compute the damping rates and phase speeds for plasma waves in the solar wind near the Earth's orbit. It was found to be a good match for the electron velocities in the superhalo with the phase speed of weakly damped plasma waves, thus providing a plausible mechanism for their acceleration.

The existence conditions and characteristics of ion-acoustic solitary waves have been studied by Abbasi and Pajouh (2008), Saini, Kourakis, and Hellberg (2009), and Chuang and Hau (2009), showing that Kappa-distributed electrons are not favorable to the existence of these solitons. A comparative study of Langmuir waves, dust-ion acoustic waves, and dust-acoustic waves in Maxwellian and Kappa-distributed plasmas is presented by Zaheer, Murtaza, and Shah (2004). The Landau damping rate of dust-acoustic waves in a dusty plasma modeled by a Kappa distribution for electrons and ions and by a Maxwellian for the dust grains has been found to be dependent on the spectral index [κ] as well as the ratio of ion density to electron density (Lee, 2007). Dust-acoustic solitons have also been studied in plasmas with Kappa-distributed electrons and/or ions and cold negative or positive dust grains (Baluku and Hellberg, 2008; Younsi and Tribeche, 2008) or with non-thermal ions having Kappa-vortex-like velocity-distribution functions (Kamel, Tribeche, and Zerguini, 2009).

5.3.2. Magnetized Plasmas

The general dielectric tensor for magnetoplasmas comprising components with generalized Lorentzian distributions has been calculated by Summers, Xue, and Thorne (1994) for arbitrary oriented wave vectors. Applied to the electrostatic or electromagnetic waves propagating parallel to the ambient magnetic field, simple dispersion relations can be derived (Summers and Thorne, 1991; Xue, Thorne, and Summers, 1993; Summers, Xue, and Thorne, 1994; Mace, 1996, 1998) in terms of the modified plasma dispersion function (3).

This dielectric tensor has also been simplified for a three-dimensional isotropic Kappa distribution in a form similar to that obtained by Trubnikov (Mace, 1996), and for a Kappa loss-cone distribution with applications to a large variety of space plasmas such as the solar wind, magnetosheath, ring-current plasma, and the magnetospheres of other planets (Mace, 1996; Xiao, Thorne, and Summers, 1998; Pokhotelov *et al.*, 2002; Xiao, 2006; Xiao *et al.*, 2006a; Singhal and Tripathi, 2007).

For wave vectors oblique to the magnetic field, Mace (2003, 2004) has described the generalized electron Bernstein modes in a plasma with an isotropic Kappa velocity distribution. In a hybrid Kappa – Maxwellian plasma, unlike the uniform Maxwellian plasma, the dispersion properties of the oblique electromagnetic waves were found to be markedly changed from an elaborate study including effects of the Kappa value, the propagation angle, and the

