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Solar wind electron temperature and density measurements on the Solar Orbiter with thermal noise spectroscopy

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Abstract

The measurement of the solar wind electron temperature in the unexplored region between 1 and 45 R_s is of prime importance for understanding the solar wind acceleration. Solar Orbiter's location, combined with the fact that the spacecraft will nearly co-rotate with the sun on some portions of its orbit, will furnish observations placing constraints on solar wind models. We discuss the implementation of the plasma thermal noise analysis for the Solar Orbiter, in order to get accurate measurements of the total electron density and electron temperature and to correct the spacecraft charging effects which affect the electron analyzers.

Keywords: Solar wind; Plasmas parameters measurements; Thermal noise spectroscopy

1. Introduction

The accurate in situ measurements of the solar wind electron density and temperature are key elements in understanding the physics of the solar wind itself and the physics of the various solar terrestrial links. Moreover, 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 and the solar wind. The measurement of the electron temperature (T_e) radial profile in the unexplored region between 1 and 45 R_s is therefore of prime importance for the Solar Orbiter mission.

One can already figure out what could be the T_e gradients in this radial range by comparing the SOHO measurements of T_e in the inner corona, with the gradients measured in the inner heliosphere. In Fig. 1, the crosses and diamonds represent, respectively, the observations by Wilhelm et al. (1998) and David et al. (1998) in coronal holes between 1 and 3 $r_\odot$. The dashed line is the power-law $T_{\dot{e}} = (215/r)^{0.6} \times 10^5$ K, where r is given in solar radii. This profile, between isothermal and adiabatic behavior, is representative of T_e gradients observed in the fast wind (see compilations of T_e gradients reported in Issautier et al. (1999a) or in Maksimovic et al. (2000)). These measurements exhibit a large scatter sketched by the two solid lines, that is $T_e = (215/r)^{0.3} \times 0.5 \times 10^5$ K and $T_e = (215/r)^{0.8} \times 1.5 \times 10^5$ K. This scatter stems from three basic reasons: first, the corruption of fast wind data by perturbations or compression regions; second, the fact, that, the radial profile is not necessarily expected to be modelized by a single power-law (Meyer-Vernet and Issautier, 1998); and third, the notorious difficulty of temperature measurements with electron spectrometers in the solar wind. Thermal noise analysis on the Solar Orbiter will remove the latter difficulty, and we show with the two vertical dotted lines the radial excursions of the Solar Orbiter during the operational orbits.

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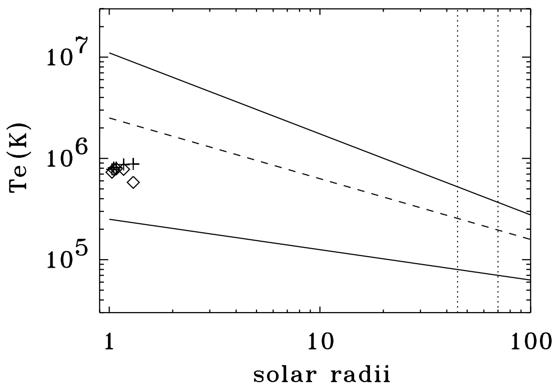

Fig. 1. SOHO temperature measurements in coronal holes (see text for explanation) together with observations in the inner heliosphere extrapolated back to the corona.

In Section 2, we present the thermal noise spectroscopy. In Section 3 we present the constraints, essentially on the antenna length, for an efficient thermal noise spectroscopy on the Solar Orbiter.

2. The thermal noise spectroscopy

The thermal noise (TN) spectroscopy is based on the use of a passive electric antenna for measuring the electrostatic field spectrum produced by the electron and ion thermal motions in a stable plasma (Meyer-Vernet and Perche, 1989; Meyer-Vernet et al., 1998). This method 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) or a cometary plasma tail (Meyer-Vernet et al., 1986).

Fig. 2 shows examples of TN observations in the Solar Wind. The left panel is a spectrogram measured by the WIND spacecraft on April 08, 2003. This spectrogram represents, as a function of time, the radio power spectral density in the frequency range between 16 and 256 kHz. One can clearly see the plasma peak varying on that day between roughly 20 and 90 kHz. This corresponds to density variations between roughly 40 and 85 cm^{-3}. The right panel of Fig. 2, adapted from Issautier et al. (2001a), shows a typical plasma spectrum on Ulysses, obtained in the solar wind, with an intense peak just above the local plasma frequency f_p. The spectral analysis yields the electron density and thermal temperature with a good accuracy, in addition to the solar wind speed (due to the Doppler-shifted thermal fluctuations of the ions), and suprathermal parameters (Issautier et al., 1999b). Note that the density measurement is independent of any calibration gain determination, since it relies directly on a frequency determination which is usually very accurate.

