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VARIATIONS IN THE MICROWAVE RADIATION OF THE MESOPHERE DURING HEATING OF THE IONOSPHERE WITH HIGH-POWER RADIO WAVES

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We present the results of microwave observations of ozone radiation in the middle atmosphere during modification of the ionosphere by high-power short radio waves on March 27–28, 2011. The modification was performed on the "Sura" heating facility of the Radiophysical Research Institute (Nizhny Novgorod, Russia) by using two ozone meters oriented towards different regions in the sky. The effect of a decrease in the radiation intensity in the ozone line when the ionosphere is heated with high-power short-wave radio emission, which was discovered earlier, has been confirmed, and new data related to its characteristic have been obtained. A possible interpretation of this phenomenon is discussed.

1. INTRODUCTION

The mesosphere of the Earth at altitudes of 50–90 km is still the least studied part of the middle atmosphere. Its ionization is rather weak and exists only in the daytime. The ionization is determined by cosmic rays of the galactic and solar origin, the highest-energy part of the solar X-ray spectrum, radiation of the intense Ly_α line of the Sun, etc. (different ionization sources are most efficient at different altitudes in the atmosphere) [1]. The weakly ionized plasma in this region has a complicated ion composition, which includes both positive and negative ions, as well as cluster ions formed as a result of complicated processes of ionization, exchange, and recombination of ions [1–3].

Allowing for the complexity of the related physical processes, the range of applicable methods of studying the mesosphere is limited. Regular observations usually employ the cross-modulation method [4–6], method of partial reflections [7–9], radar sounding of the mesosphere, stratosphere, and troposphere [10], as well as sporadic launches of geophysical rockets [11]. Recently, the method of studying mesosphere by using artificial periodic plasma irregularities [12, 13] has been applied. However, these methods are not used in combination, and each of them taken separately does not yield a sufficient set of parameters, which are required to determine the essence of the processes of formation and evolution of the mesosphere. Specifically, an important problem, which is still unsolved, is that of describing the interaction of the lower ionosphere with the ozone layer of the Earth at the mesosphere altitudes.

Characteristics of the uncharged components of the mesosphere, i.e., types of minor admixtures, temperature of neutral particles, etc., are studied successfully both by the methods of contact measurements which employ balloons and rockets, and by ground-based and airborne remote methods [14–16]. One can also study the dynamic structure of the mesosphere by the method of ground-based microwave radiometry (via measurements of radiation intensity in the ozone line), which has a high spatio-temporal resolution. The microwave method has recommended itself especially well in measurements of the middle atmosphere in the presence of various natural perturbations, namely, first of all, stratospheric warming [17], solar eclipses [18],

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and terminator waves, which are formed during the sunrise and the sunset [19]. All of them affect the vertical profile of ozone density.

In the recent decades, along with the studies of the influence of natural factors on the status of the mesosphere (lower ionosphere), the effects of artificial modification of the ionosphere with high-power short-wave RF radiation, which is generated by special heating facilities, have been studied intensely. This allows one to perform measurements with repeatable and controllable properties of the formed perturbations. The first experiments with the influence of high-power short-wave RF radiation on the neutral component (ozone) of the mesosphere started on the "Sura" facility in 2008. They revealed a 10% decrease in the intensity of microwave radiation in the line of the atmospheric ozone at a frequency of 110836.04 MHz during a modification of the lower ionosphere of the Earth in the latitude range from 50 to 110 km by high-power short radio waves [20, 21]. Based on obtained experimental data, the authors of [21] assumed that the mesospheric ozone contents can be affected by the internal gravity waves generated in the *E* region of the ionosphere during its periodic heating by a high-power microwave.

Section 2 of this paper presents the results of microwave observations of the middle-atmosphere ozone during ionosphere modification, which were performed on March 17–28, 2011 on the "Sura" heating facility (Radiophysical Research Institute, Nizhny Novgorod, Russia) located near the town of Vasilsursk in Nizhny Novgorod Oblast (Russia). The distinctive feature of these observations was the use of two microwave ozone meters oriented at different zenith angles. Section 3 proposes a theoretical model to explain physical properties of the observed phenomenon.

