rtificial ionization of the ionosphere by high-ower radio waves

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An increase was observed in the electron density of the lower ionosphere under the influence of high-power radio waves.

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The question of the possibility of changing the electron density N in the
iosphere by high-power radio waves is of considerable interest. A theoreti-
l analysis has pointed to the following mechanisms for changing N: ioniza-
n with fast electrons accelerated in the field of a high-power wave,[1,2]
ange of the recombination coefficient by heating the electrons, and isothermal
ization resulting from overall heating of the gas.[3]

Prolonged experimental investigations of the perturbation of the ionization
the ionosphere by a high-power radio wave were carried out in 1963–1967
the ionsphere sounding method.[4] They have revealed a slight increase
–5%) of the critical frequencies of the E_s layer (height $z \sim 130$ km), due ap-
rently to the corresponding increase of the electron density. In this paper we
ort observation, by the method of periodic cross modulation, of an appre-
ble increase of the ionization in the lower ionosphere at heights $z \sim 70$–90
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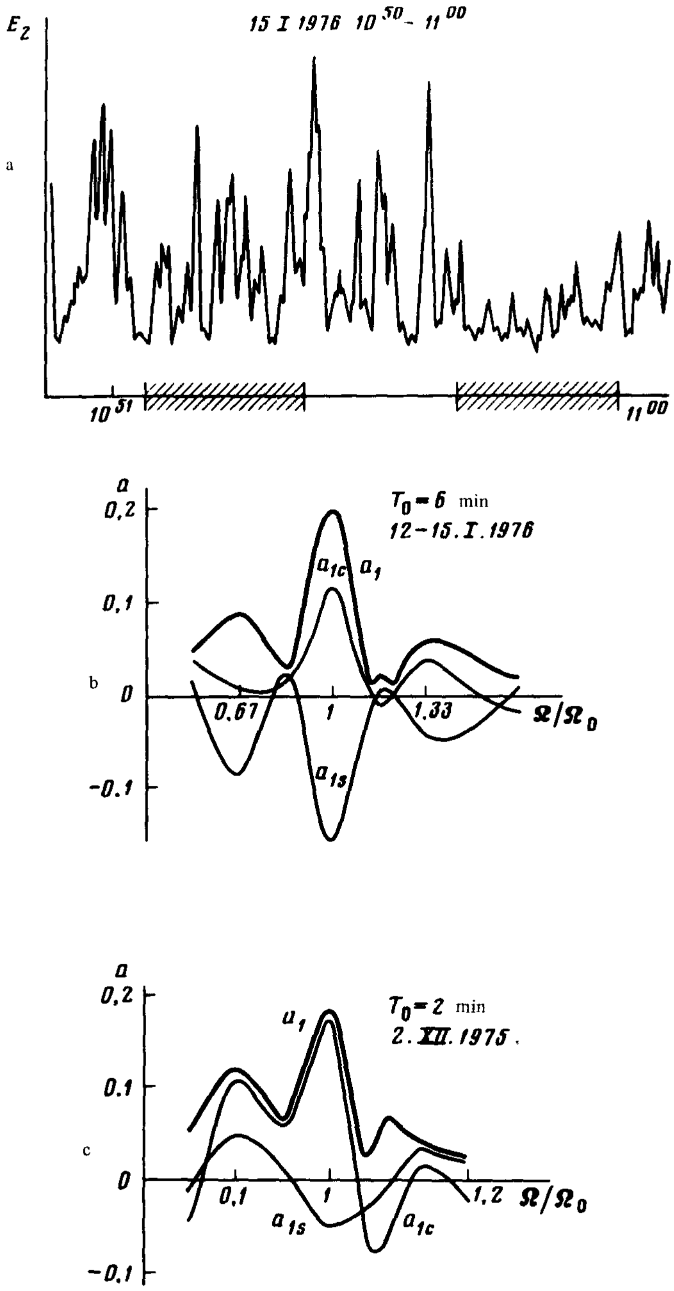

The ionosphere perturbations were produced by a high-power pulse transmitter radiating a radio wave E_1 of frequency $f_1 = 1.35$ MHz vertically upward. The pulses were rectangular and of duration $\Delta t_1 \approx 0.5$ msec. The pulse repitition frequency was 50 sec^{-1}. To observe the state of the ionosphere, we used a second transmitter of pulses E_2 on the order of 100 μ sec with carrier frequency $f_2 = 1.6-1.8$ MHz. The apparatus employed was described in detail in[4,5].

Under the influence of the high-power pulse, the electron temperature in the lower ionosphere, at heights 70—90 km, increases abruptly by 20—40 times.[4,6] After 1-5 msec, however, the temperature relaxes to the unperturbed value. If the pulse E_2 is emitted simultaneously (or almost simultaneously) with the pulse E_1, then the perturbations of T_e influence strongly the pulse E_2. This phenomenon—cross modulation of the pulses—has been well studied (see, e.g., [4]). With increasing $t_2 - t_1$ (the delay time of the pulse E_2 relative to E_1), the cross modulation weakens, becoming practically unnoticeable at $t_2 - t_1 \gtrsim 5$ msec. In our case the pulse E_2 was emitted 15 msec after the pulse E_1, thereby completely excluding effects of ordinary cross modulation.

