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A novel method to measure the solar wind speed

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Abstract. We propose a novel method to measure *in situ* the bulk speed of a space plasma. It is based on the analysis of the electrostatic field spectrum produced by the Doppler-shifted thermal fluctuations of the plasma ions which can be measured with a sensitive receiver at the terminals of a passive electric antenna. We present a preliminary application in the solar wind using the data acquired in the ecliptic plane by the Unified Radio and Plasma experiment (URAP) on the Ulysses spacecraft. This should allow us to extend to the bulk speed the method of thermal noise spectroscopy which already gives an accurate *in situ* diagnosis of the electron density and bulk temperature. This method can be complementary to classical electrostatic analyzers for both interplanetary and magnetospheric studies.

Introduction

In a stable plasma, the thermal motions of the particles produce electrostatic fluctuations, which are completely determined by the particle velocity distributions [*Rostoker*, 1961].

This quasi-thermal noise can be measured with a sensitive receiver at the terminals of a passive electric antenna. Its spectrum around the plasma frequency f_p consists of a peak close to it produced by quasi-thermal Langmuir waves, and below f_p a plateau produced by electron thermal fluctuations (see Figure 1). Thus, its analysis can yield an accurate diagnosis of the bulk density and temperature of the ambient electrons (see [*Meyer-Vernet and Perche*, 1989] and references therein).

This method, first introduced in the solar wind by *Meyer-Vernet* [1979], has been recently applied in a large range of heliocentric distances [*Hoang et al.*, 1992 ; *Maksimovic et al.*, 1995] using the data of the URAP experiment on the Ulysses spacecraft [*Stone et al.*, 1992]. It has the advantage of being relatively immune to spacecraft potential perturbations, which complicate the analysis of electrostatic analyzer data [*Scime et al.*, 1994], and can thus be used to cross-check other instruments.

In this paper, we propose an extension of this theory to measure also the plasma bulk speed V. In the solar wind, the proton and electron thermal velocities, respectively v_{thp} and v_{the}, satisfy the inequality $v_{thp} \ll V \ll v_{the}$. Hence, the bulk velocity has essentially not effect on the electron thermal noise spectrum ; on the contrary, the proton noise spectrum is strongly Doppler-shifted (see solid curve below f_p in Figure 1) and it can be observed far above the proton characteristic frequencies, and therefore be used to measure the bulk speed V.

In an attempt to calculate this proton thermal noise on a wire dipole antenna in the solar wind, it has been argued that it is maximum when the antenna is parallel to $\mathbf{V}$, and negligible when it is perpendicular [*Kellogg*, 1981]. However, a careful examination [*Meyer-Vernet et al.*, 1986] shows that the opposite is generally true, as explained below.

First, because the bulk speed satisfies the inequality $V \gg v_{thp}$, the protons contribute most to the field autocorrelation spectrum $E^2(\mathbf{k}, \omega - \mathbf{k}.\mathbf{V})$ at the angular frequency $\omega \approx \mathbf{k} \cdot \mathbf{V}$, whence $k > \omega/V$. Second, ω must not be too small with respect to ω_p, otherwise the ther-

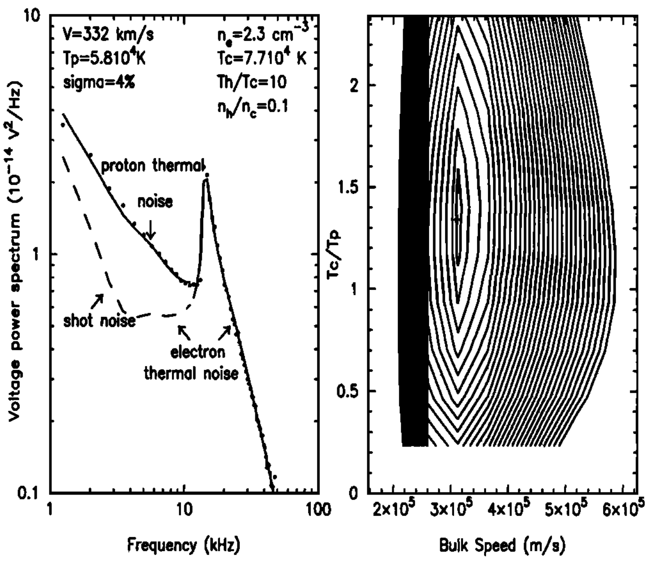

Figure 1. Example of voltage power spectrum (in 10^{-14} $\mathrm{V^2Hz^{-1}}$) measured with the URAP 2x35-m dipole antenna, at about 1.56 AU from the sun. The data are plotted as heavy dots. Above f_p, the solid line shows the theoretical electron quasi-thermal noise (QTN), with the best fit parameters shown (the dashed line shows the QTN plus the shot noise). Below f_p, the solid curve takes into account the ion thermal noise given by Eq.(1), with the best fit parameters V and T_p. On the right panel, which shows isocontours of the χ^2 (scaled every 3-sigma), one sees that the method is much more adequate to measure V than T_p.