2. DESCRIPTION OF THE EXPERIMENT AND THE OBTAINED RESULTS

The experimental procedure was as follows. The "Sura" facility emitted a beam of high-power radio waves with extraordinary polarization (X-mode waves) at a frequency of 4.3 MHz at an angle of 12° south of the zenith. The thermal radiation of the middle atmosphere at a frequency of 110836.04 MHz was received by two identical mobile microwave ozone meters [22, 23]. Each device consisted of a heterodyne receiver tuned to a frequency of 110836.04 MHz, which corresponds to the rotational transition of the ozone molecule ($6_{0.6}$—$6_{1.5}$), and a multi-channel spectrum analyzer. The receiver input was equipped with a module which includes an antenna (scalar horn) and a switching unit for calibration of the level of the radiation received from the atmosphere. The width of the radiation pattern of the horn antenna at a level of −3 dB was equal to 5.4°. The single-band noise temperature of the receiver was equal to about 2500 K. The spectrometer consisted of 32 filters with the transmission band from 1 to 10 MHz and a full analysis band of 240 MHz.

The parameters of the device allow one to measure the spectrum of the ozone radiation line for 15 minutes with an accuracy of about 2%. Basing on the measured spectrum and using a specially developed method [24], one can obtain information about the vertical distribution of ozone at altitudes from 22 to 60 km. The spectra of the thermal radiation of the atmosphere were measured by the calibration method using two "black-body" reference standards, one of which had a temperature of liquid-nitrogen boiling, and the other, the temperature of the surrounding air. The radiation pattern of the antenna of one of the ozone meters was oriented along the radiation direction of the "Sura" facility antenna. The radiation pattern of the second ozone meter was directed southward at a zenith angle of 70°. It should be noted that at a typical level of the tropospheric absorption being 0.30–0.35 Np, the sounding angle 70° is optimal from the viewpoint of the maximum signal-to-noise ratio.

The lower ionosphere was heated on March 27, 2011 from 12:02 till 14:32 MSK and on March 28, 2011 from 12:00 till 15:30 MSK in the 30-min radiation/30-min pause regime. The choice of the facility operation regime was determined by the temporal resolution of the microwave ozone meter. It was chosen such as to obtain two spectra of the atmosphere ozone line during each heating or pause period, which allowed us, when required, to average the measurement results later to reduce the statistical error. The measurements were performed 24 hours a day, which made it possible to trace also diurnal variations in the microwave radiation, which are well known and can be used to confirm the operability of the ozone meters during active experiments.

