Stimulated ionization of the upper ionosphere by an intense radio wave

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An artificial increase in the electron density has been observed in the ionospheric *F* layer. The increase is caused by an enhancement of the ionizing effectiveness of photoelectrons in an intense radio wave.

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There is considerable interest in artificial changes in the ionosphere. The usual effect of radio waves in the upper ionosphere, i.e., in the *F* layer, at altitudes $z\sim200$–300 km, is the development of a highly inhomogeneous structure, accompanied by a decrease in the plasma density as a result of the expulsion of plasma from the region heated by the radio wave.[1–4] In the present study we have observed the opposite effect: a significant increase in the electron density in the *F* layer, caused by an enhancement of the ionizing effectiveness of photoelectrons as a result of the intense radio wave.

The ionospheric perturbation was carried out from a transmitter of the Scientific-Research Institute of Radio, located near Moscow. The wave frequency was

$f_p = 4.8$ MHz, and the effective radiated power was $P_{\text{eff}} = 80$ MW. The emission was circularly polarized and corresponded to an ordinary wave. The perturbations caused in the ionosphere were studied with the Doppler radiosonde complex of the Institute of Terrestrial Magnetism, the Ionosphere, and Radio Wave Propagation. This complex could furnish high-resolution measurements of the pulse-height and spectral characteristics of the pulsed radio signals at four sonde frequencies simultaneously. The sonde transmitter was at the same site as the pump (or heating) transmitter, while the reception and recording complex was 18 km away. The trajectories of the sonde signals were thus essentially vertical. The experimental apparatus and procedure are described in more detail elsewhere.[5]

The experiments were carried out in morning hours in April 1981, under conditions such that the pump wave was reflected in the F layer, and there was no significant absorption lower in the ionosphere. Sonde waves at the frequencies $f_1 = 3.4$ MHz, $f_2 = 4.6$ MHz, $f_3 = 4.7$ MHz, and $f_4 = 4.9$ MHz were reflected below and above the altitude at which the intense pump wave was reflected. Figure 1a shows a typical altitude profile of the plasma frequency, $f_0(z)$, in the ionosphere during the experiment. The difference between the reflection altitudes of the sonde waves f_1 and f_4 is seen to be ~100 km.

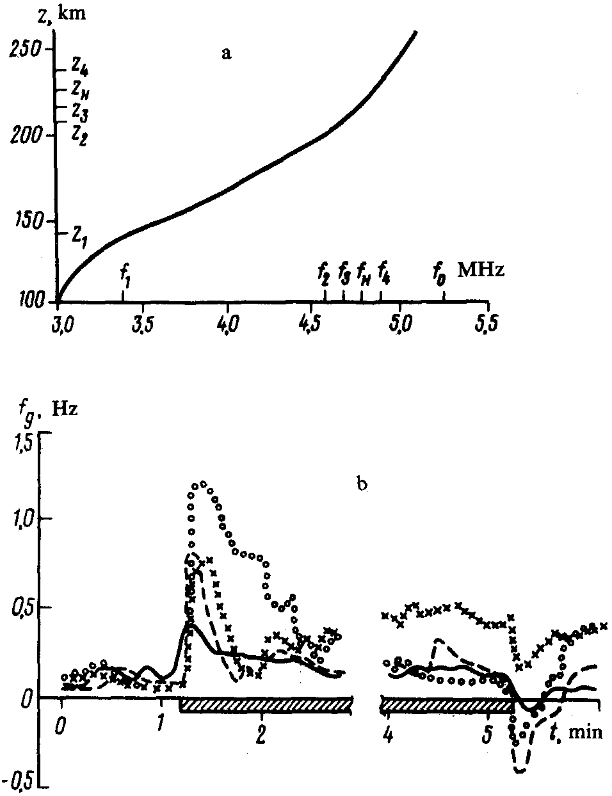

FIG. 1. a—Altitude profile of the plasma frequency $f_0(z)$ in the ionosphere at 0900 local time on 19 April 1981. $z_1 - z_4$, reflection levels of the sonde radio waves; z_p, reflection level of the intense pump wave; b—dynamics of the Doppler frequency shift of the sonde waves during the perturbation of the ionosphere by the intense pump wave. The hatching shows the time over which the pump transmitter operated. Solid curve, $f_1 = 3.4$ MHz; dashed curve, $f_2 = 4.6$ MHz; xxx, $f_3 = 4.7$ MHz; ..., $f_4 = 4.9$ MHz.