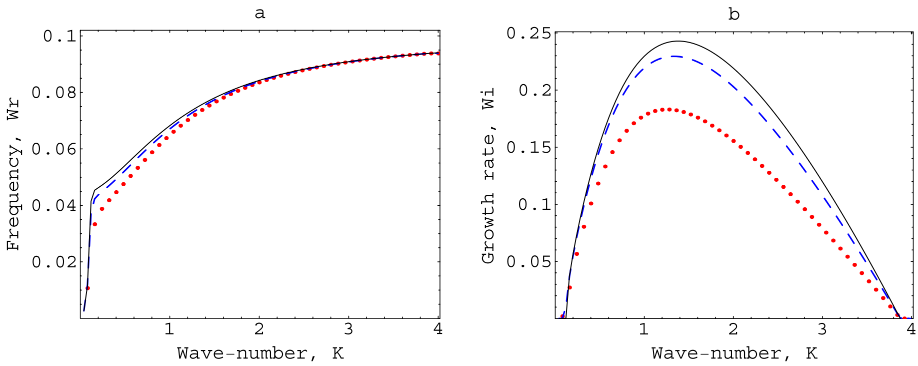

Figure 4 Dependence of dispersion curves (panel a) and growth rates (b) for the electron – cyclotron instability (R mode) on the spectral index $\kappa = 2$ (red dotted lines), 4 (blue dashed lines), and $\kappa \to \infty$ for Maxwellian plasmas (black solid lines). These are exact numerical solutions for parameters intended to simulate (low altitude) solar-wind conditions: plasma temperature $T_{\mathrm{e}} = 2.5 \times 10^7$ K, a temperature anisotropy $T_\perp / T_{\mathrm{e}} \simeq 4$, and gyrofrequency $|\Omega_{\mathrm{e}}| = 0.1\omega_{\mathrm{pe}}$. The coordinates are scaled as $W_{\mathrm{r}} = \omega_{\mathrm{r}}/\omega_{\mathrm{pe}}$ $W_i = \omega_i/\omega_{\mathrm{pe}}$ and $K = kc/\omega_{\mathrm{pe}}$. [Adapted from Lazar *et al.* (2008).]

temperature anisotropy on dispersion and damping (Cattaert, Hellberg, and Mace, 2007). Notice that, because of the anisotropy of the contours in the velocity space, such a Kappa – Maxwellian distribution is unstable in an overdense plasma near the electron-cyclotron frequency even when the parallel and perpendicular temperatures are equal.

The dispersion relations for low-frequency hydromagnetic waves in a Kappa-distributed plasma has recently been derived by Basu (2009) showing that both Landau damping and the transit-time damping (magnetic analogue of Landau damping) of the waves are enhanced in the suprathermal region of the velocity space.

5.4. Anisotropic Kappa Distributions

The effects of anisotropic Kappa distributions have also been investigated since the anisotropic velocity distributions are most probably at the origin of non-thermal emissions in astrophysical sources, and the magnetic-field fluctuations in space plasma.

For the case that both electrons and ions are modeled by an anisotropic distribution of bi-Kappa type, Summers and Thorne (1991) have derived the general dispersion relation for the parallel electromagnetic modes, right-handed (R mode) and left-handed (L mode) circularly polarized, in terms of the modified plasma dispersion function (3). The effect of suprathermal particles on the stability of these modes largely varies depending on the shape of the distribution function, and the mode frequency, whether it fits to the thermal Doppler shift of the electron gyrofrequency (the whistler instability driven by the cyclotron resonance with electrons) or the ion gyrofrequency (the electromagnetic ion-cyclotron instability). Thus, while the growth rates of the electron-cyclotron instability (R mode, lower branch, $\omega_{\mathrm{r}} \leq |\Omega_{\mathrm{e}}|$) become lower in a bi-Kappa plasma than for a bi-Maxwellian with the same temperature anisotropy (Lazar *et al.*, 2008), also see Figure 4b, at smaller frequencies ($\omega_{\mathrm{r}} \ll |\Omega_{\mathrm{e}}|$), the whistler growth rates become higher (Mace, 1998; Tripathi and Singhal, 2008). Cattaert, Hellberg, and Mace (2007) have also shown that, unlike a bi-Maxwellian plasma, the low-frequency whistler modes in a Maxwellian – Kappa plasma (described above) may be stable to the temperature anisotropy. Their study includes the effects of varying κ for both underdense and overdense plasmas, and for both parallel and oblique propagation.

The loss-cone bi-Lorentzian distribution, which allows plasma populations to have anisotropic temperatures and a loss cone, has been used extensively (although the latter is largely inconsequential in models for wave propagation parallel to the magnetic field) in space and laboratory applications (Mace, 1998; Tripathi and Singhal, 2008; Tripathi and Misra, 2000). Singhal and Tripathi (2007) obtained the components of the dielectric tensor for such a distribution function and made parametric studies of the effect of the κ-index, the loss-cone index (which is, in general, different from κ), and different temperature anisotropies (Tripathi and Singhal, 2008). The whistler-mode instability in a Lorentzian (Kappa) magnetoplasma in the presence of a perpendicular AC electric field and cold plasma injection was studied by Tripathi and Misra (2000). An unperturbed Lorentzian distribution has also been used for studying the effect of a cold plasma beam on the electromagnetic whistler wave in the presence of a perpendicular AC electric field in the Earth's atmosphere (Pandey and Pandey, 2008).

