ARTIFICIAL SATELLITES, Vol. 55, No. 4 – 2020
DOI: 10.2478/arsa-2020-0010

COMPARATIVE STUDY OF THE ENERGETIC ELECTRONS REGISTERED TOGETHER WITH THE BROAD BAND EMISSIONS IN DIFFERENT REGIONS OF THE IONOSPHERE

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ABSTRACT. ELF/VLF waves have been registered in the outer polar cusps simultaneously with high energy electrons fluxes by the satellites Magion 4 (subsatellite to Interball 1), Polar and CLUSTER. Further, we discuss similar observations in the different regions of the ionosphere, where DEMETER registered energetic electrons. The DEMETER satellite operating on the nearly polar orbit at the altitude 650 km crossed different regions in the ionosphere. Registrations of ELF/VLF/HF waves together with the energetic electrons in the polar cusp, in the ionospheric trough and over thunderstorm areas are presented in this paper. The three satellites of ESA's Swarm mission provide additional information on the ELF waves in the mentioned areas together with electron density and temperature. A brief discussion of the generation of these emissions by the so-called "fan instability" (FI) and beam instability is presented.

Keywords: Atmosphere-ionosphere-magnetosphere system, thunderstorms, energetic electrons, ELF/VLF/HF waves, plasma instabilities, DEMETER, Swarm

1. INTRODUCTION

The main reservoirs of energetic particles in the Earth's environment are radiation belts (Van Allen belts) within the magnetosphere. Nevertheless, fluxes of electrons and ions with high energy are registered in many other places of the space surrounding the Earth, even in the atmosphere. The origin of these fluxes is different and some originate from a distant astronomical object even outside our Galaxy. These are galactic cosmic rays. Some of them originate from the Sun and are solar cosmic rays. In this paper, we will present observations of energetic particles together with ELF/VLF/HF plasma waves as a result of the plasma processes going on in the vicinity of Earth. The plasma waves are the most general feature of the plasma environment. These play an important role leading to anomalous processes like diffusion, resistivity, energy redistribution and particle acceleration in collision free space plasma. Different types of waves are present in different regions of space. These are one of the characteristics of these regions with different particle populations. One of the most interesting regions is the polar cusp. Plasma particles from the magnetosheath directly enter there. The primary types of wave emissions observed in the polar cusp region are: broadband ULF-ELF magnetic noise, whistler mode bursts, broadband electrostatic noise, electron cyclotron harmonics waves, auroral hiss and auroral kilometric radiation. Earlier observations of waves in the polar cusp originate from Hawkeye—in the outer cusp, from Viking in the middle cusp, and from Freya and DE-1 in the lower cusp. These indicate the presence of Alfven, lower hybrid, electron and ion cyclotron waves as the most typical modes in this region of the magnetosphere (Scarf et al., 1972; Gurnett and Frank, 1978; Erlandson et al., 1988; Pottelette et al., 1990). Later, the Polar, Interball and Cluster satellites enabled the discovery of the presence of high energetic particles (electrons and ions) in the polar cusps. Strong wave activity is associated with this population of plasma particles (Chen et al., 1998; Blecki et al., 1999, 2005; Pickett et al., 1999; Savin et al., 2002). Further analysis of the plasma waves and energetic particles by DEMETER satellite in the ionosphere at the altitude 660 km shows the presence of fluxes of energetic electrons together with plasma waves in other areas as the ionospheric trough and over thunderstorms areas. The observations of this type of event are presented in the next sections of this paper: the polar cusp in the third section, the ionospheric trough in the fourth and thunderstorms in the fifth section. The last section is devoted to the brief discussion of the generation mechanism of plasma waves due to instabilities associated with the presence of energetic electron beams.

2. EXPERIMENTAL SYSTEM

To study the presence of energetic particles and their interaction with ionosphere and upper atmosphere, we use the data originating from the DEMETER and Swarm satellites. DEMETER was a low-altitude microsatellite operated from June 2004 until December 2010 in a polar, circular orbit initially at 710 km and slowly decaying to 660 km. DEMETER measured variations of the electric field in the very low frequency (ELF-VLF) range from 0 to 20 kHz and in the high frequency range up to 4 MHz. These measurements were performed in two modes, a survey mode and a burst mode. The spectrum of one electric component is computed on board in the VLF/HF range during both modes. During the burst mode, waveforms of the electric and magnetic field components were transmitted in the range up to 2 kHz (Berthelier et al., 2006; Parrot et al., 2006).

The plasma analyzer instrument measured variations of ion density at a 4 s time resolution. An energetic particle detector measured electrons and protons with energies from 70 keV to 2.34 MeV every 4 s in survey mode or every 1 s in burst mode.

The Swarm satellite constellation is devoted to study the magnetic field of the Earth and the influence of the effects caused by the Sun. It consists of three identical Swarm satellites (A, B, and C), launched on 22 November 2013 into a near-polar orbit. The initial constellation of satellites was formed on April 17, 2014. Satellites A and C are the lower pair flying separated by 1.4° in longitude at the equator at an altitude of about 470 km in 87.30° inclined orbit, Swarm B is operating at a higher orbit initially of about 520 km with an inclination of 87.75°. All three satellites have an identical set of instruments. The absolute scalar magnetometer, vector field magnetometer and Langmuir probe are important for our studies. The magnetometers measure regularly main magnetic field with sampling rates of 1 Hz (absolute value) and 50 Hz (3 vector components). The effects in the ionosphere we are targeting are mainly seen in variations of the electromagnetic fields in a very broad frequency range. Swarm capabilities limit our studies to very low frequencies called ULF (ultra-low frequencies) and ELF (extra low frequencies), and in our case, we are able to analyze them up to 25 Hz. Another instrument, which will be useful for our studies is the Langmuir probe giving information on the electron temperature and concentration. Swarm does not measure the energetic particle fluxes, but some effect of these fluxes can be seen in the increase of the plasma temperature (Olsen et al., 2013).

3. OBSERVATIONS IN THE POLAR CUSP

Earth’s magnetic field can be assumed in first approximation as a dipole field deformed by the stream of solar wind. Topologically, field lines can be divided into two parts according to their location on the sunward or tailward side of the Earth. Between them at the dayside, the polar cusps are located.

These structures are characterized by a depletion magnetic field intensity and it allows a plasma from the magnetosheath to directly enter into the magnetosphere. These regions of the magnetosphere can be considered as key regions for the transfer of mass, momentum and energy from the solar wind into the magnetosphere (e.g., Frank, 1971; Marklund et al., 1990; Yamauchi et al., 1996; Fritz and Zong, 2005; https://wiki.oulu.fi/display/SpaceWiki/Cusps).

The polar cusp can be divided into two parts: the high-altitude cusp, also called outer cusp and the low altitude cusp. The outer polar cusp is usually treated as a part of magnetosphere occupying altitudes over 1500 km, while low altitude cusp is located at ionospheric altitudes. Satellite measurements have shown that the cusp extends about 2.5 hours in local time around noon and about one degree or less in latitude. However, its position can vary between 70° and 80° in geomagnetic latitude and strongly depends on Interplanetary Magnetic Field (IMF) conditions: its direction and intensity and solar wind pressure.

The plasma, many types of waves and turbulent flows find its way to the ionosphere via the outer cusp due to depletion of the magnetic field. The low frequency plasma waves control the dynamics of the ions in collision free plasma and play a very important role in the formation and behavior of this region. Multi-satellite observations demonstrate that the cusp is a locus of accelerated plasma. There is evidence that cusp is a substantial source of energetic particles (Chen et al., 1998; Fritz et al., 1998; Fritz, 2001). The energizing is related to strong turbulence (Błęcki et al., 2001), which was mapped by Interball-1 (Savin et al., 1998, 1999, 2001; Romanov et al., 1999). At the boundary of the inner cusp, the correlation of the low frequency waves with the acceleration of magnetosheath plasma up to ~ 1 keV has been pointed out (Pottelette et al., 1990).

The observed fluxes of accelerated plasma particles, the electron and ion populations with higher temperature than ambient plasma and the very strong wave activity, particularly at low frequencies, suggest the existence of the wave particle interaction processes (Błęcki et al., 2001). One of the finding from the Polar, Interball 1 and Magion 4 satellites is the presence of high-energy particles (ions and electrons) in the outer polar cusp. Strong emissions of the plasma waves are associated with these fluxes (Błęcki et al. 1999; Pickett et al. 1999).

