THE ELECTRON DENSITY AROUND THE EARTH, A HIGH LEVEL PRODUCT OF THE CLUSTER/WHISPER RELAXATION SOUNDER

Trotignon J. G.[(1)], Décréau P. M. E.[(1)], Rauch J. L.[(1)], Suraud X.[(1)], Grimald S.[(1)], El-Lemdani Mazouz F.[(1)], Vallières X.[(1)], Canu P.[(2)], Darrouzet F.[(3)], Masson A.[(4)]

[(1)]LPCE/CNRS, F-45071 Orléans cedex 2, France, Jean-Gabriel.Trotignon@cnrs-orleans.fr
[(2)]CETP/CNRS, F-78140 Vélizy, France, canu@cetp.ipsl.fr
[(3)]IASB, B-1180 Bruxelles, Belgium, Fabien.Darrouzet@oma.be
[(4)]RSSD/ESA, NL-2201 AZ Noordwijk ZH, The Netherlands, Arnaud.Masson@esa.int

ABSTRACT

The WHISPER (Waves of HIgh frequency and Sounder for Probing of Electron density by Relaxation) aboard the four CLUSTER satellites performs high frequency electric field measurements in the Earth's space environment, from the solar wind down to the plasmasphere. In active mode, the WHISPER behaves like a topside sounder. It provides, via the identification of resonances that are triggered at characteristic frequencies of the encountered ionised medium, reliable and accurate determination of the total density of thermal electrons. In passive mode, when the transmitter is switched off, it becomes a classical wave receiver. The 2 to 80 kHz frequency range of the electric component of natural waves is therefore monitored. The objective of the presentation is to show that the thermal electron density may be derived from the active and/or passive measurements of the WHISPER all along the CLUSTER trajectory, and almost everywhere, with a good accuracy compared with other estimates.

1. INTRODUCTION

Different strategies [1] may be used to automatically determine the density from the electric field spectra delivered by the CLUSTER/WHISPER relaxation sounder [2]. They take advantage of the large variety of resonances that are actually excited when the WHISPER transmitter is activated and/or the frequency characteristics of the natural waves [3] that are observed in the passive mode. Some of the techniques proposed here are directly derived from the ones [4] used to process the ISEE 1 relaxation sounder data [5], in particular in the plasmasphere, where resonances at the harmonics of the electron cyclotron frequency, nFce, and Fqn resonances that are due to waves propagating in the Bernstein's modes [6] are detected. Up-to-date image processing techniques have also been tested, the most promising ones are presented hereafter. Section 2 shows how the electron plasma density can be derived in the solar wind and magnetosheath. Sections 3 and 4 are respectively devoted to the inner magnetosphere and tail. Finally, an overall path is shown in section 4 before the conclusion.

2. IN THE SOLAR WIND AND MAGNETOSHEATH

In the free solar wind and in the magnetosheath, only one strong resonance is mainly observed at, or close to, the plasma frequency from which the density is directly derived. In addition, the lower cut-off of the thermal noise recorded whenever the relaxation sounder is used as a natural wave detector is also a valuable way to determine the plasma density. The cut-off indeed occurs very close to the plasma frequency.