The Kappa loss-cone (KLC) distribution function obeys a power law not only at the lower energies but also at relativistic energies. A relativistic KLC distribution has been introduced by Xiao (2006) for an appropriate characterization of the energetic particles found in planetary magnetospheres and other plasmas, where mirror geometries occur, *i.e.* a pronounced high-energy tail and an anisotropy. The field-aligned whistler growing modes in space plasmas have been investigated by Xiao *et al.* (2006a) and Zhou *et al.* (2009) applying relativistic treatments for relativistic Kappa or KLC distributions. The threshold conditions for the whistler instability in a Kappa-distributed plasma have been derived by Xiao *et al.* (2006b). Numerical calculations were carried out for a direct comparison between a KLC distribution and the current Kappa distribution. The KLC was also adopted to model the observed spectra of solar energetic protons (Xiao *et al.*, 2008a). Recent studies (Xiao, Chen, and Li, 2008; Zhou *et al.*, 2009) have introduced a generalized relativistic Kappa distribution which incorporates either temperature anisotropy or both loss-cone and temperature anisotropy.

Purely growing ($\omega \approx 0$) mirror modes and low-frequency electromagnetic ion-cyclotron waves are widely detected in the solar wind and magnetosheath plasmas being driven by an ion-temperature anisotropy, $T_\perp > T_\|$ (or pressure anisotropy, $p_\perp > p_\|$). The effects of the suprathermal tails on the threshold conditions and the linear growth rates of these instabilities have widely been investigated in the last decade (Leubner and Schupfer, 2000, 2001, 2002; Gedalin *et al.*, 2001; Pokhotelov *et al.*, 2002). A universal mirror wave-mode threshold condition for non-thermal space plasma environments was obtained by Leubner and Schupfer (2000, 2001, 2002). The linear theory of the mirror instability in non-Maxwellian space plasmas was developed by Pokhotelov *et al.* (2002) for a large class of Kappa to suprathermal loss cone distributions in view of application to a variety of space plasmas such as solar wind, magnetosheath, ring-current plasma, and the magnetospheres of other planets. Thus, while the transition to non-thermal features provides a strong source for the generation of mirror wave-mode activity, reducing drastically the instability threshold (Leubner and Schupfer, 2002), the more realistic presence of suprathermal tails exclusively along the magnetic field (parallel κ-distribution) counteracts the growth of the mirror instability and contributes to stabilization (Pokhotelov *et al.*, 2002). In the nonlinear regime, solitary structures of the mirror waves occur with the shape of magnetic holes (Pokhotelov *et al.*, 2008) suggesting that the main nonlinear mechanism responsible for mirror instability saturation might be the magnetic trapping of plasma particles.

The ion-cyclotron wave instability driven by a temperature anisotropy ($T_\perp / T_\| > 1$) of suprathermal ions (protons) modeled with a typical Kappa distribution is investigated by Xue, Thorne, and Summers (1993, 1996a, 1996b) and Xiao *et al.* (2007a) for solar-wind conditions and for magnetosphere. The threshold condition for this instability is determined