DEMETER satellite has been operating at 660 km altitude with regular crossings of the proper polar cusp. Mainly due to operating scientific instruments in regions with magnetic latitude below 65°, measurements in the polar cusp were performed only occasionally. A French scientific campaign was organized in December 2007 to obtain simultaneous ground base registration on Spitsbergen and on DEMETER. The studies of the waves and particles in the cusp at the ionospheric altitude presented in this paper originate from the time of this campaign.

Swarm satellites with their quasi-polar orbit operate without any gaps and the entire globe is covered by registrations of parameters that are of interest to us. Figure 1 gives an example on April 1, 2016, of electron temperature along a Swarm A orbit shown in the upper panel, electron concentration (black line), electron temperature (red line) both in the middle panel and magnetic field variations spectra in the bottom panel. The satellite crossed the ionospheric trough (this formation is discussed in next chapter) twice in the northern hemisphere at 20:20 UT and in the southern hemisphere at 21:00 UT. The southern polar cusp was crossed at 21:07 UT. Strong enhancements of the magnetic field variation can be observed both during the crossing of the polar cusp and the ionospheric trough. This wave activity is accompanied by strong variations of the electron temperature and concentration. The increase in plasma density at 20:40 UT and 21:30 UT are associated with crossing of the ionospheric equatorial anomaly.

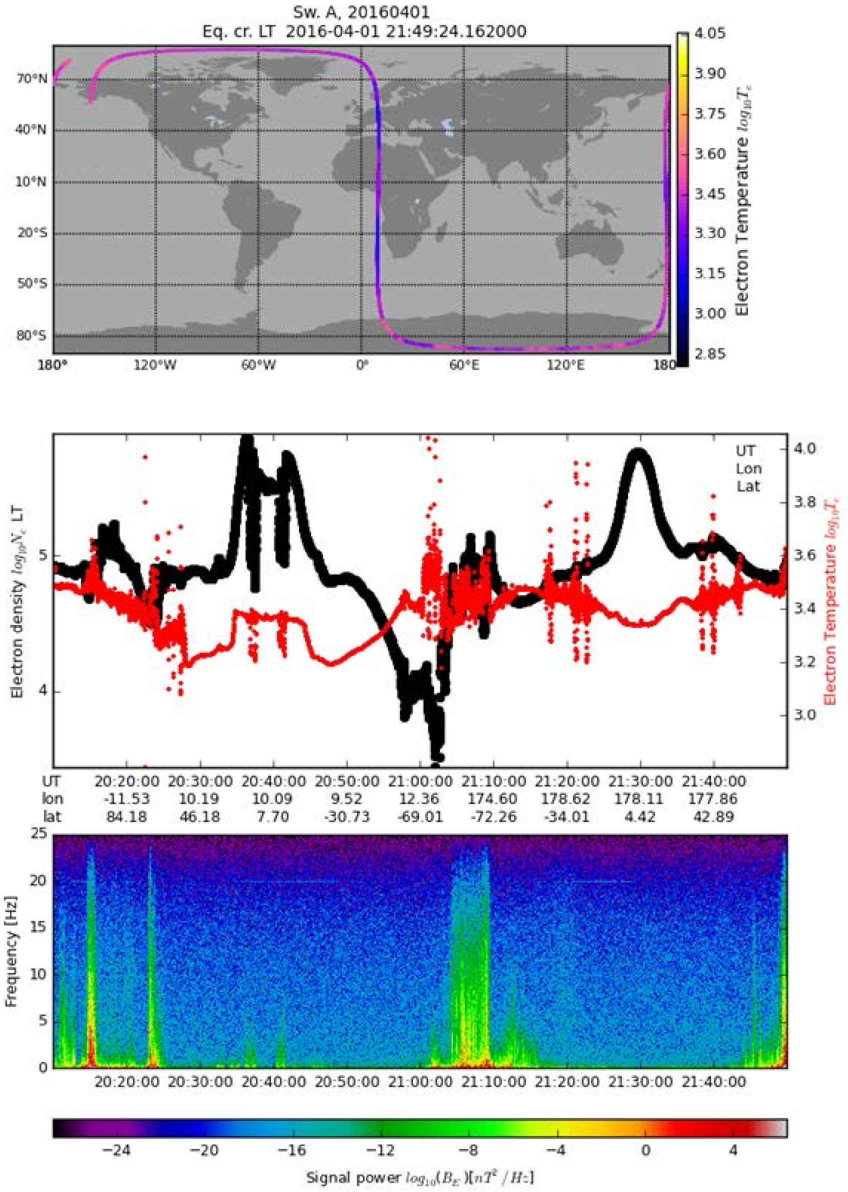

Figure 1. A plot of electron temperature along a complete Swarm A satellite orbit (upper panel) on April 1 2016. The values of the temperature measured along the orbit are shown by dots with different colors. Measurements of the electron temperature (red line) and concentration (black line) are presented in the middle panel. The bottom panel shows the dynamic spectrogram of the magnetic field variations. The registrations were done during geomagnetically very quiet time. Kp was not higher than 1 summary Kp for entire day was 4-, Dst around zero, only days later weak geomagnetic storm appears.

Figure 2 presents an example of measurements done by DEMETER on December 10, 2010 in the polar cusp at ionospheric altitude, when an event with strong wave activity and energetic electrons was registered during the ground base French campaign on Spitsbergen. Simultaneously, the DEMETER satellite, which entered polar cusp at 10:07:03 UT, observed these processes in the high latitude ionosphere. This is visible as an increase of the plasma density and the intensity of the wave activity in the ELF and VLF ranges. The exit from polar cusp was at 10:07:28 UT.