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mal noise would be hidden by the shot noise produced by plasma electron impacts on the antenna surface (and photoelectron emission), which varies as ω_p^2/ω^2. Third, for Ulysses long antenna in the solar wind, the antenna length L satisfies $\omega_p L/V \gg 1$. Hence $kL \gg 1$.

In that case, *Meyer-Vernet* [1994] showed that the antenna response is maximum when the wave vector is roughly perpendicular to the antenna. This is because a wire dipole of length L favors wave vectors $\mathbf{k}$ whose projection along its direction equals π/L (higher multiples are less favored since the response decreases with the projected wavelength because of signal averaging along the antenna). Since $kL \gg 1$, the favored $\mathbf{k}$ are roughly perpendicular to the antenna, and the Doppler-shift $\mathbf{k}\cdot\mathbf{V}$ is maximum when the antenna is perpendicular to $\mathbf{V}$. So is the Doppler-shifted ion thermal noise.

This noise was already observed by the radio receiver on ISEE-3 in the solar wind, and interpreted by *Meyer-Vernet et al.* [1986] using computations by *Couturier et al.* [1983]. But the numerical calculations were too complicated to yield a practical method of plasma diagnosis.

In this paper, we introduce an easy-to-compute formula approximating the theoretical result. Then the quasi-thermal noise, measured when the antenna is approximately perpendicular to $\mathbf{V}$, yields the plasma bulk speed.

Ion thermal noise in a supersonic plasma

The voltage power spectrum of the ion thermal noise at the terminals of an electric antenna in a plasma drifting with velocity $\mathbf{V}$ is

$$V_i^2(\omega) = \frac{2}{(2\pi)^3}\int d^3k \frac{|\mathbf{k}\cdot\mathbf{J}|^2}{k^2} E_i^2(k, \omega - \mathbf{k}\cdot\mathbf{V})$$

The first term in the integral is the Fourier transform of the current distribution along the antenna. For a thin wire dipole of total length $2L$, assumed parallel to the x-axis, we have

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

The second term in the integral is the autocorrelation function of the ion contribution to the electrostatic field fluctuations in the antenna frame (see for example [*Sitenko*, 1967]).

Hence, in general, $V_i^2(\omega)$ is given by a 3-dimensional integral, whose calculation requires complex numerical computations [*Couturier et al.*, 1983; *Meyer-Vernet et al.*, 1986]. However, when the antenna is perpendicular to the velocity and in the case $V \gg v_{thp}$, which holds in the solar wind, we can simplify this expression [*Issautier*, 1995], to obtain finally

$$V_i^2(\omega) = \frac{k_B T_e}{2\pi\epsilon_0 V}\int_0^\infty dy \times \frac{y \quad F_\perp(yL/L_D)}{(y^2+1+\Omega^2)(y^2+1+\Omega^2+t)} \quad (1)$$

$$y = kL_D, \quad \Omega = \omega L_D/V, \quad t = T_e/T_p.$$

The function $F_\perp$ is the antenna response to a wave field having a cylindrical symmetry as defined by *Meyer-Vernet et al.* [1993]. The parameter L_D means the electron Debye length generalized to a non-Maxwellian distribution, i.e, $L_D = (\epsilon_0 k_B T_e/ne^2)^{1/2}$, where n is the electron density, e the electron charge, k_B Boltzmann's constant, and T_e a generalized electron temperature [*Chateau and Meyer-Vernet*, 1991] defined by $k_B T_e/m_e = 1/\langle v^{-2}\rangle$ (the brackets denote an average over the electron velocity distribution). With a Maxwellian of temperature T, this is equivalent to the usual definition of temperature, i.e, $T_e = T$. However, the solar wind electrons are not in equilibrium and can be described at a first approximation by the superposition of a cold plus a hot Maxwellian (the so-called " core + halo "), with $\alpha = n_h/n_c \ll 1$ and $\tau = T_h/T_c \gg 1$ [*Feldman et al.*, 1975; *McComas et al.*, 1992]. In that case, $T_e = T_c(1+\alpha)/(1+\alpha\tau^{-1})$, so that the temperature T_e is roughly equal to the core electron temperature T_c.

