Multi-instrument study of the solar wind-magnetosphere-ionosphere coupling

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The CLUSTER spacecraft have been used for about three years as a multi-point probe to study the magnetosphere and the solar wind. This presentation aims at presenting another way of using the CLUSTER. We shall show how the four spacecraft can (should?) be included in a more complete chain of tools, in order to study the processes involved in the field of Sun-Earth connection, taking into account every stage, from the solar wind down to the Earths atmosphere. This chain of tools includes obviously other satellites, ground-based instruments of all kinds, and numerical models. Through several examples of multi-instrument studies of the solar wind-magnetosphere-ionosphere coupling, we shall demonstrate that we need to combine data from these various instruments and tools in order to improve our knowledge in recent topics like the double cusp, but also in older issues like the formation of plasma patches in the polar ionosphere.

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Invited

Simultaneous convection measurements by EDI on Cluster and SuperDARN radars

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The EDI instrument measures the drift velocity of artificially injected electron beams transverse to the magnetic field from which the electric field vector can be deduced.
The comparison with ground-based coherent radars of the Super Dual Auroral Radar Network (SuperDARN) is of high scientific interest for the study of magnetospheric convection and its connection with dynamical coupling processes near the ionospheric footpoints. The comparison must rely on correct mapping procedures by use of relevant geomagnetic field models and on the assumption of equipotentiality along a given magnetic field line. The comparisions show a remarkable good agreement of the electric drift vectors measured by EDI onboard the Cluster satellites and the ground–based observations by SuperDARN while the deviations in magnitude and/or direction are of interest in their own right.

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Cluster Observations of ELF/VLF signals generated by modulated heating of the lower ionosphere with the HAARP HF transmitter

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Modulated HF transmissions have been a well established method for generation of ELF/VLF signals using the so-called "electrojet antenna". Although most observations of the generated ELF/VLF signals have been realized on the ground, several low- and high-altitude satellite observations have also been reported [e.g., James et al., JGR, p. 12187, 1990]. One of the important unknowns in the physics of ELF/VLF wave generation by ionospheric heating is the spatial extent of the radiating source regions. Multiple spacecraft observations with the CLUSTER/WBD instrument provide an excellent opportunity to determine the extent of the magnetospheric

regions illuminated from the lower ionospheric regions heated by the HF transmitter, from which one can (via ray tracing) estimate the spatial extent and distribution of the ELF/VLF source regions. For this purpose, ground-satellite conjunction experiments have been conducted during the past few months between CLUSTER and the HF High-Frequency Active Auroral Program (HAARP) facility in Gakona, Alaska. The HAARP facility is a highly agile and modern instrument, which is currently being upgraded to triple its radiated power and antenna array size by 2005. Once completed, this facility will be the most powerful HF heater in the world, capable of producing ELF/VLF waves at intensities ten times higher than ever before. Being located on largely closed field lines at L=4.9, HAARP is currently also being used for ground-to-ground type of ELF/VLF wave-injection experiments, and will be increasingly used for this purpose as it is upgraded. In this talk, we present recent results of the HAARP-CLUSTER experiments.

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Local and global ionic structures inside the Ring Current region : CLUSTER/CIS and FGM and IMAGE/HENA observations