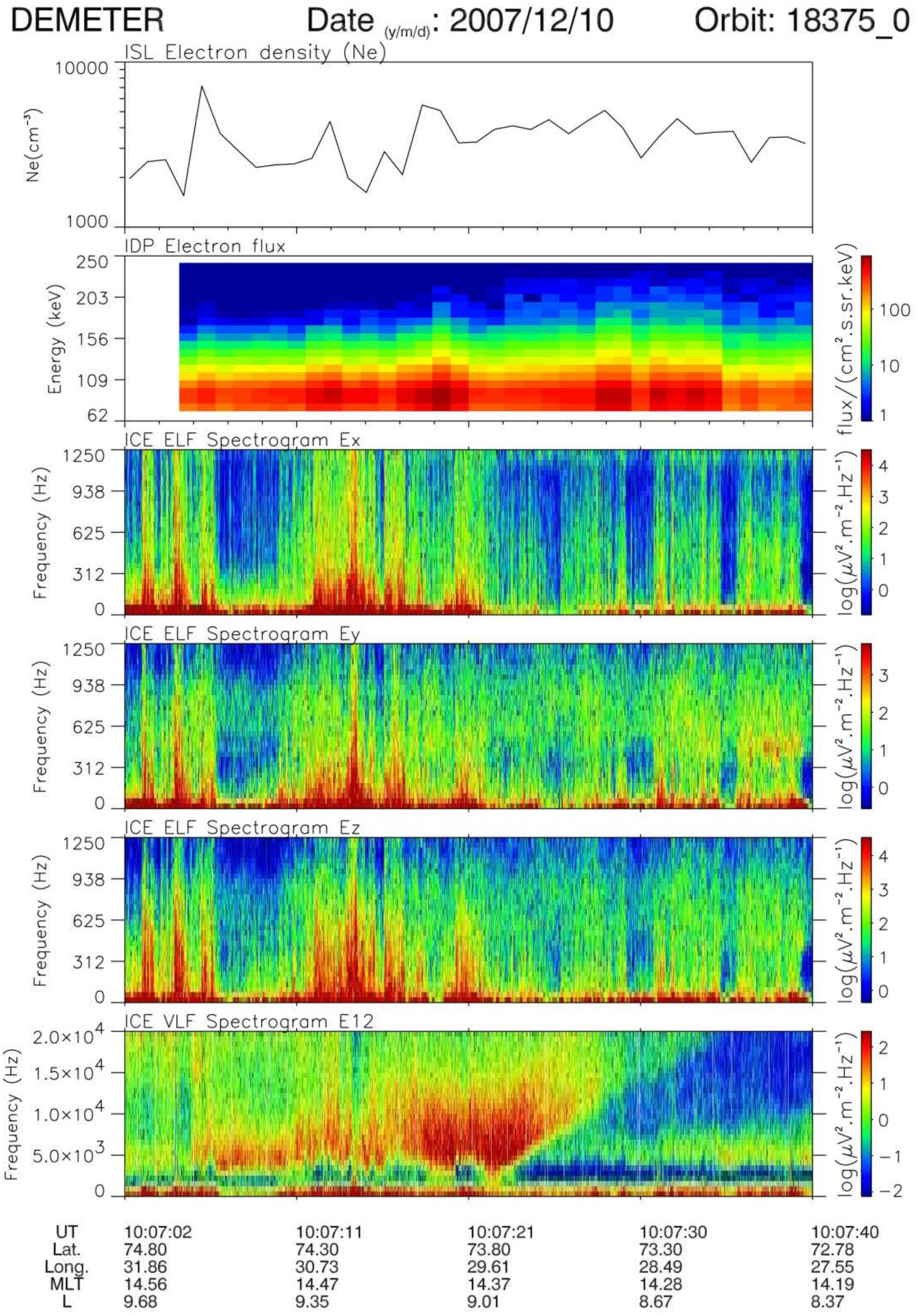

Figure 2. Electron density (upper panel), spectrogram of electron energy (second panel) and wave spectra of three components of the electric field in the ELF range and one component in the VLF range (4 bottom panels) observed by DEMETER in the polar cusp at ionospheric altitude

This case as the case from Swarm presented above were registered during very quiet time. Kp index was even lower and maximum value was 0+ and summary 1-. Dst until December 20, when very weak disturbance of this index was registered, fluctuated around zero.

The wave spectra in both frequency ranges indicate strong variability in time, which correspondents to spatial changes that can be associated with internal filamentary structure of the cusp (Błęcki et al., 2003). The broadening into higher energy (~200keV) of the electron spectrograms is clearly visible at 10:07:12 UT, 10:07:20 UT and 10:07:30 UT. At the same time, an increase of ELF emissions in frequency up to 1250 Hz appears. VLF emissions are present during the entire time of the cusp crossing.

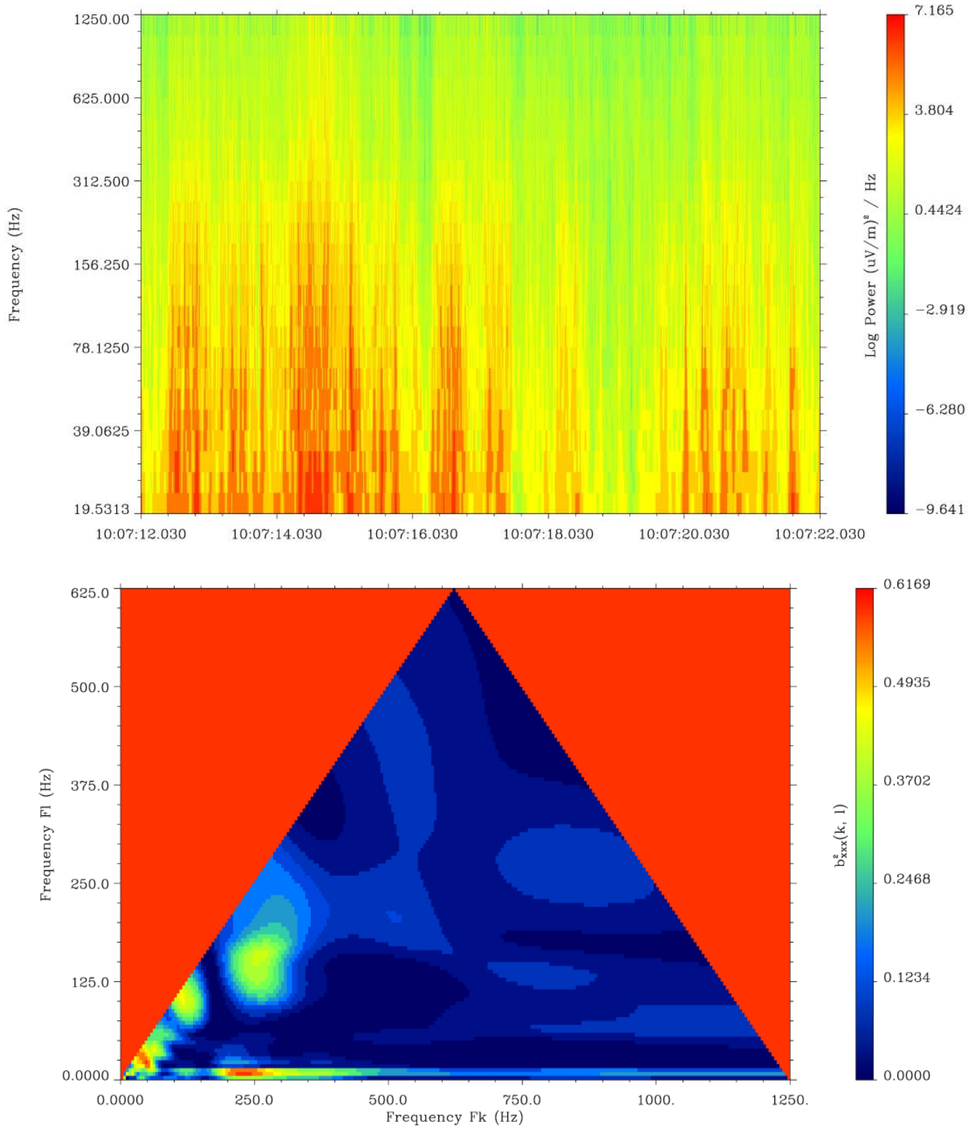

Figure 3. Wavelet spectrogram (19–1250 Hz) of the electric field variations (upper) and bispectrum of the same for time interval 10:07:12–10:07:22 UT when most intensive ELF/VLF emissions were registered (bottom)

The development of the wave processes seen during this event is nonlinear, which can be learned from wavelet and bispectral analysis shown in Figure 3. The same analysis was applied for processes in the outer polar cusp registered by the CLUSTER satellites (Błęcki et al., 2007; Savin et al., 2019). In the latter paper, the horizontal red maximum is associated with nonlinear "pumping" to be effective for the electron acceleration. The red negatively inclined maximum corresponds to the nonlinear decay at the fixed sum frequency. The nonlinearity observed in higher-order spectra of the ELF wave spectra is shown on the lower Figure 3 where the interactions of three waves in the lowest part of frequency is visible as a maximum of the bispectrum. It leads to spectra broadening in the wavelet spectrogram on the upper part of Figure 3. Similar nonlinear processes were reported in the past for the cases seen in the outer polar cusp (Błęcki et al., 2001).

More detailed information about energetic electrons spectra is provided in Figure 4. One can observe the broadening of spectra in the energy range up to 230 keV at 10:07:16–10:07:30 and 10:07:45–10:08:00 UT. This effect is accompanied by the emissions in the high frequency range 0.5–1.8 MHz as shown in Figure 5. Also, some beams of electrons can be distinguished at 10:07:13, 10:07:18, 10:07:29, 10:07:33 UT around energy 80–90 keV. They can generate beam instability, but we are not able to see it due to upper limit of frequency measured by Demeter.

