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Latitude dependence of Solar Wind plasma thermal noise: Ulysses radio observations

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Abstract. Thermal noise spectroscopy was performed on the URAP radio receiver data for the first time out of the ecliptic during the Ulysses spacecraft transit from southern to northern heliolatitudes. We present the results on the solar wind electron density and bulk temperature obtained from $-43°S$ to +$43°N$. They indicate a rough symmetry of the solar wind electron plasma about the solar equator. The latitudinal gradient of the electron bulk temperature was found to be approximately $-830K/°$ latitude southward and $-1100K/°$ northward. Within $\pm 20°$ latitude, large fluctuations in the 1-AU scaled electron density and temperature were observed and presumably linked to the corotating structures existing in the equatorial band. Effects of the solar wind speed on the thermal noise spectra were highest at high latitudes as predicted. They will be fully taken into account in future work.

Key words: solar wind – interplanetary medium – plasmas – Sun: radio radiation

1. Introduction

Since the Ulysses launch, the radio receiver on the Unified Radio and Plasma Wave (URAP) Experiment (Stone et al. 1992) has continuously recorded the solar wind plasma quasi-thermal noise (QTN), on which are sometimes superimposed various radio and plasma waves. This noise is due to the voltage induced on the antenna by the random motion of the ambient electrons which excite plasma waves near the plasma frequency, the so-called "plasma line". Theoretical interpretation of the QTN spectrum yields the density and temperature of both the cold and hot electron populations (Meyer-Vernet & Perche 1989). As noted by Meyer-Vernet et al. (1996), one of the main advantages of the thermal noise spectroscopy is its relative immunity to the spacecraft potential and photoelectron perturbations which in general affect particle analyzers. This radio method of plasma diagnostic by thermal noise spectroscopy was applied on Ulysses in the ecliptic plane to study the solar wind at various heliocentric distances (Hoang et al. 1992; Maksimovic et al. 1995; Maksimovic, Hoang & Bougeret 1996). Recently, Issautier et al. (1996) quantitatively analyzed the proton contribution to the plasma thermal noise, which is Doppler-shifted by the wind velocity so that it can be observed near the plasma frequency (Meyer-Vernet et al. 1986). From that analysis, these authors could propose a novel method to measure the solar wind speed by thermal noise spectroscopy. This work will be especially important when applying thermal noise spectroscopy to Ulysses at high latitudes where the solar wind speed is large, and hence considerably influences the plasma thermal noise.

In the present paper, we extend the observations of the solar wind plasma thermal noise from the ecliptic plane to high heliographic latitudes, by considering the pole to pole exploration of the Ulysses spacecraft from September 1994 to August 1995. During this period of time, Ulysses traversed a wide range of latitudes, in a smaller range of heliocentric distances. This is particularly favorable for studying the latitudinal variations in the solar wind plasma thermal noise.

In Sect. 2, we describe the radio observations, and in Sect. 3, the method of thermal noise spectroscopy and its extension to bulk speed measurements. In Sect. 4, the results on the plasma density and cold electron temperature are discussed, and finally in Sect. 5, some concluding remarks are made and future work indicated.

2. Observations

The observations were performed with the URAP radio receiver (Stone et al. 1992), connected to the 2 x 35 m electric thin dipole antenna located in the spacecraft spin plane and operating in the low-frequency band. The receiver is linearly swept through 64 equally spaced 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 for measuring plasma thermal noise spectra on Ulysses with a good frequency resolution.

Fig. 1 shows the radio spectrogram acquired during the Ulysses passage from the south pole in September 1994 to the north pole in August 1995, and displayed as frequency versus