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Clusters highly eccentric polar orbit at around 4 Re perigee permits sampling of the ring current population, and gives its latitudinal profile evolution. The CIS (Cluster Ion Spectrometry) experiment onboard Cluster is capable of obtaining full three-dimensional ion distributions (from about 5eV/q to 40 keV/q) with one spacecraft spin time resolution (4 sec) and with mass-per-charge composition determination.
The CIS data reveal new and very interesting structures on the ion spectrograms: the presence, for all the major ion species, of different features in energy bands, all along the CLUSTER pass inside the diffuse auroral zone. The highly structured pitch-angle distributions, which are energy dependent, confirm the presence of distinct populations.
The latitudinal profile of the ring current is also analysed. The magnetic field measurements on board the 4 CLUSTER spacecraft by the FGM (Flux Gate Magnetometer) instrument allow for the first time to calculate the ring current density profile along the spacecraft orbit, using the curlometer technique.
The combination of high time and energy resolution, good mass per charge discrimination, and favorable orbits has enabled Cluster to discern inner magnetospheric populations that have not been well-characterized in previous observations.
Events have also been selected for which the CLUSTER spacecraft are within the field of view of the HENA (High Energy Neutral Atom) imager onboard IMAGE. HENA provides energetic neutral atom images with a high geometric factor and with a 120 x 360 field of view over the spin. The H+ ion distribution functions obtained in situ by CIS are then compared to the ones deduced by inverting the HENA hydrogen neutral atom images for the overlapping energy range of the two instruments (16-40 keV). The results show the complementarity of the two approaches, i.e. local measurements and ENA global imaging.

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Spatial/temporal coherence of dayside oxygen ion outflows observed by Cluster

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We present here new results that improved our understanding of the solar wind control of the spatial/temporal coherence of non-thermal oxygen outflows observed in the dayside high-latitude and mid-altitude (3.5-6.5 Earth radii) regions by the Cluster multi-satellite system. To investigate the coherence of the outflow, 3D ion distributions recorded by the CIS/CODIF experiment are used as input to model flux tube historical effects between the initiation time in the topside ionosphere and the time of observation. Here, we compute the horizontal transport of ions using time-dependent, small-scale convection maps, as inferred from in-flight convection measurements from the oxygen distributions and the Electron Drift Instrument (EDI). For a few cases, additional convection measurements by SuperDARN radars are used to validate the technique of inferring convection maps from Cluster data. In the model, the footpoints of magnetospheric field lines or the mapping of the convection measurements in the ionosphere are obtained using the Tsyganenko 96 model, which takes into account temporal variations of the interplanetary magnetic field (IMF) and the solar wind bulk parameters, as inferred from ACE satellite measurements. Using modeling results allow us to see the first direct evidence that O+ fluxes are sensitively affected not only by solar wind pressure fluctuations, but also by the IMF Bz component [Bouhram et al., Geophys. Res. Lett., submitted, 2003]. These results are also consistent with recent observations and numerical simulation studies arguing that soft electron precipitation (<100 eV) from the magnetosheath is the major sink of free energy responsible of topside ionospheric upflows.

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FAST–CLUSTER conjunctions above the auroral oval

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The paper presents work in progress whose ultimate goal is the investigation of the auroral particle energization as well as the mapping between the magnetosphere and ionosphere. The SSCWeb/Query tool provides several hundred conjunctions for the time interval January 2001, when CLUSTER became operational, until January 2003. However, we could only select some 25 *events* when the FAST/EESA electron spectrometer detected energetic electrons (E>100eV), at altitudes between 2000 and 4000km, while the CLUSTER/CIS ion spectrometer revealed a structured signature in some or all of the ion species. We will show several events in the evening sector — data collected in September–October 2001, with CLUSTER close to the apogee ($\sim 19 R_E$) — and in the morning sector — data collected in October–November 2002, with CLUSTER at medium altitude ($\sim$5–$7 R_E$). The structure exhibited by the CLUSTER/CIS data for the evening events seems to be correlated with inverted-V signatures in FAST electrons. It is tempting to consider that CLUSTER crossed the source regions of the arcs seen by FAST. For the morning events, filaments of enhanced fluxes, suggesting multiple particle injections, can be observed at both FAST and CLUSTER level. The apparent correlation between the FAST and CLUSTER data sets on both the evening and morning sides of the auroral oval is remarkable and worth to be examined further, given the difference in the observation time scales: $\sim$1min for FAST compared to $\sim$1h for CLUSTER.