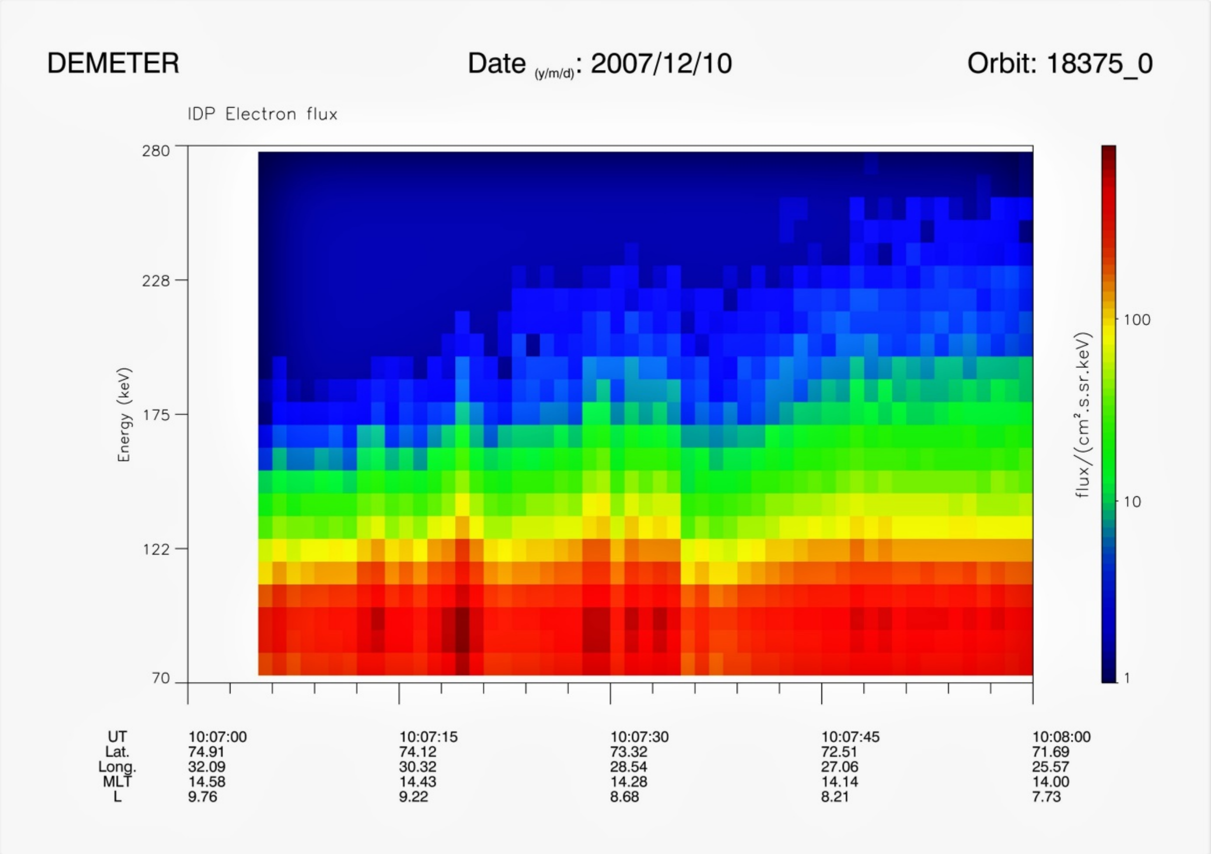

Figure 4 Spectrogram of electron energy from DEMETER in the polar cusp. Fluxes of electrons with energy up to 230 keV are seen at 10:07:16, 10:07:30 and 10:07:45 until 10:08:00 UT The beams of electrons can be distinguished at 10:07:13, 10:07:18, 10:07:29, 10:07:33 UT around energy 80–90keV.

The simultaneous presence of VLF, ELF, HF waves and fluxes of the energetic electrons suggests the following physical picture of these observed processes. The ELF and VLF waves interact in resonance with electrons. This leads to precipitation of the energetic electrons and their generated plasma instabilities creating emissions in the HF range. Two types of instabilities, fan instability and electron beam instability, need to be discussed in relation to the presented observations. A brief discussion is provided in Chapter 6 of this paper.

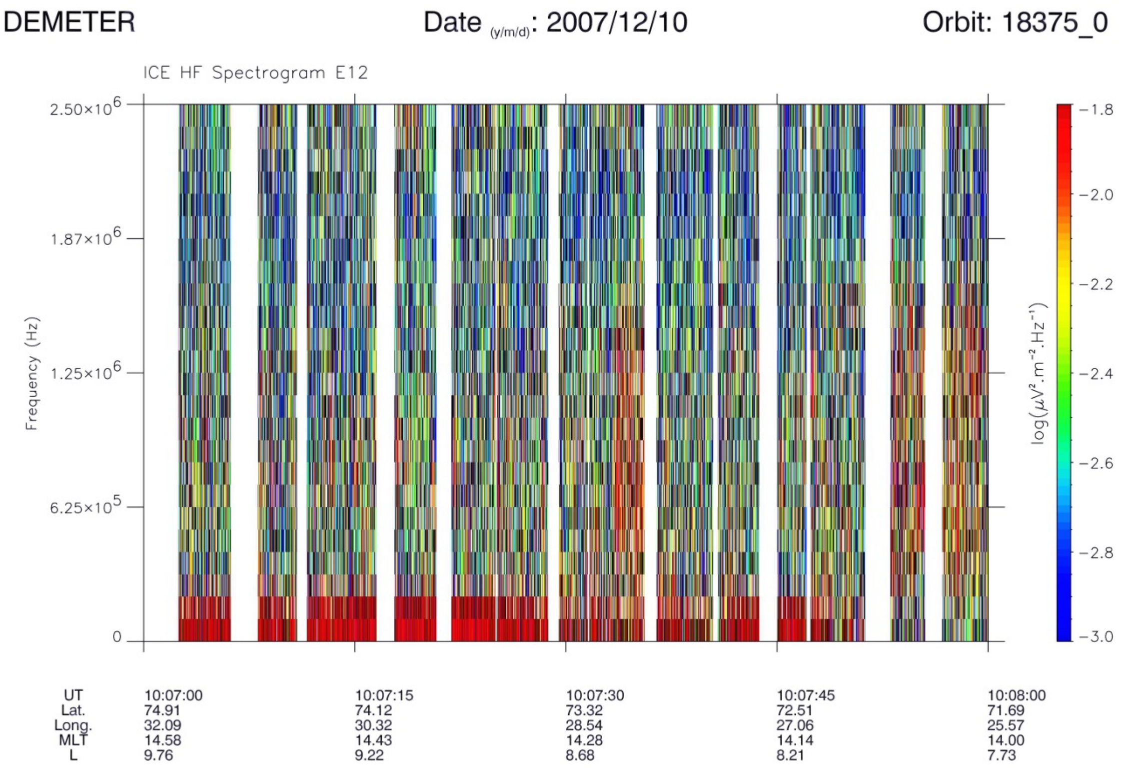

Figure 5. High frequency (0.55–1.8 MHz)—electric field variations observed by DEMETER in the polar cusp during an energetic electron event. A good correlation of energetic electrons presence (as shown in Figure 4) with enhancement of HF emissions is apparent at 10:07:30 and 10:07:45–10:08:00 UT. The plasma frequency at this epochs was fpe≈0.8 MHz and electron cyclotron frequency fce≈1.33 MHz.

4. OBSERVATIONS IN THE IONOSPHERIC TROUGH

The ionospheric trough is a location in the high-latitude region of the F layer characterized by distinct depletion of plasma density mostly seen as electron density decrease in the high-latitude ionosphere mainly determined by magnetospheric processes (Moffett and Quegan, 1983). The ionospheric trough width is several degrees in latitude and extends in longitude. The latitude changes with local time from about 70° to 55°. Contrary to polar cusp, which is dayside region, the ionospheric trough is mainly nightside phenomenon, although appears, in weaker form, at all local time (Evans et al., 1983; Collis et al., 1988). It changes its structure and position within time scales of several hours to one day. During increasing geomagnetic activity, the trough moves to lower latitudes. Satellite and ground-based observations allow determination of the large-scale structure of the high-latitude ionosphere, the main ionospheric trough can be imagined as a natural boundary between the middle and subauroral ionosphere. It is associated with another boundary—the boundary between cold plasma escaping from the ionosphere into the plasmasphere and hot plasma in the outer magnetosphere. The ionospheric trough is a projection of this boundary onto the ionosphere (Anderson et al., 2008). A new results related to the structure and its variability were recently obtained from the FORMOSAT-3/COSMIC (Lee et al., 2011) and DEMETER satellites (Rothkaehl et al., 2008; Chen et al., 2018). The ELF/VLF waves strongly interact with energetic electrons from the outer magnetosphere leading to electron precipitation into ionosphere. The energetic electrons fluxes generate high frequency emissions due to the instabilities, as mentioned in the previous chapter (Evans et al., 1983; Collis and Haggstrom, 1988). Figures 6 and 7 show the effects of these explained processes observed by DEMETER satellite.

