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Density Ducts Formed by Heating the Earth's Ionosphere with High-Power HF Radio Waves

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The parameters of plasma disturbances at altitudes 660 and 840 km, measured by the instruments onboard the French *DEMETER* satellite and the US *DMSP* satellites passing through the magnetic flux tube footed at the region of intense modification of the F_2 ionospheric layer by the high-power HF radio waves of the *Sura* heating facility, are presented. The formation of artificial enhanced-density plasma ducts in the outer ionosphere is observed experimentally. Conditions facilitating the formation of such ducts are pointed out.

Determination of the possibilities and conditions for excitation of intense large-scale geomagnetic-field-aligned plasma density irregularities (ducts) in the outer ionosphere and magnetosphere of the Earth is an important problem in contemporary geophysical research since such ducts play the role of waveguides for VLF radio waves. The solution of this problem can find a number of applications. One of the methods for their artificial formation proposed, e.g., in [1], can be ionospheric heating by high-power HF radio waves. In this case, artificial ionospheric turbulence is generated by plasma disturbances excited near the altitude of the reflection of an O-polarized pump wave due to its resonant interaction with the plasma in the F_2 ionospheric layer. In particular, magnetic-field-aligned density irregularities with a wide range of sizes (from a fraction of a meter to tens of kilometers) transverse to the geomagnetic field are formed [2]. In addition, a strong increase in the electron temperature and pressure in the region of intense plasma heating leads to the formation of a “thermal wave” propagating along the geomagnetic field and leaving a field-aligned irregularity—an artificial duct. According to theoretical models [3, 4], such an artificial duct should have a decreased density. Quiet midlatitude geomagnetic conditions are obviously more convenient to carry out experiments aimed at studying such phenomena since the high-latitude ionosphere typically exhibits fairly high and rapidly varying disturbances. In this case, the most suitable method for measuring the parameters of such ducts is

the use of instruments onboard satellites orbiting the Earth at outer-ionosphere altitudes.

Satellite measurements of the parameters of plasma disturbances induced in the outer ionosphere due to the F_2 -layer heating with high-power HF radio waves of the midlatitude *Sura* facility (Radiophysical Research Institute, Nizhni Novgorod, Russia) have been occasionally carried out many times, but were mainly aimed at determining the electromagnetic field parameters [5, 6]. The experiments studying the parameters of plasma disturbances excited by the *Sura* ionospheric heating facility became routine and were carried out annually since 2005 in March–May and August–September after the launch of the French microsatellite *DEMETER* (Detection of ElectroMagnetic Emissions Transmitted from Earthquake Regions) equipped with various detectors for measuring the parameters of the plasma and electromagnetic field. The preliminary results of these experiments were reported in [7]. In addition, such measurements were performed by the US *DMSP* (Defense Meteorological Satellite Program) satellites in August and October 2007 within the framework of the joint experiments with the AFRL (United States). The *DMSP* satellites can measure the plasma parameters and the fluxes of precipitating electrons and ions with energies 0.03–30 keV. A detailed description of the equipment borne by the satellites is given in [8, 9].

In such experiments, the *Sura* facility radiated a high-power HF radio wave in the CW mode for 15 min. The facility was switched on 10 min before the satellite passage through the center of the disturbed geomag-

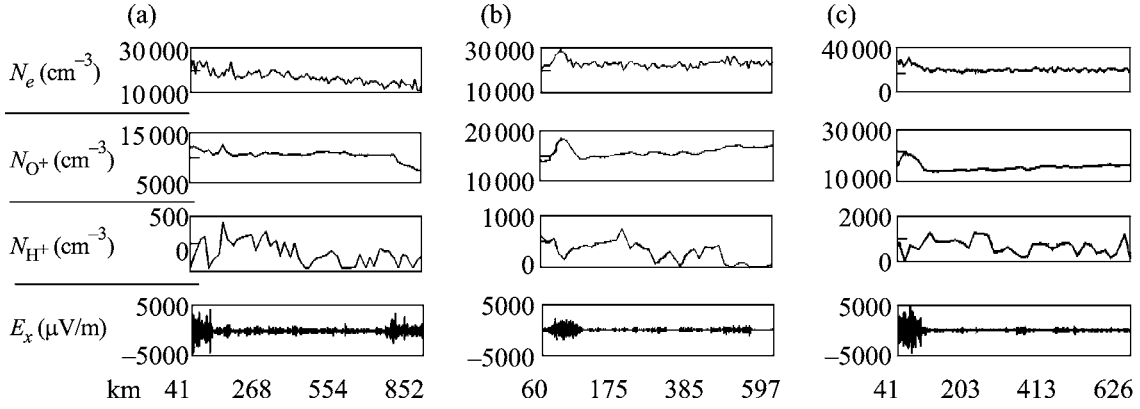


Fig. 1. Dynamical dependences of the number densities N_e , N_{O^+} , and N_{H^+} of electrons, atomic-oxygen ions, and protons, respectively, for the sessions on (a) April 30, 2005; (b) May 1, 2006; and (c) May 17, 2006. The lower panels show the time dependences of the electric field component E_x perpendicular to the geomagnetic field and satellite velocity. The horizontal axis shows the distance from the satellite orbit to the axis of the perturbed flux tube.