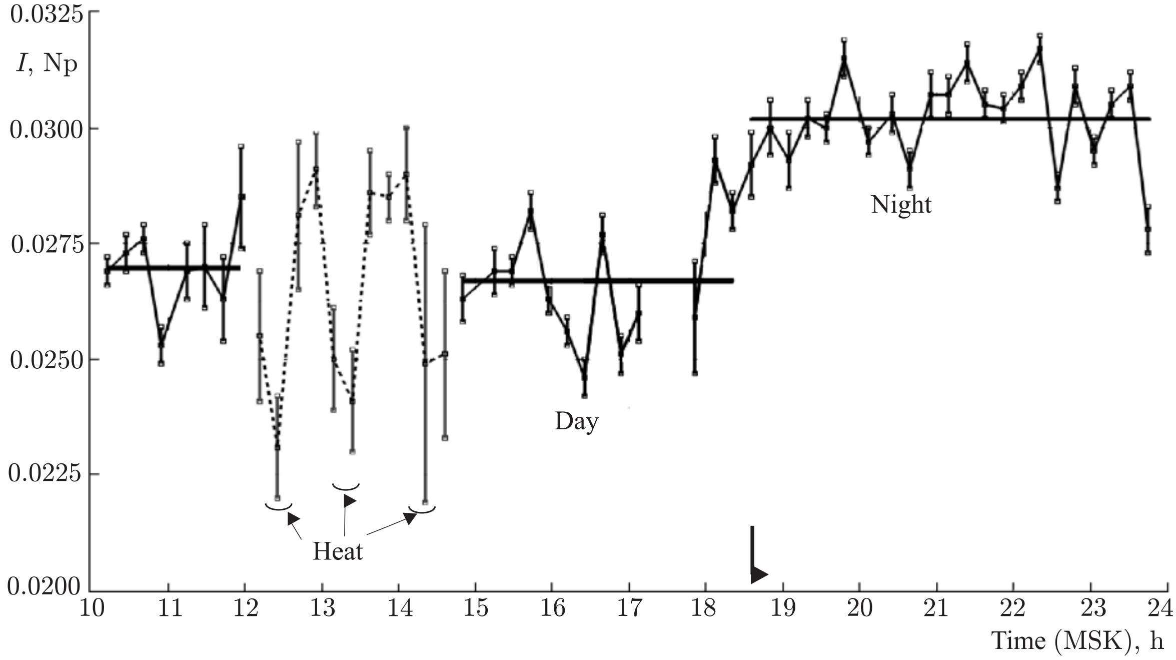

Fig. 1. Temporal variations in the intensity of the ozone line at a resonance frequency of 110.836 GHz for the observations of March 27, 2011 at the zenith angle 70°. The microwave measurements were performed during the ionosphere modification by a high-power radio wave with the extraordinary polarization at the frequency $f_{\rm PW} = 4.3$ MHz with the power $P_{\rm eff} = 40$ MW.

On March 27, 2011, two of the three facility modules were operated. The measurements were performed at the pump-wave power $P_{\rm eff} = 40$ MW. During the ionosphere heating by high-power radio waves, the intensity of the thermal radiation of the atmosphere in the ozone line reduced by 9% on the average, which was detected by the receiver, whose antenna was directed southward at a zenith angle of 70°. Figure 1 shows variations in the radiation intensity in the ozone line during the entire period of observations on March 27, 2011. Each plot point corresponds to the spectral-line intensity accumulated for 15 min. The variance for each measurement is also shown in the figure. Thick black lines represent the average intensity values basing on the daytime measurements before and after the heating series, as well as the average intensity value basing on the measurements after the Sun's setting below the horizon at 18:35 MSK (marked with an arrow). The dashed lines mark variations in the intensity of microwaves during the heating-experiment cycle, within which the periods of the pumping-wave radiation are marked with the brackets in the plot.

One can see from the presented plot that the switch-on of a high-power radio wave resulted in a decrease in the intensity of the received radiation in the ozone line and an increase in the variance. Here, the 9% decrease in the radiation intensity is counted relative to the ozone-line intensity, which was measured during the periods when the facility transmitter was not operated. It should be noted that the radiation intensity during pauses between the heating sessions exceeded the average daily level by 4%, on the average, for no explicable reason. Allowing for the above-said, the average radiation intensity during the heating was by 5% lower than the daytime intensity level.

The increase in the variance during the measurements of the radiation intensity, when the "Sura" facility was operated and during a pause between the heating cycles, can be considered evidence for a sufficiently long aftereffect of the facility radiation on the status of the mesosphere. The fact that no increase in the intensity of microwaves during pauses between the heating sessions was observed in the case of vertical modification [21] can be produced in favor of the time lag of the radiation variation during oblique modifications of the ionosphere. The experiment was performed on March 14–17, 2009, and the antenna of the mobile microwave ozone meter was directed towards the radiation of high-power microwaves.

All the above-said facts demonstrate the complexity of the physical processes in the modified region

TABLE 1

Times of measurement sessions, March 27, 2011 MSK	Density of O_3 at an altitude of 60 km, cm^{-3}	Conditions
12:02–12:32, 13:02–13:32, 14:02–14:32	$(4.81 \pm 0.24) \cdot 10^9$	Heating
09:20–12:00; 15:05–18:10	$(5.86 \pm 0.29) \cdot 10^9$	Daytime
22:00–02:00	$(9.78 \pm 0.49) \cdot 10^9$	Nighttime

of the ionosphere and show that the perturbations propagate to more than 150 km from the center of the radiation pattern of the "Sura" facility antenna.