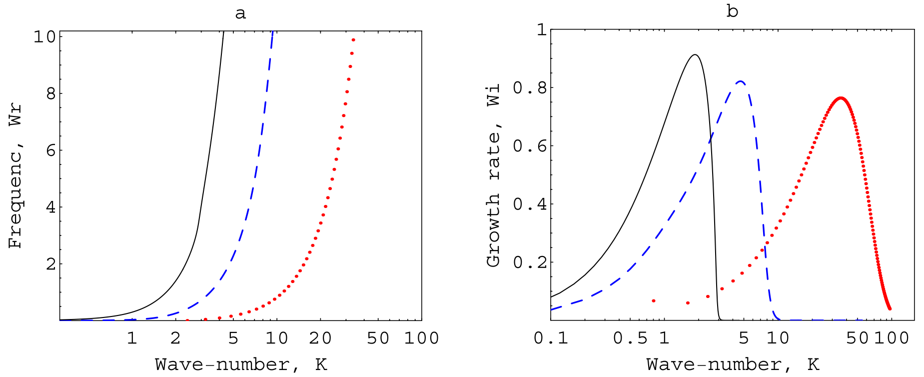

Figure 5 Dependence of dispersion curves (a) and growth rates (b) for a firehose instability on the spectral index $\kappa = 4$ (red dotted lines), 5 (blue dashed lines), and $\kappa \to \infty$ for Maxwellian plasmas (black solid lines). These are exact numerical solutions obtained with parameters estimated for solar flares: plasma density $n = 5 \times 10^{10}\ \mathrm{cm}^{-3}$, electron and proton temperature $T_{\mathrm{e},\perp} = T_{\mathrm{p},\perp} = T_{\mathrm{p},\parallel} \simeq 10^7$ K, and electron temperature anisotropy $T_{\mathrm{e},\perp}/T_{\mathrm{e},\parallel} \simeq 20$ (in a); and $\perp$ and $\parallel$ denote directions with respect to the ambient magnetic field, which has a value of $B_0 = 100$ G. The coordinates are scaled as $W_{\mathrm{r}} = \omega_{\mathrm{r}}/\Omega_{\mathrm{p}}$, $W_i = \omega_i/\Omega_{\mathrm{p}}$ and $K = kc/\omega_{\mathrm{p}}$.

by Xiao *et al.* (2007b). As the spectral index [κ] for protons increases, the maximum growth rates of R and L modes decrease (Summers and Thorne, 1992; Xue, Thorne, and Summers, 1993, 1996b; Dasso, Gratton, and Farugia, 2003) and the instability threshold generally decreases and tends to the lowest limiting values of the bi-Maxwellian ($\kappa \to \infty$) (Xiao *et al.*, 2007b). The corresponding enhancement in the growth rate of L-mode waves in planetary magnetospheres is less dramatic, but the Kappa distribution tends to produce a significant wave amplification over a broader range of frequency than a Maxwellian distribution with comparable bulk properties (Xue, Thorne, and Summers, 1993). The damping and growth rates of oblique waves are also lower for Kappa distributions, but the differences become less important for nearly perpendicular waves (Xue, Thorne, and Summers, 1996a).

In the opposite case, a surplus of parallel kinetic energy, $T_\perp < T_\parallel$ (or pressure $p_\perp < p_\parallel$), will excite two other kinetic instabilities: the firehose instability propagating parallel to the magnetic-field lines and with maximum growth rates of the order of the ion gyrofrequency (Lazar and Poedts, 2009), and the Weibel-like instability propagating perpendicularly to the hotter direction (in this case also perpendicular to the magnetic-field lines), and which, in general, is much faster, reaching maximum growth rates of the order of the electron (or ion) plasma frequency (Lazar, Schlickeiser, and Shukla, 2008; Lazar *et al.*, 2009). Recent investigations (Lazar and Poedts, 2009) of the electron-firehose instability driven by an anisotropic electron distribution of bi-Kappa type have proven that, to be compared to a bi-Maxwellian, the threshold increases, the maximum growth rates are slightly diminished and the instability extends to large wave numbers (see Figure 5). Instead, a more important reduction has been found for the growth rates of the electron Weibel instability (Figure 6a) in a non-magnetized or weakly magnetized plasma with bi-Kappa distributions (Zaheer and Murtaza, 2007; Lazar, Schlickeiser, and Shukla, 2008; Lazar *et al.*, 2008, 2009).