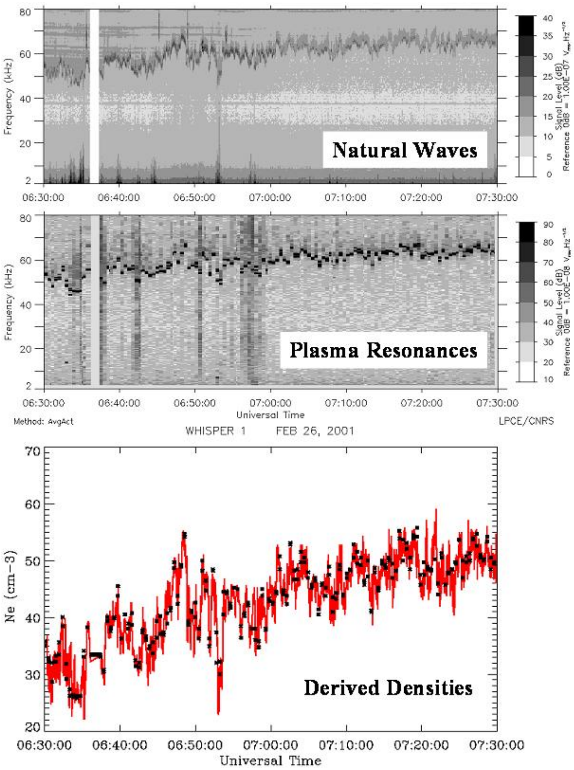

Fig. 1 Earth's magnetosheath as seen by WHISPER-1, when passive (top) and active (middle). At the bottom, plasma density inferred from plasma resonances (crosses) and from the lower cut-off frequency of the thermal noise recorded when passive (red curve) [7].

Proceedings Cluster and Double Star Symposium – 5th Anniversary of Cluster in Space, Noordwijk, The Netherlands, 19 - 23 September 2005 (ESA SP-598, January 2006)

Fig. 1 which is borrowed from [7] shows a one-hour CLUSTER-1 path in the Earth's magnetosheath on 26 February 2001. The natural wave spectrogram and the plasma frequency resonances, Fpe, detected by the WHISPER are respectively shown in the top and middle panels. In the bottom panel of Fig. 1, the total plasma densities inferred from the Fpe resonances are given by stars, while the density values derived from the lower frequency cut-off of the thermal noise are plotted as a solid line. The two density determinations are in a good agreement and the passive measurements allow the density to be determined with a higher temporal resolution.

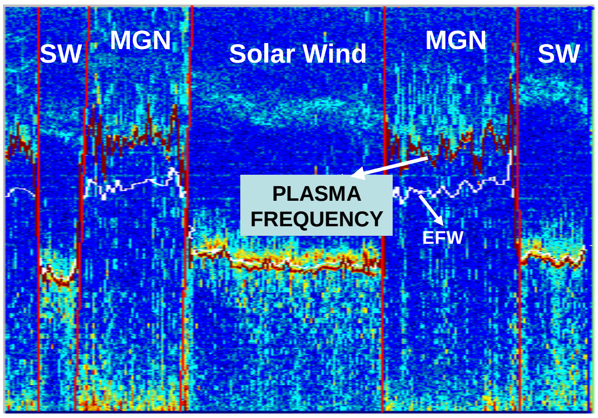

Fig. 2 Active dynamic spectrogram measured by WHISPER-1 on 13 May 2002, from 15:50 to 17:40 UT. The electron density deduced from the spacecraft potential measurements are shown in white, while the WHISPER-EFW processed density values are plotted in red [from P6-13 poster by Rauch *et al.*].

Another way to give the density is to combine the WHISPER active observations (Fpe resonances) with the spacecraft potential measurements made by the Electric Field and Wave experiment (EFW). As shown in Fig. 2, the density estimated in the solar wind from the spacecraft potential measurements (white line) is lower than the density derived from the WHISPER Fpe resonances (yellow and orange pixels). It means that the absolute values of the EFW density have, in this case, to be calibrated using the active measurements made by WHISPER. Nevertheless, the EFW density fluctuations are, or are supposed to be, valid whenever the plasma characteristics remain the same. It is therefore justified to split the time sequence under study into shorter intervals in which the EFW density does not vary too much. The EFW density pattern is then adjusted, at best, to the density time series given by the WHISPER resonances, in each of these time intervals. Pattern fitting processes are therefore applied. The result is pointed out in Fig. 2 by a red line. As can be seen, it best fits the Fpe resonances triggered by the WHISPER in the solar wind, as well as in the magnetosheath.

