

The radio HF initiation of substorm and energetic particles precipitation.

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Abstract.

The special-purpose research facilities equipped with powerful HF transmitters are used successfully for plasma experiments and local modification of the ionosphere. In this work, we are using the results of a complex space-ground experiment to show that exposure of the subauroral region to HF emission can not only cause local changes in the ionosphere, but can also trigger processes in the magnetosphere-ionosphere system that result in intensive substorm activity (precipitations of high-energy particles, aurorae, significant variations in the ionospheric parameters and, as a consequence, in radio propagation conditions).

1. Introduction

The priority task of space research nowadays, particularly as concerns the space weather forecast, is a detailed study of near-Earth space and its variability factors, as well as the possibility to control the parameters of the medium in order to reduce economical risks. A number of present-day research programs, e.g. HAARP (Alaska, USA) [1], are aimed at broad investigations in this field. In Russia, we have a single facility (“Sura”) [2] for stimulation of the ionosphere by high-power radio emission designed in the past century, whose capacity is an order lower than the capacity of the up-to-date US facility or the European Tromso facility. Here, we present the results of new experiments carried out with the use of the Sura HF transmitters.

2. The Description of the Sura-ISS Experiments

The mid-latitude facility – Sura (56.13°N, 46.1°E) makes it possible to carry out ionospheric plasma experiments outside the highly dynamic auroral zone. A series of new experiments has been carried out on its basis invoking other ground-based and space-borne facilities, in particular, the Russian segment of the International Space Station (ISS). The novelty of the Sura-ISS program consisted in the search for resonance conditions for triggering powerful natural processes by a relatively weak though purposeful action. One of such natural phenomena in near-Earth space is the substorm activity. The peculiarity of all experiments [3] was that, the critical frequency f_{oF2} of the ionospheric F2-layer was always lower than the working frequency of the heating wave (heating “by transmission”), and the powerful radio emission covered the entire column of the ionosphere within the antenna diagram. The modulation frequency was close to the frequency of natural Alfvén oscillations of plasma in the magnetic flux tube resting on the heated spot in the ionosphere. The geometry of the experiments in geographical coordinates is represented in Fig. 1. The dotted lines show the field of view of the ISS optical instruments directed horizontally towards the Sura facility (northwards). More than 12 experiments were carried out (2007-2012). According to the Intermagnet network data, the planetary magnetic activity index did not exceed 3; the auroral oval was quiet; noticeable variations in the solar wind and interplanetary magnetic field were absent (data from GOES, SOHO and other satellites). The experiments were supported both by ground-based measurements and by measurements on board the Demeter satellite. The table below gives the main parameters of the HF heating and the ionospheric characteristics for two experiments, in which the substorm-type geomagnetic disturbances were recorded.

Table 1. The main parameters of the experiments and ionosphere.

	Heating time. HF emission mode.	HF frequency, eff. emission power, and polarization. Antenna diagram.	f_{oF2}	Ionospheric conditions
Session 1. 02.10.2007	18:40–19:00 UT, ± 1 min	4300 kHz, 10 MW (one facility module working). O-mode. $12^\circ \times 36^\circ$ (N-S direction)	3.9 MHz	$F2$ -spread, more than 4 h
Session 2. 25.10.2010	18:55–19:15 UT, ± 1 min	4785 kHz, 100 MW (three facility modules working coherently). O-mode. $10^\circ \times 10^\circ$	2.5 MHz	$F2$ -spread,(in evolution).

In the experiment of 2 October 2007, the Sura facility was operating in the periodic heating mode from 18:40 to 19:00 UT (one minute heating, one minute pause). The minimum power was 10 MW. ISS observations

provided more than 1000 images of a bright local glow, which appeared within the field of view of the camera as the Space Station was passing over the Sura location site. The glow brightness reached tens of kiloRayleighs. The gray rectangles in Fig. 1 to the north of the Sura facility show the nearest and the farthest boundaries of the aurora (for its lower edge at 150 and 100 km, respectively) as estimated from ISS data for two points of time. The glow appeared northeast of Sura and moved eastward in the image plane at a significant velocity. This occurred against the quiet luminosity background (global emission layer, auroral oval) before the ISS passage over the experiment region. Fig. 2 illustrates a series of successive images (6 photos) obtained with the ISS camera during the heating experiment of 2 October 2007. The emission layer and the Earth horizon (the first photo at the top, the time 18:44:41UT at the corner) set the scale for estimating the linear parameters of the bright glow that appears in the Sura facility region on the next photo (see the arrow on the lower left panel). On the right-hand panels, one can clearly see the horizontal size of this bright feature (marked with an arrow).

