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ELECTRIC FIELD VARIATIONS IN THE MAGNETOSPHERE ORIGINATED FROM IONOSPHERIC HEATED VOLUME

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Abstract. On February 16, 2003 EISCAT-Heating experiment was carried out on observation of heating induced disturbances in the magnetosphere. A pump wave of 4.04 MHz in X-mode was used for the ionosphere modification from 19:55 to 23:59:59 UT in square modulation regime with 5 minutes ON / 5 minutes OFF cycle. During the interval of good conjugation of CLUSTER with the heating facility spacecraft 4 (Tango) recorded clear variations of electric field at modulation frequency lasting around 30 minutes. Spectral peak of the variations at 1.67 mHz is more pronounced in the y-component. Slow temporal variations of the conductivity in the heated volume due to electron density increasing in the E-region related with the heating duty cycle provide the same variations of disturbed electric field. Polarization of the disturbances is almost linear; it corresponds to constant ratio of Hall to Pedersen conductivity variations. The analysis of the signal waveform shows that at ~ 23.30 UT the phase of the variations is changed together with a sign of DC electric field. The transverse size of the disturbed structure in the magnetosphere is near 0.1 R_E. The observed behavior of the disturbances may be interpreted in terms of Alfven mode propagation of the disturbed ionospheric electric field into the magnetosphere. The electric field disturbances being uniform in the region of modified conductivity have a discontinuity at its border of the region and decay as two-dimensional dipole outside it. Field-aligned currents are related with conductivity gradients and distinct magnetic field variations are clear seen in quick-look plots around 20.30 UT. For further study of this event records of magnetic variations onboard CLUSTER satellites would be very important.

Introduction

From the first observations of artificial electromagnetic emissions (Getmantsev et al., 1974) and theoretical explanation of these (Kotik and Trakhtengerts, 1975) long lasting history of ionospheric modification experiments can be watched with review papers by Rietveld et al. (1993), Kohl et al. (1993) and Stubbe (1996). Recently new results have been obtained which have demonstrated that the ionospheric modification can lead to disturbances in the coupled magnetosphere-ionosphere system (James et al., 1984; Bösinger et al., 2000; Robinson et al., 2000; Blagoveshenskaya et al., 2001; Kotikov et al, 2001). Some results suggest possibility to produce stimulated disturbances in the magnetosphere-ionosphere system. It is very significant to show in experimental way the possibility of propagation of the relatively weak disturbances produced by the ionosphere modification into the magnetosphere, to measure their magnitude *in situ*, to compare it with theoretical estimations, and to consider possible mechanisms of the stimulation corresponding to experimental findings.

EISCAT-Heating experiment carried out at Tromso heating facility on February 16, 2003 was aimed to study the disturbances in the magnetosphere originated from modified ionosphere. During four hour heating from 19.55 to 23.59:59 UT the pump wave of 4.04 MHz has been used for ionospheric conductivity modification. The heating wave in eXtraordinary polarization (X-mode) and square modulation regime with 5 minutes ON and 5 minutes OFF cycle was employed.

The generation of the disturbances during ionospheric conductivity enhancement in presence of the background electric field has been studied by Maltsev et al. (1974), Stubbe and Kopka, (1977), and Oguti and Hayashi (1984). Maltsev et al. (1974) have found analytical solution for some kinds of conductivity inhomogeneities, for more general cases numerical modeling should be used. Their results can be summarized as follows: in the region of enhanced conductivity disturbed electric field is homogeneous, at the border of the region field-aligned currents appear, out of the region disturbances of electric field decays as two-dimensional dipole. Disturbances of the electric field and related field-aligned currents propagate into magnetosphere with Alfven speed. This propagating fields and currents in principle may be agents being responsible for stimulation of the disturbances in the coupled magnetosphere-ionosphere system of more significant power and duration than the initial ones.

A rare occasion, when CLUSTER entered into the inner magnetosphere took place on February 16, 2003 and it has been used for the study of the heating disturbances induced into the magnetosphere. Electric field data from the spacecraft 4 (Tango) for interval of good conjugation with Tromso show that variations in the magnetosphere may be interpreted in terms of highly localized oscillating dipole. Purposes of this paper are to analyse the observations and to discuss possibilities for a more detailed study of this rather interesting event.

