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THE CLUSTER MISSION PRELIMINARY RESULTS OBTAINED WITH THE WHISPER EXPERIMENT

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The Cluster programme [1] is one of the two missions (the other being the SOlar and Heliospheric Observatory, SOHO) that constitute the Solar Terrestrial Science Program (STSP) of the European Space Agency. It is designed to study the small-scale spatial and temporal characteristics of the Earth's magnetospheric plasma and the near-Earth solar wind. The mission consists of four identical spacecraft, which enable scientists to make physical measurements in three dimensions. The relative distance between the spacecraft varies between 100 and 20000 km during the course of the mission. This paper presents a general overview of the mission, the main scientific objectives, the instrumentation onboard the spacecraft, and preliminary results obtained at the Belgian Institute for Space Aeronomy with Cluster data.

1. Introduction

Four years after the failure of the first flight of Ariane-5 with the four Cluster spacecraft onboard, the rebuilt-spacecraft were successfully launched in July and August 2000 with two Russian Soyuz rockets from the Baikonur Cosmodrome in Kazakhstan, each carrying a pair of identical satellites.

After a long commissioning phase of about six months, the scientific mission phase has started on 1 February 2001 for a nominal period of 2 years.

The four spacecraft fly in a tetrahedral configuration in polar orbits with a perigee of 4 R_E, an apogee of 19.6 R_E, an inclination of 90°, and an orbital period of 57 hours. The separation distance between the spacecraft is adjusted depending on the regions of interest crossed by the tetrahedron and on the spatial scales of the structures to be studied; it varies from a few hundred kilometres to a few Earth radii. The separation manoeuvres are performed at approximately six-month intervals, synchronised with normal orbit-maintenance manoeuvres.

Each Cluster spacecraft contains 11 identical instruments: an active spacecraft potential control instrument (ASPOC), an ion spectrometry instrument (CIS), an electron drift instrument (EDI), a fluxgate magnetometer (FGM), a plasma electron and current experiment (PEACE), two adaptive particle imaging spectrometers (RAPID), a digital wave processing instrument (DWP), an electric field and wave experiment (EFW), a spatio-temporal analyser of field fluctuations (STAFF), an alternating transmitter/receiver instrument (WHISPER) and a wide band data receiver (WBD); these five last instruments forming the Wave Experiment Consortium (WEC) [2].

In the framework of the Cluster mission the Belgian Institute of Space Aeronomy participates in the experiments WHISPER and STAFF.

By measuring plasma and field characteristics simultaneously, the four Cluster spacecraft are able to make the first detailed, three-dimensional study of the changes and processes taking place in near-Earth space. It is the first time that four identical spacecraft fly in formation around the Earth. Their tetrahedral configuration permits to determine common vector differential quantities and to infer important plasma characteristics, like electrical current densities, pressure, plasma density gradients, ...

2. Scientific objectives

The main goal of the Cluster mission is to study the small-scale plasma structures in space and time and the physical processes involved in the interaction between the solar wind and the magnetosphere by visiting the key regions of geospace described below: solar wind and bow shock, magnetopause, magnetosheath, polar cusps, plasmasphere, magnetotail and auroral zones (see Figure 1).