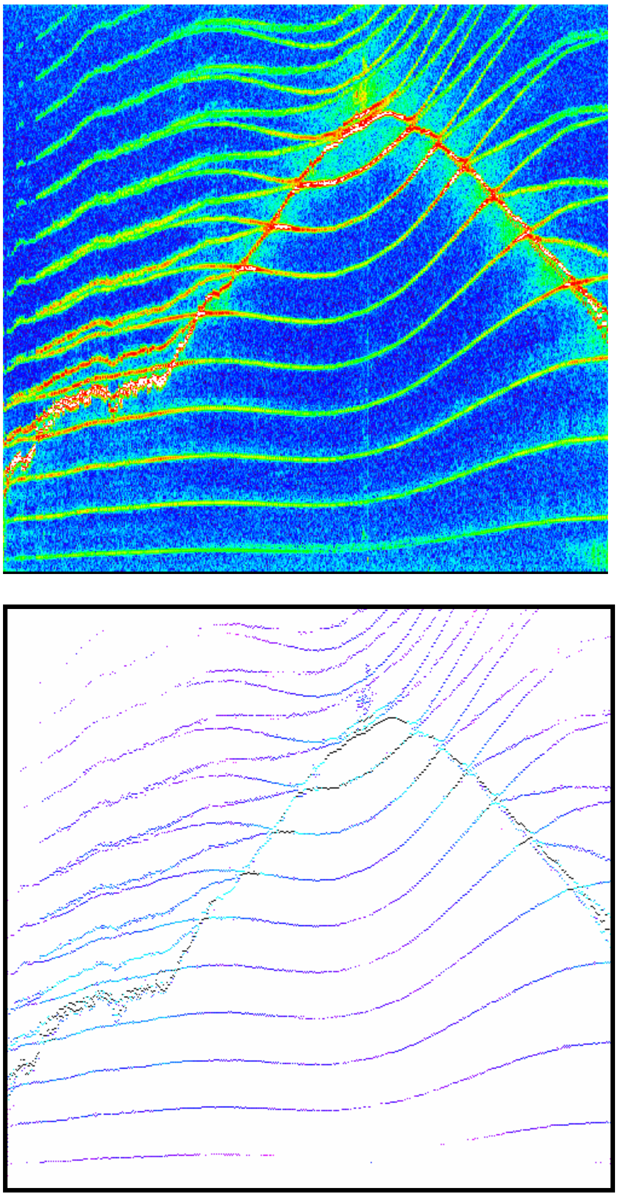

Fig. 3 Active dynamic spectrogram recorded by WHISPER-1 in the Earth's plasmasphere on 5 August 2002 between 17:00 and 20:40 UT, before (left panel) and after (right panel) image processing [from P6-13 poster by Rauch *et al.*].

3. IN THE PLASMASPHERE AND CUSP REGIONS

In the inner magnetosphere, and in particular in the plasmasphere, resonances arise at the plasma frequency, Fpe, the electron gyrofrequency, Fce, its harmonics, nFce, the upper-hybrid frequency, $Fuh=(Fpe^2+Fce^2)^{1/2}$, and the so-called Fqn that correspond to electrostatic cyclotron waves [6] whose group velocity vectors are close to zero and are almost in the direction perpendicular to the DC magnetic field direction. Fqn frequencies must verify: Fqn>2Fce, Fqn>Fuh and nFce<Fqn<(n+1)Fce. Several plasma parameters such as the total plasma density and the magnetic-field strength may be deduced from these plasma characteristic frequencies.

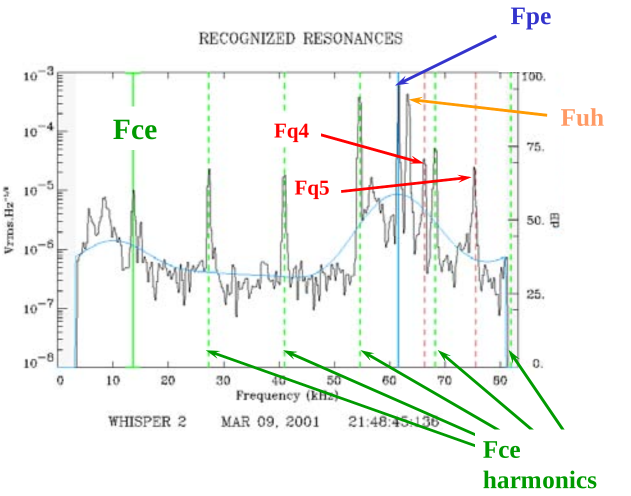

Fig. 4 Active electric-field spectrum measured by the CLUSTER/WHISPER relaxation sounder close to the Earth's plasmapause: several types of resonances are triggered.

