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ACTIVE AND PASSIVE PLASMA WAVE INVESTIGATIONS IN THE EARTH'S ENVIRONMENT: THE CLUSTER/ WHISPER EXPERIMENT

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ABSTRACT

The Waves of HIgh frequency and Sounder for Probing of Electron density by Relaxation, WHISPER, performs high frequency electric field measurements on the four satellites of the CLUSTER mission. In active mode, the WHISPER behaves like a classical topside sounder. It provides, via the identification of resonances that are excited at characteristic frequencies of the encountered plasmas reliable and accurate determination of the total electron density and magnetic field strength. Whenever the transmitter is switched off, the WHISPER becomes a simple wave receiver (passive mode). The 2 to 80 kHz frequency range of the electric component of natural waves is then monitored. The main objective of the presentation is to highlight the plasma and natural waves diagnosis capabilities of the WHISPER instrument. The way the plasma resonances are extracted and identified is pointed out and results obtained from the solar wind down to the Earth's plasmasphere are shown.

INTRODUCTION

The electron number density is a key parameter for studying the formation, dynamics and evolution of planetary space environments, and in particular the Earth's ionized medium. Its measurement is indeed essential for understanding both macroscopic and microscopic processes that govern charged particles, natural waves, and their interactions as a function of the altitude, latitude, local time, and solar wind status. It is therefore of great importance to get reliable and accurate electron plasma density determinations.

Such measurements must be insignificantly affected by the spacecraft presence, i.e., its potential variations, photoelectrons emitted by its surface, and its surrounding ion sheath. Due to these perturbations and the inherent limited energy coverage, particle experiments thus poorly suit dependable electron density quantifications. The electron plasma frequency, from which the electron density is immediately deduced, may be plausibly given by natural wave observations provided the interactions producing these waves are clearly identified. Active experiments are better candidates, insofar as they allow high signal to noise ratios and can excite waves at characteristic frequencies of the probing plasma, in particular the electron plasma frequency.

The WHISPER (Waves of HIgh frequency and Sounder for Probing of Electron density for Relaxation) instrument which is aboard the four CLUSTER spacecraft belongs to this active experiment family. It mainly aims at the thermal electron density evaluation and natural wave monitoring in the 2 kHz – 80 kHz frequency range, from the solar wind down to the Earth's plasmasphere. The electron plasma frequency is determined via the dispersion relation for radio frequency waves. As these waves propagate to a few kilometres from the spacecraft, they are not greatly influenced by its perturbations. Furthermore, the covered distance is small enough for the electron density to be considered as a point measurement. Let us also recall that the electron plasma frequency

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delivered by the relaxation sounder technique is thought to be within about 1 % of the true value (Harvey et al., 1979).

The main objectives of the current presentation is to highlight the plasma diagnosis capabilities of the CLUSTER/WHISPER sounder. First, the main characteristics of the WHISPER instrument are briefly recalled. Then, the way the total electron density and the static magnetic field strength are deduced from the WHISPER active and, possibly, passive measurements are described in the two following sections. The first one deals with the Earth's plasmasphere, while the second is devoted to the magnetosheath. In the latter region, only one wave signal ringing (resonance) is observed at the electron plasma frequency, which therefore does not allow the static magnetic field modulus to be determined. Finally, before the conclusion, a full CLUSTER pass from the Earth's plasmasphere up to the solar wind is presented.

THE WHISPER RELAXATION SOUNDER

The WHISPER experiment is a classical relaxation sounder (Décréau et al., 1997; 2001). It uses the two long double sphere antennae of the EFW (Electric Field and Wave experiment). These antennae have sphere-to-sphere separations of 88 m. The WHISPER transmitter sends, through the conductive outer braids of one of the antennae (Ey in Figure 1), a wave train during a very short time interval (1 ms or less), at a given frequency. A few milliseconds after, a radio receiver connected to two of the spheres (R1-R2 or R3-R4), via high input impedance preamplifiers housed in boxes called "hockey pucks" by the EFW experimenters, is switched on. The received signal is subsequently listened and analysed. The working frequency is then shifted for a new sounding until the whole frequency range that contains the expected electron plasma frequency is covered.