Observations and Interpretation

Figure 1 shows the variations of the electric field components recorded onboard SC4 (Tango) on February 16, 2003 for interval from 23.00 to 23.50 UT. Sine wave disturbances with period around 10 minutes and amplitude value of 5 mV/m are clear seen in the Y-component. They are less pronounced in the X-component but also can be recognized. Time interval of variation record is 23.15 – 23.40 UT. Spatial size of the region of the disturbed tube can be estimated from the spacecraft orbit parameters. The SC4 X-coordinate is changed from -3.85 R_E to -3.6 R_E, and Y-coordinate from -1.08 R_E to -1.15 R_E, so the transverse dimension of the disturbed field tube is evaluated as 0.25 R_E. In the signal waveform a phase change in the electric field alternative component of 10 minute period is seen at ~23.32 UT. Together with the phase change a transient skip of the electric field level is observed. The disturbances with period of 10 minutes are almost identical in X- and Y-components with some scaling factor. It corresponds to the linear polarization of the variations.

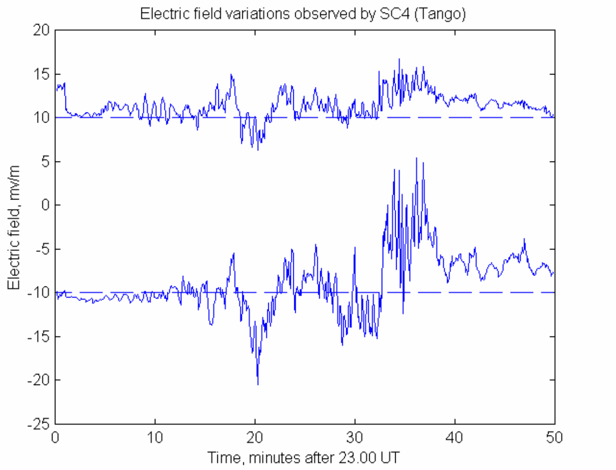

Figure 1. Electric field variations observed by SC4 (Tango) on February 16, 2003. Top line X-component, bottom one – Y-component.

The spectral content of the electric field disturbances for the both components presented in figure 2 shows strong maximums at 1.67 mHz. Correspondence of the variation frequency to the pump wave modulation frequency is main experimental evidence for artificial nature of these disturbances. The spectral peaks are rather wide, it may be due short duration of the interval of the disturbance observations relatively to their period. Phase shift of the ac disturbances in the X- and Y-components is insignificant and their polarization should be linear. Really, analysis of the electric field spectra gives no more information than those obtained from waveform consideration. Possible investigations based on the fine spectral analysis, such as measurement of the phase shift between variations of ionospheric conductivity and those of magnrtocpheric electric field or evaluation of Doppler shift of the variation frequency are broken by non-stationary character of the variations.

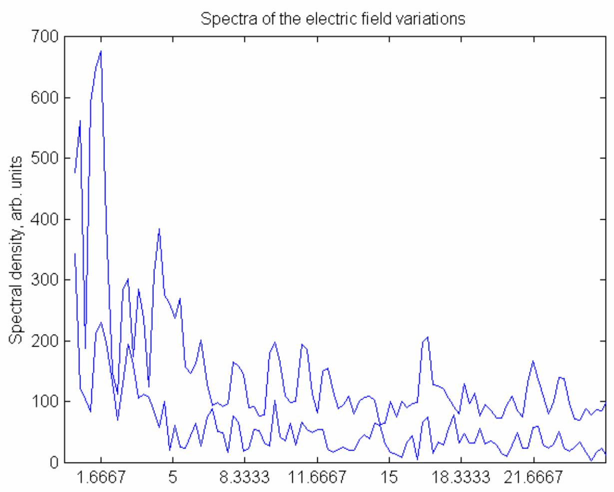

Figure 2. The spectral content of the components of electric field variations. The zero level for Y-component spectrum is brought up to 50 units. Clear spectral peak at 1.67 mHz is seen in the variations of Y-component.