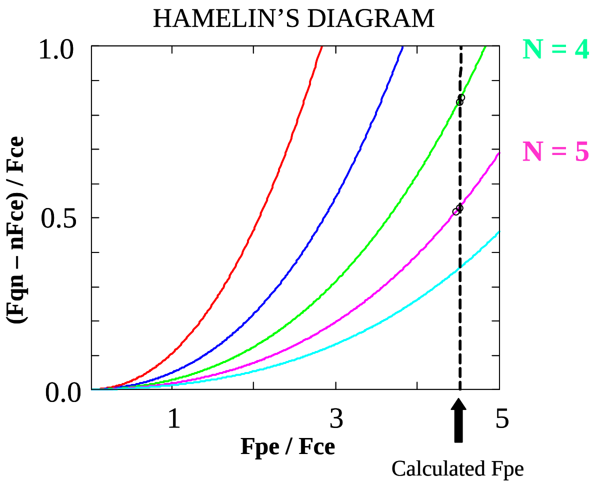

Fig. 5 The electron plasma density may be obtained from Fpe and Fuh, but also from the Fqn resonances by using the Hamelin's diagram (see spectrum in Fig. 4).

Before plasma resonance identifications, the dynamic spectrograms may be processed in order to improve the contrast, to reduce the noise, to smooth the images while preserving the edges (by applying, for example, a Nagao filter), and to extract peaks. This is illustrated in Fig. 3. The top panel shows the active spectrogram recorded by WHISPER-1 in the plasmasphere on 5 August 2002 from 17:00 UT to 20:40 UT. A new image with a high contrast and a low level of noise is then obtained as seen in the bottom panel of Fig. 3.

Once extracted from the other signals with the help of such image processing techniques, the resonances may then be used to determine the plasma density. Two other techniques that make use of natural wave properties round Fpe can also be applied in parallel in order to refine the plasma diagnosis, as we will see hereafter.

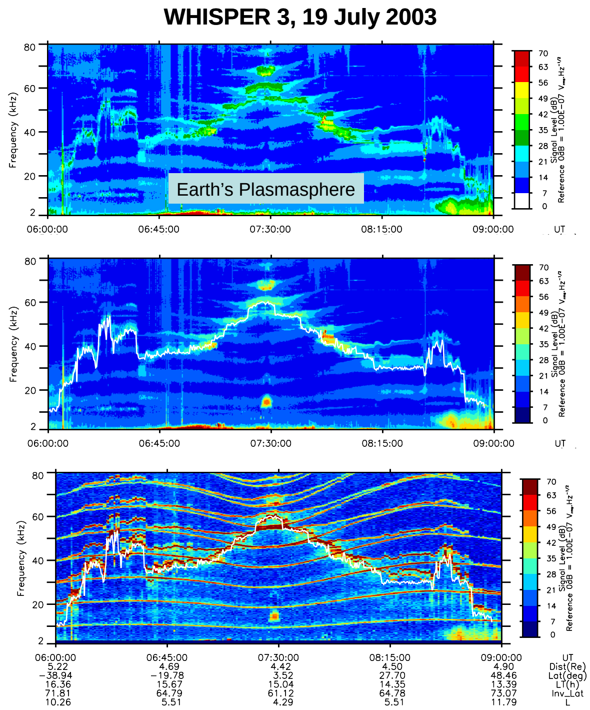

Fig. 6 Natural wave spectrogram delivered by WHISPER-3 (top panel). Total electron density, shown as a white line, derived from the lower cut-off frequency and superimposed on the natural wave spectrogram (middle), and on the active spectrogram (bottom).