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Remote sensing with wave observations: An introduction

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The detailed, three dimensionnal, study of locally sampled small scale structures, is the main goal of the Cluster mission. Beyond this prime objective of the project, the four Cluster spacecraft provide new capabilities in the remote investigation of distant region of the Earth's magnetosphere.
Although the technics based on waves properties are dating back to the first wave observations, new results results can be expected from the four point of view provided by identical instruments. We briefly recall here how informations can be derived from source regions remotly observed by three of the most used tools on Cluster, illustrated by the results presented in this session : Ray tracing, using the wave properties of propagating trapped electromagnetic emissions like whistlers, direction finding which used the spin modulation of freely propagating emissions generated close to the plasmasphere (non-thermal continuum radiation) and auroral region (AKR, Auroral Kilometric Radiation) and interferometry, investigating the source dimension, location and motion of the AKR. This last technic is the first space based application of Very Large Baseline Interferometry (VLBI), and the prototype of future instruments for space missions in astronomy.

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Invited

Spatial and Temporal Properties of AKR Burst Emission Derived From WBD VLBI Studies

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The Cluster Wideband Data instrument has been used to determine the locations of auroral kilometric radiation (AKR) using very long baseline interferometry. The technique involves cross-correlating individual AKR bursts from all six Cluster baselines using time and frequency filtered waveforms. The resulting differential delay peaks are used to determine source locations with an uncertainty as small as 500 km in a plane perpendicular to the source-spacecraft line of sight. The uncertainty along the line of sight is much larger, but this is mitigated by assuming that the emission arises from a height corresponding to the electron gyrofrequency.
We have determined the locations of over 2,500 individual AKR bursts during seventeen observing epochs between 20 June 2002 and 22 January 2003 when the Cluster constellation was high above the southern or northern hemisphere. In general we find that the AKR burst locations lie along magnetic field lines which map onto the auroral zone as expected from previous AKR studies. In the northern hemisphere, there is a strong tendency for location to be centered within the auroral oval and in the evening sector, while southern hemisphere locations favor midnight to early morning locations and have somewhat higher invariant magnetic latitudes. For both hemispheres, there is a clear seasonal dependence, with mean source location shifting westward (i.e. toward earlier magnetic local time) from early to late winter. Within each 1-3 hour observing epoch, the spread in AKR burst locations is typically $\pm 2^h$ MLT and $\pm 5^{\deg}$ invariant latitude. This range exceeds the source location uncertainty and indicates the true extent of AKR emission locations on a 1-3 hour timescale. Some epochs show a statistically significant migration of mean position within the observing time range, either in magnetic latitude or MLT.

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Invited

Four spacecraft determination of wave front normal and velocity

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Various experiments onboard a spacecraft (electric, magnetic or plasma sensors) can be used to identify the crossing of a plasma discontinuity or of a wave front and in some cases to define a crossing time with a given uncertainty. Assuming that this discontinuity or wave front is a rigid plane moving at constant velocity, a fleet of four spacecraft like CLUSTER, allows to determine the vector normal to this plane and the normal component of its velocity from the four crossing times. The hypotheses of rigidity and uniform motion are very often highly questionable for plasma discontinuities, but are reasonable for wave fronts emitted by remote sources. The so called method of timing, in its form involving the reciprocal vectors (1), and the associated uncertainties depending upon the covariance matrix of the spacecraft positions are reminded first. This formalism treats symmetrically the four spacecraft. Then the method is extended to handle situations where delays between spacecraft are measured instead of the crossing times and a theoretical procedure designed to minimise the uncertainty in direction finding is presented.
References
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electronic version available at: http://www.issi.unibe.ch/PDF-Files/analysis_methods_1_1a.pdf

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Multipoint analysis of the source region of storm-time chorus