In principle, these variations may be explained as spatial ones but for this interpretation rather complicated structure of field-aligned currents is needed. So we believe that temporal variations of the electric field predominate during the satellite pass. Moreover we will try to demonstrate that some peculiarities of these variations are in agreement with the suggestion of the disturbance propagation from the modified ionospheric region.

Starting point of the heating experiment on artificial emission excitation is ionospheric conductivity disturbances in the heated volume. Willis and Davis (1973) show that electron number density in the E-region of the ionosphere can be significantly increased due to decreasing of the recombination rate under action of the HF radio wave. This process takes place very slow and long heating pulse is needed for effective modification of the conductivity. Pashin et al. (1995) demonstrate using numerical modeling that this regime is rather effective under conditions of weak D-region, and nighttime winter ionosphere provides these conditions. Note again, that modulation scheme during experiment on February 16, 2003 was 5 min ON and 5 minutes OFF. Interesting feature of this heating regime is difference of the rate of electron and ion production and recombination rate in the heated volume. It results in non-stationary variations during few initial heating pulses and enhanced minimal value of conductivity in the modified region in compare with the background level when stationary variations are established. Calculations of the conductivity variations show that ratio of Hall to Pedersen conductivity is near constant during the heating cycle (Pashin et al., 1995).

Next step of our consideration is generation of the disturbances by a locally enhanced conductivity under conditions of background ionospheric electric field. It has been studied by Maltsev et al. (1974), Stubbe and Kopka, (1977), and Oguti and Hayashi (1984). For the consideration the artificial emission generation in the magnetosphere-ionosphere system wave conductivity should be defined (Maltsev et al. 1974). Its value determines intensities of field-aligned currents and transverse electric field propagating into magnetosphere. Oguti and Hayashi (1984) have estimated the value of wave conductivity for nighttime winter conditions approximately being equal to Pedersen one. Numerical modeling of the disturbances related with the ionosphere heating has been presented by Pashin et al. (2000). The region of the enhanced conductivity was taken as a circle with 30 km diameter. The value of the conductivity inside this area increased by factor 1.5 from background values was assumed. The ratio of Hall to Pedersen conductivity everywhere was taken 3 and wave conductivity was assigned equal to half of Pedersen one. Weak conductivity inhomogeneity along meridian was assumed and calculation of background electric field in the vicinity of the enhanced conductivity region gives south-north oriented field of 50 mV/m intensity. These initial conditions have been used for calculations of the heating effect in the eastward electrojet. Modeling of the heating induced disturbances has been made on a grid 500×500 with 2 km distance between nodes. Numerical solution of Poisson's equation for electric field potential gives disturbed potential distribution. Calculated disturbances of the ionospheric electric field are presented in figure 3. Uniform disturbances in the heated area reach up value 50 mV/m and are rotated relative background field due to anisotropy of ionospheric conductivity. These calculations have been made for moment of maximal enhancement of the conductivity. For time dependent conductivity the direction of the disturbed electric field depends on the ratio of disturbed Hall to Pedersen conductivity, linear polarization is expected when the ratio is constant. Really in the polar ionosphere the region of the enhanced conductivity is enlarged due to plasma drift motion. It should be taken into account for the ionosphere modification with long lasting heating pulses and strong background electric field. From Ohm's law one can calculate the ionospheric currents and their divergence gives field-aligned currents. Evidently the field-aligned current should appear at the border of the region of the enhanced conductivity providing continuity of the ionospheric currents. Non-uniform density of the field-aligned currents is obtained in the modeling with value of 80 $\mu A/m^2$ at their maximums located at northern and southern parts of the border (Pashin et al., 2000).