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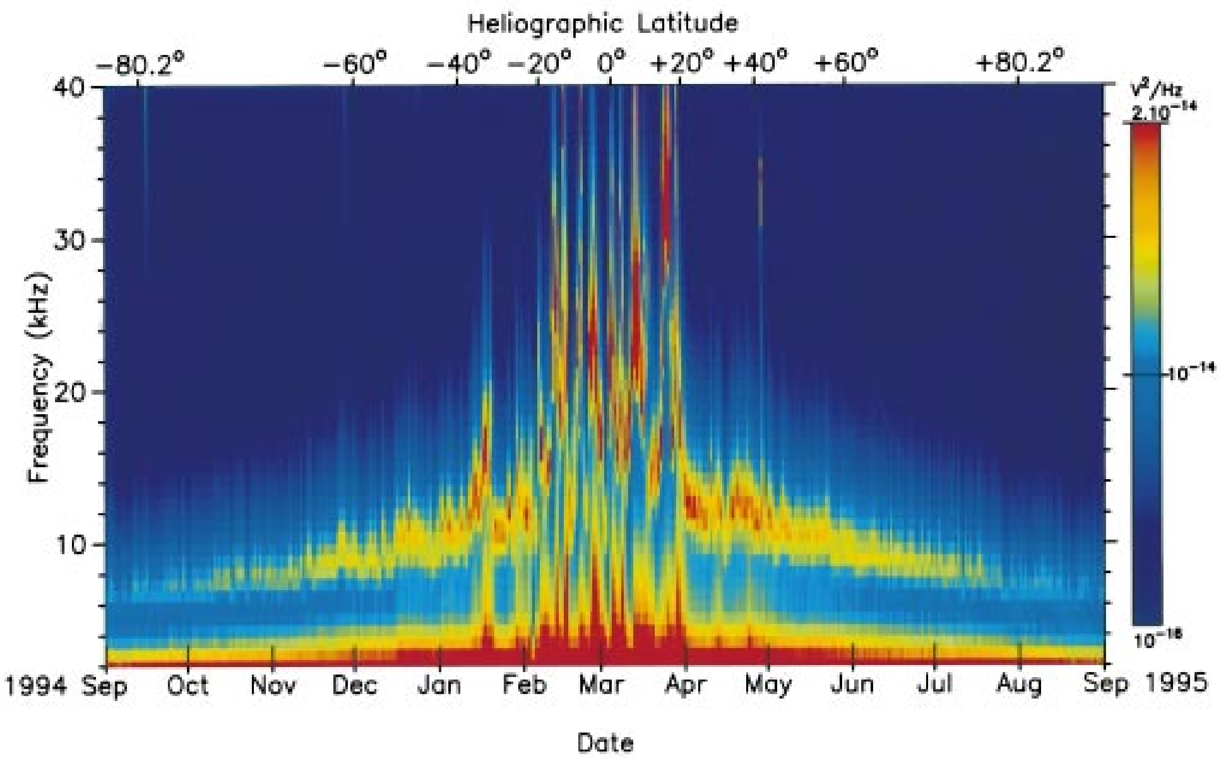

Fig. 1. Data from the URAP radio low-frequency receiver for one year from September 1994 to August 1995. Averaged data are displayed in the spectrogram as frequency versus universal time, with intensity indicated by the color bar scale. The quasi-thermal plasma line is the band more or less intense and fluctuating, beginning between 6 and 8 kHz in September 1994 and ending in the same frequency range in August 1995. The fluctuations in the plasma line are maximum at the traversal of an equatorial band between about $-20°$ and +20° heliolatitudes. At lower frequencies below the plasma line, an intense continuum band closely accompanies the plasma line; these waves are mainly proton thermal noise which is Doppler-shifted by the solar wind velocity.

universal time. The QTN plasma line can be seen clearly as an intense peak with more or less fluctuations, beginning between 6 and 8 kHz in September 1994 (Ulysses above the south pole), and ending in the same frequency band in August 1995 (Ulysses above the north pole). This indicates some symmetry in the plasma density over the poles (the density being proportional to the plasma frequency squared). Since the spectral characteristics of the QTN plasma line depend directly on the local plasma density and temperature, and on the solar wind speed, they vary with the heliocentric distance and latitude of the spacecraft, and with the heliospheric activity including solar transients, shocks, high-density structures, etc. Thus at high latitudes where Ulysses was in the high-speed solar wind which is not very variable, the plasma line appeared to be smooth with very little fluctuations. As the spacecraft approached the solar equatorial region, the plasma line exhibited larger variations. This effect increased to a maximum as the spacecraft traversed an equatorial band spanning roughly $\pm 20°$ of latitude about the solar equator. Ulysses was then alternately crossing low-speed wind and fast-speed wind corresponding to polar coronal holes, and streamer belt periodically passing the spacecraft. These high-density structures produced large variations in the plasma line as can be seen in Fig. 1.

