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# Measuring suprathermal electron parameters in space plasmas: Implementation of the quasi-thermal noise spectroscopy with kappa distributions using in situ Ulysses/URAP radio measurements in the solar wind

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[1] We discuss the implementation of the quasi-thermal noise spectroscopy using kappa velocity distribution functions for the electrons. The quasi-thermal noise spectroscopy is a powerful tool for in situ space plasma diagnostics based on the analysis of the electrostatic field spectrum produced by the quasi-thermal fluctuations of electrons. The electron parameters are obtained by fitting the voltage power spectrum calculated with a model of the particle velocity distribution to the voltage measured at the terminals of an electric antenna. In the present work, the model of spectrum due to the electrons is depending on only three parameters and computed by assuming that the electron velocity distribution is a generalized Lorentzian or “kappa” distribution. The three fitted parameters are thus the electron density, total temperature and kappa index of the distribution. We show for the first time that this model produces good quality fittings for solar wind measurements obtained by the radio receiver on Ulysses, which should enable to improve the accuracy of the measurement of the total electron temperature and give better information on the suprathermal electrons.

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## 1. Introduction

[2] Observed electron velocity distribution functions (eVDFs) of the solar wind permanently exhibit three different components: a thermal core and a suprathermal halo, which are always present at all pitch angles, and a magnetic field aligned “strahl” which is usually moving antisunward [Feldman *et al.*, 1975; Pilipp *et al.*, 1987]. At 1 AU, the core has a typical temperature of roughly  $10^5$  K and represents about 95% of the total electron number density. The halo population has a typical temperature of  $7 \times 10^5$  K and represents together with the strahl the remaining portion of the total electron number density.

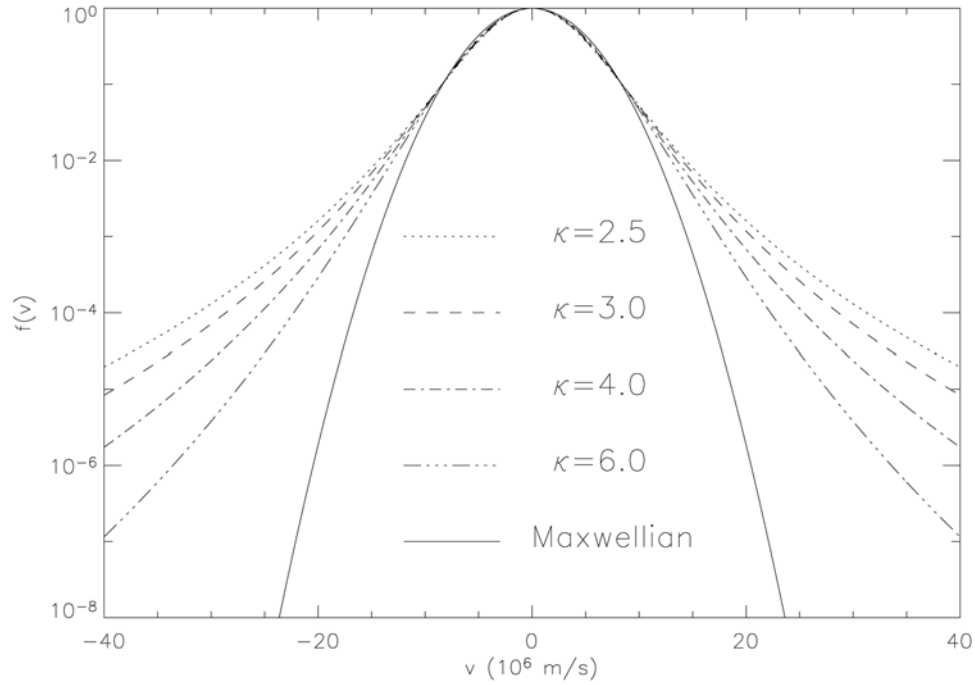
[3] What is the origin of these non-Maxwellian eVDFs observed in the solar wind? Are such distributions already present in the solar corona or are they only a consequence of the solar wind transport in the interplanetary medium? Because of their small mass and therefore large thermal speed, the solar wind electrons are expected to play a major role for the internal energy transport in the corona [Landi and Pantellini, 2003] and the solar wind [Maksimovic *et al.*, 1997; Zouganelis *et al.*, 2004, 2005]. For studying these problems, we need accurate in situ measurements of the

solar wind electron density, temperature and the nonthermal properties of the electrons.