A typical spectrum measured close to the plasmapause is displayed in Fig. 4. As several harmonics of the electron cyclotron frequency are currently observed, it is easy to determine Fce and then the magnetic-field strength with a good accuracy. The plasma frequency and upper-hybrid resonances are also often observed. It is therefore possible to determine the total plasma density and again the magnetic field strength. The plasma density may also be computed from the frequency locations of the Fqn Bernstein's resonances with the help of a specific diagram, the so-called Hamelin's diagram. The frequency locations of the Fqn are indeed vertically aligned in this diagram, provided that the velocity distribution function of the electrons is not too different from a maxwellian. Fpe and therefore the density of the cold plasma component may then be deduced from the abscissa, as shown in Fig. 5.

A three-hour sequence recorded in the Earth's plasmasphere by WHISPER onboard CLUSTER-3 is shown in Fig. 6. The natural waves are plotted in the two top panels whereas the bottom panel exhibits the resonance families. An increase in the natural wave level is currently observed close to the plasma frequency. Moreover, these waves reveal a lower cut-off frequency just below the plasma frequency from which the density may be derived. It has been done and the deduced plasma density (white line) has been superimposed in Fig. 6 on the natural wave plot (middle panel) and, for comparison purpose, on the active spectrogram (bottom panel). The result is not perfect, but the plasma frequency computed from the obtained density follows the general trend of the plasma frequency resonance and there is not a too big difference between the two determinations.

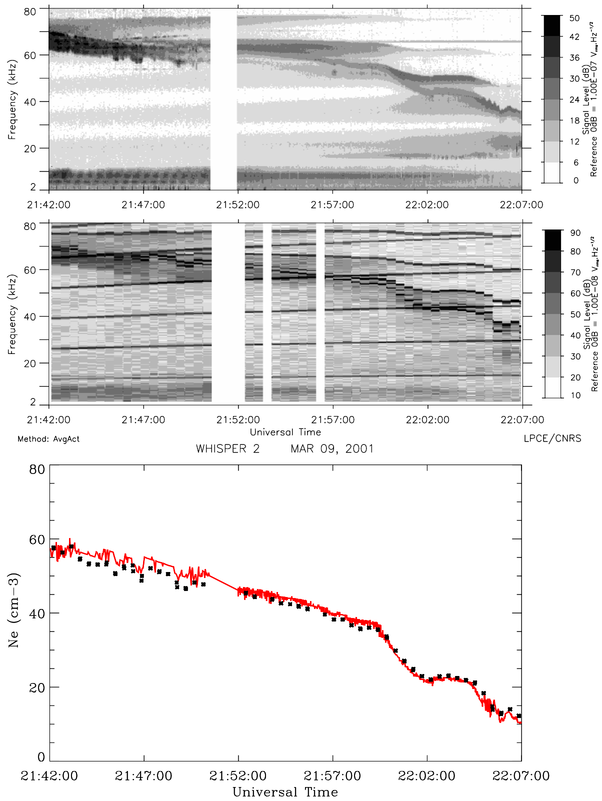

Fig. 7 WHISPER-2 dynamic spectrograms in the Earth's plasmapause: natural waves (top) and triggered resonances (middle). Deduced electron plasma densities (bottom): from the plasma frequency resonances Fpe (crosses) and from the upper cut-off frequency of the natural Bernstein's waves that are the closest to Fpe and above (red curve). This Figure is borrowed from [7].

A third method to determine the density in the plasmasphere and in the cusp regions is illustrated in Fig. 7. Natural waves occur above the plasma frequency and exhibit an upper cut-off frequency at Fqn, the frequency of the so-called Bernstein's mode resonances. Again, with the help of the Hamelin's diagram (as shown in Fig. 5) it becomes possible to give the electron plasma density. The top and middle panels in Fig. 7 show an example of a plasmapause crossing as seen by WHISPER-2. The natural waves are at the top and resonances are highlighted in the middle panel. The density deduced from the upper cut-off frequencies (red line) is compared with the density computed from the frequency locations of the plasma resonance, Fpe. There is a quite nice agreement between the two density determinations.

