Kappa distributions: theory and applications in space plasmas

V. Pierrard[1,2] · **M. Lazar**[3,4]

Review paper, gives possible rational for kappa-dependent thermal velocities

Abstract Particle velocity distribution functions (VDF) in space plasmas often show non Maxwellian suprathermal tails decreasing as a power law of the velocity. Such distributions are well fitted by the so-called Kappa distribution. The presence of such distributions in different space plasmas suggests a universal mechanism for the creation of such suprathermal tails. Different theories have been proposed and are recalled in this review paper. The suprathermal particles have important consequences concerning the acceleration and the temperature that are well evidenced by the kinetic approach where no closure requires the distributions to be nearly Maxwellians. Moreover, the presence of the suprathermal particles take an important role in the wave-particle interactions.

1 Introduction

Nonthermal particle distributions are ubiquitous at high altitudes in the solar wind and many space plasmas, their presence being widely confirmed by spacecraft measurements (Montgomery et al. 1968; Feldman et al. 1975; Pilipp et al. 1987; Maksimovic et al. 1997a; Zouganelis 2008). Such deviations from the Maxwellian distributions are also expected to exist in any low-density plasma in the Universe, where binary collisions of charges are sufficiently rare. The suprathermal populations are well described by the so-called Kappa (κ-) or generalized Lorentzian velocity distributions functions (VDFs), as shown for the first time by Vasyliunas (1968). Such distributions have high energy tails deviated from a Maxwellian and decreasing as a power law in particle speed:

V. Pierrard
[1] Belgian Institute for Space Aeronomy, av. circulaire 3, B-1180 Brussels, Belgium
[2] Center for Space Radiations, Université Catholique de Louvain, chemin du cyclotron 2, B-1348 Louvain-La-Neuve, Belgium
E-mail: viviane.pierrard@oma.be

M. Lazar
[3] Research Department - Plasmas with Complex Interactions,
Ruhr-Universität Bochum, D-44780 Bochum
E-mail: mlazar@tp4.rub.de
[4] Center for Plasma Astrophysics, Celestijnenlaan 200B, 3001 Leuven, Belgium

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

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 their number density, T their equivalent temperature, v the velocity of the particles, and $\Gamma(x)$ is the Gamma function. The spectral index must take sufficiently large values $\kappa > 3/2$ to keep away from 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 on Fig. 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 remember that $w_{\kappa i}$ in (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 to 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 relating to the average energy $k_B T = m<v^2>/3$. 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 (Livadiotis and McComas (2009) and references therein). The family of kappa distributions result from a new generalized Lorentzian statistical mechanics formulated for a collisionless plasmas far from thermal (Boltzmann-Maxwell) equilibrium but containing fully developed turbulence in quasistationary equilibrium (Treumann 1999a,b; Leubner 2002; Fisk and Gloeckler 2006; Gloeckler and Fisk 2006; Treumann and Jaroschek 2008). Thus, in phase space, the power-law distributions of Kappa type describe marginally stable Gibbsian equilibria, and the parameter κ controls the strength of the plasma particle correlation in the turbulent field fluctuations (Hasegawa et al. 1985; 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 3 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 4 parameters (n_1, T_1 and n_2, T_2 representing
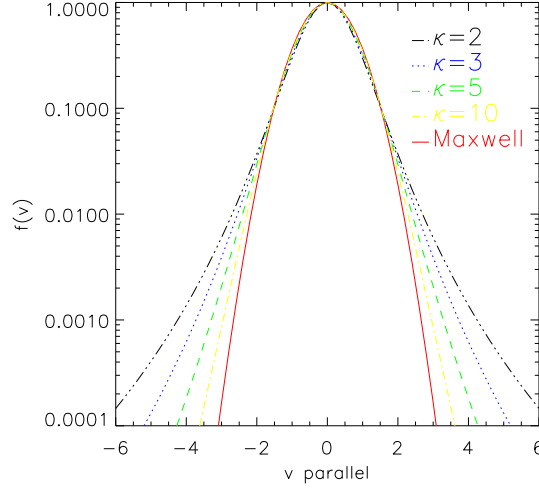
Fig. 1 The Kappa velocity distribution function for different values of the kappa parameter.

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

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

the number density and temperatures of the two populations) and they 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 yield 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 nonthermal populations in different environments. Representative theories and scenarios developed for Kappa distributed plasmas are discussed in Section 4. In Section 5 we make 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 et al. 1997a), 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. 2008c), the magnetosphere of other planets like Mercury (Christon 1987), the plasmasheet of Jupiter (Collier and Hamilton 1995), the magnetosphere of Jupiter (Krimigis et al. 1981; Mauk et al. 2004), 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 et al. 1995), Cassini (Steffl et al. 2004) and the Hubble Space Telescope (Retherford et al. 2003).

In the solar wind, electron velocity distributions are characterized by a thermal core and a halo suprathermal population (Pierrard et al. 2001b), as illustrated on Fig. 2. These electron VDF are also characterized by a strahl component aligned with the interplanetary magnetic field. Electron VDF measured by Ulysses have been fitted with Kappa functions by Maksimovic et al. (1997a). They 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). Solar wind particle VDF observed by CLUSTER have also been fitted by the generalized Kappa function (Qureshi et al. 2002). Radial evolution of nonthermal 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 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).

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 extensively been used 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 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).
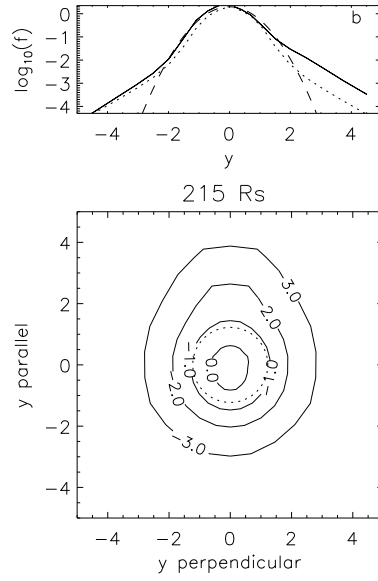
Fig. 2 Velocity distribution function observed by the satellite WIND at 1 UA (215 Rs) for high speed solar wind electrons. Bottom panel: Isocontours in the plane of velocities (normalized to the thermal velocity) parallel and perpendicluar to the interplanetary magnetic field. Top panel: Parallel (solid line) and perpendicular (dotted line) cross section of the observed VDF. The dashed line represents the Maxwellian distribution that well fits the core of observed VDF. (Pierrard et al. 1999)

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 Hasegawa et al. (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 in 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 et al. 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 maximisation 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 on 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); Vocks et al. (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 high frequency whistler mode that enhance the energy of electrons in Earth's foreshock (Ma and Summers 1998), or that of MHD waves which can accelerate both the electrons and the protons in the solar flares (Miller 1991, 1997), and in the inner magnetosphere (Summers and Ma 2000).