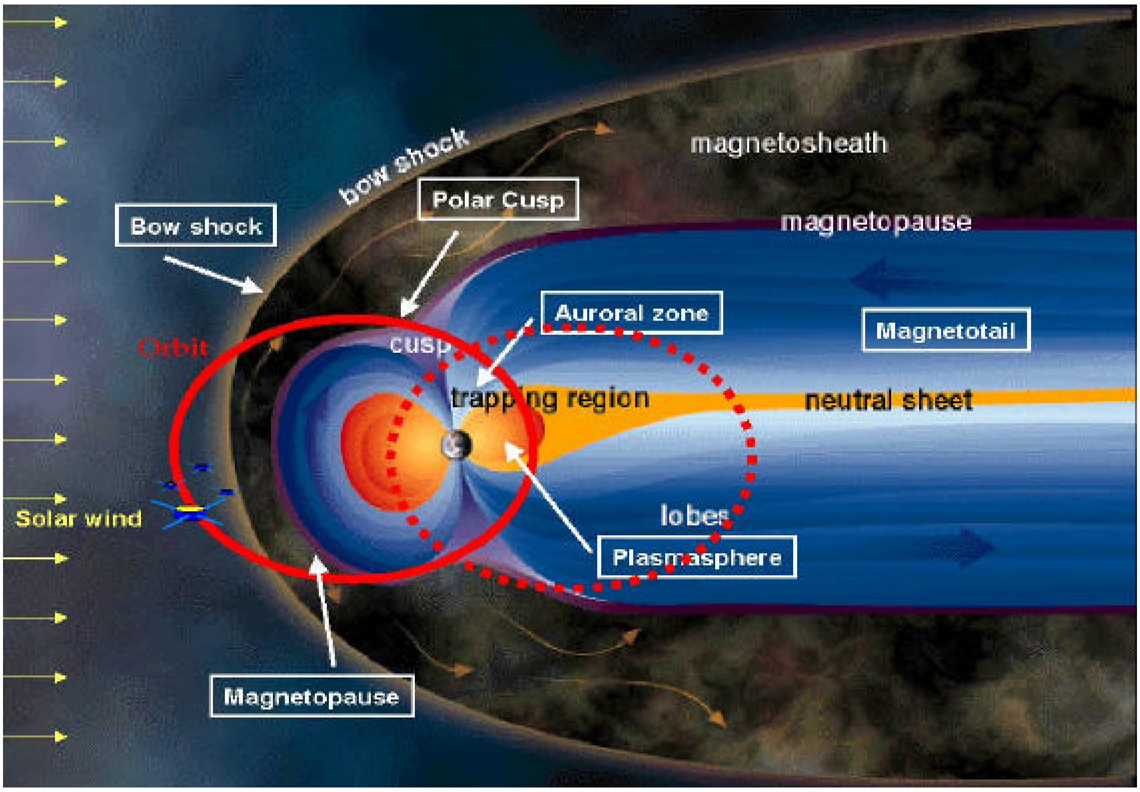


Figure 1 : Cluster orbit and regions visited during dayside (-) and nightside (- -) configurations

The solar wind originates in the lower region of the corona (the Sun's outer atmosphere), which expands outwards against gravity, carrying the solar magnetic field along with it. Close to the Sun, the wind is a hot, dense and subsonic plasma moving outwards. It is accelerated radially and reaches supersonic speeds inside Mercury's orbit. With the five instruments measuring electromagnetic waves onboard the Cluster spacecraft, we can improve our understanding of the spectral and spatial distributions of electromagnetic and in particular the mechanisms of their transmission through the magnetospheric bow shock.

The bow shock is a sharp front formed in the solar wind ahead of the magnetosphere, marked with a sudden transition of the wind from supersonic to subsonic speeds, before being deflected around the Earth by the geomagnetic field. Multi-point measurements can help to define the shape and structure of the disturbances observed near the bow shock, and to understand their origin.

The region between the bow shock and the magnetosphere is called the magnetosheath. The plasma flow from the bow shock to the magnetosphere is studied, as well as the waves propagating in this region.

The magnetopause is the thin current layer (≅ 500 - 1000 km) that separates the solar wind magnetic field from the Earth's magnetic field. This is the boundary of the magnetosphere. Magnetopause motions occur frequently because of solar wind pressure changes. The four-point measurements of Cluster will help to distinguish between the different physical processes which occur at the magnetopause: Kelvin-Helmholtz instability, Rayleigh-Taylor instability, magnetic reconnection, and impulsive penetration of magnetosheath plasma elements inside the magnetosphere [3]. Critical problems about magnetopause structure, local geometry, and dynamics could be solved with this multi-spacecraft mission.

The polar cusps are regions of weak magnetic field, on the sunward boundary of the magnetosphere, one on each side of the equator. They contain stagnant magnetosheath plasma because in these regions, the geomagnetic field lines are connected to the interplanetary field lines. One of the major objective of the mission is the study of plasma turbulence in these regions.

The plasmasphere is the region of the extraterrestrial environment consisting of a cold dense plasma originating in the ionosphere and trapped by the Earth's magnetic field. The outer surface of the plasmasphere is called the plasmapause. It is crossed by the Cluster spacecraft on only a few occasions, near perigee and under favourable magnetic activity conditions. Structure and motion of this boundary are observed in greater details and with higher time and spectral resolution with the four-point measurements. These new observations fully support the theory for formation of the plasmapause boundary that has been developed at the Belgian Institute for Space Aeronomy [4]. This theory based on the mechanism of plasma interchange has also been confirmed by recent observations of Cassini [5].

The magnetotail is characterised by magnetic field lines stretched by the solar wind flow in the anti-sunward direction. In the plasmasheet, the central part of the magnetotail, earthward acceleration of plasma during substorms can be studied with more details and accuracy.

The auroral zones are rings of emission of light, around the magnetic poles. They are created by precipitation of electrons and sometimes protons in the upper atmosphere above 100 km altitude. Although Cluster does not cross the most active parts of these regions, the spacecraft probe the vast auroral current circuit associated with field-aligned currents and solitary kinetic Alfvén waves which are thought to play a role in the acceleration of auroral electrons.