netic flux tube footed at the region of intense artificial ionospheric turbulence excited by a high-power O-polarized radio wave near the altitude of its reflection in the F_2 ionospheric layer. The antenna pattern was inclined 12° southward from the zenith during the majority of ionospheric heating sessions. In this case, the generation of artificial ionospheric turbulence is enhanced due to the “magnetic-zenith” effect [10, 11], since the pump wave in the region of its resonance interaction with the plasma propagates along the geomagnetic field lines and the field-aligned plasma density irregularities.

In this work, we present the results of satellite measurements of the parameters of plasma disturbances excited in the outer ionosphere by high-power radio waves of the *Sura* facility and detected by instruments onboard the *DEMETER* and *DMSP* satellites. The last section contains a discussion of the results, a summary, and concluding remarks.

RESULTS OF MEASUREMENTS WITH THE ONBOARD INSTRUMENTS OF THE *DEMETER* SATELLITE

The *DEMETER* solar-synchronous orbit with an altitude of 710 km before December 2005 and 660 km later on. The satellite passes over the *Sura* facility (56.1° N and 46.1° E) in the daytime at about 8:00 UT and in the late evening at about 18:30 UT. A few tens of heating sessions for which the satellite orbit was closer than 200 km to the center of the disturbed flux tube were performed in the three years of the experiments. Note that daytime measurements have yielded no significant results to date. Evening observations revealed the presence of artificial plasma disturbances in the sessions when the ionosphere was modified using a pump wave with the effective radiation power $P_{\text{eff}} \geq 40$ MW and a frequency below the critical frequency of the F_2

ionospheric layer ($f_0 \leq f_{0F2}$), while the distance between the satellite and the axis of the disturbed flux tube was less than 100 km. Only 10 sessions in three years of observations obeyed these conditions. The following conclusions can be drawn from these measurement data.

(i) Three sessions showed the presence of strong large-scale disturbances with the plasma density increased by 25–35% and sizes of ~ 80 km along the satellite trajectory. Such structures were not observed in reference sessions when the satellite passed over the switched-off facility or when the ionospheric heating was carried out under conditions of low critical frequencies $f_0 > f_{0F2}$ (transmission heating). Examples of observations of such plasma disturbances are shown in three panels in Fig. 1 for the sessions on April 30, 2005 ($D = 27$ km and $T = 18:25:36$ UT), May 1, 2006 ($D = 42$ km and $T = 18:28:39$ UT), and May 17, 2006 ($D = 39$ km and $T = 18:28:34$ UT). The minimum distance D between the satellite orbit and disturbed-flux tube axis and the closest-approach time O are given in the parentheses. Note that, in addition to an average increase in the plasma density, its strong fluctuations on scales about 25–35 km, as well as electron-temperature fluctuations absent in the session on May 1, 2006, were also observed in the sessions on April 30, 2005 and May 17, 2006.

(ii) In all cases where disturbances with a strong plasma density increase were formed, vertical-sounding ionograms showed the development of strong F_{spread} , the suppression of the O-mode, and the appearance of the Z-mode. This is indicative of the highly efficient interaction of the pump radio wave with the plasma and the generation of intense irregularities whose sizes across the geomagnetic field ranged from ~ 1 m up to ~ 10 km near the level of pump wave reflection.