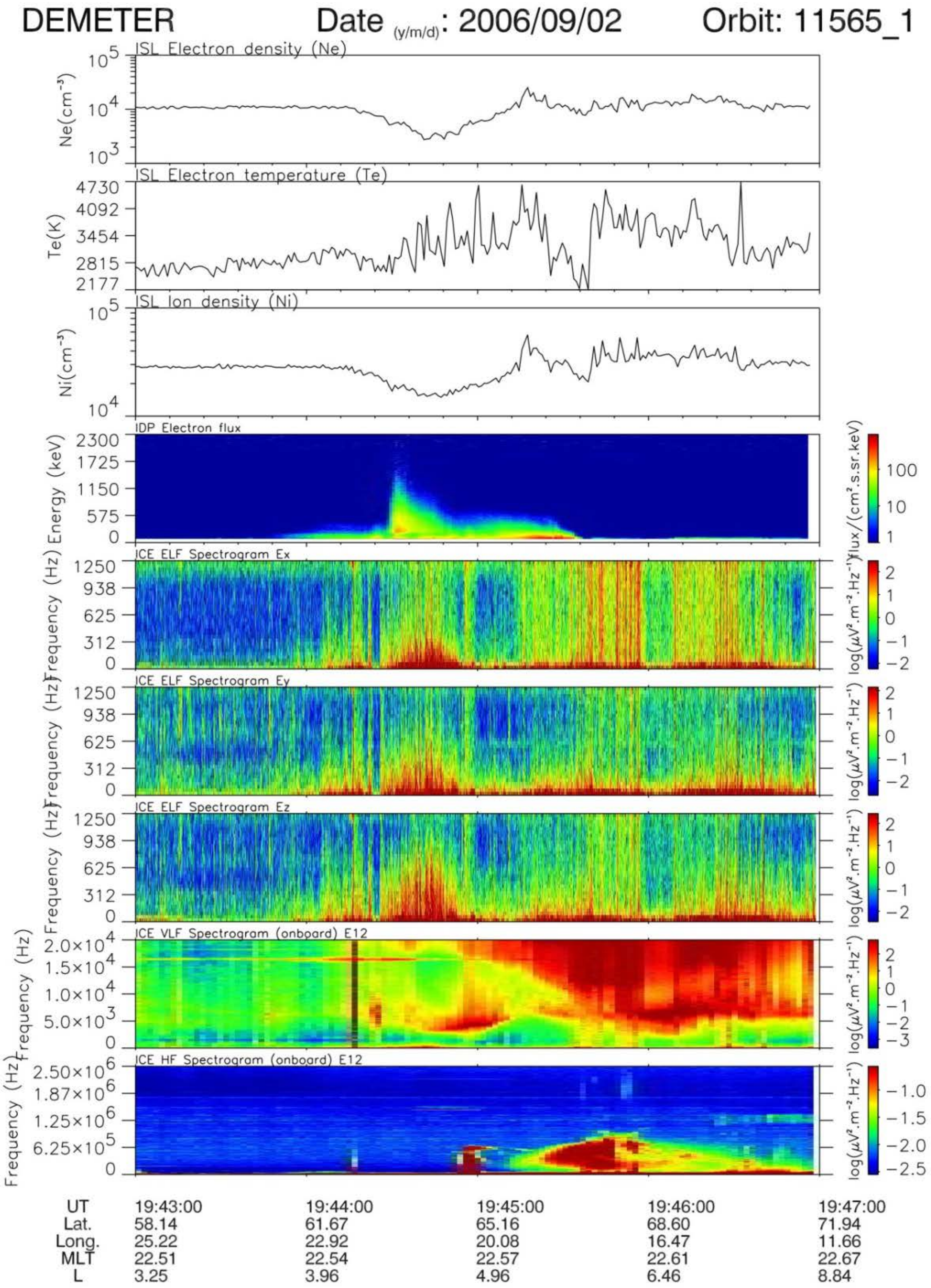

Figure 6. The measurements (from top to bottom) of the electron density, electron temperature, ion density, spectrogram of the electron energy, spectrograms of the electric field variations—three components in ELF, one component in VLF and one in HF frequency range. The entry of DEMETER satellite in the ionospheric trough was around 19:44:00 and exit around 19:45:00 UT

The entry of the satellite on September 6, 2006 into the ionospheric trough results as depletion of electron and ion density and an increase of ELF/VLF wave activity, which reaches a maximum around 19:44:21 UT co-incident with a maximum of the energetic electrons flux.

Strong variations of the electron temperature are present during crossing of the trough. The wavelet and bispectral analysis show the non-linear development and broadening of the wave spectrum. These waves are able to resonantly interact in very broad range with electrons and accelerate them. As one can see in the bottom panel in Figure 6, it leads to the generation of emission in the HF range up to 0.8 MHz (around 19:45:00 UT). The time of this case was related to very weak disturbance of the geomagnetic filed. Kp was 1 during trough crossing by DEMETER.

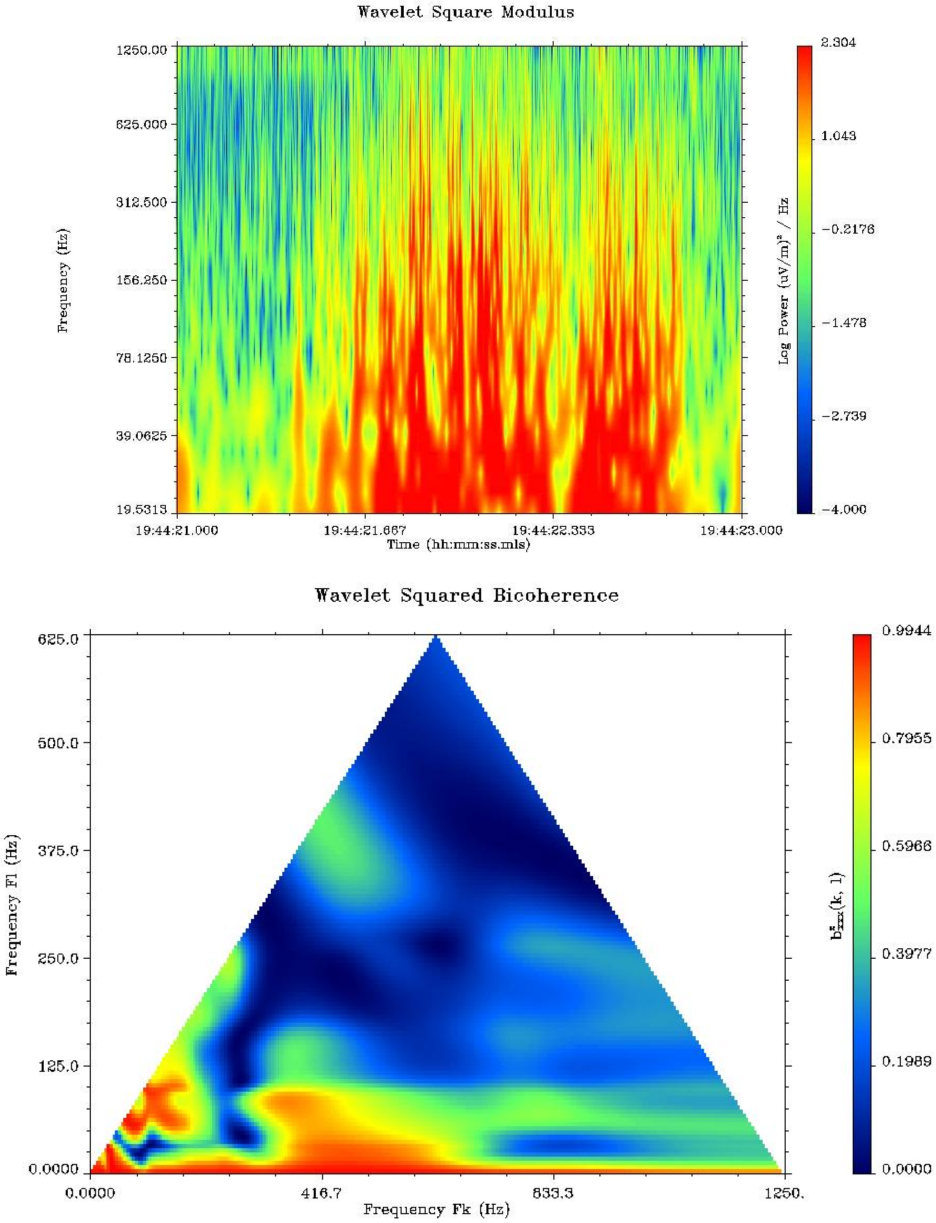

Figure 7. The wavelet spectrogram and bispectrum of ELF electric field variations during the presence of most energetic electrons and the strongest wave activity (19:44:21–19:44:23 UT). Strong nonlinear "pumping" (horizontally spread maxima at fixed vertical frequencies) supports the strong particle heating (cf. Fig. 3).