All these regions and boundaries are explored in great detail by Cluster, depending on the configuration of the orbit. At the beginning of the scientific phase in February 2001, the orbits of Cluster were initially in the dawn-dusk meridian with the apogee at dusk (as illustrated in Figure 2). As the Earth is moving around the Sun, the apogee was located in the solar wind around local noon 3 months later, around the flank of the magnetosphere at dawn after 3 additional months, in the plasmasheet around midnight local time 3 months later and then again on the flank of the magnetosphere in the dusk local time sector after 1 complete year of orbit. The same scenario is repeated for the second year of Cluster mission operations.

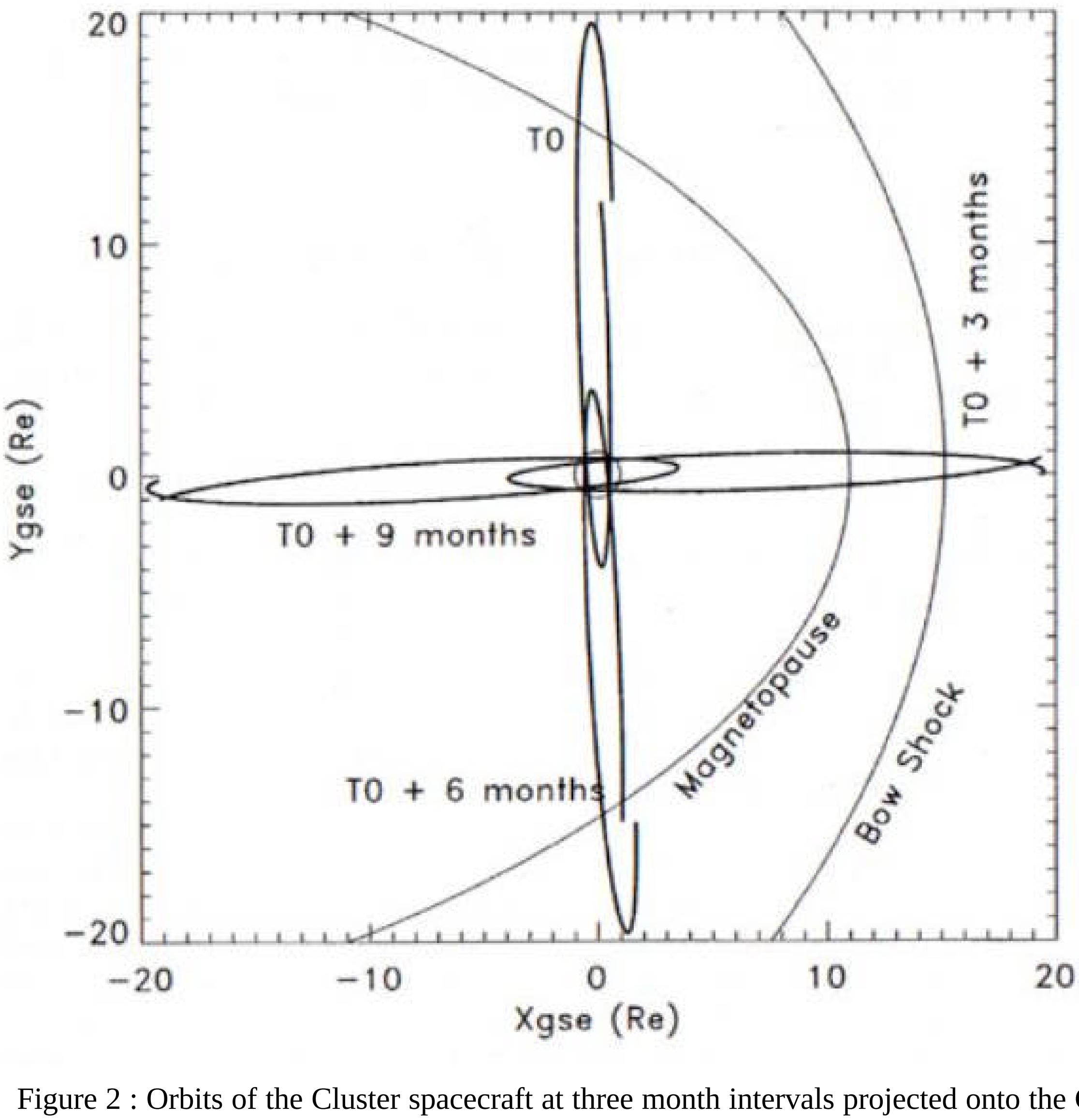


Figure 2 : Orbits of the Cluster spacecraft at three month intervals projected onto the GSE equatorial plane, starting with the 2nd launch in August 2000 (Source ESA)