The change of the electron density could also affect the amplitude of the pulse E_2. It is characterized by the electron lifetime τ_N, which is appreciable in the lower ionosphere—on the order of 10^2 sec. However, the ionosphere is very unstable and fluctuates strongly within a time on the order of τ_N, thereby leading to corresponding fluctuations of the amplitude of the wave E_2. It is this which makes it difficult to observe the ionization effect. The following observation method was used: The perturbing station was periodically turned on and turned off for a long time (1—3 h) at a constant period T_0 equal to 2—6 min. The observed pattern of time variation of the amplitude of the wave field E_2 (a typical plot of the E_2 signal is shown in Fig. 1(a), with the segments of time during which the perturbing field was turned on shown shaded) differed outwardly little from the picture usually obtained in the absence of the perturbation. However, when expanded in a Fourier integral with respect to time, the periodic perurbation with a given period T_0 was always clearly distinguishable [Figs. 1(b) and 1(c)]. Cross modulation of the E_2 wave appears, as it were, at the infraow frequency $\Omega_0 = 2\pi/T_0$. It is important that an appreciable phase shift between he oscillations of the amplitude of the perturbing field E_1 and the amplitude of the wave E_2 is always observed here. This means that the cross-modulation process is characterized by a prolonged relaxation time $\tau \sim T_0 \sim 10^2$ sec. It can be caused therefore only by changes of the electron density in the ionosphere.$^{1)}$

For a quantitative estimate of the observed effect, we consider the ionization balance in the ionosphere

$$dN/dt = q - \alpha N^2. \tag{1}$$

Here q is the external radiation source and α is the effective recombination coefficient. Under the influence of a perturbing field turned on and off periodically with frequency Ω_0 ($E_1 = E_{10} + E_{11}\sin\Omega_0 t + \cdots$), the dissociative recombination coefficient decreases[3] and the ionization is enhanced[1,2]

$$\alpha = \alpha_0 - \alpha_1 \sin\Omega_0 t + \dots, \quad q = q_0 + q_1 \sin\Omega_0 t + \dots, \quad \Omega_0 = 2\pi/T_0. \tag{2}$$

Substituting (2) in (1) we obtain the periodic perturbation of the concentration n the form

$$N = N_0 + N_{1s}\sin\Omega_0 t + N_{1c}\cos\Omega_0 t + \dots = N_0 + N_1 \sin(\Omega_0 t - \phi) + \dots$$

$$-\frac{N_{1c}}{N_{1s}} = \mathrm{tg}\,\phi = \Omega_0 \tau_N, \quad \sqrt{N_{1c}^2 + N_{1s}^2} = \frac{N_0}{\sqrt{1 + \Omega_0^2 \tau_N^2}} \left(\frac{2\alpha_1}{\alpha_0} + \frac{q_1 \tau_N}{N_0} \right). \tag{3}$$

Here $\tau_N = (2\alpha_0 N_0)^{-1}$ is the electron lifetime. Taking into account, finally, the influence of the density perturbations on the amplitude of the wave E_2, we have

$$E_2 = E_{20}(1 + a_{1s}\sin\Omega_0 T + a_{1c}\cos\Omega_0 t + \cdots)$$

$$a_{1s} = -2\frac{\omega_2}{c}\int\frac{N_{1s}}{N_0}\kappa_{20}dz, \quad a_{1c} = -2\frac{\omega_2}{c}\int\frac{N_{1c}}{N_0}\kappa_{20}dz. \tag{4}$$

Here κ_{20} is the absorption coefficient of the wave E_2.

The result of the measurement of the coefficients a_{1s}, a_{1c}, and $a_1 = \sqrt{a_{1s}^2 + a_{1c}^2}$ is shown in Figs. 1(b) and 1(c). From the phase of the periodic oscillations of the wave E_2 we can determine, in accordance with (3) and (4), the electron lifetime $\tau_N = -a_{1c}(\Omega_0)/a_{1s}(\Omega_0)\Omega_0$. In our experiments, $\tau_N \approx 40-70$ sec. The amplitude of the oscillations $a_1(\Omega_0)$ allows us to assess the magnitude of the ionization shift. In our case $a_1 \sim 0.2 + 0.3$. This means that the ionization shift in the perturbed zone is appreciable,

$$\frac{\Delta N}{N_0} = \frac{2N_1}{N_0}\sqrt{1+\Omega_0^2\tau_N^2} \sim 1.$$

The main mechanism of the change of the plasma concentration is in this case the ionization by fast electrons.

Investigations of the perturbed ionosphere by other methods, particularly by the method of partial reflections and by measuring the emission in the optical band will yield additional information on the artificial ionization of the ionosphere.

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1) The electron temperature relaxation time is smaller by 4—5 orders of magnitude.

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