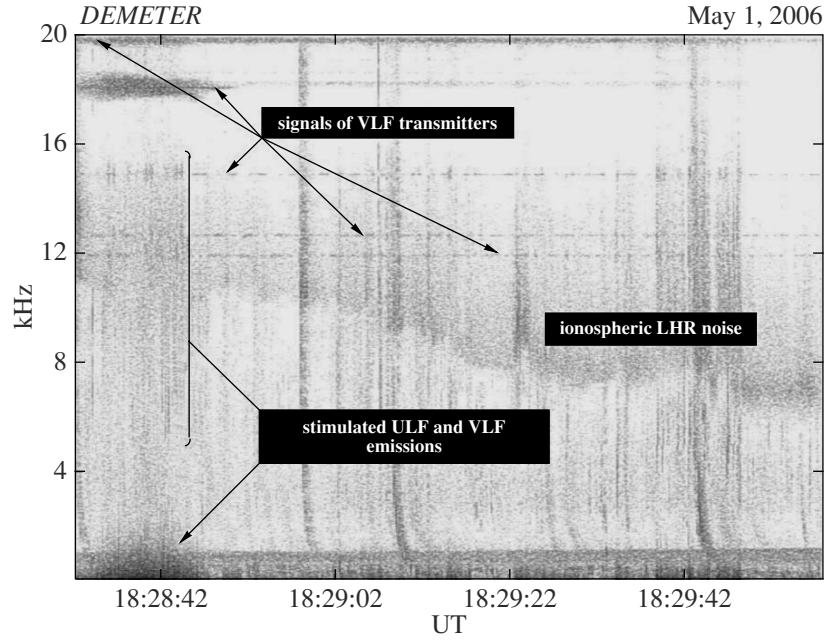


Fig. 2. Dynamic spectrogram of the electric field component E_x for the session on May 1, 2006. The vertical and horizontal axes show the frequency in kHz and time, respectively. The signal power is grey scaled (white is the absence of the signal).

(iii) A feature of disturbances with a large plasma density increase is the presence of strong electromagnetic field fluctuations at frequencies from a few Hz to tens of kHz. In a number of cases, a significant (by tens of dB) increase in the intensities of VLF station signals and a broadening of their frequency spectra were also observed. Figure 2 shows a spectrogram obtained during the session on May 1, 2006. Here, the above-mentioned effects are distinctly seen, in particular, the appearance of intense electric field fluctuations at frequencies from ~ 10 Hz up to ~ 1 kHz and noise in the frequency range 5–16 kHz, a significant increase in the intensity of the VLF station signal at 18.1 kHz and a broadening of its spectrum up to 500 Hz. At the same time, the latter signal outside the large-scale plasma density irregularity is almost indistinguishable and has a narrow spectrum. There are solid grounds for supposing that the localization of the fields inside such an irregularity and the significant increase in the VLF station signal and the broadening of its spectrum are attributed to the channeling of radiation in a density duct formed due to the ionospheric heating by a high-power HF radio wave.

(iv) According to the measurement results, the excess in the number density of the ion component of the plasma is due to higher mass O^+ ions dominating at altitudes ~ 700 km. On the contrary, the densities of lower mass H^+ and He^+ ions typically decrease by a percentage amount comparable with or even larger than the relative increase in the density of O^+ ions.

It should be noted that the high sampling rate mode (*burst* mode) used in the experiments could only be

switched on in the *DEMETER* satellite upon completion of the *survey*-mode duty cycle. Thus, the optimal interval of observations by the satellite passing near the disturbed-flux tube center (e.g., within ± 1 min from the closest approach time) did not coincide with the actually scheduled interval of operation in the appropriate mode. This influenced the measurement results presented below.

RESULTS OF MEASUREMENTS WITH THE ONBOARD INSTRUMENTS OF THE *DMSP* SATELLITES

The *DMSP* satellites also have solar-synchronous orbits and pass over the *Sura* facility at an altitude of 840 km in the morning and evening at 4:00–6:00 and 13:00–15:00 UT. Two months of experiments included eight heating sessions. Only four of them—two sessions in August and two sessions in September 2007—obeyed the conditions that $f_{0F2} > f_0$, $P_{\text{eff}} \geq 40$ MW, and the minimum distance between the satellite orbit and the disturbed-flux tube axis is less than 100 km. One of these four sessions was during the evening and the three other sessions were in the morning. Note that no artificial plasma disturbances were observed in the other four sessions not obeying the above-mentioned conditions.

The following conclusions can be drawn from the experimental results.

(i) Two morning sessions on August 23 ($D = 46$ km and $T = 05:11:00$ UT) and October 10 ($D = 19$ km and $T = 05:45:00$ UT) revealed the presence of a large-scale

disturbance with a plasma density enhanced by 2 and 5% and sizes ~ 160 and ~ 130 km along the satellite orbit, respectively (Fig. 3). Such structures were not observed in reference sessions when the satellites passed over the switched-off facility or during underdense heating of the ionosphere.

(ii) No variations in the geomagnetic field or ion drift velocities induced by the heating of the F_2 ionospheric region were observed.

(iii) Moderate suppression of the O-mode and the development of weak F_{spread} were observed in the ionograms obtained during the morning heating sessions in which strong large-scale plasma density irregularities were revealed. This is indicative of the moderate level of artificial ionospheric turbulence near the pump wave reflection level.

SUMMARY AND CONCLUDING REMARKS

Direct measurements of the plasma parameters in the outer Earth's ionosphere at altitudes of 660 and 840 km with instruments onboard the *DEMETER* and *DMSP* satellites revealed the formation of large-scale disturbances with a strongly increased plasma density due to the modification of the F_2 ionospheric layer by high-power O-polarized HF radio waves of the *Sura* heating facility. Such disturbances can be classified as density ducts. Analysis of the entire data obtained to date makes it possible to point out the following conditions under which the formation of such ducts was observed.