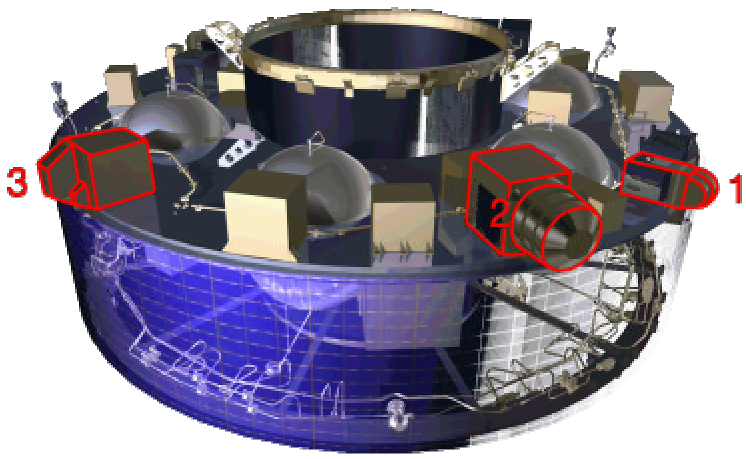
3. Instrumentation

The four Cluster spacecraft are identical. Each contains 11 instruments. Their location on the spacecraft is shown in Figures 3, 4 and 5. Their complete description can be found in reference 1.

FGM (Fluxgate Magnetometer) consists of two tri-axial fluxgate magnetometers. In order to minimise the magnetic background of the spacecraft, one of the sensors is located at the end of one of the two 5.2 m radial booms of the spacecraft, the other at 1.5 m inboard from the end of the boom. They measure the magnetic field vector along the Cluster orbit with a time resolution up to 67 samples per second.

EDI (Electron Drift Instrument) consists of two sets of electron guns/detectors at 180° to each other. Each gun sends a weak beam of electrons 10 km or more into the space around the spacecraft, and when emitted in certain directions, the electrons return to receivers on the opposite side of the spacecraft. The returning beams being affected by the strength of the electric field in space and by the gradient in the ambient magnetic field, one can determine the intensity of these two field by emitting and receiving two electron beams with two different energies.

ASPOC (Active Spacecraft Potential Control) is an ion emitter designed to minimise the electrostatic charging of the spacecraft. Since the spacecraft emits photoelectrons when it is illuminating by sunlight, a positive electrostatic potential develops. ASPOC emits indium ions into space to cancel out this positive electric charge that the satellite acquired. The ion current is adjusted by using other Cluster instruments measuring the spacecraft potential (EFW and PEACE).



1 **FGM** (A. Balogh, UK)
Magnetic field

2 **EDI** (G. Paschmann, D)
Plasma drift velocity
(0.1<E<10 mV/m, 5<B<1000 nT))

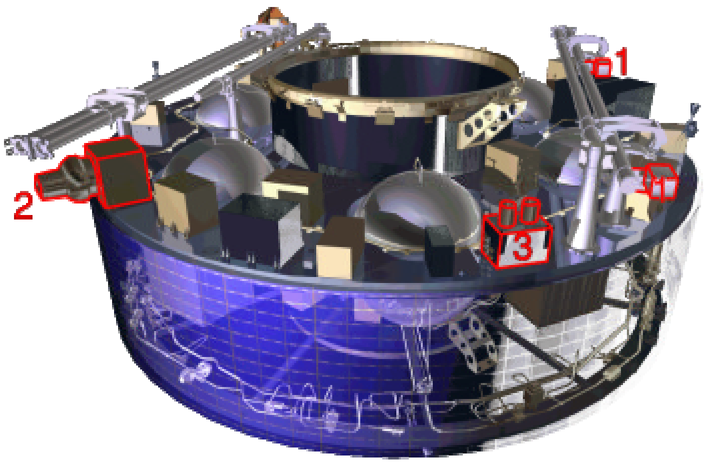
3 **ASPOC** (K. Torkar, A)
Spacecraft potential control

Figure 3 : Cluster instrument location on the spacecraft (Source ESA)

PEACE (Plasma Electron and Current Experiment) consists of two sensors mounted opposite to each other on the spacecraft to allow the three-dimensional electron distribution function to be measured: a low-energy electron analyser (LEEA) and a high-energy electron analyser (HEEA). They measure the distribution of electrons from 0.6 eV to 26.4 keV.

CIS (Cluster Ion Spectrometry) consists of two different sensors to analyse the composition, mass and energy distribution functions of ions in the plasma. A time-of-flight ion composition and distribution analyser (CODIF) measures the distribution of the major species of ions populating the magnetosphere and the solar wind (H^+, He^+, He^{++} and O^+) from 0 to 40 keV/q and a hot ion analyser (HIA) measures the distribution of the ions without mass resolution from 5 eV/q to 32 eV/q.