The TN spectroscopy is almost immune to the limitations due to spacecraft charging. This immunity is essentially due to the fact that, close to the local plasma frequency, the antenna is sensitive to Langmuir waves with very large wavelengths (Meyer-Vernet et al., 1998). At the plasma peak the antenna samples an average over a large plasma volume. Therefore, the TN spectroscopy has been used to calibrate the density and temperature obtained by the electron analyzers, which are usually polluted by the spacecraft charging effects. Maksimovic et al. (1995) and Issautier et al. (2001b) performed detailed comparisons between the two kind of instruments, on Ulysses, and emphasized that TN spectroscopy method is a complementary tool to cross-check other techniques for electron determinations. Moreover, it is important to note that using the electron density from quasi-thermal noise method, it is possible to improve the determination

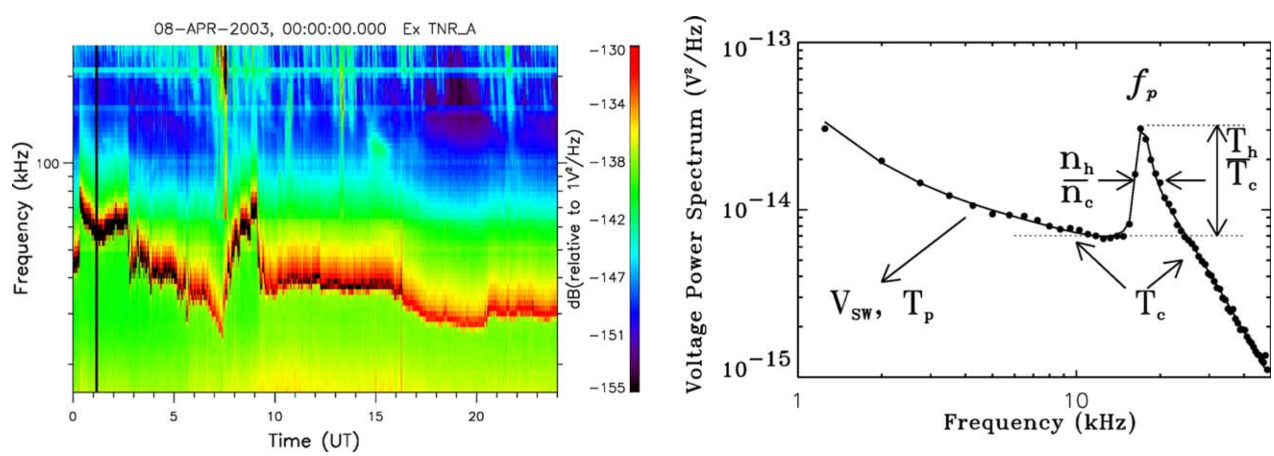

Fig. 2. Left panel: spectrogram measured by the WIND spacecraft on April 08, 2003. This spectrogram represents, as a function of time, the radio power spectral density in the frequency range between 16 and 256 kHz. One can clearly see the plasma peak varying on that day between roughly 20 and 90 kHz. This corresponds to density variations between roughly 40 and 85 cm^{-3}. Right panel: typical spectrum measured on Ulysses. The solid line is the theoretical thermal noise spectrum which best fits the data (points) within 1.6% of standard deviation.

of the spacecraft potential, and thus to correct the electron parameters determined by particle spectrometers, as developed for Wind data (Maksimovic et al., 1998; Salem et al., 2001).

However, TN spectroscopy requires an antenna length, L, larger than the local Debye length, L_D, in order to measure adequately the electron temperature. In addition, in order to minimize the shot noise the antenna must have a radius smaller than L_D (Meyer-Vernet et al., 1998). Finally, to determine accurately the temperature and other solar wind parameters, it is crucial to have a sensitive and well-calibrated receiver. Note, that this is not necessary to obtain the electron density since it is based on the detection of the cutoff frequency in a spectrum.

3. The thermal noise spectroscopy for the Solar Orbiter

In Fig. 3, we plot the ratio L/L_D for different models of temperature and density variations and for $L = 5$ m, which is the antenna length given in the current strawman payload of the mission. The solid lines represent, L/L_D for a fixed density variation $N_e = (215/r)^2 \times 3\ \mathrm{cm}^{-3}$, which corresponds to observations in the fast, wind, while the three T_e radial profiles are the same as those given in Fig. 1. The dashed lines represent the same three T_e temperature profiles but with $N_e = (215/r)^2 \times 20\ \mathrm{cm}^{-3}$, which is typical of slow and dense solar wind.

As discussed before, to measure the electron temperature with the TN spectroscopy method, L/L_D has to be larger than 1. From Fig. 3, one can see that this condition is not always strictly met. The ratio L/L_D may be smaller than 1 for some solar wind conditions corresponding to tenuous density. Thus, a bit larger antenna length should be more suited.

However, implementing the thermal noise spectroscopy on the Solar Orbiter even with a 5 m long antenna, would still be useful to determine the electron density since the electron analyzer measurements of the cold electron population are expected to be very perturbed by the fact that the spacecraft will not spin and that, non uniform charging effects and possible current, circulations around the spacecraft could be present.

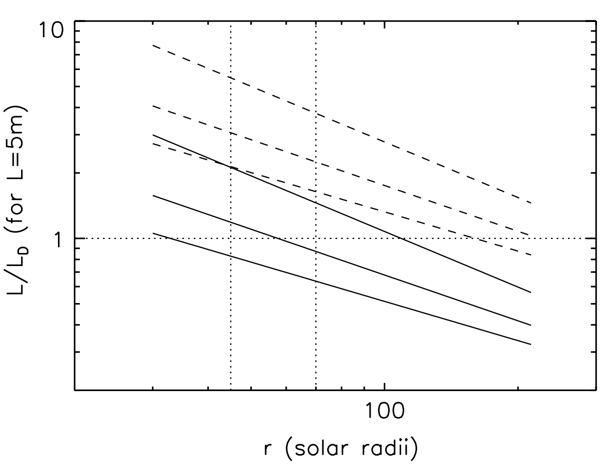

Fig. 3. Typical ratio L/L_D in the Solar Orbiter radial range, given for $L = 5$ m and for various models of electron density and temperatures as explained in the text, corresponding to the fast (continuous lines) and slow (dashed lines) wind.

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