[4] However, traditional electron analyzers are usually polluted by the spacecraft charging effects and the photoelectrons as was the case of the Ulysses/SWOOPS experiment [Issautier *et al.*, 1999] or the Wind/3DP experiment [Salem *et al.*, 2001]. For this reason, in order to measure accurately the electron properties, we need to implement an alternative method, the quasi-thermal noise spectroscopy (QTN) [Meyer-Vernet and Perche, 1989], which is immune to the limitations due to spacecraft charging and photoelectrons [Meyer-Vernet *et al.*, 1998; Neugebauer, 2001].

[5] When a passive electric antenna is immersed in a stable plasma, the thermal motion of the ambient particles produces electrostatic fluctuations, which can be adequately measured with a sensitive wave receiver connected to a wire dipole antenna. This quasi-thermal noise (QTN) is completely determined by the particle velocity distributions in the frame of the antenna. The problem is simpler in the absence of a static magnetic field or at frequencies much higher than the electron gyrofrequency, since in this case the plasma can be considered to be an assembly of dressed test particles moving in straight lines. The QTN spectrum around the plasma frequency  $f_p$  consists of a noise peak just above  $f_p$  produced by electron quasi-thermal fluctuations. Since the plasma density  $n_e$  is proportional to  $f_p^2$ , this allows an accurate measurement of the electron density. In addition, since the shape of the spectrum is determined by

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**Figure 1.** Several examples of kappa functions with  $\kappa = 2.5, 3.0, 4.0$  and  $6.0$ , all normalized to the same value at  $v = 0$ :  $f(0) = 1$ . In the limit  $\kappa \rightarrow \infty$ , the functions degenerate to a Maxwellian (solid line).

the electron velocity distribution, the analysis of the spectrum reveals its properties.

[6] This method was first introduced for studies of the solar wind by *Meyer-Vernet* [1979]. It has been extensively used in space missions and has yielded routine measurements of the solar wind electron plasma parameters for space missions such as *Ulysses* [Maksimovic et al., 1995; Hoang et al., 1996; Issautier et al., 1998] or *WIND* [Maksimovic et al., 1998; Salem et al., 2001]. It has been also used in various environments, magnetized or not, as planetary media [Moncuquet et al., 1995, 1997, 2005] or a cometary plasma tail [Meyer-Vernet et al., 1986].

[7] Until now, only a sum of two Maxwellian functions has been used for modeling the electron velocity distributions. The observations have shown that this is not the case as the suprathermal electrons are better fitted by kappa functions [Maksimovic et al., 2005]. In order to make the QTN spectroscopy more reliable we need to use this kind of functions that better represent the real observations in the solar wind. In this paper we show that the quasi-thermal noise produced with generalized Lorentzian (“kappa”) distributions for the electrons calculated by *Chateau and Meyer-Vernet* [1991] can be applied successfully to *Ulysses*. This form has the advantage of being analytically tractable, while representing rather well the electron distribution in different media such as the solar wind or planetary magnetospheres.

[8] The present paper uses *Ulysses* data to show that kappa functions can be implemented in the QTN spectroscopy, providing an impressive agreement between the computed and observed voltage power spectra. This new method provides directly the total electron temperature and gives, for the first time, an estimation of the kappa parameter, which quantifies simply the amount of suprathermal electrons. This new technique will be used in future space

missions such as the *BepiColombo* mission to Mercury [Moncuquet et al., 2006], as well as the *Solar Orbiter*, the *Sentinels* and possibly the *Solar Probe* (PHOIBOS) mission [Maksimovic et al., 2008].