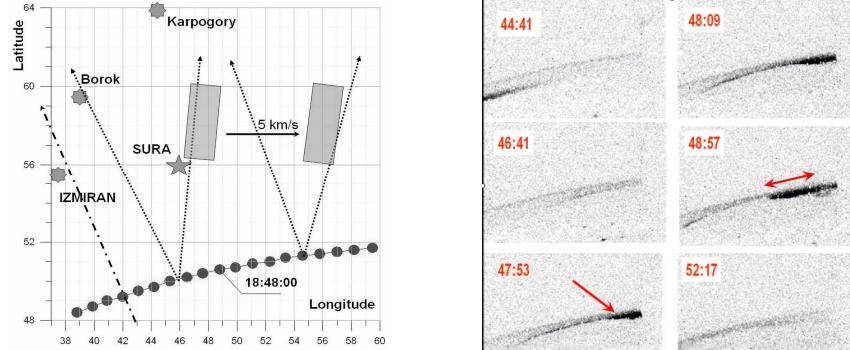


Fig. 1. The scheme of observation. The circles represent the projection of the ISS orbit, the dotted lines show the recorder field of view, and the dash-dotted line is the orbit of the Demeter satellite.

Fig. 2. Anomalous glow – the time sequence of 6 photos (from 18:00UT).

A bright local glow (Fig. 2) was recorded at an estimated distance of 100-300 km north of the heating facility (with the lower aurora edge at a height of 100-150 km). Note that the glow coincided with the magnetic burst “b” (Fig. 3, left panel) and was apparently due to the injection of electrons to the magnetic tube by the double layer, which developed at the explosive stage of the substorm triggered by the heater operation. The size of the glow was about 200-250 km in longitude. The experiment started under quiet geomagnetic conditions. A weak magnetic disturbance (Fig.3, left panel) that could be interpreted as a substorm began in the course of the experiment. Below, we provide evidence that this natural phenomenon might have been stimulated by the work of the Sura heating facility.

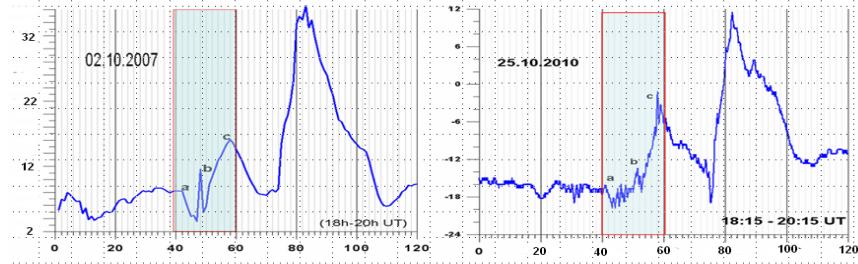


Fig 3. An anomalous variations in the geomagnetic field recorded by the IZMIRAN magnetic observatory.

The event recorded during the heating experiment of 02 October 2007 (Fig.3, left panel) shows the geomagnetic variations recorded during two hours from 18:00 UT by the Karpogory magnetic observatory located closest to the Sura heating facility north of it, virtually in the geomagnetic meridian plane (see Fig. 1). During the heating, a positive magnetic burst **b** (Fig. 3) with the amplitude of 7-8 nT was recorded in the horizontal component. It occurred in the pause between the 4th and 5th heating pulses. The duration of the event was tens of seconds. A comparison with the Intermagnet network data revealed its global nature. At all network stations (even those located in the auroral zone), the amplitude of this pulse did not exceed 2-3 nT. This is a direct indication that the burst of the ionospheric current responsible for this magnetic impulse was localized in the Karpogory area (by some evidence, south of the station in the direction of the Sura facility). This impulse was followed by a magnetic disturbance lasting for about an hour and possessing typical features of a microsubstorm. Thus, there is every reason to believe that in the period 18:40 – 19:00 UT and after the injection of powerful HF radio pulses from the Sura facility (in the vicinity of generation region of the western branch of the substorm current wedge), the metastable state of the magnetosphere was violated. The onset of a microsubstorm coincided with the appearance of a bright local glow recorded on board the ISS in the modified ionospheric zone.