The propagation of the disturbed ionospheric electric field and field-aligned currents into magnetosphere occur with Alfven speed and for transient conductivity changes closer currents on the disturbance front flow due to inertial drift (Maltsev et al., 1974). For the time dependent conductivity variations closer currents compensate alternative component of the field-aligned currents. Field tube with uniform magnetic field and plasma density is the perfect guide for Alfven mode. Almost homogeneous Alfven speed along magnetic field line provides the conditions for the propagation of the disturbance without significant damping and distortion. In this case decreasing of the disturbance amplitude takes place due to increasing of the transverse size of the field tube. For the heating experiment on February 16, 2003 one should expect a formation in the magnetosphere the field tube with the time dependent dipole-like structure of the electric field in a cross-section. A spacecraft passing this tube should record as temporal variations and spatial ones. We already discussed temporal variations of the electric field disturbances onboard Tango spacecraft and mentioned the shift of the oscillation phase at 23.32 UT. This phase shift is accounted for crossing of the projection of the border of the enhanced conductivity region and the region of the field-aligned currents by the Sc4. A transient variation of the electric field of less amplitude and simultaneous decreasing of the oscillation amplitude in Y-component are seen at 23.24 UT. This feature may be explained by another crossing of the heated tube border where density of the field-aligned currents is smaller. Figure 3 allows to find point of enter and point of exit being in qualitative correspondence to these different variations of the electric field. Accepting this interpretation one could estimate the projection of the region of enhanced conductivity into the magnetosphere, it should be around 0.08 R_E. Factor of scaling of linear transverse dimension from the near equatorial plane magnetosphere to footpoint in the ionosphere is estimated as 20.

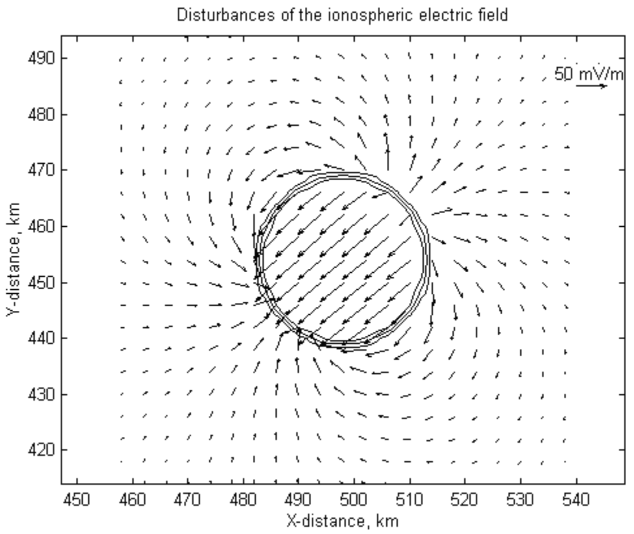

Figure 3. The ionospheric electric field disturbances in the vicinity of the heated area. The region of the enhanced conductivity is shown with triple line. The scaling vector of 50 mV/m is in the top right corner (after Pashin et al., 2000).

Discussion

Observations of electric field variations onboard CLUSTER SC4 (Tango) on February 16, 2003 show that the possible source of the disturbances may be the region of the enhanced conductivity produced by the HF radio wave heating over Tromso. Variation frequency is equal to modulation frequency of the heater, namely 1.67 mHz. The transverse spatial size of disturbed region also is in agreement with the projection of the modified area into magnetosphere. More detail study of this event could give additional arguments for the artificial nature of the disturbances observed in space by SC4.

Most reliable verification would be observations of the magnetic field variations onboard CLUSTER. Intensity and localization of the field-aligned currents may be deduced from the measurements of the magnetic field variations. Well-known relationship between electric and magnetic field components in Alfven wave may be verified and Pointyng vector of the wave may be calculated. For the propagating Alfven wave oscillations of the magnetic field should be in phase with those of the electric field. Vector of the magnetic field variations at the modulation frequency should be oriented in perpendicular direction to the electric field vector. Their amplitudes are related by simple formula $E=v_A B$, where v_A is Alfven speed, E and B are intensities of the electric and magnetic field correspondently.

Note, that propagating in the magnetosphere disturbances reflect from southern ionosphere may propagate in the opposite direction. As a result a standing wave may be formed with oscillations of the electric and the magnetic fields phase shifted on $\pi/2$. However, we expect rather strong background electric field during this event and the disturbances should drift from the fixed source region. Withdrawal of the reflected wave makes unlikely the formation of the standing wave but the observation of the reflected wave in the magnetosphere is possible.

Data of ground-based observation and numerical modeling for this event also are very desirable. Analisys of conditions providing effective generation of the artificial emission propagating into magnetosphere is especially interesting for further modification experiments aimed on stimulation of the disturbances in the magnetosphere-ionosphere system.

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