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We report measurement of whistler-mode chorus by the four Cluster spacecraft at close separations. We focus our analysis on the generation region close to the magnetic equatorial plane at a radial distance of 4.4 Earths radii. We use the data recorded during geomagnetically disturbed periods. The purpose of this paper is (1) to define perpendicular dimensions of the sources of chorus wave packets below one half of the electron cyclotron frequency; (2) to analyze time delays and fine structure of chorus wave packets using multispacecraft measurement of electric field waveforms.
Results of our analysis show that the perpendicular characteristic scale of the sources of chorus wave packets is comparable to the wavelength of observed waves. The electric field waveforms show a fine structure consisting of subpackets with a maximum amplitude above 30 mV/m. The subpackets typically start with an exponential growth phase, and after reaching the saturation amplitude, they often show an exponential decay phase. Using delays of time-frequency curves obtained on different spacecraft, we have found the same propagation direction as obtained from the simultaneous Poynting flux calculations. The delays roughly correspond to the whistler-mode group velocity estimated from the cold plasma theory. We have also observed delays corresponding to antiparallel propagation directions for two neighboring chorus wave packets, less than 0.1 s apart.

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Multi-point measurements of the source structure and motion of discrete electro-

magnetic waves

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The wideband instrument (WBD) on the CLUSTER spacecraft provides an unprecedented opportunity to measure the spatial extent and motion of what are believed to be highly compact source(s) of discrete electromagnetic whistler-mode emissions such as whistler-mode chorus. Chorus emissions are believed to be responsible for the acceleration of electrons to MeV energies in the outer radiation belts, as well as being responsible for the scattering loss of electrons in the energy range of tens to hundreds of keV. In view of the emerging importance of high energy radiation in the context of Space Weather and resultant effects on space-based instrumentation and systems, understanding the mechanisms and effects of interactions of energetic particles with discrete chorus waves have recently come to the forefront as a matter of renewed and imminent importance. CLUSTER observations of chorus near the perigee of its orbit have led to surprising new features, such as frequency shifts of up to a kHz between emissions observed on different (but nearby) satellites, allowing the first-ever determination of the rapid motions of the source(s) of these discrete and intense electromagnetic emissions. In view of the compact nature of the source(s), such frequency shifts are expected to be highly dependent on the separation distance of the spacecraft. In this talk, we summarize the highlights of CLUSTER observations of chorus, and quantify the dependence of the frequency shift on the separation distance of the observing spacecraft, in the context of highly compact but rapidly moving sources which produce these emissions.

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Continuum radiations characteristics close and far from sources: case events observations from the four CLUSTER spacecraft

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Non thermal Continuum radiations have been first discovered in the seventies on Imp 6, their main characteristics, including directivity properties, reported as early as 1975. Other findings (like various detailed spectral and temporal behaviours) were later derived from other single spacecraft observations (GEOS, ISEE, Dynamics Explorer, GEOTAIL, POLAR). The generation mechanisms are yet not fully elucidated, and different explanations have been proposed. The first multi-spacecraft studies, based on GEOS and ISEE simultaneous observations, confirmed the general position of sources to be in the vicinity of the Earth plasmapause, a fact compatible with the main generation mechanisms proposed. The CLUSTER constellation, comparing four spacecraft observations, brings forward new findings and new questions about the source properties. In this presentation, we concentrate on reporting about electric field spectral features (wave frequency, intensity, directivity properties) from the four Whisper instruments in three event cases. Escaping continuum radiations observed in the solar wind region confirm that sources are localized in the vicinity of the Earth, at dusk local time sector for that particular case. Observations in the close vicinity of the sources demonstrate quite complex behaviours in the details, indicative of the presence of multiple sources in a broad region.

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Magnetospheric Radio Tomography Experiments using Cluster and IMAGE

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To validate and demonstrate the potential of magnetospheric radio tomography, we have performed a series of experiments using the Radio Plasma Imager (RPI) on the IMAGE spacecraft as the signal source. The first experiments employed the WAVES instrument on WIND as the receiver, and ongoing improved experiments are using the WBD instruments on the four Cluster spacecraft. These experiments are designed to measure the Faraday rotation of the transmitted wave electric field polarization due to propagation through a magnetized plasma. In the proper frequency range, Faraday rotation is proportional to the path-integrated product of the magnetospheric electron density and magnetic field, enabling large-scale measurements of these quantities on the propagation paths in each of these experiments. In this presentation we describe the series of successful experiments, discuss the scientific interpretation and conclusions that can be drawn from the data, and discuss the IMAGE/Cluster operations planned for late May 2003.