When large amplitude waves are present, the nonlinear Landau damping can 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 occured throughout the heliosheath downstream from the termination shock of the solar wind (Fisk and Gloeckler 2006; Fisk and Glockler 2007). A mechanism for the generation of electron distribution function with suprathermal tails in the upper regions of the solar atmosphere in the presence of collisional damping was suggested by Viñas et al. (2000) as due to finite-amplitude, low-frequency, obliquely propagating electromagnetic waves. The nonthermal features of the VDFs can also result from superdiffusion processes (Treumann 1997), and 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 VDF was also investigated with a FP model by Lie-Svendsen et al. (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 Kappa velocity distribution was also illustrated in Hau and Fu (2007) by the problem of low-frequency waves and instabilities in uniform magnetized plasmas with bi-Maxwellian distribution.

Whatever the mechanisms of suprathermal tails formation, 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 Star's corona

Scudder (1992a,b) was pioneer to show the consequences of a postulated nonthermal 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 (Scudder 1992b) determined also the value of the kappa parameter for different groups of stars. Scudder (1994) showed that the excess of Doppler line widths can 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 et al. 2007) and should be also by a Kappa. 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 reinterpretation of many observations.

The mechanism of velocity filtration in solar corona has been proposed to explain the high energy electrons at higher altitudes in the solar wind (Scudder 1992a,b). Velocity filtration was also applied to heavy ions in the corona to explain their temperatures 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 non-Maxwellian velocity distribution such as 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 3RS (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 VDF based on a balance of ionization and recombination processes (Wannawichian et al. 2003) for typical temperatures in astrophysical plasmas. Low kappa 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 et al. (2004). Plasma screening effects on elastic electron–ion collision processes in a Lorentzian (Kappa)-distribution plasma are 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 et al. (1997b) and predicts the high speed solar wind velocities with reasonable temperatures in the corona and without additional acceleration mechanism. The presence of suprathermal electrons increases the electrostatic potential difference between the solar corona and the interplanetary space and accelerates the solar wind. The collisionless or weakly collisional models in corona (Scudder 1992b; Maksimovic et al. 1997b; 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 Fig. 3. 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.

The acceleration of the solar wind heavy ions is investigated in Pierrard et al. (2004): due to their different masses and charges, the minor ions reach different velocities. Even if their mass on 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 et al. 1999, 2001a). Typical electron VDFs measured at 1 AU by WIND have been used as boundary condition to determine the VDFs at lower altitudes and it was proved that, for several solar radius, the suprathermal populations must be present in the corona as well (Pierrard et al. 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 submitted to collisions. High energy tails can develop for Knudsen numbers (i.e. ratio of mean free path over scale height) as low as 10^{-3} (Shoub 1983). Marsch and Livi (1985) have studied the collisional relaxation process and the associated rates (diffusion and friction) for a nonthermal solar wind with Kappa VDFs. The Fokker-Planck model (Pierrard et al. 2001a) illustrated also 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 VDF became more and more anisotropic in the transition region. Contrary to exospheric models that are analytic, these collisional kinetic models have to be solved numerically. The spectral method of expansion of the solution in orthogonal polynomials converges faster for suprathermal plasmas by using polynomials based on the Kappa function weight developed by Magnus and Pierrard (2008).

As a result of 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
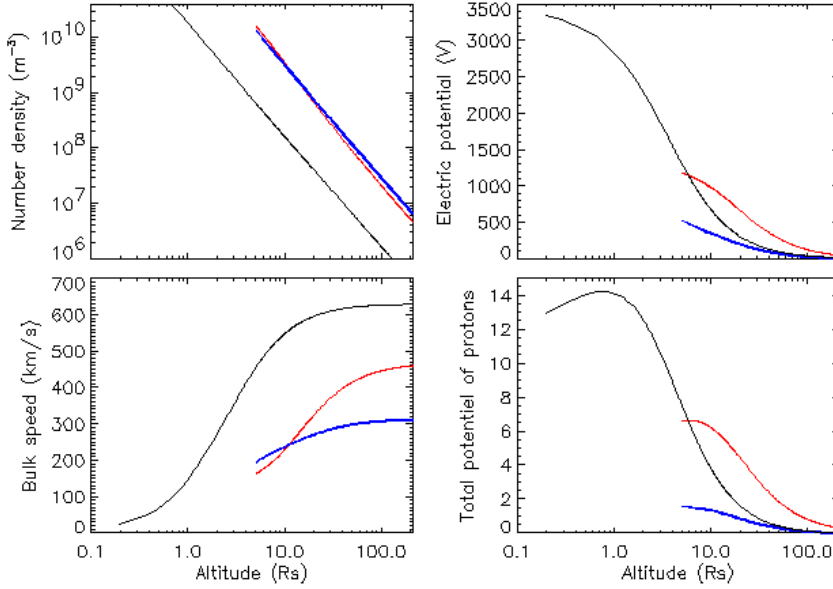
Fig. 3 Number density, electrostatic potential, bulk speed and potential of protons for different solutions of the Kappa kinetic model of the solar wind. The lowest blue velocity curve (u=320 km/s at 215 Rs) in the bottom left panel corresponds to a Maxwellian model with a starting radial distance (called exobase) at $r_0 = 6$ Rs. The middel red line (u=460 km/s at 215 Rs) corresponds to a Kappa VDF with $\kappa = 3$ and $r_0 = 6$ Rs. The upper black line (u=640 km/s at 215 Rs) corresponds to a Kappa VDF for $\kappa = 3$ with an exobase at $r_0 = 1.2$ Rs (Adapted from Lamy et al. (2003b)).

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 nonthermal 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 Vinas (2008) have assumed two populations of electrons in magnetic clouds: a core Maxwellian and a halo Kappa-like distribution. They found that kappa values exhibit either minor differences or, for some events, can 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 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 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 ion-exosphere (Pierrard and Lemaire 1996b) has been used to study different plasma regions in the magnetosphere of the Earth. Pierrard (Pierrard 1996; Pierrard et al. 2007) obtained new current-voltage relationships in auroral regions when suprathermal particles are 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 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 et al. 2005).