Analysis of the shape of the ozone line spectrum showed that heating of the ionosphere leads to a notable decrease in the radiation intensity in the ozone line at the detuning $|\Delta f| \leq 40$ MHz relative to the center frequency of the line, and that the less the detuning, the stronger is the decrease in the intensity. Note that it is the mesospheric ozone at altitudes from 50 to 90 km, i.e., at the altitudes of the D region of the modified ionosphere, this makes the greatest contribution to this part of the spectral line.

The measured spectra were used to evaluate the vertical profile of the ozone density using the method described in [24]. It showed that if one reduces all the variations in the ozone content in the mesosphere to the variation at an altitude of 60 km, then the average decrease in the radiation intensity during the heating of the lower ionosphere can be related to the decrease in the mesospheric ozone content at this altitude by 18% on the average compared with the average daytime value. Based on the evaluations made, Table 1 presents the calculated results for the ozone density at an altitude of 60 km in all the measurement sessions performed during the heating on March 27, 2011, as well as for the daytime and nighttime conditions without heating. The measurements were made by the receiver whose antenna was directed southward at a zenith angle of 70°.

On March 27, 2011, the receiver with the antenna directed southward at the zenith angle 12° measured a decrease in the radiation intensity, which was equal to approximately 4% of the average daytime level of the microwave intensity. One can see that its value is close to the value obtained in the measurements with the zenith angle 70° at the same heating power.

On March 28, 2011, all three facility modules were heating the atmosphere, and the effective power of the pump wave was equal to 80 MW. On this day, thermal radiation of the atmosphere was measured only by means of the ozone meter directed into the modified region of the atmosphere (the second device was not operating due to technical reasons). For a pump-wave power of 80 MW and other identical experimental conditions, a decrease in the radiation intensity in the ozone line by approximately 8% was observed in three heating sessions. Therefore, in the range of pump-wave powers $P_{\text{eff}} = 40$–80 MW, the amplitude of the decrease in the radiation intensity increases approximately in direct proportion to P_{eff}.

3. THEORETICAL INTERPRETATION OF THE OBSERVED PHENOMENON

Basing on the results of the above-considered experiments, one can conclude that they reveal the influence of the heating of the ionosphere by a high-power radio wave on the neutral component of the mesosphere (ozone, in our case). Since the ionization degree is very low in the mesosphere environment, one can neglect the energy transfer through the ionized component (i.e., via electron heating in the field of the high-power radio wave). In [21], it was assumed that the observed effect can result from the influence of the internal gravity wave excited during periodic heating of the dynamo region of the ionosphere at altitudes of about 110 km.

It is important to note that formation of large-scale disturbances of the neutral component of the atmospheric gas (traveling ionospheric disturbances), which are typical of internal gravity waves, was detected as a result of cyclic operation of high-power short-wave radio transmitters in the ionosphere. Recently, the traveling ionospheric disturbances generated during the operation of the "Sura" facility have been detected regularly at a distance of 800 km, near Kharkov (Ukraine), where they were identified as internal gravity waves. One should also note that during cyclic operation of the “HIPAS” heating facility (Alaska, USA) at a frequency of 2.85 MHz with an effective power of 80 MW, oscillations of the atmospheric pressure with a period of 10 min were detected in the troposphere of the Earth [30].

In the literature, the mechanisms of excitation of acoustic-gravity waves were discussed, and the efficiency of these mechanisms for operation of high-power radio transmitters was evaluated [31, 32]. Based on [31, 32], we will compare the theoretical results with the observation data.

First, let us present briefly the basic spatial characteristics of the internal gravity waves produced by harmonic sources in the isothermal atmosphere [33]. It is known that perturbations of the medium velocity increase in the spatial region above the source, whereas the perturbations of the pressure and density increase in the region below the source. The rates of these changes for the above-specified parameters are identical and depend on the altitude z as $\exp[(z - z_0)/(2H)]$, where z_0 us the altitude of the source and H is the height of the uniform atmosphere. Therefore, if one aims at detecting the effects related to variations in the density or pressure ($\Delta\rho$ and Δp, respectively), measurements should be made in the spatial regions below the source, whereas the Doppler effect related to the motion of the medium should be detected at the altitudes above the source. It is also evident that for the isothermal model of the atmospheric gas, whose pressure and density change obeying the barometric law, within which the unperturbed density $\rho_0(z)$ increases faster, as the altitude decreases, than the deviation $\Delta\rho(z)$, the amplitude of the ratio $\Delta\rho/\rho_0$ in wave perturbations decrease with decreasing altitude z.