RAPID (Research with Adaptive Particle Detectors) is an advanced particle detector which records the highest energy electrons and ions. It consists of two spectrometers: an imaging ion mass spectrometer (IIMS) designed to measure the ion distribution function from 30 to 1500 keV/q and an imaging electron spectrometer (IES) which measures electrons from 20 to 450 keV.



1 **PEACE** (A. Fazakerley, UK) Electrons (E<27 keV)

2 **CIS** (H. Rème, F) Ions (E<40 keV/q)

3 **RAPID** (P. Daly, D) High energy electrons and ions ($40<E_{ion}<1500$ keV/q, $20<E_{ele}<400$ keV)

Figure 4 : Cluster instrument location on the spacecraft (Source ESA)

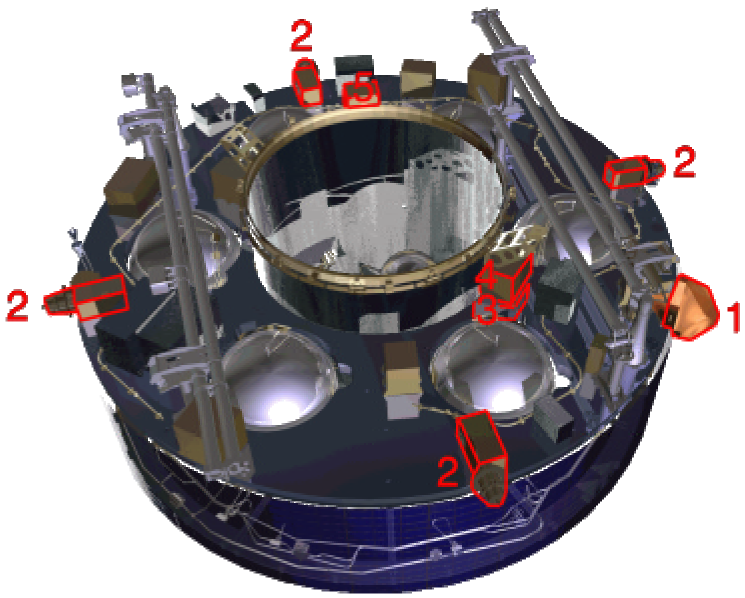
STAFF (Spatio-Temporal Analysis of Field Fluctuation) has two main parts: a three-axis search-coil magnetometer mounted on the end of a five metre long boom to measure the magnetic components of the electromagnetic fluctuations at frequencies up to 4 kHz and a spectrum analyser to perform auto-and cross correlation between electric and magnetic components.

EFW (Electric Field and Wave) is designed to measure the electric field and density fluctuations with sampling rates up to 36000 samples per second. It consists of four orthogonal cable booms carrying spherical sensors, which are deployed to 50 m in the spin plane of the spacecraft. The instrument is also capable of measuring the spacecraft potential and the electron density and temperature.

DWP (Digital Wave Processing) is designed for on-board control of the five wave experiments (forming the WEC). It includes also a particle and wave/particle correlator.

WHISPER (Waves of High Frequency and Sounder for Probing of Electron density by Relaxation) is a relaxation sounder that fulfils two functions: the measurement of the total electron density, via an active radio frequency technique, and the continuous survey of the natural plasma emissions in the 2 to 80 kHz frequency band. The combination of both capabilities provides absolute density variations with a good time resolution (0.3 to 3s) within the range 0.2 to 80 electrons per cubic centimetre.

WBD (Wide Band Data) is a wide-band receiver system designed to provide high-resolution measurements of both electric and magnetic fields in selected frequency bands from 25 Hz to 577 kHz. The inputs consist of two electric components from EFW and two magnetic components from STAFF.



1 **STAFF** (N. Cornilleau-Wehrlin, F) Magnetic and electric fluctuations

2 **EFW** (M. André, S) Electric fields and waves

3 **DWP** (H. Alleyne, UK) Wave processor

4 **WHISPER** (P. Décréau, F) Electron density and plasma waves

5 **WBD** (D. Gurnett, USA) Electric field wave-form

Figure 5 : Cluster instrument location on the spacecraft (Source ESA)

4. Some results

Early results obtained with the Cluster spacecraft demonstrate that the four-point measurements are unique and most important. They give a completely new perspective on the physics in the many regions explored by the spacecraft [6].