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 the plasmasphere. The effects of suprathermal particles on the temperature in the terrestrial plasmasphere were illustrated using Kappa functions in 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 et al. 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 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 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 et al. (1995) and Moncuquet et al. (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 kappa index gives an additional parameter to fit observations of Cassini. The polar wind and plasmasphere of Jupiter and Saturn were also recently modeled with Kappa functions (Pierrard 2009): the suprathermal particles increase significantly the escape flux from these giant planets, so that the ionosphere 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 made 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 nonthermal populations. Thus, the waves and instabilities in Kappa distributed plasmas, where collisions are sufficiently rare, are investigated using kinetic approaches based on Vlasov-Maxwell equations.

5.1 Vlasov-Maxwell kinetics. Dielectric tensor

Using a kinetic approach, Summers et al. (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 complicate 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 a weak damping or growth of plasma waves by resonant interactions with plasma particles.

The approach developed in Summers et al. (1994) also restricts to the distributions functions which are even functions of 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 an usual condition in practice. This condition fails only in some extreme situations (Summers et al. 1994) as are, 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. 2008a, 2009a; 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 remember the most important analytical changes introduced by the power law distributions of plasma particles.

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

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

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

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

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); 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 an hybrid Kappa-Maxwellian distribution function, one-dimensional Kappa along the magnetic field lines and Maxwellian perpendicular to this direction. The new dispersion function $Z_{\kappa M}$ 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. Relation between these two integral functions takes two forms (Hellberg and Mace 2002; Lazar et al. 2008b)

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

and both $Z_{\kappa M}(f)$ and $Z_\kappa(f)$ functions approach 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 et al. (2000b) and Hellberg et al. (2005).

5.3.1 *Unmagnetized* plasma

The fluctuations are, in general, enhanced in low-κ plasmas, and the electromagnetic and electrostatic dispersion relations show significant dependence on the spectral index κ (Thorne and Summers 1991; Summers and Thorne 1992; Mace and Hellberg 1995; Mace et al. 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 et al. 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 narrowband 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. 2000a; Mace et al. 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 orbit. It was found a good match for the

electron velocities in the superhalo with the phase speed of weakly damped plasma waves, and 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 et al. (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 in Zaheer et al. (2004). 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 (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 nonthermal ions having Kappa-vortex-like velocity distributions functions (Kamel et al. 2009).

5.3.2 Magnetized plasmas

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

This dielectric tensor has also been simplified for a 3-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 like the solar wind, magnetosheath, ring current plasma, and the magnetospheres of other planets (Mace 1996; Xiao et al. 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 temperature anisotropy on dispersion and damping (Cattaert et al. 2007). Notice that, because of the anisotropy of the countours 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 the 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 nonthermal emissions in astrophysical sources, and the magnetic field fluctuations in space plasma.
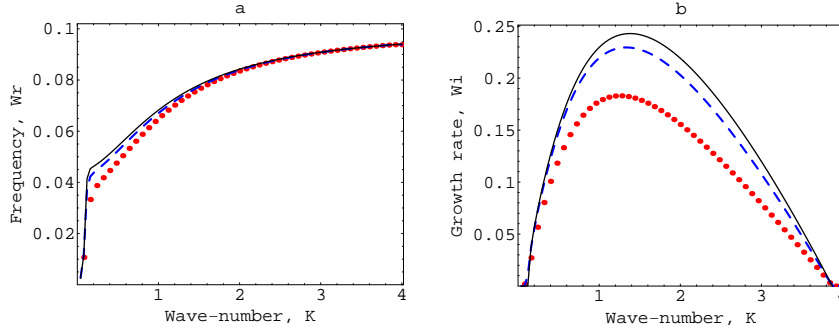
Fig. 4 Dependence of dispersion curves (panel a) and growth rates (b) for the electron cyclotron instability (R mode) on the spectral index $\kappa = 2$ (red dotted lines), 4 (blue dashed lines), and $\kappa \to \infty$ for Maxwellian plasmas (black solid lines). These are exact numerical solutions for parameters intended to simulate (low altitude) solar wind conditions: plasma temperature $T_e = 2.5 \times 10^7$ K, a temperature anisotropy $T_\perp/T_e \simeq 4$, and gyrofrequency $|\Omega_e| = 0.1\omega_{pe}$. The coordinates are scaled as Wr$= \omega_r/\omega_{pe}$ Wi$= \omega_i/\omega_{pe}$ and K $= kc/\omega_{pe}$. (Adapted from Lazar et al. (2008a).)

When 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 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, $\omega_r \leq |\Omega_e|$) become lower in a bi-Kappa plasma than for a bi-Maxwellian with the same temperature anisotropy (Lazar et al. 2008a), also see Fig. 4, b, at smaller frequencies ($\omega_r \ll |\Omega_e|$), the whistler growth rates become higher (Mace 1998; Tripathi and Singhal 2008). Cattaert et al. (2007) have also shown that, unlike a bi-Maxwellian plasma, the low-frequency whistler modes in a Maxwellian-Kappa plasma (described above), can be stable to the temperature anisotropy. Their study includes 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 to 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 κ-index, the loss-cone index (which is, in general different from κ), and different temperature anisotropies (Tripathi and Singhal 2008). Whistler mode instability in a Lorentzian (Kappa) magnetoplasma in the presence of 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 the 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. 2008b). Recent studies (Xiao et al. 2008a; 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 ($\omega \simeq 0$) 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, $T_\perp > T_\parallel$ (or pressure, $p_\perp > p_\parallel$). 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). An universal mirror wave-mode threshold condition for nonthermal 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 like the solar wind, magnetosheath, ring current plasma, and the magnetospheres of other planets. Thus, while transition to nonthermal features provides a strong source for the generation of mirror wave mode activity, reducing drastically the instability threshold (Leubner and Schupfer 2002), a 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 ($T_\perp/T_\parallel > 1$) of suprathermal ions (protons) modeled with a typical Kappa distribution is investigated by Xue et al. (1993); Xiao et al. (2007a); Xue et al. (1996a,b) for solar wind conditions and for magnetosphere. The threshold condition for this instability is determined by Xiao et al. (2007b). As the spectral index κ for protons increases, the maximum growth rates of R, L modes decrease (Summers and Thorne 1992; Xue et al. 1993; Dasso et al. 2003; Xue et al. 1996b) 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 et al. 1993). The damping and growth rates of oblique waves are also lower for Kappa distributions, but differences become less important for nearly perpendicular waves (Xue et al. 1996a).