Fig. 2 represents a series of typical thermal noise spectra (which are vertical cuts of the spectrogram in Fig. 1) taken every 10° of latitude from pole to pole, together with the spacecraft trajectory, to illustrate the variation of the plasma line as a function of heliolatitude and solar distance. The causes for the latitude dependence of the plasma line are explained in Sect. 3.3 below.

3. Plasma measurements from thermal noise spectroscopy

3.1. Basics of the method

In a stable plasma, the thermal motion of the particles produce electrostatic fluctuations, which are completely determined by the velocity distributions. Hence, this quasi-thermal noise, which can be measured at the terminals of an electric antenna, allows to deduce parameters of the ambient plasma (Meyer-Vernet & Perche 1989).

This method has produced accurate measurements of the electron density and bulk temperature in a number of space media, and has unique features which make it complementary of classical particle analyzers (see Meyer-Vernet et al. 1996 and references therein). In particular, being based on wave measurements, it senses a large plasma volume; hence it is relatively

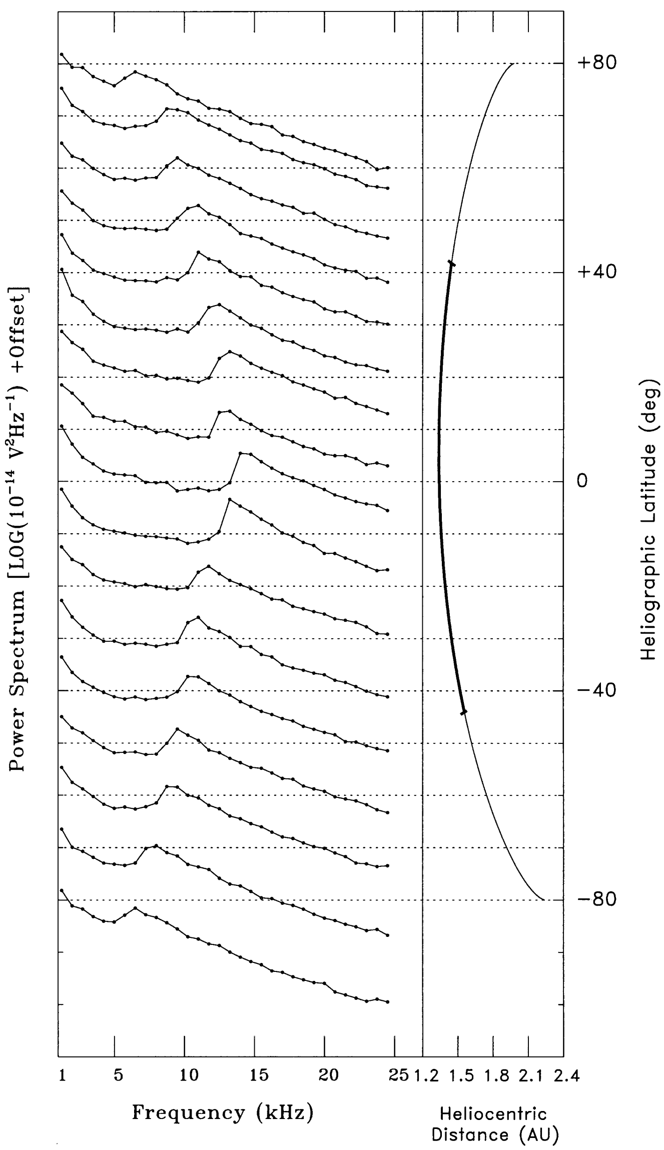

Fig. 2. Typical plasma thermal noise spectra (intensity scale at left, frequency scale at bottom) observed by the URAP radio receiver during the Ulysses transit from south pole to north pole. The Ulysses trajectory is plotted in the right panel, with heliocentric distance scale at bottom and heliolatitude scale at right. For each of the spectra, taken every 10° latitude from $-80°$ S to +80° N, the horizontal dashed line shows the $10^{-14}V^2Hz^{-1}$ level (scale at left) and the heliolatitude of observation (scale at right). All the spectra shown are taken from quiet solar wind periods out of heliospheric disturbances or density structures, in order to show more clearly the latitudinal and radial effects in the observations. These effects result mainly in lowering the frequency of the spectral peak and cutoff and smoothing out the spectral shape at increasing latitudes.

immune to spacecraft potential and photoelectron perturbations, contrary to classical analyzers which measure particles impacting on a small target.