The WHISPER experiment has obtained outstanding results; it demonstrates the ability of the sounder to show transitions between magnetospheric regions [7]. The two panels of the Figure 6 display the electric field intensities as a function of time (x axis) and frequency (y axis) measured by the WHISPER sounder on 26 February 2001 in passive and active mode, respectively. The Cluster 4 spacecraft (named Tango) is moving from the magnetosphere to the solar wind, through the magnetosheath and crossing the polar cusp, the magnetopause and then the bow shock. On the lower panel, strong plasma resonance wave intensities are observed in the magnetosheath and solar wind at, or close to the plasma frequency. In the magnetosphere, additional types of wave resonances are also observed at the electron gyrofrequency, its harmonics, and at the Bernstein mode frequencies. From these characteristic frequencies, we can derive both the electron density and the magnetic field strength.

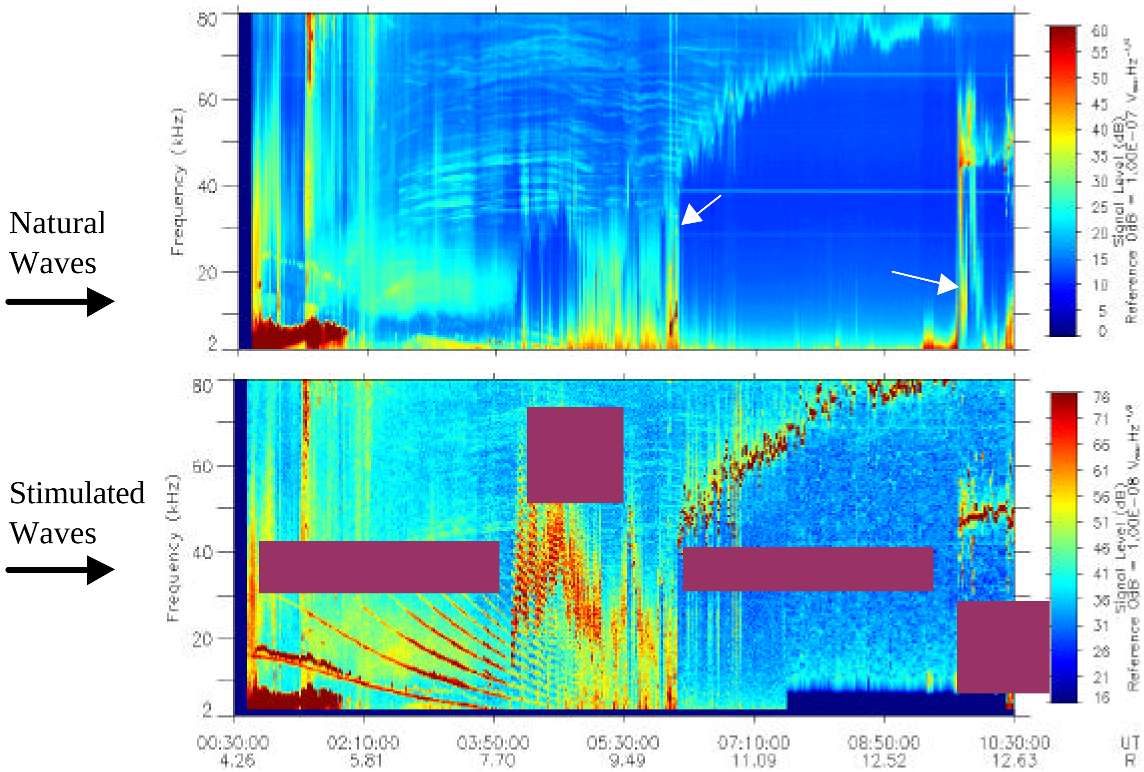


Figure 6 : Spectrograms obtained with the WHISPER sounder showing the regions crossed by the spacecraft 4 (Tango) on 26 February 2001

By using a least squares method the spatial gradient of any measured parameter can be determined from data acquired simultaneously on all four spacecraft. This method has been described by Harvey [8]. We have applied this method and developed the software to compute and plot the electron density gradient along the Cluster orbit. Figure 7 shows the successive values of the density gradient during two successive magnetopause crossings around 06:00 UT on 26 February 2001 (short duration entry in the magnetosheath). The vectors are projected onto the three planes of the GSE co-ordinate system along the orbital segment of the centre of mass of the constellation (a triangle at the end of the segment indicates in which direction the spacecraft move). The separation between spacecraft is shown on the right side of the figure, and the four density profiles are also given (lower right panel). The variation of the magnitude and direction of the gradient along the orbital trajectory is clearly seen. When entering the electron density enhancement, the density gradient points in a different direction than when it is leaving it a few minutes later.