In the opposite case, a surplus of parallel kinetic energy, $T_\perp < T_\parallel$ (or pressure $p_\perp < p_\parallel$) will excite other two kinetic instabilities: the firehose instability propagating parallel to the
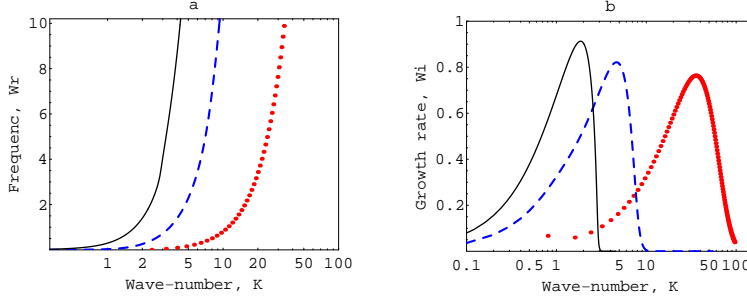
Fig. 5 Dependence of dispersion curves (a) and growth rates (b) for firehose instability on the spectral index $\kappa = 4$ (red dotted lines), 5 (blue dashed lines), and $\kappa \to \infty$ for Maxwellian plasmas (black solid lines). These are numerical exact solutions obtained with parameters estimated for solar flares: plasma density $n = 5 \times 10^{10}$ cm^{-3}, electron and proton temperature $T_{e,\perp} = T_{p,\perp} = T_{p,\parallel} \simeq 10^7$ K, the electron temperature anisotropy $T_{e,\perp}/T_{e,\parallel} \simeq 20$ (in a), and $\perp$ and $\parallel$ denote directions with respect to the ambient magnetic field $B_0 = 100$ G. The coordinates are scaled as Wr= ω_r/Ω_p, Wi= ω_i/Ω_p and K = kc/ω_p. (Adapted from Lazar and Poedts (2009))
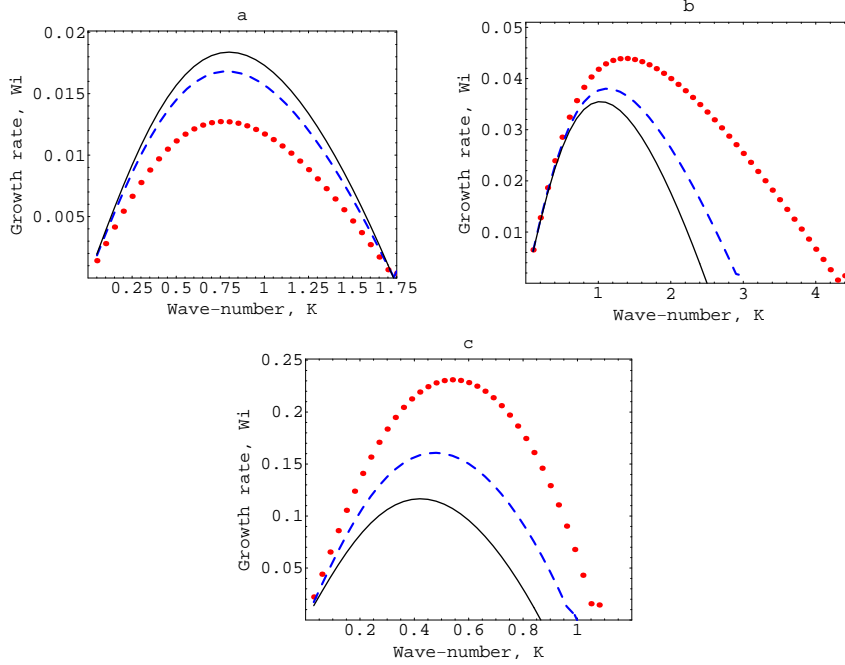

Fig. 6 Dependence of growth rates for Weibel instability (panel a), filamentation (b) and two stream instability (c), on the spectral index $\kappa = 2$ (red dotted lines), 4 (blue dashed lines), and $\kappa \to \infty$ for Maxwellian plasmas (black solid lines). Here the parameters are typical for solar 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 $c = 3 \times 10^8$ m/s is the speed of light in vacuum). The coordinates are scaled as Wi=ω_i/ω_{pe} and K = kc/ω_{pe} in panels a and b, and K = kv_0/ω_{pe} in c. (Adapted from Lazar et al. (2008b,a).)

magnetic field lines and with maximum growth rates of the order of ion gyrofrequency (Lazar and Poedts 2009), and the Weibel like instability propagating perpendicular 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 electron (or ion) plasma frequency (Lazar et al. 2008b, 2009a). Recent investigations (Lazar and Poedts 2009) of the electron firehose instability driven by an anisotropic electron distribution of bi-Kappa type, have proven that, by comparison to a bi-Mawellian, the threshold increases, the maximum growth rates are slightly diminished and the instability extends to large wave-numbers (see Fig. 5). Instead, a more important reduction has been found for the growth rates of the electron Weibel instability (Fig. 6, a) in a non-magnetized or weakly magnetized plasma with bi-Kappa distributions (Zaheer and Murtaza 2007; Lazar et al. 2008b,a, 2009a).

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 (Fig. 6, b) (Lazar et al. 2008b, 2009a). 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 perpendicular direction, the effective anisotropy decreases, diminishing the growth rates of filamentation instability (Lazar et al. 2008b, 2009a). 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 Weibel. Furthermore, suprathermal populations enhance the electrostatic instability leading to larger growth rates for lower κ (Fig. 6, c). The same behavior has been observed for the modified two-stream instability driven by the relative motion of ions, assumed Kappa-distributed, with respect to the electrons (assumed Maxwellian): maximum growth rates decrease with κ and with plasma β (Langmayr et al. 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 beta (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 Outlines and perspectives of Kappa distributions

The Kappa function has been proved 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 distributions functions with suprathermal tails decreasing as a power law of the velocity. Thus, models based on the kappa distribution allow 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 the presence of these suprathermal particles, and especially the velocity filtration which makes the kinetic temperature increase upwards. This mechanism has been proposed to explain the heating of the corona. The suprathermal particles increase also the escape flux in planetary and stellar wind and can explain the acceleration of the fast solar wind. For low values of κ, the heat flux changes of sign compared to

Spitzer-Harm 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 generalizes 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 Gibbsian 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 for 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 (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 to deviate from isotropy and drive kinetic instabilities. In space plasmas embeded by the interplanetary magnetic field, heating and instability are, in general, resonant, and both will be enhanced in Kappa distributed plasmas because there are more particles 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 a significant progress is expected to be done involving Kappa distributions.