As a conclusion, different techniques may be applied to determine the density in the plasmasphere and cusp regions from both the active and passive E-field measurements made by the WHISPER relaxation sounder. These techniques can be combined to estimate the density determination uncertainty and to estimate whether the maxwellian electron-velocity distribution function hypothesis is well-founded or not.

4. IN THE TAIL

The density determination in the tail is not an easy task. This is mainly because the plasma characteristics are often not trivial. In most cases the density is very low, the plasma frequency is close to the gyrofrequency of the electrons and it is sometimes lower. In addition, the plasma frequency is most often close to 4 kHz which is the lowest working frequency of the WHISPER. Another difficulty comes from the polarization of the resonance emissions. The resonance amplitude indeed presents strong modulations as a function of the angle between the electric-field antenna axis and the DC magnetic-field vector.

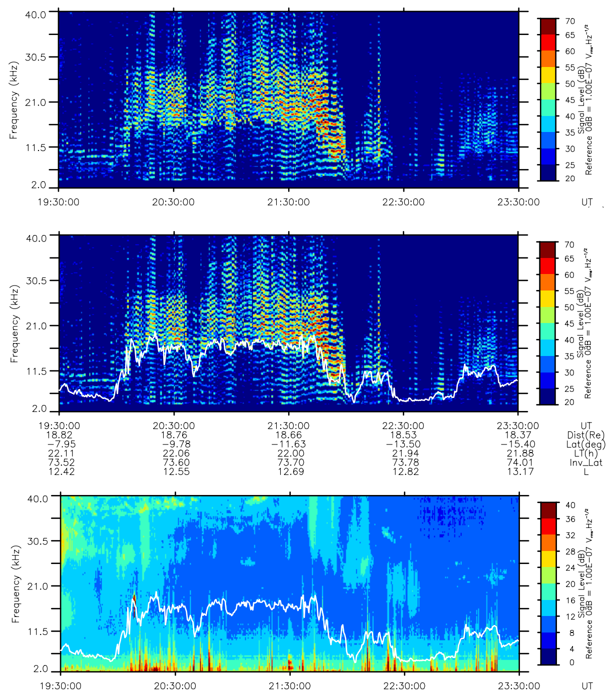

Fig. 8 Electric-field resonances (top and middle panels) and natural waves (bottom panel) observed by the WHISPER-1 relaxation sounder in the far magnetic tail on 30 September 2002, at a geocentric distance of 18.4-18.8 Earth's radii in the dusk sector (22 LT). The plasma frequency, from which the density is derived, is shown as a white line in the middle and bottom panels.

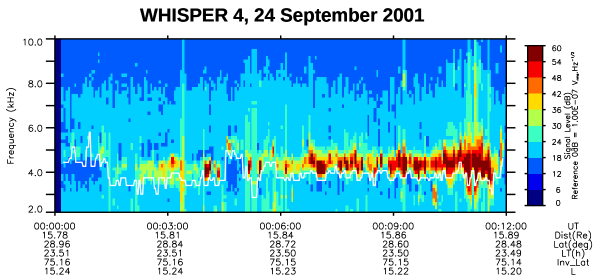

Fig. 9 Electron density (white line) superimposed on the natural wave spectrogram measured by the WHISPER-4 in the Earth's magnetic tail on 24 September 2001, between 00:00 UT and 00:12 UT.

The passive and active spectrograms recorded by WHISPER-1 in the far Earth's magnetic tail on 30 September 2002, from 19:30 to 23:30 UT, are presented in respectively the bottom panel and the two top panels of Fig. 8. It may be seen that the resonance amplitudes are strongly modulated, Fce is low (B is weak), and Fpe/Fce is rather high here. In this case the techniques recommended to extract the density in the inner magnetosphere (cusp and plasmasphere) may be applied. Nevertheless due to the limited frequency resolution of the WHISPER analyser (162 Hz) and because the magnetic field is weak, it is rather difficult to see and identify each of the triggered resonances. Another technique has therefore been proposed. Its principle looks like the one discussed in section 2. The density pattern derived from the EFW spacecraft measurements are used together with the plasma frequency resonance, whenever the latter may be identified, to determine a high-resolution density profile. Pattern recognition and/or fitting techniques are therefore used. The white lines in the middle and bottom panels in Fig. 8 show the plasma density (in fact the electron plasma frequency) thus obtained.