The event recorded during the heating experiment of 25 October 2010 (Fig.3, right panel) can also be classified, by all indications, as a microsubstorm of duration 1-1.5 hours. One can readily note the similarity of

characteristic variations in the geomagnetic field horizontal component in both cases (see points a, b, and c in Fig. 3): a decrease after the 1st heating pulse, a burst in the vicinity of the 5th and 6th pump wave pulses, then, a positive bay whose maximum lasted until the end of the heating session, and, finally, the main bay with amplitude of about 30 nT. Besides the similarity of variations, both events were virtually equal in duration (a little more than an hour). The subsequent analysis of magnetograms from the Karpogory station for several years did not reveal such a combination of geomagnetic variations. This is an additional argument for artificial origin of the microsubstorms recorded during active experiments with the Sura heating facility.

3. Discussion and Radio Tracing of the Sura HF emission

In 2007, the experiment was performed simultaneously with the passage of the Demeter satellite (see the its orbit projection in Fig. 1). Fig. 4 represents the results of Demeter measurements (at an altitude of ~660 km) obtained during the experiment of 2 October 2007, when the satellite was passing between Moscow and Sura location at the shortest distance of ~ 400 km west of the latter.

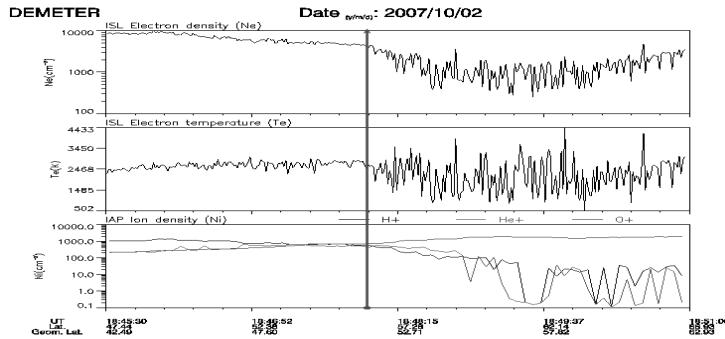


Fig. 4. Density and temperature of the ionospheric plasma as measured with the Demeter equipment.

The upper and middle panels in Fig. 4 illustrate the behavior of the plasma electron density and temperature along the satellite orbit. The lower panel shows variations in the plasma ion composition. The time when the satellite crossed the Sura latitude (i.e., when the distance between the satellite and the center of the magnetic flux tube disturbed by plasma heating was minimal) is marked with an arrow across all panels. To judge from a sharp decrease in plasma density recorded as the satellite crossed the latitude of 56° and the signatures of strongly non-stationary distribution of the plasma electron density and temperature (middle panel), it is obvious that the plasmasphere boundary was precisely at that place, i.e., much further to the south of its usual position. The qualitative transition to the plasma turbulence zone is corroborated by the ion temperature measurements on board the Demeter satellite. Also the density of heavy oxygen ions and the high-energy (up to 100 keV) electron component began to increase dramatically in this zone.

Oxygen ions become predominant (see Fig. 4, lower panel), which fact indicates that the satellite entered the zone of a longitudinal current flowing out of the ionosphere. The plasma instability in the same region is corroborated by the ionospheric radio-wave scattering of F2-spread type detected at the latitude of the heating facility by the network of ionosphere stations in the longitudinal sector, at least, from Kaliningrad to Kazan. This is additional evidence [4] that a field-aligned current had been present in this vast region before the experiment started.

Measurements on board the Demeter satellite revealed a large gradient of the ionospheric plasma density along the orbit at a distance of 100-150 km from the heating facility as the satellite moving north crossed the latitude of the latter. One can readily see that the drop of plasma density (in other words, the decrease of plasma frequency) occurred in the latitude range of 56°-58°. Qualitative and quantitative variations in ionospheric parameters at the heater latitude at the height of the Demeter orbit, such as a fast decrease in plasma density (Ne) and lower hybrid resonance (LHR) frequency, electron density and temperature disturbances, and predominance of heavy ions in plasma suggest that the satellite might have crossed the plasmasphere boundary north of the Sura location. This is important to further interpretation of the possibility of triggering substorm activity through the action of the Sura facility.