Many solar models have been developed on a questionable existence of a Maxwellian equilibrium, so that, now, the presence of Kappa distributions asks for more realistic reinterpretations that are expected to provide better fits to the observations. The new techniques developed for measuring the electron density, temperature, and the suprathermal parameters will also offer important clues to understanding transport properties in space plasmas.

References

Abbasi, H., and Pajouh, H. H.: 2008, *Phys. Plasmas Control. Fus.* **50**, 095007.

Baluku, T. K., and Hellberg, M. A.: 2008, *Phys Plasmas* **15**, 123705.

Bame, S. J., Asbridge, J. R., Felthauser, H. E., Hones, E. W., Strong, I. B.: 1967, *J. Geophys. Res.* **72**, 113-129

Barghouthi, I., Pierrard, V., Barakat A. R., and Lemaire, J.: 2001, *Astrophys. Space Sci.* **277**, 427.

Basu, B.: 2008, *Phys. Plasmas* **15**, 042108.

Basu, B.: 2009, *Phys. Plasmas* **16**, 052106.

Califano, F., and Mangeney, A.: 2008, *J. Geophys. Res.* **113**, A06103.

Cary, J. R., Thode, L. E., Lemons, D. S., Jones, M. E., and Mostrom, M. A.: 1981, *Phys. Fluids* **24**, 1818.

Cattaert, T., Hellberg, M. A., and Mace, R. L.: 2007, *Phys. Plasmas* **14**, 082111.

Chateau, Y. F., and Meyer-Vernet, N.: 1991, *J. Geophys. Res.* **96**, 5825.

Chotoo, K., N. Schwadron, G. Mason, T. Zurbuchen, G. Gloeckler, A. Posner, L. Fisk, A. Galvin, D. Hamilton, and M. Collier: 2000, J. Geophys. Res., 105(A10), 23107.

Christon, S. P.: 1987, *Icarus* **71**, 448.

Christon, S. P., Mitchell, D. G., Williams, D. J., Frank, L. A., Huang, C. Y., and Eastman, T. E.: 1988, *J. Geophys. Res.* **93**, 2562.

Christon, S. P., Williams, D. J., Mitchell, D. G., Frank, L. A., and Huang, C. Y.: 1989, *J. Geophys. Res.* **94**, 13409.

Chuang, S.-H., and Hau, L.-N.: 2009, *Phys. Plasmas* **16**, 022901.

Collier, M. C.: 1993, *Geophys. Res. Lett.* **20**, 1531.

Collier, M. C.: 1995, *Geophys. Res. Lett.* **22**, 2673.

Collier, M. C.: 2004, *Adv. Space Res.* **33**, 2108.

Collier, M. R., and Hamilton, D. C.: 1995, *Geophys. Res. Let.* **22**, 303.

Collier M. D., Hamilton, D. C., Gloeckler, G., Bochsler, P., and Sheldon, R. B.: 1996, *Geophys. Res. Lett.* **23**, 1191.

Dasso, S., Gratton, F. T., and Farugia, C. J.: 2003, *J. Geophys. Res.* **108**, 1149.

Decker, D. T., Basu, B., Jasperse, J. R., Strickland, D. J., Sharber, J. R., and Winningham, J. D.: 1995, *J. Geophys. Res.* **100**, 21409.

Decker, D. B., Krimigis S.M., Roelof E.C., Hill M.E., Armstrong T.P., Gloeckler G., Hamilton D.C., Lanzerotti L.J., Science 23, 309, 2020.

De la Haye, V., Waite Jr., J. H., Johnson, R. E., Telle R. V., Cravens, T. E., Luhmann J. G., Kasprzak, W. T., Gell, D. A., Magee, B., Leblanc, F., Michael, M., Jurac, S., and Robertson I. P.: 2007, *J. Geophys. Res.* **112**, A07309.

Dialynas K., Krimigis S.M., Mitchemm D.G., Hamilton D.C., Krupp N., and Brandt P.C.: 2009, *J. Geophys. Res.* **114**, A01212. J. D.: 1999, *Geophys. Res. Lett.* **23**, 3537.

Dorelli J. C., and Scudder, J. D.: 1999, *Geophys. Res. Lett.* **23**, 3537.

Esser R., and Edgar R. J.: 2000, *ApJ. (Letters)* **532**, L71.

Fainberg, J., Osherovich, V. A., Stone, R. G., MacDowall, R. J., and Balogh, A.: 1996, in D. Winterhalter, J. T. Gosling, S. R. Habbal, W. S. Kurth and M. N. Eugebauer, (eds.), *Proc. Solar Wind 8 Conference*, AIP Conference Proceedings **382**, Melville, NY, US, p. 554.

Feldman, W. C., Asbridge, J. R., Bame, S. J., and Montgomery, M. D.: 1974, *Rev. Geophys.* **12**, 715.

Feldman, W. C., Asbridge, J. R., Bame, S. J., Montgomery, M. D., and Gary, S. P.: 1975, *J. Geophys. Res.* **80**, 4181.

Fisk, L. A., and Gloeckler, G.: 2006, *Astrophys. J.* **640**, L79.

Fisk, L. A., and Gloeckler, G.: 2007, *Space Sci. Rev.* **130**, 153.

Formisano, V., Moreno, G., Palmiotto, F., Hedgecock, P. C.: 1973, *J. Geophys. Res.* **78**, 3714.

Fried, B. D., and Conte, S. D.: 1961, *The Plasma Dispersion Function*, Academic Press, New York, US.

Garrett, H. B., and Hoffman, A. R.: 2000, *IEEE Trans. Plasm. Sci.* **28**, 2048. M.

Gedalin, M., Lyubarsky, Yu. E., Balikhin, M., and Russell, C. T.: 2001, *Phys. Plasmas* **8**, 2934.

Gloeckler, G., Geiss, J., Balsiger, H., Bedini, P., Cain, J. C., et al.: 1992, *Astron. Astrophys. Suppl. Ser.* **92**, 267.

Gloeckler, G., and Fisk, L. A.: 2006, *Astrophys. J.* **648**, L63.

Gloeckler, G., and Hamilton, D. C.: 1987, *Phys. Scripta* **T18**, 73.

Gosling, J. T., Bame, S. J., Feldman, W. C., McComas, D. J., and Phillips, J. L.: 1993, *Geophys. Res. Lett.* **20**, 2335.

Hasegawa, A., Mima, K., and Duong-van, M.: 1985, *Phys. Rev. Lett.* **54**, 2608.