The results are illustrated in Fig. 1b, with the measurements taken on 19 April 1981. Essentially immediately after the pump transmitter is turned on, a substantial Doppler shift, of up to 1 Hz, appears in the frequencies of all of the sonde signals. This shift means that the reflection altitudes for the sonde waves moved downward at $v \sim 50$–100 m/s. A steady state is reached in about 1 min, so that the overall displacement of the ionospheric plasma is 3–6 km. Working from the actual ionospheric gradients, we conclude that this shift corresponds to a change of 2–10% in the electron density over the entire plasma layer from z_1 to z_4 (Fig. 1a). After the pump transmitter is turned off, the sonde signals exhibit a Doppler frequency shift of the opposite sign, corresponding to a relaxation of the plasma to its original state. This pattern was observed in essentially all transmitting sessions.

It is important to note that the sign of the Doppler shift in the sunlit part of the ionosphere is always positive during the perturbation. This positive shift corresponds to an increase in the electron density. In the unlit part of the ionosphere the Doppler shift is usually of the opposite sign, because of a density decrease caused by the expulsion of plasma upon its heating of the pump wave.

Let us examine the physical nature of the effect. In the F layer near the reflection point of the pump wave, there is an intense conversion of this wave into resonant plasma waves, which causes an anomalous absorption of wave energy.[1,2,6] An anomalous absorption of pump energy, of up to 70–90%, was regularly observed in these experiments. The plasma waves dissipate, transferring some of their energy to thermal electrons and some to fast electrons. The fast electrons are accelerated near the plasma resonance, which is 0.5–1.5 km below the pump reflection point.[6] The mechanisms for this process are direct Landau absorption and the nonlinear absorption associated with the formation of density wells or cavitons.[7] The energy of the plasma waves is transferred to electrons with an energy $\mathscr{E}$ an order of magnitude or greater than T_e. For our experimental conditions, we estimate the energy acquired by the fast electrons in the plasma-resonance region to be

$$\Delta \mathscr{E} \sim 0{,}5 \div 1 \text{ eV}. \tag{1}$$

This result agrees with data from the artificial emission from the ionosphere observed under corresponding conditions.[8] The electron temperature in the F layer is $T_e \approx 0.1$–0.2 eV. The ionization energies $\mathscr{E}_i$ of the primary constituents of the ionosphere are 12.0, 13.6, and 15.6 eV. Obviously, the change $\Delta\mathscr{E}$ in (1) in the energy of the fast electrons could not lead to any significant ionization effect in an equilibrium (Maxwellian) plasma under these conditions, and this is the situation observed in the unilluminated ionosphere.

The picture changes completely in the sunlit ionosphere, where the presence of photoelectrons must be taken into account. The photoelectrons are found predominantly in the F layer at energies $\mathscr{E} > 2$–3 eV, and although they are few in number (amounting to 10^{-4}–10^{-3} of the total number of electrons), they make a significant contribution to the ionization of the ionosphere: At altitudes 200–250 km, they are responsible for 30-50% of the photoionization q_s (Ref. 9). Determining the change in the ionization effect of the photoelectrons, Δq_f, upon an increase $\Delta\mathscr{E}$ in their energy, we can show that

$$\Delta q_f = \frac{\Delta \mathcal{E}}{T_{ef}}\, q_f \,, \quad T_{ef} = \left(f \Big/ \frac{\partial f}{\partial \mathcal{E}} \right)_{\mathcal{E} = \mathcal{E}_i}$$

$$\frac{\Delta N}{N_0} = \frac{\Delta \mathcal{E}}{T_{ef}} \, \frac{q_f}{q_f + q_s} \,, \quad \Delta \mathcal{E} < T_{ef} \,. \tag{2}$$

Here q_f is the ionization caused by the photoelectrons (i.e., the number of electron-ion pairs formed per second per cubic centimeter by the photoelectrons), T_{eff} is the effective temperature in the ionization-energy region, f is the photoelectron energy distribution, and $\Delta N/N_0$ is the perturbation of electron density. At altitudes 200–250 km the effective temperature is $T_{\text{eff}} \sim 2$–3 eV (Ref. 9). It thus follows that the change in the ionization in (1), (2) agrees completely with the observed effect. Only a few percent of the total power of the radio wave is expended on intensifying the ionization in this case.

If we calculate the power required to produce the observed effect in an equilibrium plasma, we easily see that it is very high—approaching the total power of the radio wave. It is thus clear that the density increase results from the stimulation of lthe ionizing effect of the photoelectrons.

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