[9] In section 2 we recall the properties of the kappa function and its importance in space physics. In sections 3 and 4 we recall the theory of the QTN in a drifting electron plasma and give the relevant analytical expressions including the exact calculations of the QTN with kappa functions. In section 4 we apply our method in the solar wind using the radio receiver on the *Ulysses* spacecraft.

## 2. Kappa Velocity Distribution Functions

[10] The kappa function is defined as:

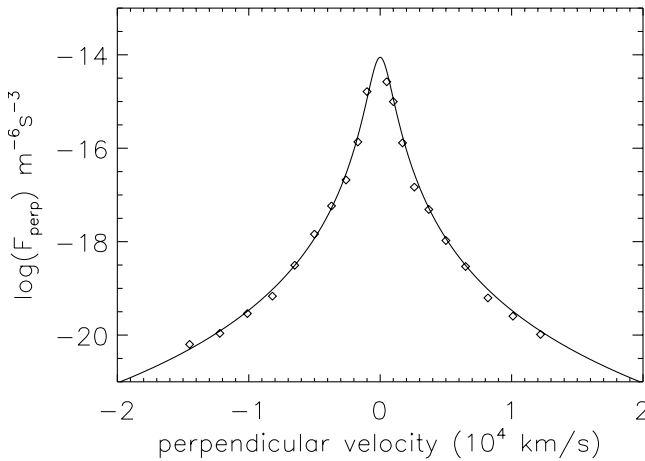
$$f_{\kappa}(v) = \frac{n_{e0}}{(\pi \kappa v_{\kappa}^2)^{3/2}} \frac{\Gamma(\kappa + 1)}{\Gamma(\kappa - 1/2)} \left(1 + \frac{v^2}{\kappa v_{\kappa}^2}\right)^{-(\kappa+1)} \quad (1)$$

where  $\Gamma(x)$  is the Gamma function and  $v_{\kappa}$  is the thermal speed defined by:

$$v_{\kappa} = \left(\frac{2\kappa - 3}{\kappa} \frac{k_b T_e}{m_e}\right)^{1/2} \quad (2)$$

where  $k_b$  is the Boltzmann constant and  $m_e$  the electron mass.

[11] Figure 1 displays various examples of kappa functions for  $2.5 \leq \kappa < \infty$ . They are all normalized to the same value at  $v = 0$ :  $f(0) = 1$ . For  $v \gg v_{\kappa}$ , the kappa distribution decreases with  $v$  as a power law ( $f_{\kappa} \propto v^{-2(\kappa+1)}$ ). From Figure 1, we can also see that in the limit  $\kappa \rightarrow \infty$ ,  $f_{\kappa}(v)$  reduces to a Maxwellian distribution.



**Figure 2.** Typical electron velocity distribution function measured in the solar wind. The boxes are observations of the perpendicular velocity distribution obtained by the Ulysses/SWOOPS electron analyzer at 1.5AU. The solid curve is a fitted kappa function with  $\kappa = 2.6$ .

[12] These functions were introduced to describe the departure of actual electron distributions from Maxwellians in the interplanetary medium and the Earth's magnetosphere [Vasyliunas, 1968]. From the theorist's point of view, the kappa functions have the interest of being analytically easily tractable. Furthermore the electron velocity distribution functions (VDFs) in the solar wind are not Maxwellian. They exhibit high-energy (nonthermal) tails that have been modeled by a halo Maxwellian population [Feldman et al., 1975] or, more recently, by the power-law part of a kappa function [Maksimovic et al., 1997]. Figure 2 shows an example of an electron velocity distribution function obtained by the Ulysses/SWOOPS electron analyzer at 1.5 AU. At high energies the distribution is no longer Maxwellian but has high-energy tails which are better fitted by a kappa function.