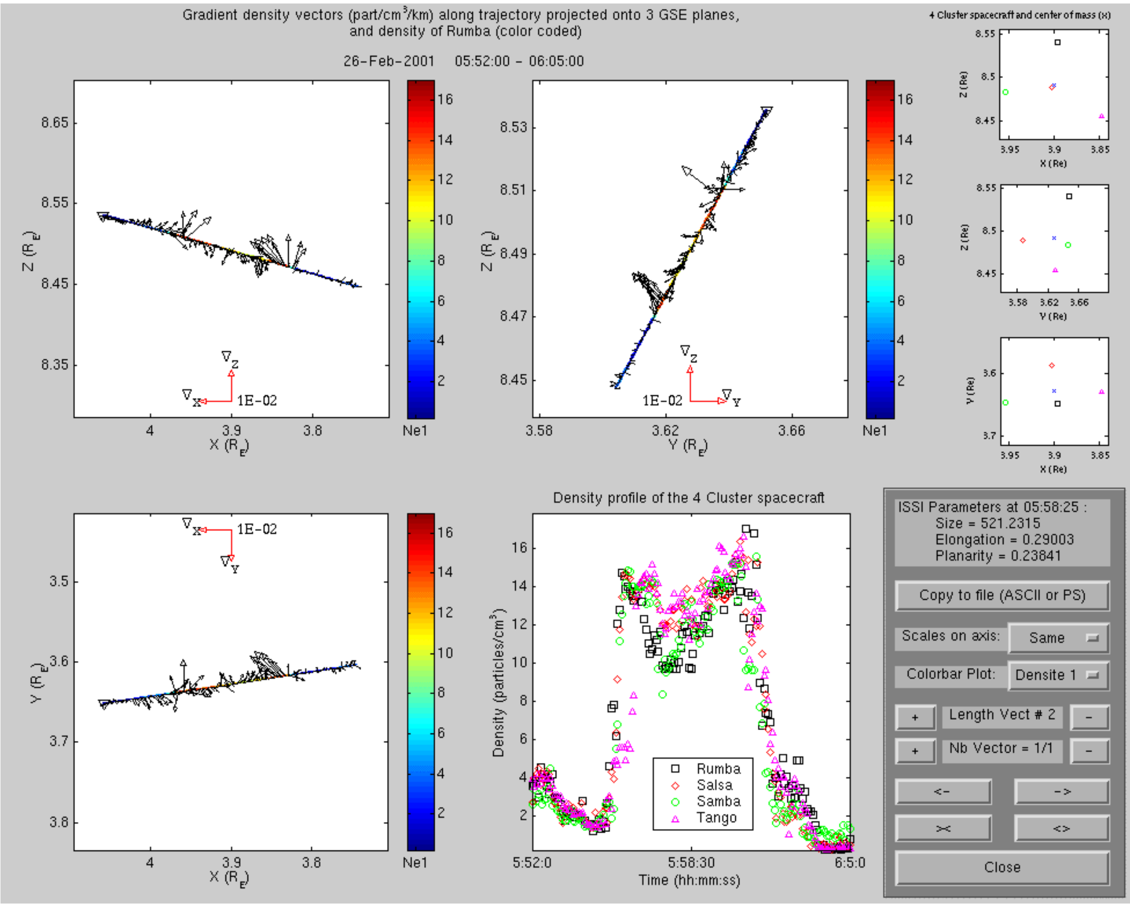


Figure 7 : Density gradient of the 4 Cluster spacecraft along the trajectory of the centre of mass projected onto the XZ, YZ and XY GSE planes

For dayside orbits (see Figure 1), the four Cluster spacecraft penetrate occasionally into the plasmasphere at perigee, when this region has expanded far beyond 4 Earth radii during an extended quiet period. The electron density profiles are determined from the WHISPER instrument for two plasmapause crossings on 5 June 2001. The upper panel of Figure 8 corresponds to the inbound passes and the lower panel to the outbound passes when the spacecraft leave the plasmasphere. In each panel the four upper curves are the logarithm of the electron densities measured at the positions of the four satellites along their orbits as a function of the equatorial distance R_{equat} of the magnetic field lines passing through the positions of the spacecraft. The lower curves correspond to the expected electron density in the equatorial plane along the same field lines. This density is assumed to decrease along the field lines as the inverse of the magnetic field intensity.