In the 30 September 2002 tail event, no natural wave signature are present close to the plasma frequency, as shown in the bottom panel of Fig. 8. This is not always the case in the magnetic tail. An example of natural wave cut-off that can be useful to determine the plasma frequency and therefore the electron plasma density is given in Fig. 9. Langmuir waves were indeed observed on 24 September 2001 by WHISPER-4 from 00:00 UT to 00:12 UT. The density that is derived from the lower frequency cut-off of these waves is superimposed on the natural wave spectrogram, it is displayed as a white line in Fig. 9.

5. AN OVERALL PATH

In order to illustrate the ability of the available WHISPER data processes to determine the total plasma density, in most of the key regions of the Earth's space environment, let us consider the 26 February 2001 path that is shown in Fig. 10.

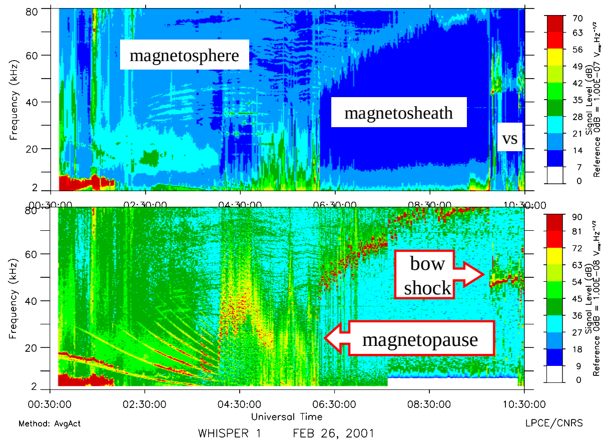

Fig. 10 Dynamic spectrograms of the E-field measured by WHISPER onboard CLUSTER-1 (Rumba): natural waves (top), triggered resonances (bottom). The Earth's magnetosphere is probed until 0610 UT, next the spacecraft is travelling into the magnetosheath before entering the solar wind at 0945 UT. Resonances are used to interpret the natural wave emissions and to determine the total plasma density and the B-field strength all along the orbits (borrowed from [8]).

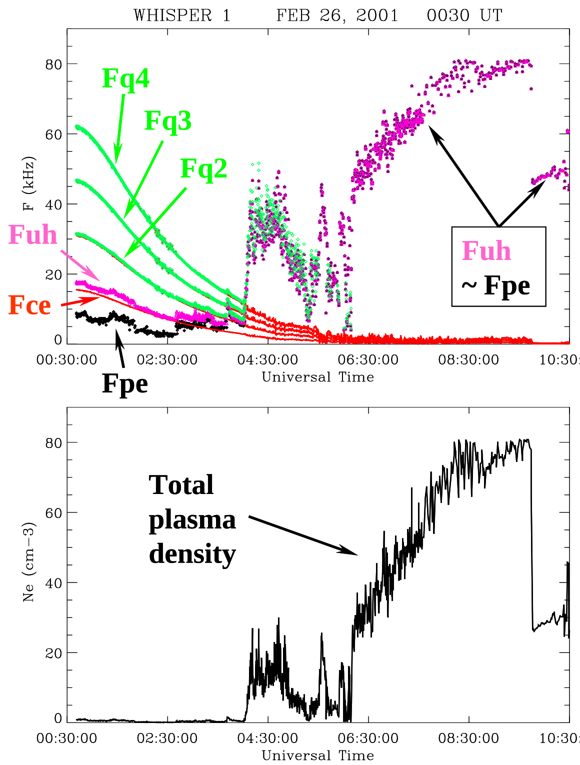

Fig. 11 Resonance identification and density results obtained from WHISPER-1 observations, from the plasmasphere to the solar wind. The CLUSTER-1 (Rumba) spacecraft crossed the magnetopause and bow shock at respectively 0610 UT and 0945 UT, so that the plasmasphere, the cusp regions, the magnetosheath and the solar wind were successively visited. This Figure is borrowed from [7].