[13] These tails can develop even in moderately collisional plasmas as a result of the rapid increase of the particle free paths with speed ( $\propto v^4$ ). For instance, the existence of such electron VDFs in the upper chromosphere has been suggested to be the reason for the rapid rising of the temperature in the chromosphere-corona transition region through the mechanism of gravitational velocity filtration [Scudder, 1992] as well as the main reason for the acceleration of the fast solar wind [Zouganelis et al., 2004, 2005]. Indeed, there is an increasing amount of observational evidence showing that nonthermal VDFs may exist in the corona and even in the high chromosphere [Owocki and Ko, 1999; Pinfield et al., 1999; Esser and Edgar, 2000; Chiuderi and Chiuderi Drago, 2004; Doyle et al., 2004]. Some theoretical works on the possible generation mechanisms of such nonthermal electron distributions in the chromosphere [Roberts and Miller, 1998; Viñas et al., 2000] and the corona [Vocks and Mann, 2003] have been published. Others have been trying to show that kappa distributions can be a natural, and quite general, state of weakly collisional plasmas and not merely a convenient mathematical way of describing non thermal VDFs

[Collier, 1993; Ma and Summers, 1999; Treumann, 1999; Leubner, 2002; Collier, 2004; Yoon et al., 2006].

### 3. Quasi-thermal Noise

#### 3.1. Basics of the Method-Electron Thermal Noise

[14] The voltage spectral density measured at the terminals of an electric antenna, which is immersed in a plasma drifting with velocity  $\mathbf{V}$ , is

$$V_{\text{QTN}}^2(\omega) = \frac{2}{(2\pi)^3} \int d^3k \frac{|\mathbf{k} \cdot \mathbf{J}|^2}{k^2} E^2(\mathbf{k}, \omega - \mathbf{k} \cdot \mathbf{V}) \quad (3)$$

The first term in the integral represents the spatial Fourier transform  $\mathbf{J}(\mathbf{k})$  of the current distribution on the antenna. For a wire dipole antenna made of two thin filaments, each of length  $L$  and radius  $a \ll L$ , parallel to the  $x$  axis, we have

$$\mathbf{k} \cdot \mathbf{J} = 4 \frac{\sin^2(k_x L/2)}{k_x L} \quad (4)$$

where we assume that the current has a linear variation (i.e., the charge distribution is constant on each antenna arm). This approximation holds, in general, whenever the filament radius is much smaller than the electrostatic wavelengths, i.e.,  $a \ll L_D$  and  $\omega L/c \ll 1$  [Schiff, 1971].

[15] The second term in the integral is the Fourier transform of the autocorrelation function of the electrostatic field fluctuations in the antenna frame. Since we consider frequencies much above the Larmor frequencies, so that the ambient static magnetic field can be neglected, we have

$$E^2(\mathbf{k}, \omega) = 2\pi \sum_i \frac{q_i^2 \int d^3v f_i(\mathbf{v}) \delta(\omega - \mathbf{k} \cdot \mathbf{v})}{\epsilon_0^2 k^2 |\epsilon_L(\mathbf{k}, \omega)|^2} \quad (5)$$

where  $f_i$  is the velocity distribution function of the  $i$ th species of charge  $q_i$  and  $\epsilon_L(\mathbf{k}, \omega)$  is the plasma longitudinal dielectric function.

#### 3.2. Proton Thermal Noise

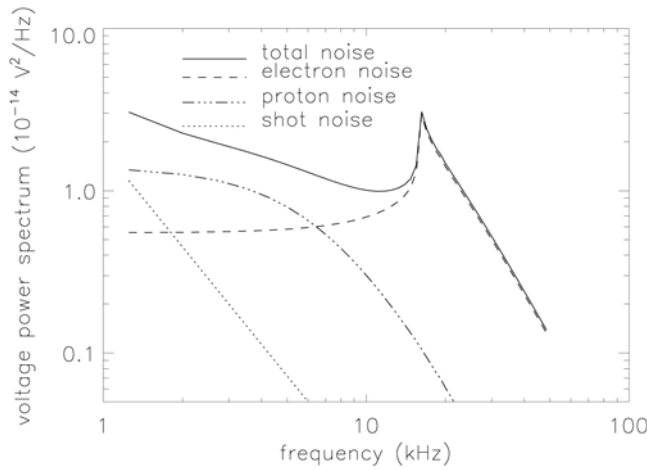
[16] The proton contribution to the voltage power spectrum given in (3) has been extensively studied by Issautier et al. [1999]. If the antenna is perpendicular to the solar wind velocity  $\mathbf{V}$ , the proton thermal noise may be approximated by:

$$V_p^2(\omega) = \frac{(2m_e k_B)^{1/2} \sqrt{T_e}}{4\pi\epsilon_0 M} \int_0^\infty dy \times \frac{y F_\perp(yL/L_D)}{(y^2 + 1 + \Omega^2)(y^2 + 1 + \Omega^2 + t)} \quad (6)$$

$$\Omega = \omega L_D / V, \quad t = T_e / T_p, \quad M = V / v_{the} \quad (7)$$

[17]  $F_\perp(x)$  is the antenna response to a wave field having a cylindrical symmetry [Meyer-Vernet et al., 1993]:

$$\begin{aligned} F_\perp(x) &= \frac{64}{\pi} \int_0^x ds \frac{\sin^4(s/2)}{s^2(x^2 - s^2)^{1/2}} \\ &= \frac{8}{x} \left[ 2 \int_0^x dt J_0(t) - \int_0^{2x} dt J_0(t) \right. \\ &\quad \left. + J_1(2x) - 2J_1(x) \right] \end{aligned}$$



**Figure 3.** A typical theoretical thermal noise spectrum with a kappa velocity distribution for the electrons (solid line). There are three main different contributions: the electron quasi-thermal noise (dashed line), the doppler-shifted proton noise (dashed-dotted line) and the shot noise (dotted line). The peak of the spectrum occurs at the plasma frequency.

where  $J_0$  and  $J_1$  denote the Bessel functions of the first kind and  $L_D$  is the electron Debye length.

### 3.3. Shot Noise and Antenna Impedance

[18] Since the wire dipole antenna used is not a grid antenna, there is an additional noise due to the particles whose trajectory intercepts the antenna and also to the photoelectrons which are emitted by the antenna surface. This shot noise becomes important only for  $f \ll f_p$  and decreases as  $1/f^2$ . Although it is generally small for the antenna used on Ulysses, we have to take it into account to make an accurate plasma diagnostic. A good approximation for the total noise at the antenna terminals below  $f_p$  can be obtained by simply adding to the electron-plus-ion QTN the term representing the shot noise [Meyer-Vernet and Perche, 1989],

$$V_I^2 = 2e^2 N_e A |Z|^2 \quad (9)$$

where  $N_e$  is the electron impact rate on one antenna arm, the factor  $A \approx 1 + e\phi/k_B T_e$  comes from a first-order approximation of the shot noise (the DC potential  $\phi$  is estimated to be  $\sim 4$  V) and  $Z$  is the antenna impedance, defined by

$$Z(\omega) = \frac{j}{(2\pi)^3 \epsilon_0 \omega} \int d^3 k \frac{|\mathbf{k} \cdot \mathbf{J}(\mathbf{k})|^2}{k^2 \epsilon_L(\mathbf{k}, \omega - \mathbf{k} \cdot \mathbf{V})} \quad (10)$$

which takes into account the effect of the ambient plasma. Note that the uncertainty on the determination of  $\phi$  does not affect significantly our results because we only take into account the data for which the shot noise contribution  $V_I^2$  to the total noise is very small.

[19] The terminals of the antenna of impedance  $Z$  are connected through an input circuit to a receiver with a finite input impedance  $Z_R$  which is mainly due to the antenna base

capacitance [Couturier et al., 1983]. Then the voltage spectral density measured at the receiver input terminals is

$$V_R^2 = V_\omega^2 \left| \frac{Z_R}{Z_R + Z} \right|^2 \quad (11)$$

where the total quasi-thermal noise  $V_\omega^2$  is the sum of  $V_p^2(\omega)$ ,  $V_e^2(\omega)$ , and  $V_I^2(\omega)$ , given by expressions (6), (3), and (9), respectively.

[20] In Figure 3, we can see a typical QTN spectrum in the solar wind (solid line) and the different contributions explained in this section: the electron thermal noise (dashed line), the doppler-shifted proton noise (dashed-dotted line) and the shot noise (dotted line).