The method of thermal noise spectroscopy, documented by Meyer-Vernet & Perche (1989), is based on the following principle. The electron thermal motions excite Langmuir waves, which produce a spectral peak just above the plasma frequency f_p, and a cutoff at f_p. Since the density $n \propto f_p^2$, this allows a straightforward measurement of the density. In addition, the electrons passing closer than a Debye length from the antenna induce voltage pulses on it, producing a smooth wave spectrum on both sides of f_p, which is mainly determined by the bulk (core) electrons. The analysis of this spectrum allows a precise measurement of the bulk electron temperature T_c (see Fig. 3).

In practice, a plasma diagnostic is performed by (i) assuming a model for the velocity distribution, (ii) calculating the theoretical spectrum produced by this distribution, and (iii) deducing the parameters of the model by fitting the theory to the observations. The implementation of the fitting procedure was described in detail by Maksimovic et al. (1995). These authors also discussed the dependence of the derived plasma parameters on the electron velocity distribution used. Specifically, as shown by Chateau and Meyer-Vernet (1991), the determination of the electron core temperature is quite insensitive to the shape of the halo electron distribution function.

3.2. *Extension to speed measurements*

Up to now this method, being based on the analysis of the electron quasi-thermal spectrum, allowed only to measure the electron density and bulk temperature (and to estimate the suprathermal electron population). It is presently being generalized to measure the ion bulk speed (Issautier et al. 1996). This extension in addition considers the proton thermal noise, whose Doppler-shift depends on the proton relative velocity with respect to the antenna, and which contributes to the quasi-thermal noise at low frequencies.

In many space plasmas, and in particular the near-ecliptic interplanetary medium, the plasma bulk velocity is much smaller than the electron thermal velocity and the ion temperature is smaller than the electron temperature. Under these conditions, the bulk velocity barely changes the electron thermal noise, and the proton quasi-thermal noise is negligible near the plasma frequency. In this case, the electron density and core temperature can be deduced from the spectrum measured near and above f_p ; the bulk speed is then obtained from the analysis of the Doppler-shifted proton contribution below f_p, and found to be generally within a few percents of SWOOPS measurements (Issautier et al. 1996). Fig. 3 illustrates two typical examples of such fittings. This method can be applied near the ecliptic.

3.3. *Latitudinal variations*

As the latitude increases, the bulk velocity becomes larger, whereas the proton-to-electron temperature ratio increases. This increases the contribution of the protons to the quasi-thermal