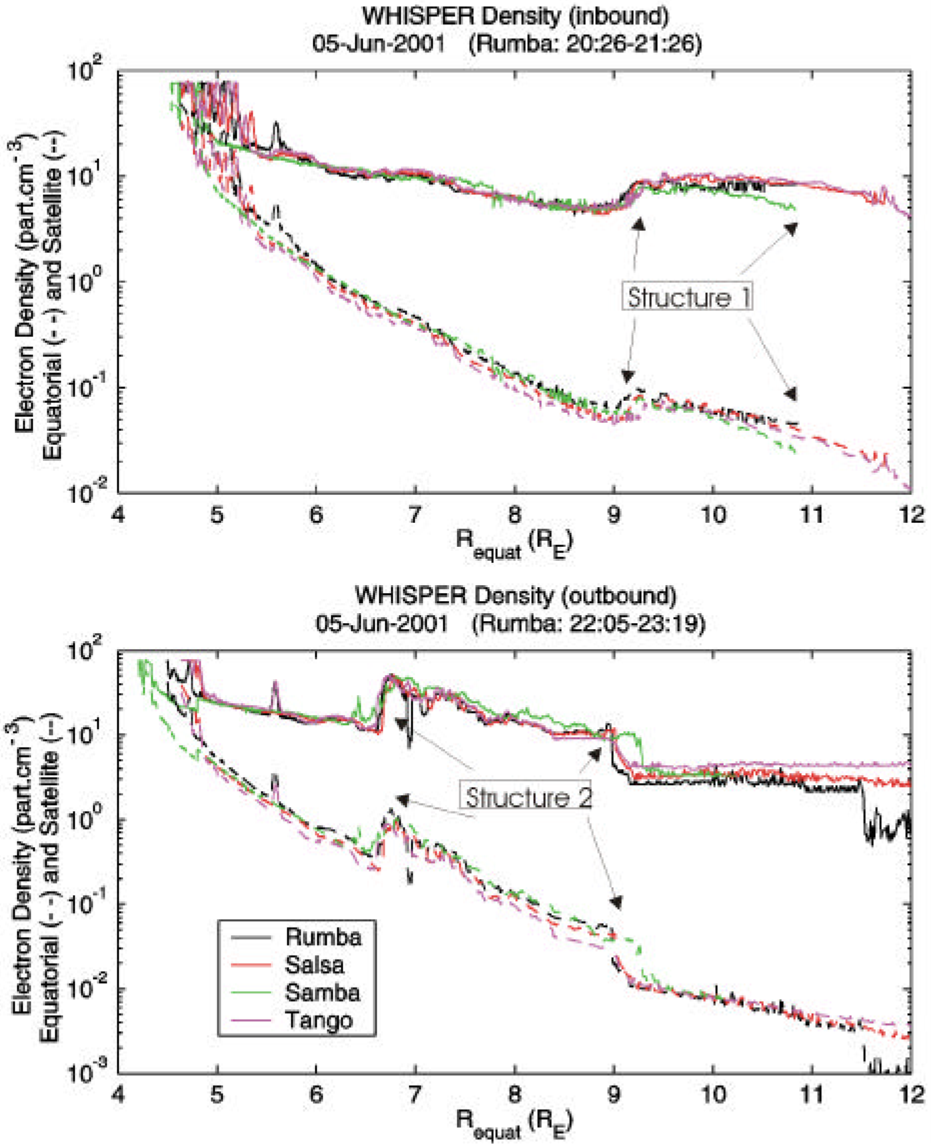


Figure 8 : Electron density as a function of equatorial distance

Two electron density structures are observed by the four spacecraft in both hemispheres of the plasmasphere, at different times but nearly along the same magnetic field lines (although Salsa crossed both structures 1 hour after the three other spacecraft). This indicates that these structures are aligned along magnetic field lines. They are stagnating detached plasma irregularities rather than temporarily changing structures evolving on a time scale of the order of one hour. With single spacecraft measurements one can not distinguish between both interpretations.

At the plasmapause (around 5 R_E) we also observe small scale irregularities with cross-R_{equat} width ranging from less than 1.7 seconds (8 km) up to several minutes (thousands km), which could be interpreted as signatures of diamagnetic plasma elements produced by interchange instabilities.

The STAFF results will also help to find the origin of the very high level of fluctuations observed in all frequency ranges during magnetopause crossings. It has been suggested at the Belgian Institute for Space Aeronomy that these fluctuations are generated in the magnetosheath and are amplified at the magnetopause [9]. Cluster data should be able to test this theoretical hypothesis [10].

5. Conclusion

The four-point Cluster mission is very successful. During its first year of operation Cluster has already yielded unique and outstanding results on the distribution of plasma and waves in the Earth's magnetosphere, in the near-Earth solar wind, and at the boundaries between these regions. The four identical satellites allow us to observe the small and medium scale structures of the magnetosphere in three dimensions. The combination of simultaneous measurements made on the four spacecraft offers the possibility to derive important physical quantities, such as electron current density and electron density gradients.

During its January 2002 meeting, the Solar System Working Group of ESA mentioned in its report [11]: "The initial phase of the [Cluster] mission has revealed an enormous range of length and time scales that cannot be fully explored during the nominal mission with its limited range of spacecraft separations", and concluded with the following recommendation: "In recognition of these potential achievements, the SSWG unanimously recommends that the Cluster mission be extended for 35 months."

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