## 4. Kappa Electron Thermal Noise

[21] Chateau and Meyer-Vernet [1991] have shown that for a kappa function with integer kappa, the longitudinal dielectric permittivity is given by the following relation:

$$\epsilon_L = 1 + \frac{z^2}{r^2} \cdot \left( 2\kappa - 1 + \frac{(-2)^{\kappa+1}}{(2\kappa - 3)!!} i z \sum_{p=0}^{\kappa} \frac{(\kappa + p)!}{p!} \frac{1}{(2i)^{\kappa+1+p} (z + i)^{\kappa+1-p}} \right) \quad (12)$$

where  $z = \omega/\kappa^{1/2} k v_\kappa$  and  $r = \omega/\omega_p = f/f_p$ , and that the fluctuations of the electrostatic field are given by:

$$V_e^2 = \frac{2^{\kappa+3}}{\pi^2 \epsilon_0} \frac{\kappa!}{(2\kappa - 3)!! \kappa^{1/2}} \frac{m v_\kappa}{r^2} \int_0^\infty dz z \cdot F\left(\frac{ru}{z(2\kappa - 1)^{1/2}}\right) \left[ (1 + z^2)^\kappa |\epsilon_L|^2 \right]^{-1} \quad (13)$$

where  $u = L/L_D$  with  $L_D$  the Debye length for this kind of plasma given by:

$$L_D = \frac{1}{\omega_p} \left( \frac{k_B T}{m} \frac{2\kappa - 3}{2\kappa - 1} \right)^{1/2} \quad (14)$$

and  $F$  a function that depends on the geometry of the antenna and for a wire dipole is given by:

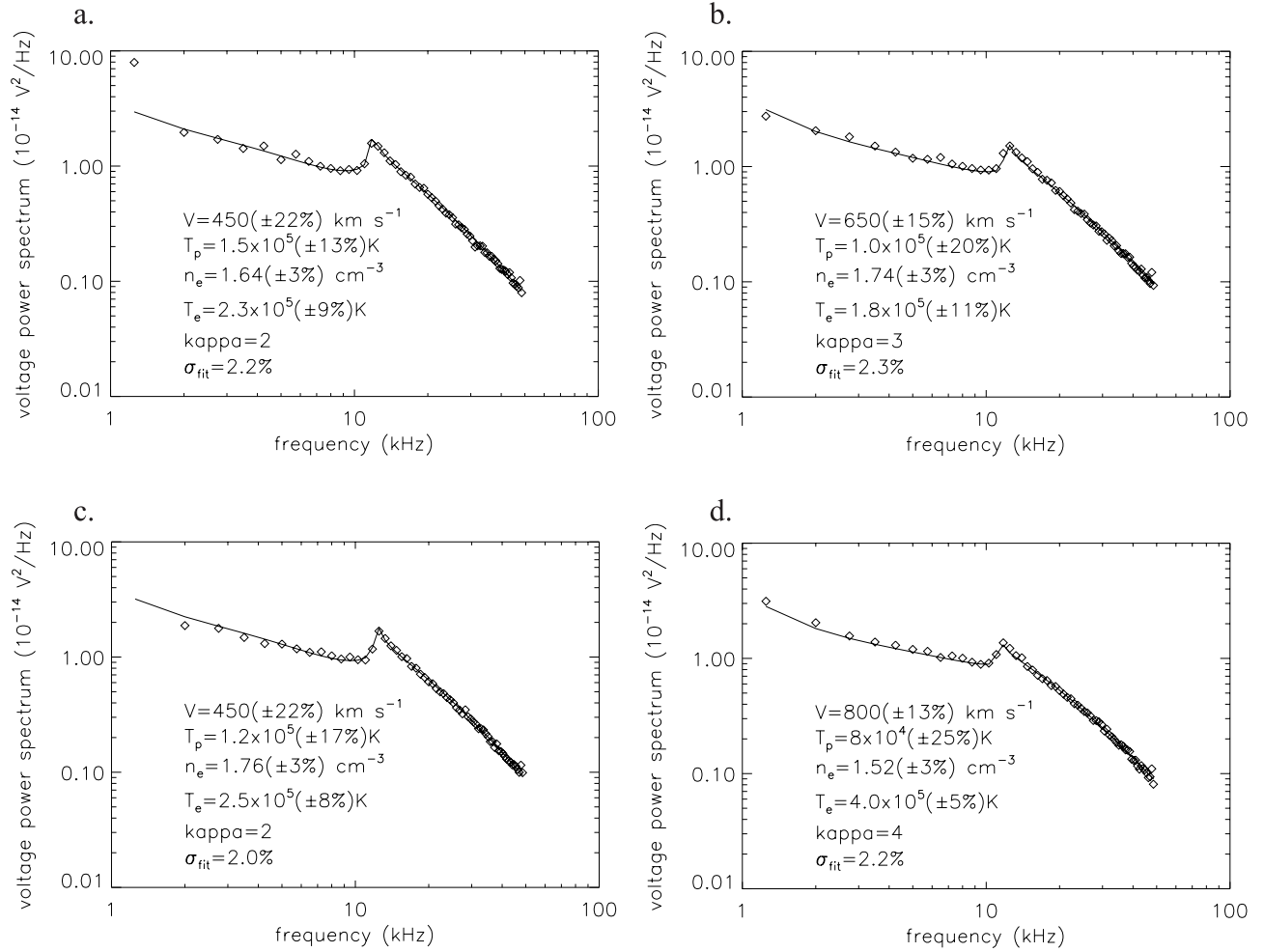
$$F(x) = \frac{1}{x} \left[ Si(x) - \frac{1}{2} Si(2x) - \frac{2}{x} \sin^4\left(\frac{x}{2}\right) \right] \quad (15)$$