Hau, L. -N., and Fu, W. -Z.: 2007, *Phys. Plasmas* **14**, 110702.

Hellberg, M. A., and Mace, R. L.: 2002, *Phys. Plasmas* **9**, 1495.

Hellberg, M. A., Mace, R. L., Armstrong, R. J., and Karlstad, G.: 2000, *J. Plasma Phys.* **64**, 433.

Hellberg M., Mace R., and Cattaert T.: 2005, *Space Sci. Rev.* **121**, 127.

Hellberg, M. A., Mace, R. L., and Verheest, F.: 2000, in F. Verheest, M. Goosens, M. A. Hellberg, and R. Bharuthram (eds.), *Waves in Dusty, Solar and Space Plasmas, Leuven, 2000*, AIP Conference Proceedings **537**, Melville, NY, US, p. 348.

Hellberg, M. A., Mace, R. L., Baluku, T. K., Kourakis, I., and Saini, N. S.: 2009, *Phys. Plasmas* **16**, 094701.

Heerikhuisen, J., Pogorelov, N. V., Florinski, V., Zank, G. P., and Roux, J. A.: 2008, *Astrophys. J.* **682**, 679.

Jung, Y.-D., and Hong, W.: 2000, *J. Plasma Phys.* **63**, 79.

Kamel, A., Tribeche, M., and Zerguini, T. H.: 2009, *Phys Plasmas* **16**, 083701.

Kasparova, J., and Karlicky, M.: 2009, *Astron. Astrophys.* **497**, L13.

Kim, Y. -W., Song, M. -Y., and Jung, Y. -D.: 2004, *Phys. Scr.* **70**, 361.

Kletzing, C. A.: 2003, *J. Geophys. Res.* **108**, 1360.

Ko, Y. -K., Fisk, L. A., Gloeckler, G., and Geiss, J.: 1996, *Geophys. Res. Let.* **20**, 2785.

Krimigis, S. M., Carbary, J. F., Keath, E. P., Bostrom, C. O., Axford, W. I., Gloeckler, G., Lanzerotti L. J., and Armstrong, T. P.: 1981, *J. Geophys. Res.* **86**, 8227.

Krimigis, S. M., Carbary, J. F., Keath, E. P., Armstrong, T. P., Lanzerotti L. J., and Gloeckler, G.: 1983, *J. Geophys. Res.* **88**, 8871.

Krimigis, S. M., Armstrong, T. P., Axford, W. I., Cheng, A. F., Gloeckler, G., Hamilton, D. C., et al.: 1986, *Science* **233**, 97.

Lamy H., Pierrard, V., Maksimovic, M., and Lemaire, J.: 2003a, *J. Geophys. Res.* **108**, 1047.

Lamy H., M. Maksimovic, V. Pierrard, and J. Lemaire: 2003b, Proceedings of the Tenth International Solar Wind Conference, edited by M. Velli, R. Bruno and F. Malara, American Institute of Physics, 367.

Landi, S., and Pantellini, F. G.: 2001, *Astron. Astrophys.* **372**, 686.

Langmayr, D., Biernat, H. K., and Erkaev, N. V.: 2005, *Phys. Plasmas* **12**, 102103.

Lazar, M., and Poedts S.: 2009, it Astron. Astrophys. **494**, 311.

Lazar, M., Schlickeiser, R., Poedts, S., and Tautz, R. C.: 2008, *Mon. Not. R. Astron. Soc.* **390**, 168.

Lazar, M., Tautz, R. C., Schlickeiser, and R., Poedts, S.: 2009, *Mon. Not. R. Astron. Soc.* **401**, 362.

Lazar, M., Schlickeiser, R., and Shukla, P. K.: 2008, *Phys. Plasmas* **15**, 042103.

Le Chat, G., Issautier, K., Meyer-Vernet, N., Zouganelis, I., Maksimovic, M., and Moncuquet, M.: 2009, *Phys. Plasmas* **16**, 102903.

Lemaire, J. and Pierrard, V.: 2001, *Astrophys. Space Sci.* **277**, 169.

Lee, M. -J.: 2007, *Phys. Plasmas* **14**, 032112.

Leubner, M. P.: 1982, *J. Geophys. Res.* **87**, 6331.

Leubner, M. P.: 1983, *J. Geophys. Res.* **88**, 469.

Leubner, M. P.: 2000, *Planet. Space Sci.* **48**, 133.

Leubner, M. P.: 2002, *Astrophys. Space Sci.* **282**, 573.

Leubner, M. P.: 2004a, *Phys. Plasmas* **11**, 1308.

Leubner, M. P.: 2004b, *Astrophys. J.* **604**, 469.

Leubner, M. P.: 2008, *Nonlin. Proc. Geophys.* **15**, 531.

Leubner, M. P., and Schupfer, N.: 2000, *J. Geophys. Res.* **105**, 27387.

Leubner, M. P., and Schupfer, N.: 2001, *J. Geophys. Res.* **106**, 12993.

Leubner, M. P., and Schupfer, N.: 2002, *Nonlin. Processes Geophys.* **9**, 75.

Leubner, M. P., and Viñas, A. F.: 1986, *J. Geophys. Res.* **91**, 13,366.

Leubner, M. P., and Voros, Z.: 2005, *Astrophys. J.* **618**, 547.

Lie-Svendsen, O., Hansteen, V. H., and Leer, E.: 1997, *J. Geophys. Res.* **102**, 4701.

Livadiotis, G., and McComas, D. J.: 2009, *J. Geophys. Res.* **114**, A11105.

Ma, C., and Summers, D.: 1998, *Geophys. Res. Lett.* **25**, 4099.

Ma, C., and Summers, D.: 1999, *Geophys. Res. Lett.* **26**, 1121.

Mace, R. L.: 1996, *Phys. Scr.* **T63**, 207.

Mace, R. L.: 1998, *J. Geophys. Res.* **103**, 14643.

Mace, R. L.: 2003, *Phys. Plasmas* **10**, 2181.

Mace, R. L.: 2004, *Phys. Plasmas* **11**, 507.

Mace, R. L., Amery, G., and Hellberg, M. A.: 1999, *Phys. Plasmas* **6**, 44.

Mace, R. L., and Hellberg, M. A.: 1995, *Phys. Plasmas* **2**, 2098.

Mace, R. L., and Hellberg, M. A.: 2009, *Phys. Plasmas* **16**, 072113.

Mace, R. L., Hellberg, M. A., and Treumann, R. A.: 1998, *J. Plasma Phys.* **59**, 393.