Contact: Steven Cummer, cummer@ee.duke.edu
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Multipoint observations of ionic structures in the Plasmasphere by CLUSTER - CIS and comparisons with IMAGE-EUV observations

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The 4 Cluster spacecraft orbit the Earth in a highly eccentric polar orbit at 4 RE perigee, and this permits them to sample the ring current, the radiation belts and the outer plasmasphere. Data provided by the Cluster Ion Spectrometry (CIS) instruments are used to analyse Cluster crossings of the plasmasphere. The low-energy ion distribution functions, obtained by CIS-RPA during the perigee passes, reveal new and interesting features. The ion discrimination capability of CIS reveals how the density profile is different for each of the main ion species (H+, He+, O+): H+ and He+ present mostly similar profiles; O+, however, is not observed as trapped plasmaspheric population at the Cluster orbit altitudes ($R > 4$ Re). Low-energy O+ is observed only as upwelling ion, on auroral field lines.
Detached plasmasphere events, that are observed by CIS during some of the passes at about 0.5 RE outside the plasmapause, are also present. The bi-directional distribution functions of these detached plasmaspheric populations allow us to distinguish them from upwelling ion populations.
The CIS local ion measurements have also been correlated with global images of the plasmasphere, obtained by the EUV instrument onboard Image, for an event where the Cluster spacecraft were within the field-of-view of EUV. The EUV images show, for this event, that the difference observed between two Cluster spacecraft was temporal (boundary motion).
They thus show the necessity for correlating local measurements with global images, and the complementarity of the two approaches, local measurements giving the "ground truth" (including plasma composition, distribution functions etc.) and global images allowing to put local measurements into a global context, and to deconvolute spatial from temporal effects.

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Cluster multipoint observations of high altitude oxygen ion energization and outflow

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A case study of oxygen ion energization and outflow is presented. The data show oxygen ions being energized to energies of up to 40 keV, the upper energy limit for the CLUSTER CIS ion spectrometer. The outflowing ions show signatures of both velocity dispersion and high altitude heating over extended altitude intervals. The temperature tend to be isotropic at high altitude, in contrast lower altitude measurements which typically show a higher perpendicular temperature. In the region where the highest energy oxygen ions are observed some of the high energy oxygen ions are going downward. It is discussed whether these ions may have been reflected at the magnetopause. Furthermore the multi-spacecraft configuration is used to analyze the observed structures in detail. It is discussed what we can expect to observe for different situations, and this is compared with actual observations. In particular a detailed study of a mesoscale structure of strong heating and associated outflow appears to reveal a temporal decay which is similar for the two observing spacecrafts. This indicate that both spacecrafts were situated in a coherent region where all field-lines had a similar history, as could for example be expected in the flux bundle of a flux transfer event.

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On the evolution of transversely heated oxygen ion distributions along the cusp/cleft field lines

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This presentation focuses on the altitude dependence of oxygen ion conics in the dayside cusp/cleft region. Here, combining oxygen data from the Akebono, Interball Auroral and Cluster satellites allows for the first time to follow the global development of energetic (up to ∼10 keV) ion outflow over a complete and broad altitude range up to 6 Earth's radii (RE). According to earlier statistical studies, the results are consistent with a height-integrated energization of ions at altitudes up to 3.5 RE. Higher up, the results inferred from Cluster observations put forward evidence of a saturation of the transverse energization rate. We suggest that such results may be interpreted as finite perpendicular wavelength effects (∼10 km) in the wave-particle interactions. To support this suggestion, we carry out two-dimensional, Monte Carlo simulations of ion conic production that incorporate such effects and limited residence times due to the finite latitudinal extent of the heating region. Finally, we also present a few examples of Cluster multi-satellite data showing how can we investigate the spatial/temporal coherence of the underlying energization processes (e.g. those acting below Cluster altitude) in the future.