In Fig. 10, which shows the natural waves (in the top panel) and the resonances that are excited by the WHISPER (in the bottom panel), CLUSTER-1 is moving from the inner magnetosphere at 00:30 UT up to the solar wind at 10:30 UT. The cusp regions are probed between about 04:00 UT and 06:10 UT where the magnetopause is crossed. Three hours and a half later, at 09:45 UT, the Earth's bow shock is crossed. These three boundaries are here easily identified by abrupt gradients in the plasma frequency (density).

Both the natural wave characteristics and the resonances in the electric field may be used, as said above, to reliably determine the total plasma density with a very high accuracy. The resonances identified in the WHISPER active AC electric-field measurements are displayed in the top panel of Fig. 11, which is borrowed from [7]. The density gradients that occur at the bow shock, at the magnetopause, and at the transition region between the plasmasphere and the cusp regions, are clearly seen in the bottom panel of Fig. 11.

6. CONCLUSION

For more than 20 years, relaxation sounders have proved to be efficient in providing absolute measurements of the total plasma density (see for example [5], [9], and [10]). The WHISPER is in the tradition of these efficient instruments. Taking into account the characteristic frequencies of the magnetoplasmas encountered by the four CLUSTER spacecraft, the electron plasma density may be reliably and accurately determined from the active and passive measurements of the WHISPER. Successful tools have been, or are on the way to be, developed to automatically provide the density from the solar wind down to the plasmasphere. The next step, would be to find a way to automatically provide the density whatever the region is. In this way the program would automatically determine the suitable algorithm without knowing the encountered plasma regime, in advance.

References

1. Trotignon J. G., et al. How to determine the thermal electron density and the magnetic field strength from the Cluster/Whisper observations around the Earth, *Ann. Geophysicae*, 19, 1711-1720, 2001.

2. Décréau P. M. E., et al. Whisper, a resonance sounder and wave analyser : performances and perspectives for the Cluster mission, *Space Science Rev.*, 79, 157-193, 1997.

3. Canu P., Identification of natural plasma emissions with the Cluster-Whisper relaxation sounder, *Ann. Geophysicae*, 19, 1697-1709, 2001.

4. Trotignon J. G., Etcheto J. and Thouvenin J. P., Automatic determination of the electron density measured by the relaxation sounder on board ISEE 1, *J. Geophys. Res.*, 91, 4302-4320, 1986.

5. Etcheto J., de Feraudy H. and Trotignon J. G., Plasma resonance stimulation in space plasmas, Adv. Space Res., 1, 183-196, 1981.

6. Bernstein I.B., Waves in a plasma in a magnetic field, *Phys. Rev.*, 109, 10-21, 1958.

7. Trotignon J. G., Rauch J. L., Décréau P. M. E., Canu P. and Lemaire J., Active and passive plasma wave investigations in the Earth's environment: the Cluster/Whisper experiment, *Adv. Space Res.*, 31, 1449-1454, 2003.

8. Trotignon J. G., Décréau P. M. E., Rauch J. L., Le Guirriec E., Canu P. and Darrouzet F., The whisper relaxation sounder onboard Cluster : a powerful tool for space plasma diagnosis around the Earth, *Cosmic Research*, 41, 345-348, 2003.

9. Perraut S., et al. Density measurements in key regions of the Earth's magnetosphere: cusp and auroral region, *J. Geophys. Res.*, 95, 5997-6014, 1990.

10. Belmont G., et al. Advances in magnetospheric plasma diagnosis by active experiments, in *Proc. Conf. Achievements of the IMS*, 26-28 June 1984, Graz, Austria, ESA SP-217, 695-699, 1984.