Despite the similar features of the electromagnetic filamentation instability, which is a Weibel-like instability that grows in a counterstreaming plasma or a beam – plasma system perpendicular to the streaming direction, the effect of suprathermal populations is opposite enhancing the filamentation growth rates, see Figure 6b (Lazar, Schlickeiser, and Shukla,

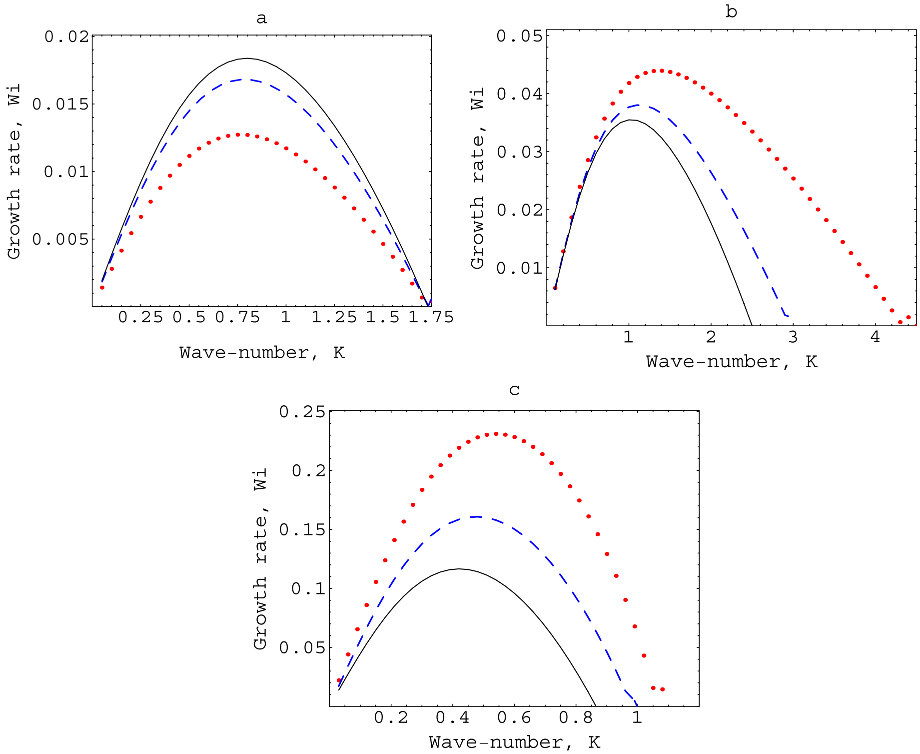

Figure 6 Dependence of growth rates for Weibel instability (panel a), filamentation (b) and two-stream instability (c), on the spectral index $\kappa = 2$ (the red dotted lines), 4 (blue dashed lines), and $\kappa \to \infty$ for Maxwellian plasmas (black solid lines). Here the parameters are typical for solar-wind conditions: plasma temperature $T_e \simeq 2 \times 10^6$ K, a temperature anisotropy $T_\perp / T_e \simeq 4$ (in a), and symmetric counterstreams in b and c, with the same temperature, and the bulk velocity $v_0 = 0.1c$ (where $c = 3 \times 10^8\ \mathrm{m\,s^{-1}}$ is the speed of light in vacuum). The coordinates are scaled as $W_i = \omega_i / \omega_{\mathrm{pe}}$ and $K = kc/\omega_{\mathrm{pe}}$ in panels a and b, and $K = kv_0/\omega_{\mathrm{pe}}$ in c.