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Characteristics of chorus emissions observed by the CLUSTER satellites

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STAFF SA provides the cross spectral matrix of three magnetic and two electric field components which is used to determine, for each satellite, the direction of propagation as a function of frequency and of time. Three chorus events, observed during different levels of magnetic activity, show that the component of the Poynting vector parallel to the magnetic field changes its sense when the satellites cross the magnetic equator which indicates that the chorus waves propagate away from the equator. Detailed analysis indicate that the source is located in close vicinity of the plane of the geomagnetic equator. Another study concerns the propagation characteristics of a chorus emission recorded simultaneously by the 4 satellites on October 29, 2001 between 0100 and 0500 UT. During this day, the spacecraft (SC) 1, 2, and 4 are relatively close to each other but SC3 has been delayed by half an hour. The wave normal directions relatively to the Earth's magnetic field is calculated for the 4 satellites at different times and different frequencies. The most intense chorus waves propagate away from the equator. But it is also observed on SC1, SC2, and SC4 that lower intensity waves propagate toward the equator simultaneously with the SC3 intense chorus waves propagating away from the equator. Both waves are at the same frequency. Using the wave normal directions of these waves, a ray tracing study shows that the waves observed by SC1, SC2, and SC4 are the same waves which are observed by SC3. Their origin in the equatorial plane is similar. SC3 which is 30 minutes late observes the waves which originate first from the equator, meanwhile SC1, SC2, and SC4 observe the same waves which have suffered a Lower Hybrid Resonance (LHR) reflection at low altitudes and now return to the equator at a different location with a lower intensity. In order to check the nature of the returning waves, another event is shown where WBD data is recorded with a much better time resolution.

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Statistical study of equatorial noise below the local lower hybrid frequency observed by Cluster

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We report preliminary results of a statistical study of the equatorial noise below the local lower hybrid frequency observed by the Cluster spacecraft. The study is based on the data of the STAFF-SA wave analyzers. We use the power spectral matrices collected during two years of measurement in the equatorial magnetosphere at a radial distance of approximately 4.5 Earth radii. This allows us to analyze the distribution of the wave power, but also to take into account the polarization and propagation properties of these electromagnetic waves. The results show a narrow latitudinal extent of the emissions centered close to the equator.

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2Fpe Emissions Observed in the Earth's Foreshock Regions by the WHISPER Experiment Onboard CLUSTER: Event Studies

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Radiations at twice the plasma frequency have been commonly observed in the foreshock regions upstream of the Earth's bow shock and far beyond. They have indeed been detected onboard several spacecraft, such as OGO 1 and 3, IMP 6 and 8, ISEE 1 and 2, and GEOTAIL. The 2Fpe electromagnetic radiations are thought to be produced in the electron foreshock and most probably close to the interplanetary magnetic field line tangent to the shock surface. They are often seen simultaneously with suprathermal electrons that are energized at the shock and are backstreaming from it. The objective of the current presentation is to show and discuss 2Fpe radiation events recorded on the CLUSTER spacecraft by the WHISPER experiment. In passive mode, in addition to the 2 Fpe radiation an intense broadband noise is usually observed above and/or below the plasma frequency, Fpe, when the spacecraft is in the electron foreshock, while a weak narrow band noise may be seen a little bit above Fpe in the free solar wind. This means that sometimes the Fpe determination is somewhat uncertain. Fortunately, the strong resonance triggered by the WHISPER relaxation sounder, when active, allows us to reliably and accurately give this frequency value. Then the observed strong modulations of the 2Fpe signal intensity have been used to determine the apparent location of the 2Fpe radiation source. Surprisingly the source extension seems to be limited. This could be due to the current solar wind behaviour. The interplanetary magnetic field direction and the solar wind density were indeed varying abruptly.

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