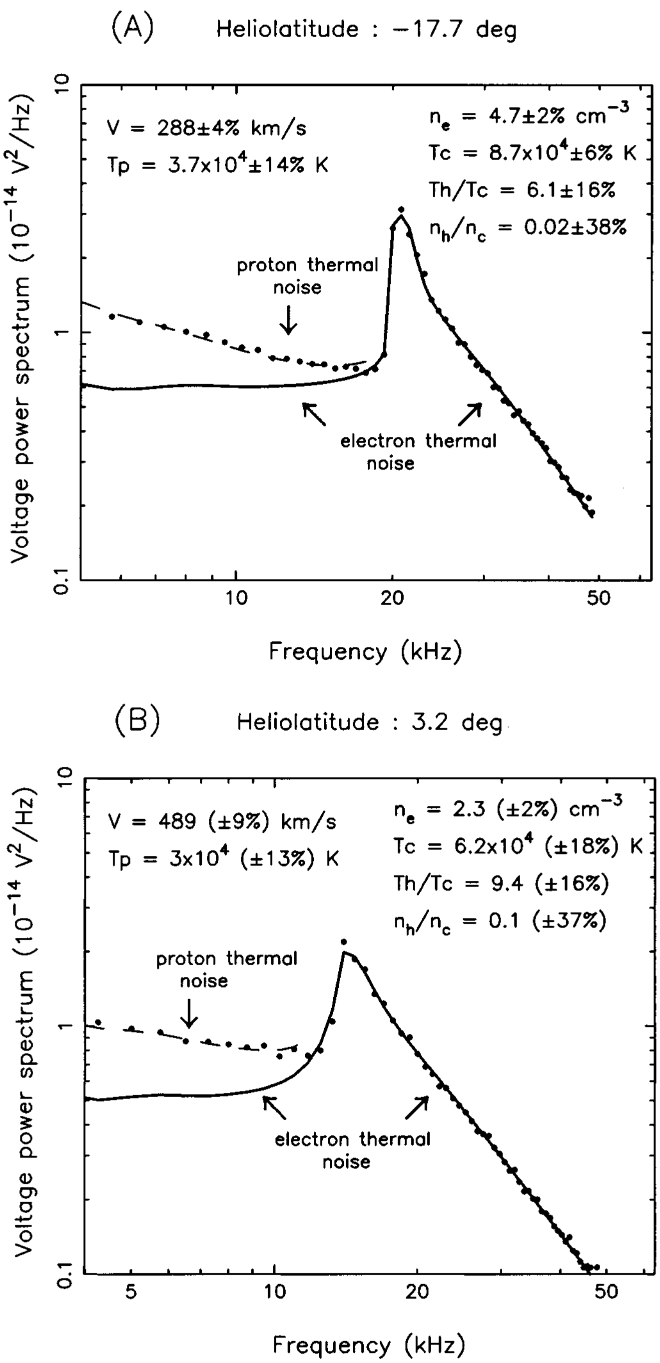

Fig. 3. A Example of voltage power spectrum measured by the URAP radio receiver on Ulysses (dots), and deduced plasma parameters. The curve is the theoretical electron(solid)-plus-proton(dashed line) quasi-thermal noise with a core-halo electron velocity distribution made of two Maxwellians (densities n_c, n_h, temperatures T_c, T_h), and Maxwellian protons (in the plasma frame). **B** Same as **A**, but with a larger value of the plasma bulk speed, which smooths out the spectral cutoff and increases the level below f_p.

noise, and smooths out the spectral cut-off at f_p. This behavior is illustrated in Fig. 2 which shows the evolution of the measured spectra during the Ulysses latitude transit. As the latitude increases, starting from the ecliptic region shown in the middle of Fig. 2:
– the density decreases, shifting the spectral peak to lower frequencies,
– the corresponding increase of the Debye length ($L_D \propto \sqrt{T_c}/f_p$) flattens the peak, as predicted by Meyer-Vernet & Perche (1989),
– both the bulk velocity and the proton temperature increase, smoothing out the spectrum cut-off and increasing the low-frequency spectral level.

The increasing role of the proton thermal noise near f_p requires a modification of the method, which is not yet implemented. Therefore, the results shown in the following section do not take the velocity into account, so that the derived temperature values are only preliminary, and the accuracy of the density measurements is not as good as it will be when the velocity will be fully included.

4. Results

Fig. 4 shows the scaled electron density and bulk temperature versus heliographic latitude from $-43°S$ to $+42°N$. The corresponding part of the trajectory is shown in heavy line in Fig. 2.

These parameters were scaled to 1 AU as r^{-2} for the density, and $r^{-0.7}$ for the temperature, to compensate for their variations with the heliocentric distance which varied between 1.34 and 1.56 AU. Our temperature scaling is somewhat arbitrary, since there is an important discrepancy between the different published determinations of the temperature radial variation. This lack of agreement is due to the dependence of this parameter on the heliospheric conditions in which it is measured, and to the limited accuracy of bulk temperature measurements. The chosen value roughly matches many empirical determinations ; in particular, it is intermediate between the empirical laws found respectively by Maksimovic et al. (1996) and Phillips et al. (1995a) using Ulysses in-ecliptic data.

Fig. 4 exhibits a rough symmetry about the solar equator, and large fluctuations in both electron density and bulk temperature in a latitude band spanning -22^o to +21^o. This band matches the region of low-to-medium wind speed found by the SWOOPS particle analyzers (Phillips et al. 1995b), which is associated with the streamer belt, with occasional occurrence of faster streams associated to the north and south coronal holes. Poleward of this band, the density is less variable and typical of fast wind, ranging between 2 and 4 cm^{-3}.