Magnus, A. P., and Pierrard, V.: 2008, *Journal of Computational and Applied Mathematics* **219**, 431.

Maksimovic, M., Pierrard, V., and Riley, P.: 1997, *Geophys. Res. Let.* **24**, 1151.

Maksimovic, M., Pierrard, V., and Lemaire, J. F.: 1997, *Astron. Astrophys.* **324**, 725.

Marsch, E., and Livi, S.: 1985, *Phys. Fluids* **28**, 1379.

Marsch, E., Muhlhauser, K. H., Schwenn, R., Rosenbauer, H., Pilipp, W. G., and Neubauer, F. M.: 1982, *J. Geophys. Res.* **87**, 52.

Mauk, B. H., Keath, E. P., Kane, M., Krimigis, S. M., Cheng, A. F., Acuna, M. H., Armstrong, T. P., and Ness, N. F.: 1991, *J. Geophys. Res.* **96**, 19061.

Mauk, B. H. et al.: 2004, *J. Geophys. Res.* **109**, A09S12.

Meyer-Vernet, N.: 1999, *Eur. J. Phys.* **20**, 167.

Meyer-Vernet, N.: 2001, *Planet. Space Sci.* **49**, 247.

Meyer-Vernet, N.: 2007, *Atmosph. Spa. Sc. Series* Cambridge, 463 p.

Meyer-Vernet, N., Moncuquet, M., and Hoang, S.: 1995, *Icarus* **116**, 202.

Miller, J. A.,: 1991, *Astrophys. J.* **376**, 342.

Miller, J. A.: 1997, *Astrophys. J.* **491**, 939.

Moncuquet, M, Bagenal, F., and Meyer-Vernet, N.: 2002, *J. Geophys. Res.* **107**, 1260.

Montgomery, M. D., Bame, S. J., and Hundhause, A. J.: 1968, *Geophys. J. Res.* **73**, 4999.

Moore, L., and Mendillo, M.: 2005, *J. Geophys. Res.* **110**, A05310.

Nieves-Chinchilla, T., and Viñas, A. F.: 2008, *Geofisica Internacional* **47**, 245.

Olsson, A., and Janhunen, P.: 1998, *Ann. Geoph.* **16**, 298.

Pandey, R. S., and Pandey, R. P.: 2008, *Prog. in Electromagn. Res. C* **2**, 217.

Pierrard V.: 1996, *J. Geophys. Res.* **101**, 2669.

Pierrard V.: 2009, *Planet. Space Sci.* **57**, 1260.

Pierrard, V., Khazanov, G. V., and Lemaire, J.: 2007, *J. Atmosph. Sol. Terr. Phys.* **69** issue 12, Recent Advances in the Polar Wind Theories and Observations, 2048-2057, guest editors: Tam, Pierrard and Schunk.

Pierrard, V., and Lamy, H.: 2003, *Solar Physics* **216**, 47.

Pierrard, V., Lamy, H., and Lemaire, J.: 2004, *J. Geophys. Res.* **109**, A02118.

Pierrard, V., and Lemaire, J.: 1996a,*J. Geophys. Res.* **101**, 7923.

Pierrard, V., and Lemaire, J.: 1996b, *Radiat. Meas.* **26**, 333.

Pierrard, V., and Lemaire, J.: 1998, *J. Geophys. Res.* **103**, 4117.

Pierrard, V., and Lemaire, J.: 2001, *J. Atmospheric and Solar-Terrestrial Physics* **63**, 1261.

Pierrard, V., Maksimovic, M., and Lemaire, J. F.: 1999, *J. Geophys. Res.* **104**, 17021.

Pierrard, V., Maksimovic, M., and Lemaire, J. F.: 2001, *J. Geophys. Res.* **106**, 29,305.

Pierrard, V., Maksimovic, M., and Lemaire, J.: 2001, *Astrophys. Space Sci.* **277**, 195.

Pierrard, V., and Stegen, K.: 2008, *J. Geophys. Res.* **113**, A10209.

Pilipp, W. G., Miggenrieder, H., Montgomery, M. D., Muhlhauser, K. H., Rosenbauer, H., and Schwenn, R.: 1987, *J. Geophys. Res.* **92**, 1075.

Pilipp, W. G., Miggenrieder, H., Montgomery, M. D., Muhlhauser, K. H., Rosenbauer, H., and Schwenn, R.: 1990, *J. Geophys. Res.* **95**, 6305.

Podesta, J. J.: 2005, *Phys. Plasmas* **12**, 052101.

Podesta, J. J.: 2008, *Phys. Plasmas* **15**, 122902.

Pokhotelov, O. A., Treumann, R. A., Sagdeev, R. Z., Balikhin, M. A., Onishchenko, O. G., Pavlenko, V. P., and Sandberg, I.: 2002, *J. Geophys. Res. A* **107**, 1312.

Pokhotelov, O. A., Sagdeev, R. Z., Balikhin, M. A., Onishchenko, O. G., and Fedun, V. N.: 2008, *J. Geophys. Res.* **113**, A04225.

Qureshi, M. N. S., Pallocchia, G., Bruno, R., Cattaneo, M. B., Formisano, V., Rème, H., Bosqued, J. M., Dandouras, I., Sauvaud, J. A., Kistler, L. M., Möbius, E., Klecker, B., Carlson, C.,W., McFadden, J. P., Parkjs, G. K., McCarthy, M., Korth, A., Lundin, R., Bologh, A., and Shah, H. A.: 2003, in M. Velli, R. Bruno and F. Malara (eds.), *Solar Wind Ten Proc.*, AIP Conference Proceedings **679**, p. 489.

Qureshi, M. N. S., Shi, J. K., and Ma, S. Z.: 2006, in Plasma Sci. IEEE Conf. Rec., 234.

Ralchenko, Yu., Feldman, U., and Doschek, G. A.: 2007, *Astrophys. J.* **659**, 1682.

Retherford, K. D., Moos, H. W., Strobel, D. F.: 2003, *J. Geophys. Res.* **108**, 1333.

Saini, N. S., Kourakis, I., and Hellberg, M. A.: 2009, *Phys. Plasmas* **16**, 062903.

Saito, S., Forme, F. R. E., Buchert, S. C., Nozawa, S., and Fujii, R.: 2000, *Ann. Geoph.* **18**, 1216.

Salem, C., Hubert, D., Lacombe, C., Bale, S. D., Mangeney, A., Larson, D. E., Lin, R. P.: 2003, *Astrophys. J.* **585**, 1147.