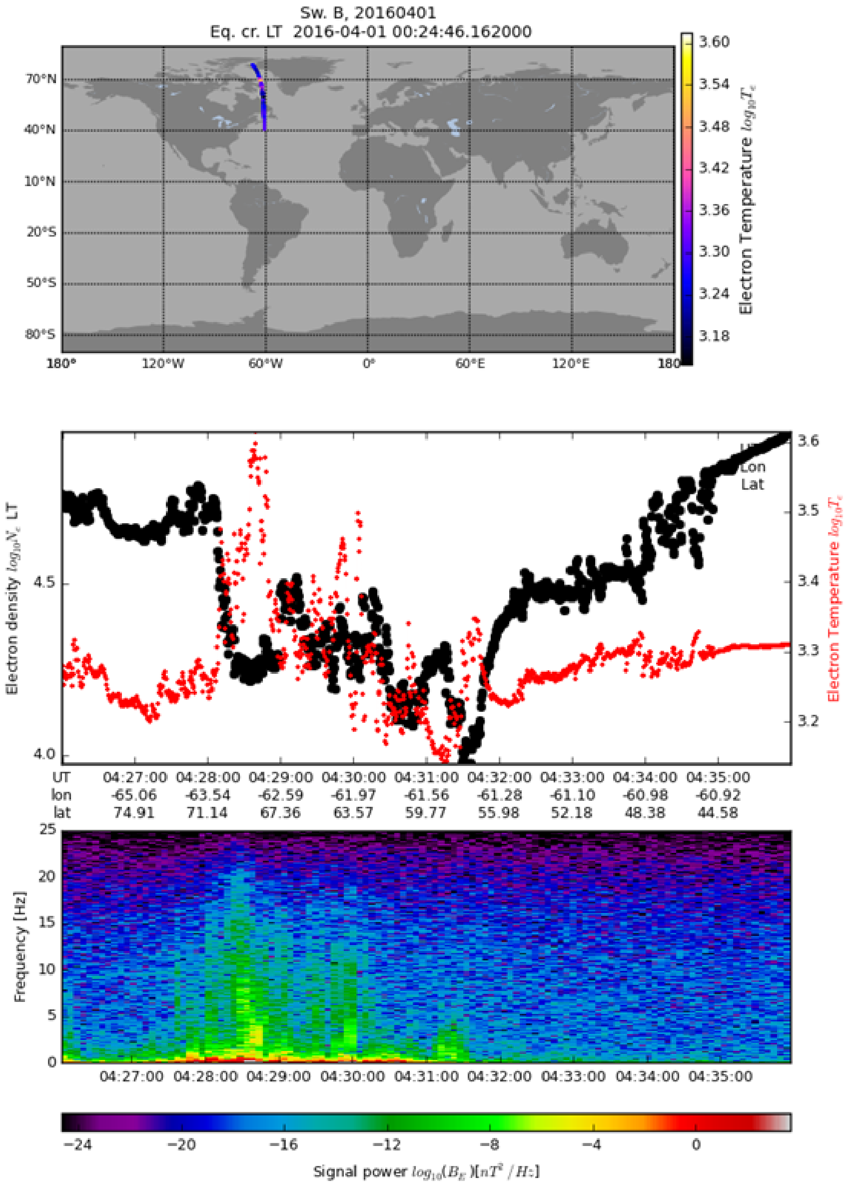

Figure 8. The trough crossing by the Swarm B satellite. The upper panel shows the part of orbit related to measurements presented in the middle and bottom panels. The colors of dots along the orbit correspond to the value of the electron temperature. The plots in the middle panel represent the electron concentration (black line) and temperature (red line). The bottom panel gives the spectrogram of the magnetic field variations.

Swarm satellites crossed the polar trough regularly. As already mentioned, Swarm can measure electron density and temperature, but not energetic particles. These effects, which have been registered by DEMETER as a fluxes of energetic electrons, would only be seen as variation of electron temperature being a consequence of heating of ionospheric plasma by fluxes of energetic electrons. Figure 8 presents an example of a trough crossing on April 1, 2016. As it was mentioned above, it was a very quiet day. The depletion of electron density at 4:28:10 UT indicates the entry of Swarm B into the trough. Its entrance from higher latitude is associated with strong enhancement (at 4:28:15 UT) of ELF waves for frequencies in the lowest part of this range (up to 20 Hz). At the same time, a strong jump of electron temperature (from 1990 K to 3900 K) is visible. Swarm exits the trough at 4:31:30 UT. Much weaker emissions and variations of the temperature are registered at this edge of the trough.

5. OBSERVATIONS IN THE IONOSPHERE OVER STRONG THUNDERSTORM

Thunderstorms are one of most powerful, beautiful, but also dangerous natural phenomena. Lightning events are associated with many physical processes of interactions in the atmosphere-ionosphere-magnetosphere system. The separation of the charge in thunderstorm clouds leads to the accumulation of a great amount of energy. This energy is released as lightning discharge on time scales less than 1 sec in a very localized area in space causing formation of plasma channels with temperatures ~25000 K and with electron densities exceeding 10^{17} cm^{-3}. The temperature of plasma in lightning discharge reaches a value higher than that characterizing solar chromosphere. These values are higher than average values measured in Earth's ionosphere.

So a powerful lightning discharge is a source of disturbances in the ionosphere. Lightning is also a source of acoustic gravity waves, which can propagate over long distances without damping creating a good way of energy transfer into the ionosphere.

The DEMETER satellite delivered new results about the influence of thunderstorms, lightning and particularly TLE (Transient Luminous Event) on the ionosphere. The electromagnetic and plasma effects were clearly observed in a broad range of electromagnetic emissions, changes in electron density and temperature and in energetic electron fluxes (Parrot et al., 2008, 2013; Bourriez et al., 2016). Below we discuss an example of DEMETER registrations over a strong thunderstorm in Poland on June 30, 2009. This day was geomagnetically very quiet, Kp index during discussed thunderstorm was on the level 0+, Dst close to zero. So influence on the ionosphere from outer space is negligible in the discussed thunderstorm region. The 136 IC (inter clouds), 89 CG- (cloud to ground negative) and 3 CG+ (cloud to ground positive) discharges has been detected by PERUN system in time interval 19:58–20:03 UT during DEMETER flight above this thunderstorm active region. Table 1 gives the time, locations and values of the maximum current for the most powerful strokes. These parameters are evaluated from the system PERUN run by Institute of Meteorology and Water Management-National Research Institute. The value of the currents during positive cloud to ground discharge on 19:57:54 and 20:00:47 UT could suggest that the effects observed by DEMETER are related to sprite, but there was no optical evidence to support that. Figure 9 presents spectra of the electric field variations in ELF (upper panel) and VLF (lower panel) range during flight over this thunderstorm. The spectrogram of ELF variations is limited only to time interval when burst mode was on. Emissions are present during the entire time of the flight over the thunderstorm area. The characteristic vertical lines in the spectra represent the so called sferics connected with direct transmissions of signal from the lightning discharge to the satellite.

Table 1. The time, locations and values of the maximum current for the most powerful strokes

Date	Time UT	Latitude	Longitude	Current max in kA
30/06/2009	19:57:54	52,4105	15,0033	103,380
30/06/2009	20:00:47	53,0546	23,4310	107,170
30/06/2009	20:02:07	51,9554	21,0176	63,700
30/06/2009	20:02:32	52,4673	15,3552	60,980
30/06/2009	20:03:25	52,3102	14,3756	94,850