In order to determine the latitudinal trend in the normalized electron bulk temperature, we fitted a linear law to the measurements for northern and southern latitudes separately. The gradients were found to be respectively -830 K/^{o} latitude southward, and -1100 K/^{o} latitude northward, showing a rough symmetry about the solar equator. These values are not much affected by the assumed temperature radial variation as $r^{-0.7}$: varying the

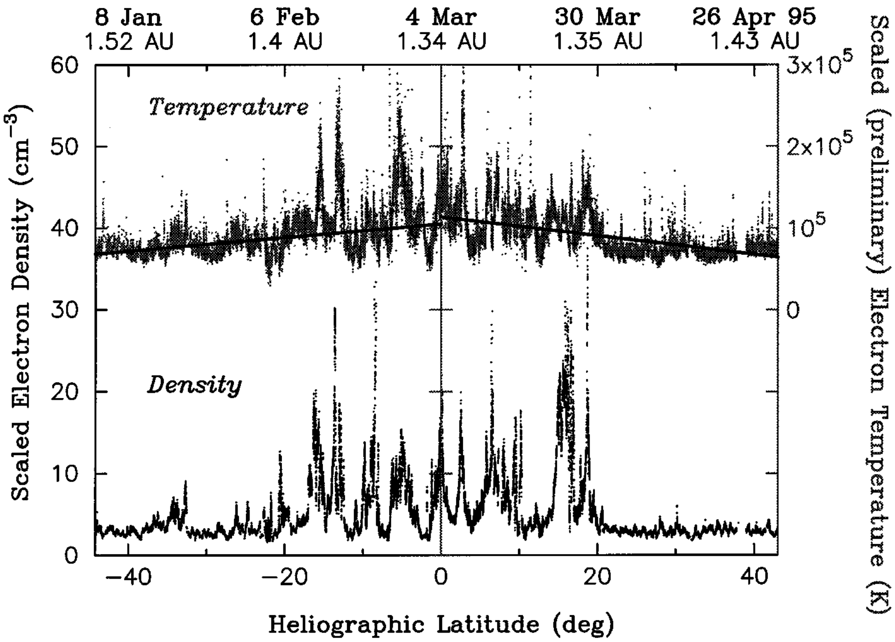

Fig. 4. Scatter plot of solar wind electron density and (preliminary) bulk temperature versus heliographic latitude. The parameters were scaled to 1 AU, assuming variations as r^{-2} for the density and $r^{-0.7}$ for the temperature. The fitted linear temperature variations are drawn as heavy lines.

exponent betwen -0.5 and -1 introduces no significant change in the measured latitudinal gradient. Note that this gradient has only an empirical meaning since the data are a superposition of low and fast winds.

This gradient is similar to that determined by the SWOOPS instrument in the latitude range -6 to -45^o in 1992-1993, where the heliocentric distance was much larger (varying in the range 5.4-3.8 AU), and the phase of the solar activity cycle was different (Phillips et al. 1995a).

5. Concluding remarks

During the Ulysses transit from southern to northern heliolatitudes, the URAP radio receiver yielded the solar wind electron density and core temperature, measured in situ for the first time out of the ecliptic using thermal noise spectroscopy. The 1-AU scaled electron density and bulk temperature, measured from -43 to +43° heliolatitudes, show a rough symmetry about the solar equator. Within ±43° latitude, the latitudinal gradient of the electron bulk temperature was found to be approximately $-830K/°$ latitude southward and $-1100K/°$ northward. The large fluctuations in the scaled electron density and temperature within ±20° latitude are linked to corotating “jets”. These results compare well with SWOOPS observations (Phillips et al. 1995a and 1995b).

Although the results presented here are limited for now to low latitudes, and somewhat preliminary regarding the electron temperature, they demonstrate the capability of the QTN method to address key space plasma parameters in various conditions. Work is in progress to fully include the effect of the wind speed in the QTN spectroscopy in view of a future extension of the method to high latitudes.

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