Deducing the bulk speed

The electron density and core temperature are deduced by fitting the computed result of the electron contribution $V_e^2(\omega)$ to the thermal noise spectrum measured in the frequency range $f \geq f_p$, where the ion contribution is negligible (see *Meyer-Vernet and Perche*, [1989] ; *Maksimovic et al.* [1995]). On the other hand, for $f < f_p$, the noise is given by the sum $V_i^2(\omega)+V_e^2(\omega)$, plus the shot noise, which is important only for $f \ll f_p$. We can then deduce the bulk speed by fitting the theoretical result to the noise observed below f_p when the antenna is roughly perpendicular to $\mathbf{V}$ (which is close to the antisunward direction), with only two unknown parameters, V and T_p.

The left panel of Figure 1 shows a typical example of such a fitting. For low frequencies, the best fit (the sigma is a few %) between the theoretical formula (1) and the URAP data points yields the speed and the proton temperature. The right panel shows isocontours of a χ^2 merit function : the speed is well determined by a narrow valley and an error in the estimated T_p does not affect the measurement of V. The uncertainty on our speed determination is given by the χ^2 method ; the first contour shows the 1-sigma level and so represents the numerical speed error which is less than 10%. The method is thus better adapted to determine V.

The upper panel of Figure 2 represents an example of the time evolution of power spectra such as shown in Figure 1, as the solar wind blows past Ulysses. The

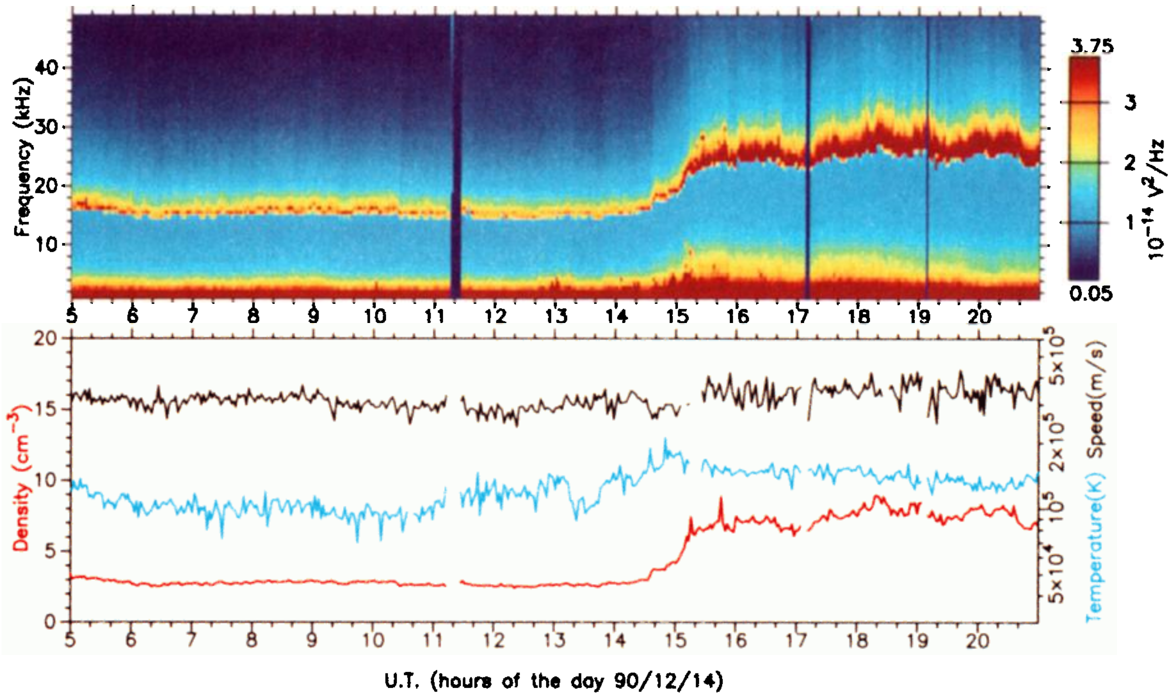

Figure 2. Example of plasma diagnosis obtained from quasi-thermal noise spectroscopy. These spectra were acquired on 90/12/14 and the Ulysses heliocentric distance was about 1.40 AU. The upper panel shows a radio spectrogram plotted as frequency versus time, with relative intensity (in 10^{-14} V^2Hz^{-1}) indicated by the color bar chart on the right. The time resolution is a point every 2 minutes. The bottom panel shows the values of electron density (red line), core temperature (blue line), and bulk speed (black line) deduced from the data fitting as explained in the text.

highest level near 20 kHz corresponds to quasi-thermal Langmuir waves near the plasma frequency and gives directly the evolution of the plasma density, as shown in the bottom panel. We have also plotted the core electron temperature as obtained by *Maksimovic et al.* [1995]. The bulk speed variations, which have been corrected for the spacecraft speed (about 20 km/s), are deduced from the proton noise level (spectral range below 10 kHz). The structure shown near 15h10 corresponds to Ulysses crossing an interplanetary shock where our measured parameters abruptly increase.