Schippers P., et al.: 2008, *J. Geophys. Res.* **113**, A07208.

Scudder, J. D.: 1992a, *Astrophys. J.* **398**, 299.

Scudder, J. D.: 1992b, *Astrophys. J.* **398**, 319.

Scudder, J. D.: 1994, *Astrophys. J.* **427**, 446.

Shizgal, B. D.: 2007, *Astrophys. Space Sci.* **312**, 227.

Shoub, E. C.: 1983, *Astrophys. J.* **266**, 339.

Singhal, R. P., and Tripathi, A. K.: 2007, *J. Plasma Phys.* **73**, 207.

Steffl, A. J., Bagenal, F., and Stewart, A. I. F.: 2004, *Icarus* **172**, 91.

Steinberg, J. T., Gosling, J.T., Skoug R.M., and Wiens, R. C. F.: 2005, *J. Geophys. Res.* **110**, A06103.

Stverak, S., Maksimovic M., Travnicek, P. M., Marsch, E., Fazakerley, A. N., and Scime, E. E.: 2009, *J. Geophys. Res.* **114**, A05104.

Stverak, S., Travnicek, P., Maksimovic, M., Marsch, E., Fazakerley, A. N., and Scime, E. E.: 2008, *J. Geophys. Res.* **113**, A03103.

Summers, D., and Ma, C.: 2000, *J. Geophys. Res.* **105**, 15,887.

Summers, D., and Thorne, R. M.: 1991, *Phys. Fluids B* **3**, 1835.

Summers, D., and Thorne, R. M.: 1992, *J. Geophys. Res.* **97**, 16827.

Summers, D., Xue, S., and Thorne, R. M.: 1994, *Phys. Plasmas* **1**, 2012

Tam, S. W. Y., Chang, T., and Pierrard, V.: 2007, *J. Atmosph. Sol. Terr. Phys.* **69**, issue 12, Recent Advances in the Polar Wind Theories and Observations, p. 1984, guest editors: Tam, Pierrard and Schunk.

Thorne, R. M., and Summers, D.: 1986, *Phys. Fluids* **29**, 4091.

Thorne, R. M., and Summers, D.: 1991, *Phys. Fluids B* **3**, 2117.

Treumann, R. A.: 1997, *Geophys. Res. Lett.* **24**, 1727.

Treumann, R. A.: 1999, *Phys. Scripta* **59**, 19.

Treumann, R. A.: 1999, *Phys. Scripta* **59**, 204.

Treumann, R. A.: 2001, *Astrophys. Space Sci.* **277**, 81.

Treumann, R. A., and Jaroschek, C. H.: 2008, *Phys. Rev. Lett.* **100**, 155005.

Treumann, R. A., Jaroschek, C. H., and Scholer, M.: 2004, *Phys. Plasmas* **11**, 1317.

Tripathi, A. K., and Misra, K. D.: 2000, *Earth, Moon and Planets* **88**, 131.

Tripathi, A. K., and Singhal, R. P.: 2008, *Planet. Space Sci.* **56**, 310.

Tsallis C.: 1995, *Phys. A* **221**, 277.

Valentini, F., and D'Agosta, R.: 2007, *Phys. Plasmas* **14**, 092111.

Vasyliunas, V. M.: 1968, *J. Geophys. Res.* **73**, 2839.

Viñas, A. F., Wong, H. K., and Klimas, A. J.: 2000, *ApJ.* **528**, 509.

Viñas, A. F., Mace, R. L., and Benson, R. F.: 2005, *J. Geophys. Res.* **110**, A06202.

Vocks, C., and Mann, G.: 2003, *Astroph. J.* **593**, 1134.

Vocks, C., Mann, G., and Rausche, G.: 2008, *Astron. Astrophys.* **480**, 527.

Vocks, C., Salem C., Lin R.P., and Mann, G.: 2005, *Astroph. J.* **627**, 540.

Wannawichian, S., Ruffolo, D., and Kartavykh, Yu. Yu.: 2003, *Astrophys. J. Suppl. S.* **146**, 443.

Xiao, F., Thorne, R. M., and Summers, D.: 1998, *Phys. Plasmas* **5**, 2489.

Xiao, F.: 2006, *Plasma Phys. Control. Fusion* **48**, 203.

Xiao, F., Zhou, Q., He, H., and Tang, L.: 2006, *Plasma Phys. Control. Fusion* **48**, 1437.

Xiao, F., Zhou, Q., Zheng, H., and Wang, S.: 2006, *J. Geophys. Res.* **111**, A08208.

Xiao, F., Zhou, Q., He, H., Tang, L., and Jiayuan, F.: 2007a, *Plasma Sci. Technol.* **9**, 545.

Xiao, F., Zhou, Q., He, H., Zheng, H., and Wang, S.: 2007b, *J. Geophys. Res.* **112**, A07219.

Xiao, F., Chen, L., and Li, J.: 2008, *Plasma Phys. Contr. Fusion* **50**, 105002.

Xiao, F., Zhou, Q., Li, C., and Cai, A.: 2008, *Plasma Phys Control Fusion* **50**, 062001.

Xiao, F., Shen, C., Wang, Y., Zheng, H., and Wang, S.: 2008, *J. Geophys. Res.* **113**, A05203.

Xue, s., Thorne, R. M., and Summers, D.: 1993, *J. Geophys. Res.* **98**, 17475.

Xue, s., Thorne, R. M., and Summers, D.: 1996a, *J. Geophys. Res.* **101**, 15457.

Xue, s., Thorne, R. M., and Summers, D.: 1996b, *J. Geophys. Res.* **101**, 15467.

Younsi, S., and Tribeche, M.: 2008, *P*hys. Plasmas **15**, 073706.

Zaheer, S., and Murtaza, G.: 2007, *Phys. Plasmas* **14**, 022108.

Zaheer, S., Murtaza, G., and Shah, H. A.: 2004, *Phys. Plasmas* **11**, 2246.

Zhou, Q. H., Jiang, B., Shi, X. -H., and Li, J. -Q.: 2009, *Chin. Phys. Lett.* **26** 025201.

Zouganelis, I.: 2008, *J. Geophys. Res.* **113**, A08111.

Zouganelis, I., Maksimovic, M., Meyer-Vernet, N., Lamy, H., and Issautier, K.: 2004, *Astrophys. J.* **606**, 542.

Zouganelis, I., Meyer-Vernet, N., Landi, S., Maksimovic, M., and Pantellini, F.: 2005, *Astrophys. J. Lett.* **626**, L117.