2008; Lazar *et al.*, 2009). Extended investigations have included counterstreaming plasmas with an internal bi-Kappa distribution, when the filamentation and Weibel effects cumulate, leading again to increased growth rates, but only for plasmas hotter in the streaming direction. Otherwise, if counterstreaming plasmas are hotter in the perpendicular direction, the effective anisotropy decreases, diminishing the growth rates of the filamentation instability (Lazar, Schlickeiser, and Shukla, 2008; Lazar *et al.*, 2009). However, in this case, two other unstable modes are expected to arise, both along the streams: a Weibel-like electromagnetic instability and a two-stream electrostatic instability, which is, in general, faster than the Weibel instability. Furthermore, suprathermal populations enhance the electrostatic instability leading to larger growth rates for lower κ (Fig. 6c). The same behavior has been observed for the modified two-stream instability driven by the relative motion of ions, assumed to be Kappa-distributed, with respect to the electrons (assumed Maxwellian): maximum growth rates decrease with κ and with plasma β (Langmayr, Biernat, and Erkaev, 2005).

Recently, Basu (2008, 2009) provided a systematic study for the stability of a magnetized plasma at low frequencies and in various limits of low or high plasma β (plasma pressure/magnetic pressure), showing that the threshold values for the excitation of the unstable hydromagnetic waves in Kappa-distribution plasma are increased as a consequence of enhancing the resonant wave – particle damping.

6. Summary and Perspectives of Kappa Distributions

The Kappa function has been proven to be a convenient tool to describe plasma systems out of thermodynamic equilibrium. Since the fast particles are nearly collisionless in space plasmas, they are easily accelerated and tend to produce nonequilibrium velocity-distribution functions with suprathermal tails decreasing as a power law of the velocity. Thus, models based on the Kappa distribution allow one to analyze the effects of the suprathermal particles and to fit distributions for ions and electrons measured *in situ*, in the solar wind, and in the magnetosphere of the planets.

Major consequences follow from the presence of these suprathermal particles, and especially the velocity filtration which makes the kinetic temperature increase upward. This mechanism has been proposed to explain the heating of the corona. The suprathermal particles also increase the escape flux in planetary and stellar wind and may explain the acceleration of the fast solar wind. For low values of κ, the heat flux changes sign compared to the Spitzer – Harm case, so that heat can flow from cold to hot. The future solar missions *Solar Orbiter* and *Solar Probe* should improve the observations concerning the presence of suprathermal particles in the corona.

Valuable theories have been proposed concerning the origin and the fundamental physical arguments for a Kappa-family distribution function. The universal character of these distribution functions suggests that they can be attributed to a particular thermodynamic equilibrium state related to the long-range properties of Coulomb collisions. Thus, Kappa distributions generalize the notion of equilibrium for collisionless plasmas far from thermal (Boltzmann – Maxwell) equilibrium, but containing fully developed quasistationary turbulent fields. A new statistical mechanical theory has been proposed, extending Gibbs theory and relaxing the independence of subsystems (no binary collisions) through introducing a generalized Kappa-function dependence on entropy. In the absence of binary collisions, the Kappa parameter has been found to be a measure of the strength of the subsystem correlations introduced by the turbulent-field fluctuations. Particular forms for a nonextensive (superadditive) entropy and for temperature have been derived to satisfy the fundamental thermodynamic relations and recover exactly the family of Kappa distributions from Equation (1).

An isotropic Kappa distribution will therefore be stable against the excitation of plasma instabilities. This function replaces the Boltzmann – Maxwell distribution in correlated collisionless equilibria of plasma particles and turbulent fields. But such dilute plasmas easily develop flows and temperature anisotropies making Kappa distributions deviate from isotropy and drive kinetic instabilities. In space plasmas with embedded interplanetary magnetic field, heating and instability are, in general, resonant, and both are altered in Kappa-distributed plasmas because more particles are available at high energies to resonate with waves. Revisiting transport theories and calculation of the transport coefficients in solar environments is therefore an important task, and significant progress is expected involving Kappa distributions.

Common models based on the questionable existence of a Maxwellian equilibrium are presently improved by the new approaches assuming the existence of Kappa populations and providing more realistic interpretations and better fits to the observations. The new techniques developed for measuring the electron density, temperature, and the suprathermal distributions will also offer important clues to a better understanding of the transport properties in space plasmas.

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