- The ducts were formed during the morning or evening modification of the ionosphere. The more intense generation of artificial ionospheric turbulence and the larger (25–35%) increase in the plasma density were observed in the late evening hours in comparison with the morning hours (a plasma density increase of 2–5%). No positive results were obtained in the case of daytime ionospheric heating. Measurements under nighttime conditions were not possible because of the low critical frequency f_{0F2} .

- The formation of ducts was observed only if pump waves with sufficiently high power $P_{\text{eff}} > 40$ MW were used for ionospheric heating.

- In view of the “magnetic-zenith” effect, to enhance the generation of artificial ionospheric turbulence, it is expedient to heat the ionosphere by a high-power radio wave beam inclined (in the case of midlatitude *Sura* facility and $f_0 \sim 5$ MHz) by $\sim 10^\circ$ – 12° southward [11].

- Since the transverse size of the ducts is ~ 100 km, they can be observed only if the distance from the satellite to the center of the disturbed magnetic flux tube is < 50 km.

The absence of intense large-scale plasma density irregularities in almost all other heating sessions is explained by the violation of these conditions. It is

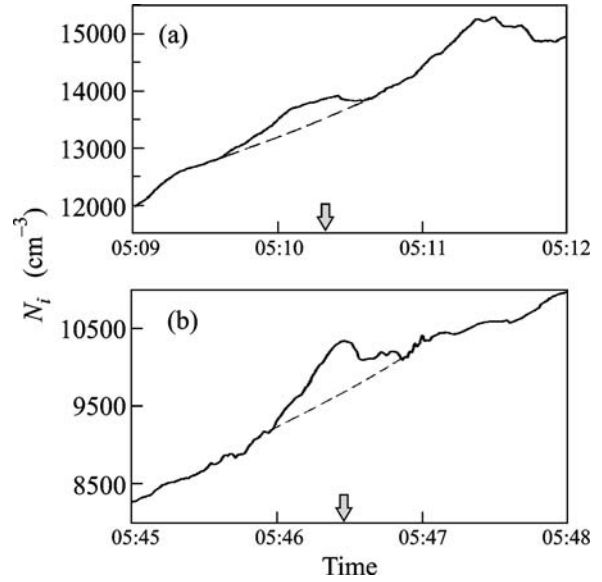


Fig. 3. Dynamic dependences of the ion number density N_i for the sessions on (a) August 23, 2007 and (b) October 10, 2007. The arrows mark the region of the closest approach of the satellite to the axis of the disturbed flux tube.

important to emphasize that the frequency f_0 of the pump wave used for ionospheric heating should be 0.5–1 MHz below the critical frequency f_{0F2} . Such plasma density disturbances were not observed in all the experiments for which f_0 was close to f_{0F2} . This can be explained by the penetration of the radiated power behind the F_2 ionospheric layer due to a decrease in its maximum plasma density by 10–20% during the heating [2, 12].

According to the measurements, the time of duct development at altitudes of 660–840 km is no longer than 10 min. This time is shorter than the time of plasma density establishment under the action of the gas-kinetic pressure force found in the model calculations [3, 4]. Moreover, according to these calculations, a steady-state duct should have a decreased plasma density, whereas an increased plasma density inside the duct can exist only during the “thermal wave” propagation. In this respect, it is worthy to mention the results of tomographic measurements [12] directly indicated the existence of a large-scale plasma irregularity with an enhanced density which is not necessarily located on the same field line as the cavity with a decreased plasma density formed near the pump wave reflection level. Thus, the duct is formed not only due to geomagnetic-field-aligned plasma ejection from the strongly heated region in which, according to the above-mentioned model calculations, the pump wave energy is mainly deposited. It is also important to note that the formation of ducts in our experiments was observed for pump wave reflection altitudes of ~ 200 – 220 km. On the contrary, model calculations showed that the duct formation should be expected only if the latitude of pump

wave reflection exceeds 300 km, since the significant decrease in the thermal conductivity scale length makes the heat transport to the outer ionosphere inefficient.

A drawback of the models proposed in [3, 4] is that they disregard the effect of suprathermal electrons accelerated by plasma turbulence in the regions of resonance pump wave interaction with the plasma and penetrating to the outer ionosphere on transport processes in the plasma. Meanwhile, up to 15% of the pump wave power is spent on this acceleration [11]. In addition, the above-mentioned models do not take into account bulk plasma motion that accompanies the ionospheric heating [13] and leads to the formation of vortices, which can initiate the appearance of artificial plasma density irregularities far outside the ionospheric region irradiated by a high-power radio wave. All this implies that new experimental and theoretical efforts are needed for a more comprehensive analysis of the observed phenomena and the development of an experimentally substantiated theoretical model for the generation of plasma disturbances in the Earth's ionosphere.

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