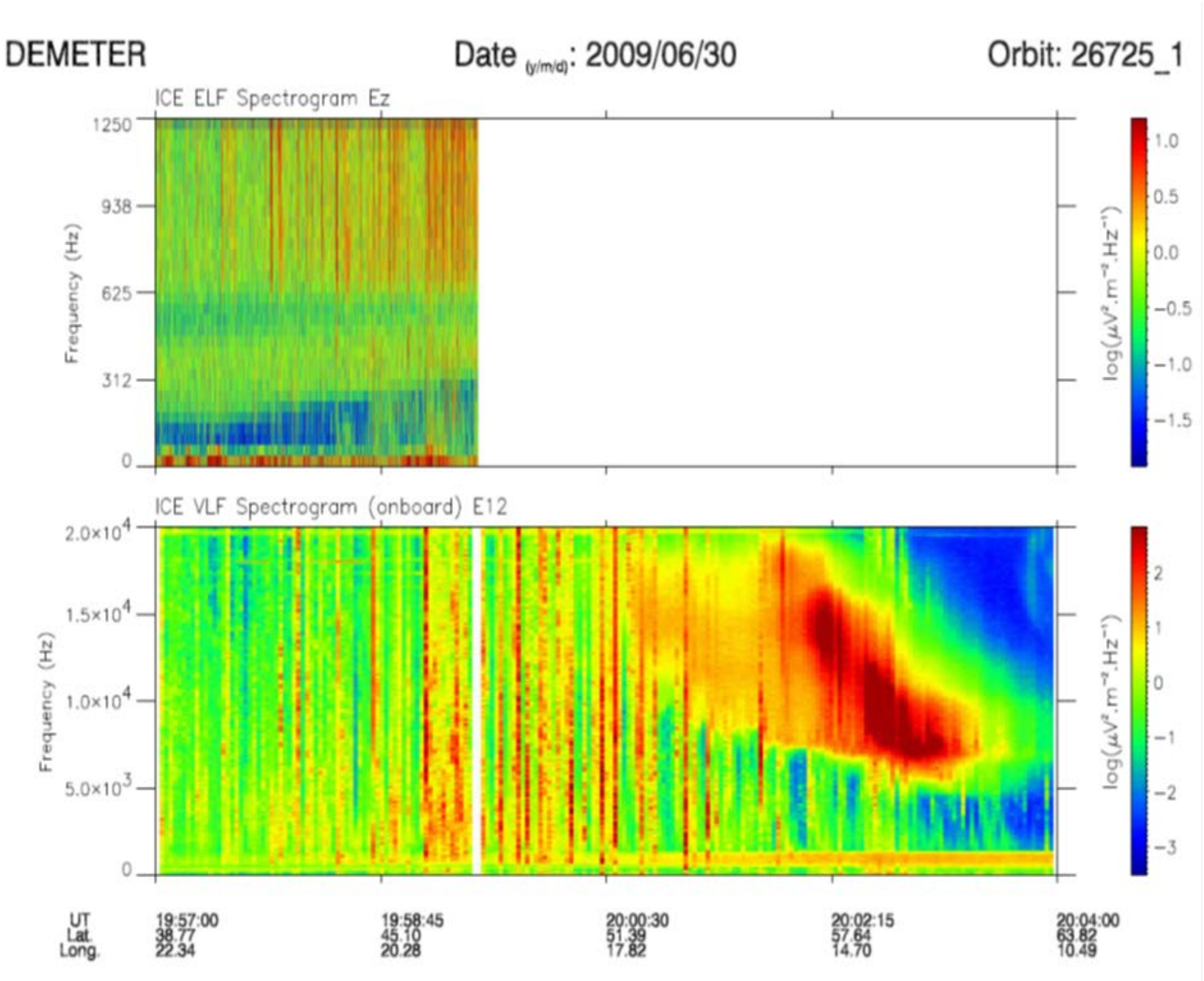

Figure 9. Spectra of the electric field variations in the ELF (upper panel) and VLF (bottom panel) ranges observed by DEMETER in the ionosphere over strong thunder-storms in Poland. ELF spectra are presented for the time interval related to burst mode.

The detailed spectrograms for this time interval together with ELF wave form are given in Figure 10. Strong variations of electric field up to 0.5 mV/m are present 20:57:54 in the ELF wave form as well as in spectrogram. Developing of VLF whistler following the stroke is seen in the spectrogram in the lower panel of Fig 10. Second very short impulse appears 4 seconds later and reaches value more than 0.6 mV/m, which is not related to any registrations by PERUN system. The characteristic delay of the ELF waves in relation to VLF in order of 0.05 sec is due to dispersion of the velocity, which is proportional to square root of the wave frequency.

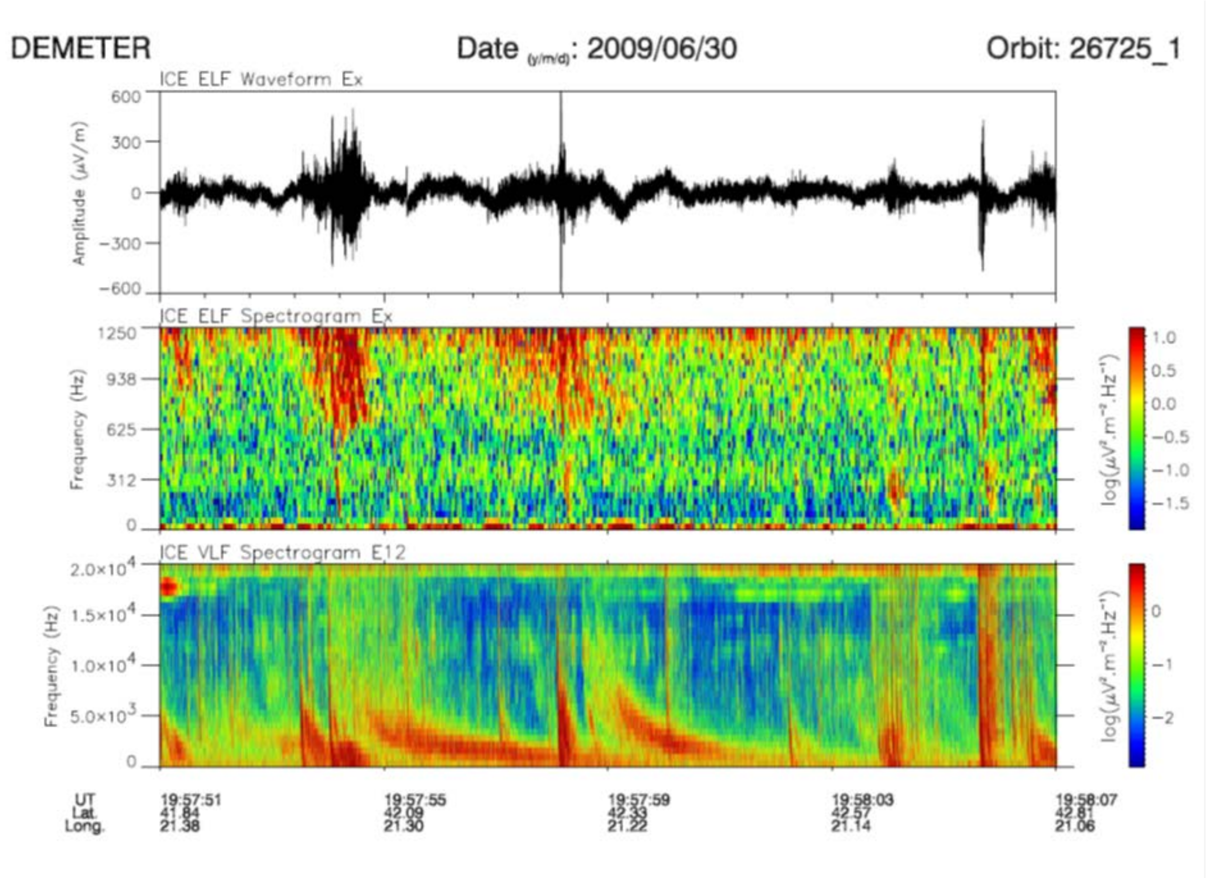

Figure 10. The wave form of the ELF electric field variations (upper panel) and spectrogram of it (middle panel) and spectrogram of VLF—whistler waves (bottom panel).

Figure 11 presents the measurements of the electron temperature, the energetic electrons spectrum, the energetic electron flux together with spectrograms of the VLF variations of the electric field and HF (high frequency) electromagnetic emissions. The spectrogram of the high frequency waves in this area is shown in the bottom panel of Figure 11. The strong enhancements of the HF wave intensity and broadening of the spectra up to 0.25 MHz are present in time interval 20:00:30–20:00:45 when Perun did not registered any CG discharge, but many interclouds ones. The electron temperature increases at 20:00:30 and 20:00:45 UT are present. Broadening of HF and VLF spectra appears after that shortly.

Weak enhancements of the energetic electrons fluxes are seen at 20:01:58 and 20:02:30 UT, the second one is also seen in the spectrogram with energy up to 122 keV. The presence of the energetic electrons in the ionosphere above the thunderstorm areas is well known experimental fact and were reported in many papers (see, e.g., Fullekrug et al, 2013). Their origin is related to the precipitation of energetic electrons from radiation belts due to resonant interaction of the VLF waves with trapped electrons.