where Si is the sine integral function.

## 5. Application on Ulysses and Discussion

[22] The scope of this paper is to show that the observed quasi-thermal noise spectra can be well fitted assuming a kappa function as a description of the electron velocity distributions. The interest of using kappa functions is bifold. First, we are able to deduce the kappa parameter and therefore have information on suprathermal electrons. Second, we are able to directly deduce the total electron temperature using a presumably better model of the electron velocity distribution.





**Figure 4.** Typical voltage power spectra (in  $10^{-14} \text{V}^2 \text{Hz}^{-1}$ ) measured with the Unified Radio and Plasma Wave radio instrument on Ulysses. Solid lines are the best fits to the data (boxes), with the deduced parameters indicated.

### 5.1. Unified Radio and Plasma Wave Receiver

[23] The observations were performed with the Unified Radio and Plasma Wave (URAP) radio receiver [Stone *et al.*, 1992], connected to the long wire  $2 \times 35$  m electric dipole antenna, located in the spacecraft spin plane. The receiver is linearly swept through 64 equally spaced and contiguous frequency channels (of bandwidth 0.75 kHz and duration 2 s), covering the low-frequency band from 1.25 to 48.5 kHz in 128 s. This receiving mode is well suited to measure thermal noise spectra on Ulysses with a good frequency resolution. Besides the receiver is extremely sensitive, and the ratio of the signal to receiver noise is higher than in most previously flown instruments, which enables us to analyze accurately the plasma thermal noise.

### 5.2. Numerical Implementation

[24] Practically, the plasma diagnostic is performed by (1) assuming the above velocity distributions, (2) calculating the theoretical spectrum  $V_R^2$  produced by these distributions, and (3) deducing the five unknown parameters of the model by fitting the theory to the whole measured spectrum, using a classic least squares fitting procedure. The five unknown parameters are the electron density  $n_e$  (or equivalently the plasma frequency  $f_p$ ), the electron temperature  $T_e$ , the

parameter  $\kappa$ , the proton temperature  $T_p$  and the solar wind bulk speed  $V$ .