Unlike previous relaxation sounders, the WHISPER receiver frequency bandwidth covers the whole 4 kHz – 83 kHz bandwidth instead of the limited transmitted frequency spectrum, which does not exceed 2 kHz (1 kHz in nominal WHISPER modes). In this way, the received signal may be analysed by a Fast Fourier Transform (1024 samples) over the whole frequency range after each transmitting frequency step. This means that the frequency bins recorded around the transmitted frequency (usually 6 bins, 162 Hz in bandwidth) are used to build an active wave spectrum, while the bins whose frequency is far away may be retained as part of a natural wave spectrum. As a consequence, after about 80 transmitting frequency steps, usually 1 kHz in frequency bandwidth and 13,33 ms in time duration, both an active wave spectrum and a passive (natural) one are nominally completed.

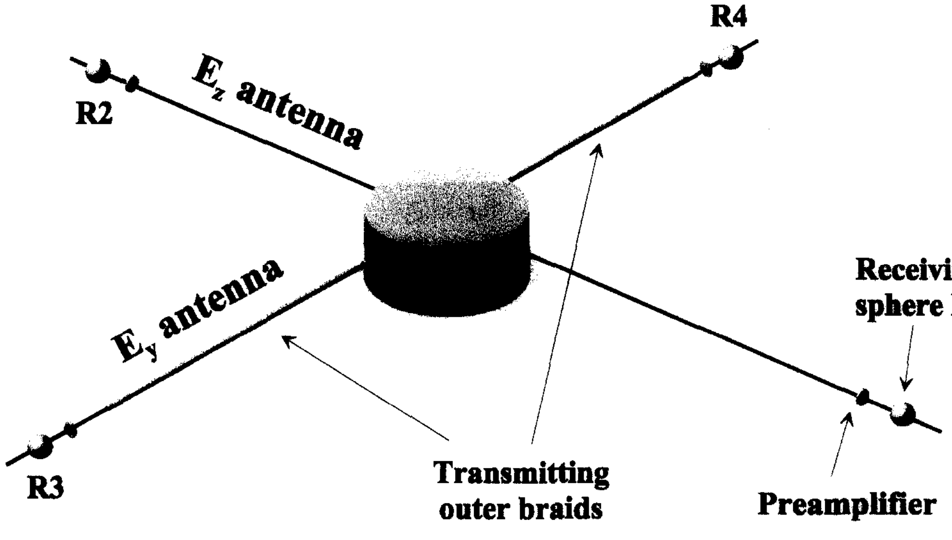

Fig. 1. Sketch showing the EFW (Electric Field and Wave experiment) electric field antennae used by the WHISPER relaxation sounder onboard the four CLUSTER spacecraft. Preamplifiers are housed in "hockey pucks" close to the receiving spheres, 8 cm in diameter.

If the transmitter is switched off, the WHISPER naturally becomes a simple radio receiver aimed at the natural wave monitoring in the 2 kHz – 80 kHz frequency range, which is slightly different from the 4 kHz – 83 kHz frequency range of the active mode. Even though one natural wave spectrum is available every 13,33 ms, due to the limited telemetry allocation (1 kbits/s in nominal bit rate and 5 kbits/s in high bit rate) and in order to lower the spectrum variance, 16 or more natural wave spectra are accumulated and averaged. In that way, natural wave spectra are nominally delivered every about 0.3 s.

When the active (sounding) mode of operation is activated, it takes about 1.1 s to compute a full active wave spectrum, but according to the telemetry mode that is selected the time resolution is often worse.

ELECTRON PLASMA DENSITY AND STATIC MAGNETIC FIELD STRENGTH DETERMINATION IN THE EARTH'S PLASMASPHERE

When the transmitted pulse frequency is close to characteristic frequencies of the encountered plasma, very intense and long lasting echoes, called resonances, are received. They are monochromatic in nature and correspond to frequencies for which the group velocity of the excited waves is very small and close to spacecraft velocity. Due to the dispersive behaviour of the plasma close to its natural characteristic frequencies, the resonant waves may be reflected by small plasma density gradients before being intercepted by the sounder receiver. Alternatively, when resonant waves are well directed they can simply accompany the spacecraft (Etcheto et al., 1981).

In the Earth's magnetosphere resonances arise at the electron cyclotron frequency (*Fce*) and harmonics (*nFce*) of it. They correspond to waves propagating in the Bernstein's modes (Bernstein, 1958) with wave vectors nearly perpendicular to the static magnetic field, **B**. From the frequency locations of these resonances, it is easy to determine the strength of **B**. The accuracy of the **B** modulus quantification is actually related to the order of the observed electron gyroharmonics, the higher the order the more accurate the determination. As an example, the **B** intensity is within 0.2 % of the true value when the seventh harmonic of the electron cyclotron frequency occurs at 80 kHz (162 Hz being the uncertainty in the resonance frequency identification).