Strong enhancements are seen in VLF spectrograms in band around 15 kHz in first case and around 10 kHz and is associated with this precipitation. Another effect is the action of the energetic electrons with ionospheric plasma and generation of plasma instability. It is shortly discussed in the next part.

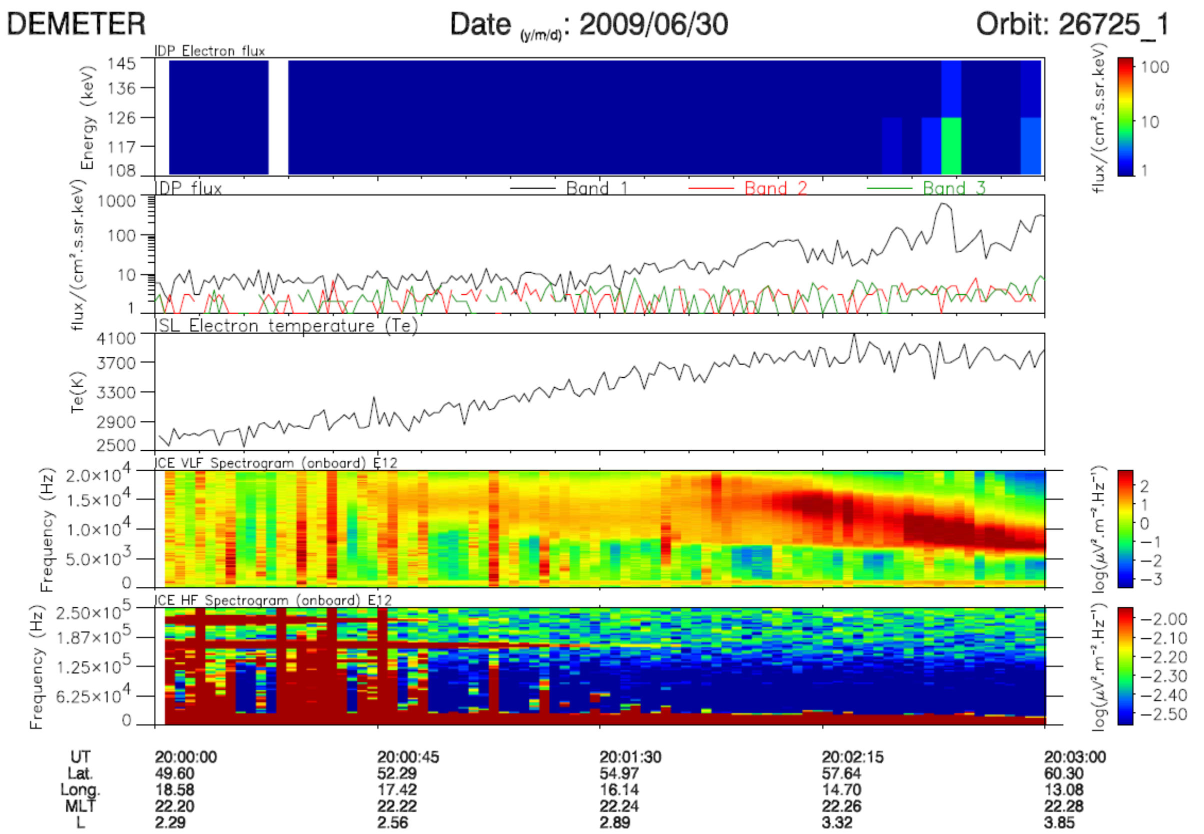

Figure 11. The parameters of ionospheric plasma at 660 km altitude observed by DEMETER together with VLF and HF over thunderstorms in Poland on June 30, 2009. The panels present from the top to the bottom: energetic electrons energy spectrum, integrated flux of energetic electrons in three ranges: band 1 – 971-2350 keV, band 2 – 526- 971 keV and band 3 – 72-526 keV, electron temperature and spectrograms of VLF and HF emissions.

6. DISCUSSION

The presented observations of simultaneous presence of energetic electrons and plasma waves in different regions of the near-Earth space from the DEMETER and Swarm satellites can be interpreted as a development of an unstable plasma state. All these events were registered during very quiet geomagnetic conditions. It can suggest that registered effects are associated with internal conditions in the discussed structures (polar cusp, ionospheric trough, lightning) and no influence from outer space. One can consider taking into account the presence of energetic electrons fluxes, two types of plasma instabilities—fan instability and beam instability. These are briefly discussed in the next two subsections.

6.1. Fan instability

Kadomtsev and Pogutse (1967) first studied this instability for a case where energetic electrons were present in Tokamak. Omelchenko (1994) and Vaivads (1995) discussed this phenomenon in relation to the auroral region, Krafft and Volokitin (2003) for the solar wind and Savin (2004) in case of the magnetopause.

A particle beam along magnetic field lines is needed to develop this instability, but in contrast to the usual beam-plasma instabilities, it does not require a threshold in relative velocity and a positive slope in the distribution function. The presence of the long superthermal tail in the distribution function is enough for developing of this instability. This condition is relevant to observations of DEMETER inside energetic particles fluxes. The maximum intensity seen in the wave spectrogram is related to the maximum of growth rate of the instability, which was calculated in the aforementioned theoretical works and would appear in the ionosphere at frequency of $0.2\ \omega_{ce} < \omega < 0.4\ \omega_{ce}$, It results in values at DEMETER altitude between 0.256 and 0.512 MHz in the ionosphere above a thunderstorm and 0.56 to 1.12 MHz in polar regions. This condition is in good agreement with the spectra of the high frequency emissions shown in figures 5, 6 and 11.

6.2 Beam instability

The presence of fluxes of the energetic electrons on a background of thermal plasma suggests the possibility of another instability: beam instability. This instability can develop when the strong beam of electrons is present on a background of ambient, thermal plasma. The threshold for the development of it is associated with the velocity of the beam. This should be higher than the thermal plasma velocity. This condition is fulfilled in the cases considered in the previous chapters. Beams of electrons can be distinguished at 10:07:13, 10:07:18, 10:07:29, 10:07:33 UT around energy 80–90 keV in Fig. 4. They can generate beam instability, with frequencies of waves around the local plasma frequency (cf. Treumann and Baumjohann 1997), but we are not able to see them, because it is over upper limit of frequency measured by DEMETER.

7. SUMMARY AND CONCLUSIONS

This paper presents observations of waves appearing together with plasma and energetic electrons in the polar cusp, ionospheric trough and over thunderstorms from the DEMETER satellite. These show that broad band (ELF/VLF/HF) wave phenomena can occur in these regions when energetic electrons are present. The same type of event was reported for the outer polar cusp observed by Prognoz 8, Magion 4 and CLUSTER satellites (Błęcki et al., 2005, 2006). The interpretation of the observations suggests multi-steps processes. ELF/VLF waves resonantly interact with energetic particles (electrons) in the magnetosphere, which leads to precipitation of electrons into the ionosphere. The next step is the stimulation of plasma instabilities. In the presented cases, two types of instabilities can develop generating HF waves. These are: fan and beam instability. Previous registrations done by CLUSTER and Interball show that fan instability should be seen as one of the important mechanism of waves generation in the outer polar cusp responsible for the redistribution of the energy in cusp plasma. The results from DEMETER presented in the present paper confirm that frequencies of registered waves are in the ranges related to prediction based on the theory of these instabilities. The plasma frequency calculated on the basis of the electrons concentration in examined regions is in the range from 0.6 MHz in polar cusp to 3.6 MHz over thunderstorm, while the electron cyclotron frequency from 2.8 MHz to 1.28 MHz respectively. These values correspond to the registrations given in figures 5, 6 and 11. Swarm satellites cannot perform directed measurements of energetic particles, but results presented in figures 1 and 8 contain the information about strong variations of the electron temperature and density, which are considered to result from the aforementioned processes.

Acknowledgements. The studies were conducted with financial support of the National Science Centre, grant No. 2017/27/B/ST10/02285. We express our gratitude to M. Parrot, J-A. Sauvaud, J-J. Berthelier, J-P. Lebreton, PI’s of DEMETER instruments from which data were used; ESA is acknowledge for access to Swarm data in the context of activities performed for the Swarm4Anom contract 4000112769.

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***Received**: 2020-06-25*

***Reviewed**: 2020-08-22 (undisclosed name), 2020-11-03 (undisclosed name)*

***Accepted**: 2020-12-06*