[25] The numerical process basically consists of fitting the theoretical voltage spectral density  $\log V_R^2$  to each measured spectrum by minimizing a  $\chi^2$  merit function with the five free abovementioned parameters. In this paper, because of the use of only integer values of kappa, we used a high-resolution five-dimensional grid of precomputed spectra and fit the data by minimizing the  $\chi^2$ . An improved numerical approach based on a Levenberg-Marquardt method and real kappa values will be given in a forthcoming paper but is beyond the scope of the present paper, which aims to show the usefulness of kappa functions in the QTN spectroscopy.

### 5.3. Results and Discussion

[26] Figure 4 shows several typical examples of spectra routinely obtained with the Ulysses low-frequency receiver in the solar wind. The bold solid lines represent the best fit of the theoretical QTN spectrum (electron, proton and shot noise divided by the gain factor) to the observed spectrum plotted as boxes. As explained by Issautier *et al.* [1999], we do not take into account the two lowest frequencies of the spectrum for which the thermal noise is not sufficiently

large compared with the receiver noise level. These spectra are taken in different types of winds (slow or fast wind and dense or dilute flows) encountered by the spacecraft during its first pole to pole exploration in 1994–1995. The five deduced parameters are indicated on the plots as well as the overall standard deviation  $\sigma_{fit}$  of the theory from the data. This latter parameter quantifies the quality of the fit. The fittings are as good as in previous works ( $\sigma_{fit} < 2.5\%$ ) using a sum of two Maxwellians [Issautier *et al.*, 1999], even if there is one less free parameter. The determination of the plasma frequency  $f_p$  is the same as in previous results, as it does not depend on the distribution function, so that we obtain the total electron density with a very low uncertainty. It is interesting to note that this frequency measurement is also independent of the receiver gain calibration which makes the result even more reliable.

[27] The peak shape strongly depends on the distribution of the high-energy electrons. For a power-law tail the peak is exactly at the plasma frequency (in contrast to what happens with a Maxwellian tail). However, there is a basic constraint for the measurement of the high-energy electron parameters. Even if the receiver has a sufficient frequency resolution around the plasma frequency, the observed peak is broadened because of the density fluctuations, since in practice the spectrum is acquired over a finite time. Ideally, a frequency resolution of the order of 1% and a time resolution better than a fraction of a second are needed, which is not the case of Ulysses. Indeed, on Ulysses, the spectrum peak is generally defined by three consecutive frequencies acquired in 6s, so that the plasma density fluctuations can broaden the spectral peak and limit the accuracy on the measurements of the suprathermal parameters. However, the kappa parameter deduced, which is mainly in the range 2–5 indicates the presence of conspicuous suprathermal tails and is in agreement with the results by Maksimovic *et al.* [1997] who fitted the SWOOPS electron distribution functions on Ulysses and found a kappa within the same range of values.

## 6. Conclusion

[28] In this work, the quasi-thermal noise spectroscopy has been used for the first time to fit in situ electron measurements using kappa velocity distributions for the electrons. We have shown that this is possible, thus making this method even more reliable when dealing with plasmas that exhibit a large fraction of suprathermal electrons. The kappa parameter ranges between 2–5 in agreement with previous analysis done on electron distribution functions. This method is expected to provide directly the total electron temperature with a better precision. The main question about the solar wind electrons is the origin of the non-Maxwellian distributions that are observed. Are such distributions already present in the solar corona or are they only a consequence of the solar wind transport in the interplanetary medium? For answering this question we need to know the kappa parameter as a function of the heliocentric distance. A recent work by Maksimovic *et al.* [2005] who used Helios, Wind and Ulysses data between 0.3 and 1.5 AU has shown that the kappa parameter is decreasing with distance, providing some useful insight in the origin of these non-Maxwellian distributions. The pres-

ent method of kappa quasi-thermal noise spectroscopy will be used for further analyzing these electron properties and constraining solar wind models. It would be also applied to future solar missions such as the Solar Orbiter, the Sentinels and the Solar Probe that would visit the solar wind acceleration region of the corona as the QTN spectroscopy is immune to the spacecraft potential and photoelectron perturbations which, in general, affect particle analyzers.

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