Other Bernstein's mode resonances, the so-called Fqn, are also observed above the electron plasma frequency between two successive electron gyroharmonics. According to the convention, the *n* suffix refers to the order of the dispersion branch, so that $nFce < Fqn < (n+1)Fce$. The *Fqn* resonances correspond to electrostatic cyclotron waves whose group velocity vectors are close to zero and are almost in the direction perpendicular to **B** (Tataronis and Crawford, 1970). The *Fqn* have the distinctive feature to be excited, for a given *Fpe*/*Fce* ratio, at frequencies that are farther away from *nFce* whenever *n* decreases. As their frequency locations depend upon the *Fpe*/*Fce* ratio, *Fqn* can then be used to determine the electron plasma frequency whenever *Fce* is known.

In addition to the *nFce* and *Fqn* resonances two other electric field signal ringings are usually detected at the electron plasma frequency (*Fpe*) and the upper-hybrid frequency ($Fuh = (Fce^2 + Fpe^2)^{1/2}$). Again, the electron plasma density can readily be deduced from the frequency location of these two plasma resonances.

It is worth pointing out that a large body of work on resonance observations in the ionosphere has clearly shown diffuse plasma D resonances in the frequency region below *Fpe*, near the midpoints between successive harmonics of *Fce* (Oya, 1971; Benson et al., 2001). For the time being, D resonances have not been observed by the WHISPER. As no convincing explanation has unfortunately been done, it would be useful to have current generation mecanisms revisited.

The middle panel of Figure 2 displays the plasma resonances triggered in the Earth's plasmasphere by the WHISPER-2 sounder on the 11 July 2001. At 1450 UT (1514 MLT) the CLUSTER-2 (Salsa) satellite was at a geocentric distance of 4.17 Earth's radii, a L position of 4.2, and an invariant latitude of 61°. In the middle panel of Figure 2, the intensity of the measured electric field is coded in decibels above 10^{-8} Vrms $Hz^{-1/2}$, according to the scaling shown on the right-hand side. As can be seen, several monochromatic frequency resonances are excited. For example, at 1410 UT resonances are observed, from bottom to top, at *Fce*, *2Fce*, *3Fce*, *Fpe*, *Fuh*, *Fq3*, *4Fce*, *Fq4*, *5Fce*, *Fq5*, *6Fce* and *Fq6*. At this time, $6Fce = 69$ kHz and $Fpe = 35.8$ kHz, so that the static magnetic field modulus was 411 nT and the electron plasma density was 15.8 cm^{-3}. An automatic process for deriving the latter parameters has been developed (Trotignon et al., 1986; 2001). The bottom panel in Figure 2 shows the total electron plasma density thus obtained.

Let us now consider the natural waves detected by the WHISPER experiment, their intensity is plotted as a function of time (x-axis) and frequency (y-axis). Several cyclotron harmonics waves are actually excited between electron cyclotron frequencies, almost in the middle (Pottelette et al., 1981), and close to *Fqn* frequencies (Bernstein, 1958; Tataronis and Crawford, 1970). As the latter waves often exhibit a clear upper frequency cut-off at the *Fqn* frequencies (Canu et al., 2001), it becomes possible to routinely deliver the associated electron plasma density value. Figure 3 clearly illustrates this point. Figure 3 indeed shows, from top to bottom, the natural waves (passive WHISPER mode), the triggered resonances (active mode), and the density automatically derived from the