It is natural to assume within the adopted model of the atmosphere that similar dependences of the altitude z are also retained for the characteristics of minor admixtures $\Delta\rho_{\mathrm{A}}(z)$ and $\Delta\rho_{\mathrm{A}}(z)/\rho_{0\mathrm{A}}(z)$. However, it should be noted that this is valid only in the case where the distribution $\rho_{0\mathrm{A}}(z)$ of the admixtures over altitudes corresponds to the distribution profile $\rho_0(z)$ of the main component. However, according to the data of various authors (see, e.g., [34]), the distribution of the unperturbed ozone density over altitudes differ strongly from the barometric law and can be represented as individual layers. In such a situation, the altitude dependence of the relative variation $\Delta I/I_0$ in the microwave intensity can differ noticeably from the behavior of the parameter $\Delta\rho/\rho_0$ in the gravity wave. In this case, if the variations in the ozone intensity $\Delta I \propto \Delta\rho_{\mathrm{A}}$ increase and $\rho_{0\mathrm{A}}$ decrease as the altitude decreases in the region below the source, then the relative value $\Delta I/I_0$ can remain unchanged or even increase in the specified direction, rather than decrease.

The second factor which should be taken into account is the resonance character of radiation of harmonic sources in the isothermal atmosphere. For example (see, e.g., [32]), the internal gravity waves, which are emitted by a pulsing source at a frequency of ω, propagate in the angle range $\theta_0 \leq \theta \leq \pi - \theta_0$, $0 \leq \varphi \leq 2\pi$. Here, θ and φ are the polar and azimuthal angles in the spherical system of coordinates, respectively, the angle θ is reckoned from the vertical z, and $\theta_0 = \arccos(\omega/\omega_g)$, where ω_g is the Brunt–Väisälä frequency. In this case, the perturbation amplification in the resonance direction θ_0 compared with the direction $\theta = 90^\circ$ can reach $\Delta\rho(\theta = \theta_0)/\Delta\rho(\theta = 90^\circ) = 10$.

Under the conditions of our experiments, the ozone-line intensity of the microwave radiation received on the Earth's surface is the integral characteristic $I \propto \int_{z_1}^{z_2} N(z)\,\mathrm{d}z$, where N is the density of the radiating particles, and $z_2 - z_1$ is the range of the altitudes at which the received radiation originates. Under the equilibrium conditions, $I_0 \propto \int N_0\,\mathrm{d}z$, whereas in the presence of perturbations, $I_1 \propto \int N_1\,\mathrm{d}z$ (here, the subscript 1 denotes minor deviations of the values from their equilibrium values under the effect of an internal gravity wave). One can easily evaluate the relative change $\delta I = I_1/I_0$ for the vertical distribution of the ozone density $N(z)$ with two maxima: one distribution is specified as a parabolic curve (the altitude of the maximum being 25 km), and the other, as a Gaussian layer with the characteristic width L and the maximum altitude $z_{\mathrm{m}} \approx 85$ km. Without going into the details of the calculations, we will present the results of estimating possible changes δI at the following values of the parameters: $L = H = 10$ km, $\omega = 3 \cdot 10^{-3}$ s^{-1}, $z_0 - z_{\mathrm{m}} = 60$ km, and $V_0 = 3$ m/s, where H is the height of the uniform atmosphere, ω is the frequency of the gravity wave, and V_0 is the velocity amplitude of the internal gravity wave at the source level z_0.

It turned out that for the two adopted layer models, relative changes in the ozone radiation intensity can range from one percent to several percent. This completely corresponds to the results of the measurements, which were obtained in [21] and the experiments described in this work, thus confirming the conclusion that a possible reason for the changes in the microwave intensity in the ozone line can be internal gravity waves generated during periodical heating of the dynamo range in the ionosphere by high-power radio waves. This also explains the observed variations in the radiation intensity at distances over 150 km from the "Sura" facility.