According to the ionograms obtained in the heating facility zone and characterizing the situation in the ionosphere in the period of the experiment, the critical frequencies of the main ionospheric layers were lower than the heater working frequency. The modification of the ionosphere in the Sura emission zone could be of transmission type, i.e., the ionosphere could be modified by a transmitted powerful radio wave within the Sura antenna beam ($12^\circ \times 36^\circ$). Ionospheric plasma electrons had to be heated [5] in the volume irradiated by the facility emission at altitudes from 100 km and higher. However, the anomalous glow recorded on board the ISS and the observed substorm activity evidently do not coincide with the heater location being displaced by hundreds of kilometers north of it. The position of the plasmapause north of the facility detected by Demeter

observations during the experiment, certainly, facilitates the interpretation, since the plasma at the plasmaspheric boundary is unstable, which is favorable for triggering processes by external action. Based on the experiment conditions, let us try and explain how the emission from the Sura heating facility could result in the auroral activity observed north of its location. It is known that inhomogeneity of the ionosphere in horizontal direction affects radio propagation substantially. The critical frequency gradients are maximal in the morning hours, when they reach 0.4 MHz per 100 km, and increase with increasing solar activity. In a horizontally inhomogeneous ionosphere, the symmetry of the trajectory of HF radio waves is disturbed and their group delay time, jump distance, and maximum usable frequency (MUF) change.

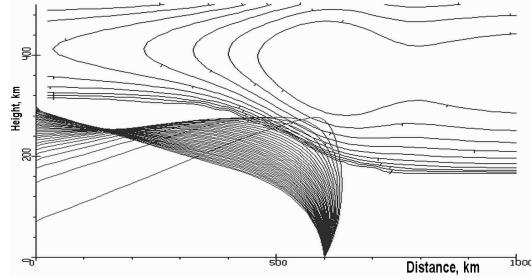


Fig. 5. The radio tracing for the experiment of 2007 (north is on the left) were performed for $Ne = 5 \cdot 10^3 \text{ cm}^{-3}$ ($h=660 \text{ km}$ – Demeter); $f_0F2=3.8 \text{ MHz}$; $h_m=280 \text{ km}$; $f_{SURA}=4.3 \text{ MHz}$; $\text{FOV}=(36^\circ * 12^\circ)$.

We analyzed the ray radio tracing using the Demeter and GPS satellite measurements and ground-based radio sounding data. The analysis showed (Fig. 5) that the density decrease (critical frequency and MUF gradient) north of the heating facility created favorable conditions for redistribution and refocusing of the emitted powerful HF beam due to refraction. In this case, the ionosphere region irradiated by the Sura facility could extend (in the meridional plane) as far as the latitudes of 60–62°. This, apparently, resulted in noticeable interference of the Sura HF radio emission in subauroral processes. Note that focusing at altitudes of ~240–280 km occurs north of the Sura facility, at a distance of ~300–340 km and can redistribute (destabilize) a field-aligned current [4] flowing out of the ionosphere. Under such conditions in the ionosphere-magnetosphere system, the inclination of the main ionosphere layer, F2, favors the redirection northward and nearly horizontal propagation of the heating emission and its possible focusing at a distance of hundreds of kilometers from the heater. These results show that the ground-based service systems that employ powerful HF transmitters may, under certain conditions, trigger a substorm – an energetic phenomenon in the magnetosphere-ionosphere circuit, which results in high-energy particle precipitations, auroral glows, and noticeable variations in the ionospheric parameters.

4. Conclusion

Two active experiments on modification of the ionosphere by the Sura heating emission supported by ground-based and space-borne diagnostic facilities (magnetic observatories, ISS, Demeter satellite, etc.) revealed highly similar active events of substorm type stimulated by the heater operation. The propagation and geometry of irradiation of the ionosphere were simulated taking into account the real parameters of the medium and radio wave beam. It was shown that the main condition for triggering the activity was such a state of the ionosphere over the heater that allowed redistribution and focusing of radio emission north of the facility at altitudes of 200–300 km and, as a result, ensured the intrusion of a powerful beam into the ionospheric subauroral region. This could violate the metastable state of the ionosphere-magnetosphere system and cause a substorm with the corresponding variations in the magnetic field and a bright local glow (precipitations and artificial aurora).

We are grateful to Prof. M.Parro for the Demeter satellite data and to Dr. Kh.Kanonidi for the magnetic data.

5. References

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