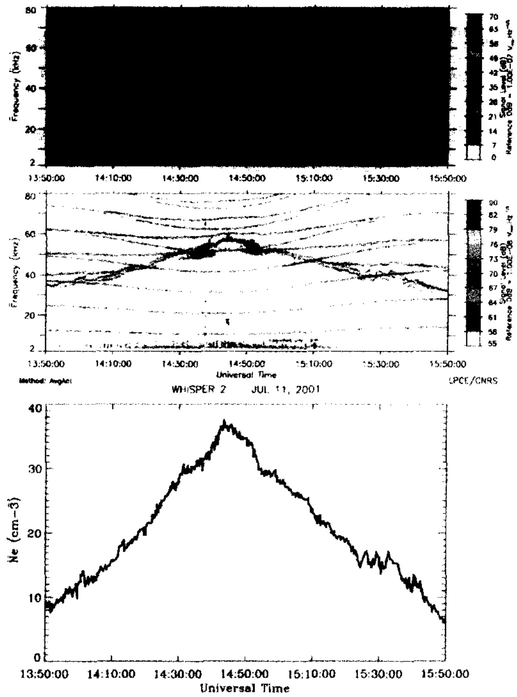

Fig. 2. E-field dynamic spectrograms recorded by the CLUSTER/WHISPER-2 relaxation sounder in the Earth's plasmasphere: natural waves (top) and triggered resonances (middle). The total plasma density computed from the observed resonances is shown in the bottom panel.

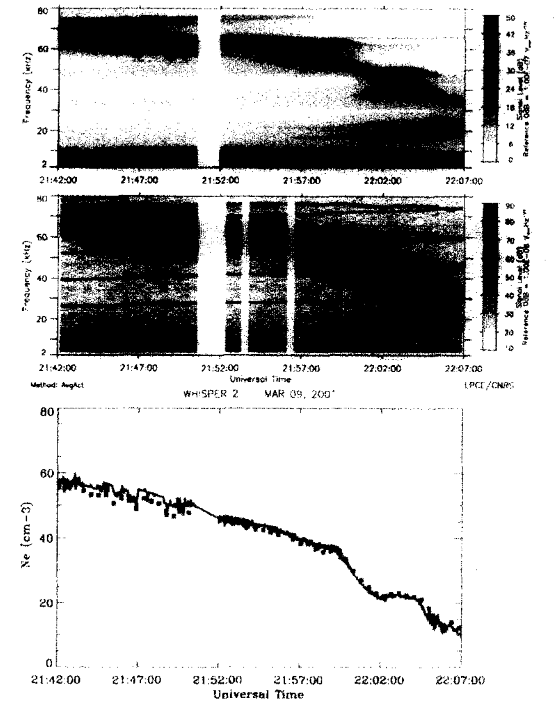

Fig. 3. WHISPER-2 E-field spectrograms in the plasmapause: natural waves (top) and triggered resonances (middle). Deduced plasma density (bottom): from the *Fpe* resonance (crosses) and from the upper cut-off frequency of the *Fqn* natural wave that is the closest to *Fpe* (solid red line).

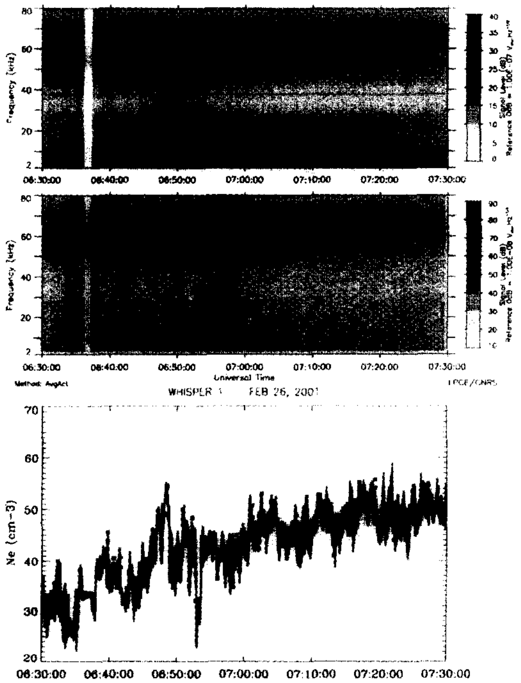

Fig. 4. Natural waves (top) and *Fpe* resonance (middle) measured by WHISPER-1 in the magnetosheath. Electron plasma density inferred from *Fpe* resonance observations (crosses) and from the lower cut-off frequency of the thermal noise recorded in passive mode (solid red line).