Figure 3 compares the speed thus obtained (plotted as points) with that given by the on-board SWOOPS particle analyzer (thin line) [*Bame et al.*, 1992]. Figure 3 (a) corresponds to a case where the antenna is roughly perpendicular to **V** (within 3°). One sees that, on an average (bold line), our measurements are within a few percents of those of SWOOPS. The vertical bar represents a typical error on our speed measurements by the χ^2 method, and one sees that it is comparable to the scatter in the data points. Figure 3 (b) corresponds to the spectrogram shown in Figure 2. In that case, the proton thermal noise is overestimated because it is calculated for an angle between the antenna and **V** of 90°, and this angle actually varies in the range 90°-75°during a spin period. As expected, our method then gives speed values which are underestimated, within 10% of SWOOPS data.

Discussion

The above results suggest that the proposed method might be implemented to make a routine diagnosis of the solar wind speed. In general, the proton thermal noise (see Eq.(1)) is much more sensitive to the bulk speed than to the proton temperature, except at very low frequencies , where the main contribution to the noise comes from the shot noise which is difficult to estimate accurately. Hence, this technique does not appear well suited to measure T_p. A preliminary comparison showed that the T_p values obtained are twice smaller than those of SWOOPS. But, even if in that case the fitting gives a false value of T_p, the derived value of V remains correct. The method should give better T_p results at high heliocentric latitudes, where T_e/T_p is smaller, producing a larger contribution of protons to the thermal noise.

To determine the speed the present method has three main limitations. (i) Since we use the range $f > f_p$ of the voltage power spectrum to determine T_e, our method does not work in the presence of strong solar or Jovian radio bursts which pollute the high frequency spectra, making the electron temperature unmeasurable[*Maksimovic et al.*, 1995]. Furthermore, for high densities, i.e, for high plasma frequencies, there are not enough data points in this spectral range to measure correctly T_e. To overcome these limitations, we

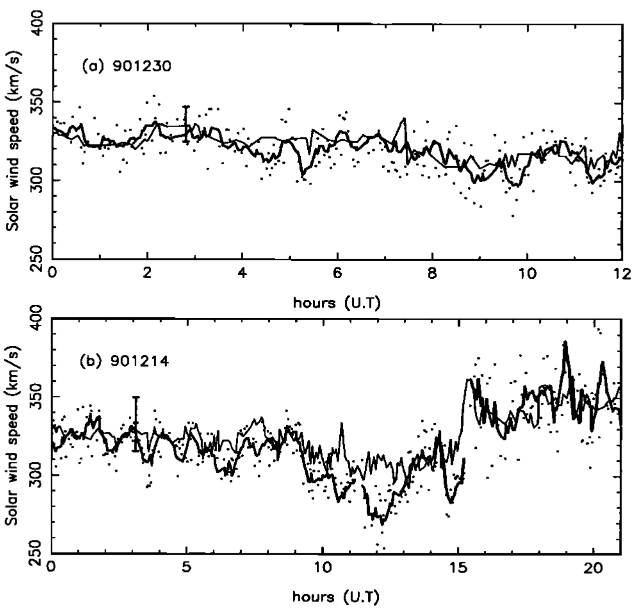

Figure 3. Comparison between the solar wind speed obtained in this paper (dots) and that given by the Ulysses SWOOPS particle analyzer (thin line). We represent our speed measurements which are better than one standard deviation (calculated from the 20 minutes average of all the available data points). The bold line represents the 20 minutes sliding average of these points. The vertical bar is a typical speed error. (a) On 90/12/30, Ulysses is about 1.57 AU from the sun and the antenna is nearly perpendicular to the velocity. (b) On 90/12/14, (as Fig.2), the antenna makes an angle between 90°and 75°(depending on the phase of the spacecraft spin) with the velocity ; as expected, the measurements are less accurate in the latter case.

will have to determine T_e using only the low frequency range $f < f_p$. (ii) Our method cannot yield the bulk speed when T_p is too small with respect to T_e because the proton thermal noise (Eq.(1)) becomes too small as compared to the total noise ; in that case the fitting is insensitive to V. (iii) The basic assumption when using Eq.(1) to determine the bulk speed is that the antenna must be roughly perpendicular to **V**. However, this is not a real limitation when using data from a spinning spacecraft, since one has just to select the part of the spin period when the antenna is nearly perpendicular to **V** (or to calculate the theoretical spectrum for any antenna orientation).

All of these constraints may be eased in a future analysis. As yet, the first results we obtained are promising and show that the thermal noise method can provide an accurate determination of the bulk speed in addition to the electron density and bulk temperature. It is complementary of particle analyzers and can be used to cross-check other instruments.

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