It is clear that the estimations made are approximate. They can be refined by specifying the shape and spatial position of the radiating layers with greater accuracy, as well as by determining the actual position of the electrojet. However, this goes beyond the scope of this paper and will be considered in a separate publication with allowance for the results of the experiments which are planned in what follows. Moreover, a drawback of the above-described considerations is the fact that the effects observed by us take place in the near zone of the antenna field of the "Sura" facility. Therefore, the effect of the ponderomotive force induced by the "Sura" facility can differ from the case of the harmonic wave considered in [32] already beyond the limits of the near field of the antenna.

If the model proposed above is valid, then, since the natural background of internal gravity waves is always present at the stratospheric and mesospheric altitudes, it should also manifest itself in the measurements of microwave intensity in the ozone line in the absence of ionosphere modifications by high-power radio waves. Indeed, in [19, 35] during the passage through the solar terminator, when intense internal gravity waves are excited, changes in the ozone content at the stratospheric and mesospheric altitudes were detected. Specifically, at the stratospheric altitudes, these changes reached 100% and were significantly less (up to 10%) at the mesospheric altitudes.

Note that our measurements were fulfilled under very quiet geomagnetic conditions (the total $K_{\rm p}$ index was $\Sigma K_{\rm p} = 4$–5) beyond the time interval of the terminator influence and, hence, at a low natural background level of internal gravity waves. One can assume that the variations in the intensity of the received radiation with periods up to 30–60 min and an amplitude of 2–5% of the average level of microwave radiation, which can be seen in Fig. 1 and go beyond the level of measurement errors, are manifestations of the influence of natural internal gravity waves on the results of our measurements. Periods of 30–60 min are usually observed periods for natural middle-scale internal gravity waves. Moreover, according to [31], responses of the ionospheric plasma on the motion of the solar terminator and the periodic heating of the plasma by high-power short-wave RF radiation are comparable in terms of their magnitude, which is actually what follows from our measurements at the mesospheric altitudes.

4. CONCLUSIONS

Let us briefly formulate the results obtained in this work.

(i) As a result of the experiment on artificial modification of the lower ionosphere by high-power short-wave RF radiation, which was performed on March 27–28, 2011, the new physical phenomenon discovered in [21] was confirmed, namely, the decrease in the microwave intensity in the ozone line.

(ii) It was found that this effect was observed not only in the modified region of the mesosphere directly, but also at a distance of 150–170 km south of this region.

(iii) It was ascertained that an increase in the power of the pump wave emitted by the heating facility led to a proportional increase in the attenuation of the radiation in the ozone line.

(iv) Based on [28], we propose a physical model for the effective power source generating internal gravity waves, which, according to the estimations in this work, can affect variations in the altitude distribution of the mesospheric-ozone content and, hence, the intensity of the received microwave radiation.

Validity of the proposed hypothesis for the influence of internal gravity waves generated during modification of the E layer of the ionosphere by high-power short-wave RF radiation admits a simple experimental verification. Up to now, we have made experiments mainly in the near-noon hours, when the highest-density E and D layers are observed, and a significant portion of the pump-wave energy is absorbed in these layers, thus heating the plasma in the lower ionosphere noticeably. Additionally, these experiments employed high-power X-modes as the most effective source of its Joule heating. Under these conditions, the above-proposed mechanism is most efficient. It is clear that its efficiency will decrease sharply during modifications of the ionosphere in the evening hours and, especially, in the nighttime. Therefore, in further experiments, we should make measurements in different times of the day and obtain the daily dependence of the variation in the microwave intensity in the ozone line, as well as compare the values of the increase in the intensity of this radiation for application of high-power waves with different polarizations. Such measurements with the "Sura" facility are scheduled for 2012.

It is also important to obtain results of direct measurements of the electron temperature variations in the lower ionosphere, which can be fulfilled, e.g., by the method of partial reflections. Such joint experiments started in August–September 2011, and the data obtained in them are being processed now. Implementation of the scheduled research program will allow obtaining new important data, which will be crutial for understanding the physical nature of the studied phenomenon.

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