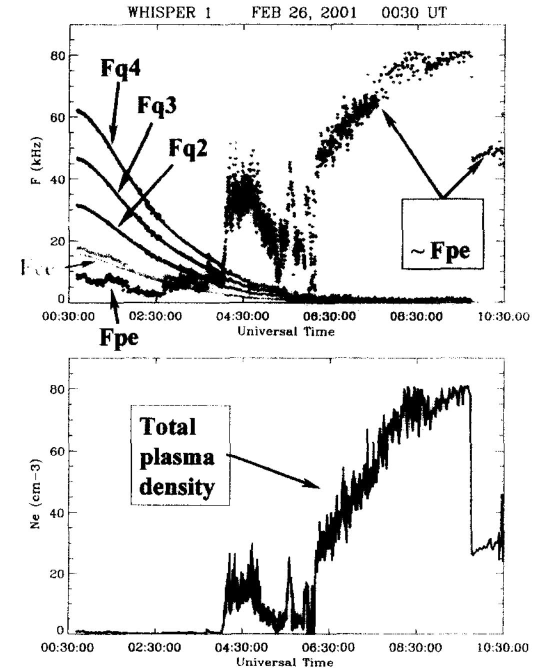

Fig. 5. Results obtained from WHISPER-1 observations from the plasmasphere to the solar wind. The CLUSTER-1 (Rumba) spacecraft crossed the magnetopause and bow shock at respectively 0610 UT and 0945 UT, so that the plasmasphere, the cusp regions, the magnetosheath and the solar wind were successively visited.

resonances identification (stars) and the upper frequency cut-off of natural Bernstein's waves (solid red line). There is a fairly good agreement between the two density evaluations.

ELECTRON PLASMA DENSITY DETERMINATION IN THE EARTH' MAGNETOSHEATH

In the solar wind and magnetosheath, where the static magnetic field is low, only one strong and long lasting resonance is actually observed at, or very close to, the electron plasma frequency, from which the electron plasma density is directly inferred. The lower frequency cut-off of the thermal noise detected during the WHISPER passive (natural) mode, can also be used to estimate the plasma density (Meyer-Vernet et al., 1998). The top and middle panels in Figure 4 show respectively the thermal noise and the electron plasma frequency resonance measured by the CLUSTER/WHISPER-1 sounder in the Earth's magnetosheath, on 26 February 2001. The inferred total electron plasma density is displayed in the bottom panel of Figure 4: stars are from the resonances detection, while the solid red line comes from the thermal noise measurements. As can be seen the two density determinations are very similar.

THE 26 FEBRUARY 2001 PASS FROM THE PLASMASPHERE TO THE SOLAR WIND

On the 26 February 2001, the CLUSTER-1 (Rumba) spacecraft moved in the north hemisphere from the nearly anti-sunward direction, at about 4 Earth's radii from the planet centre, to the solar wind. In its journey, the spacecraft successively encountered the plasmasphere (until 0403 UT), the cusp regions (until 0610 UT), the magnetosheath (until 0945 UT), and finally the solar wind. The plasma resonances identified in the active WHISPER-1 electric field measurements (Trotignon et al., 2002) are shown in the top panel of Figure 5. The bottom panel in Figure 5 illustrates how powerful the CLUSTER/WHISPER relaxation sounder is to determine the total electron plasma density in the Earth's environment (Décréau et al., 2001). As said before, in the solar wind and magnetosheath regions only one sharp and intense resonance is usually detected by the WHISPER at *Fpe*, from which the electron plasma density is simply derived. Conversely, many other resonances are currently triggered in the plasmasphere and cusp regions, they are successfully handled thanks to appropriate theoretical approaches and dedicated softwares so that the electron plasma density and magnetic field strength may again be delivered with a good accuracy.

CONCLUSION

It has long been recognized that plasma diagnosis via active wave experiments is efficient in space. The WHISPER relaxation sounder that is onboard the four CLUSTER satellites brillantly confirms this assertion in the Earth's space environment. It measures the frequency spectrum of one electric field component of natural waves in the 2 kHz – 80 kHz frequency range and is mainly designed to trigger plasma resonances, from which the electron plasma density and the intensity of the static magnetic field are quantified. As the measurements are reliable, accurate, and cover a large variety of plasma conditions the WHISPER is actually used as as a reference in correlative studies with the other CLUSTER experiments. For example, the electron plasma density determination is free from spacecraft charging or photoelectron cloud effects. It is thought to be within 1 % of the true value and the time resolution of the total electron plasma density determination reaches 0.3 s when the WHISPER works in passive mode, and a few seconds in the sounding mode.

Finally, it is worth noting that natural wave characteristics such as cut-off and/or intensity peak frequencies can valuably be exploited, insofar as plasma characteristic frequencies are known from sounding frequencies. It is actually the case of the CLUSTER/WHISPER experiment. The time resolution of the electron density measurement may be in this way as high as 0.3 s.

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