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Parameters of a High-Frequency Source Located in the Tropopause

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Parameters of a High-Frequency Source Located in the Tropopause

G. V. Sklizkov[α] & A. V. Shelobolin[σ]

Abstract- A model of a transionospheric pulse pair, previously obtained experimentally and not having a satisfactory explanation, is proposed. The physical parameters of the emitting object in the form of a flat ionized structure, the electron density in it, and the electron temperature are considered. Two estimates are given for each of these parameters, where $n = 10^7 cm^{-3}$, and T_e is in the range from 600 K to 3000 K.

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I. Introduction

In [1], from the analysis of the spatial structure of giant jets recorded in [2, 3], it was found that there is a coherent source of HF radiation in the tropopause. However, the parameters of the source remained unexplored. In this work proposed below, an attempt is made, on the basis of the analysis of transionospheric pulse pairs [4, 5] (TIPP) to estimate the spatial dimensions, energy parameters, frequency spectrum, and divergence of a similar source.

Transionospheric pulse pairs of electromagnetic pulses in the atmosphere (TIPP) were recorded in [4], and then analyzed in [5]. The indicated registration was carried out from a satellite in orbit close to circular with height over Earth surface from 800 to 1725 km. The TIPPs themselves were a double electromagnetic pulse in the frequency range 28 - 80 MC, which corresponded to a wavelength range from 3.8 to 11 m and critical electron densities from $9.7 \cdot 10^6 cm^{-3}$ to $810^7 cm^{-3}$. The duration of each pulse was from 0.5 μs to 20 μs, with an average duration of 5 μs with intervals between them from 10 μs to 100 μs with an average value of 50 μs. In addition, it was recorded that their power was significantly higher than the power expected and observed for HF radio emission from ordinary lightning at all stages of its development, and the temporary structure of the TIPP was not found anywhere in atmospheric discharges. Solar radiation did not play a decisive role on the effect of TIPP, since the maximum frequency of observations of this phenomenon occurred both at midnight and at noon.

The main observations were carried out in equatorial regions at latitudes of $\pm 8^0$ with a field of view of $\pm 35^0$ (a circle of 8000 km) both in latitude and longitude (though some of the TIPP observations had been made in the mid-latitudes). In approximately 1% of cases, only one impulse was observed. Equally rarely, the second impulse was superior in intensity to the first. In the remaining cases, the former was more powerful, although there was no significant difference in their amplitudes. An analysis of the signal dispersion during the passage of the ionosphere made by the authors of [4, 5] gave a qualitative coincidence of the time – frequency characteristic with the same characteristic for a calibration pulse from the ground. However, if the calibration pulse was linearly polarized and therefore produced a noticeable splitting associated with birefringence near the lower boundary of the frequency range, then a similar splitting for the studied pulse was visible not in all the spectrograms presented, but only in one recorded at latitude 6^0. Was it due to the lack of polarization in individual experiments or it was insufficient frequency-time resolution of the equipment, had been unclear from [4, 5].

An attempt made in [5] to identify the nature of these pulses has not yet been successful. The main attention of the authors [5] was focused on determining the nature of the pairing of these pulses. Although the authors were inclined to believe that the second pulse was a reflection of the first one from the surface of the earth, a number of contradictions did not allow them to confirm it. Below we will try, using the previously proposed nonlinear plasma-waveguide model of electric gas breakdown (NPWM) [6-8], and the results of [9 - 12] to build a general model of the process leading to TIPP, and to analyze on its basis the contradictions noted in [5].

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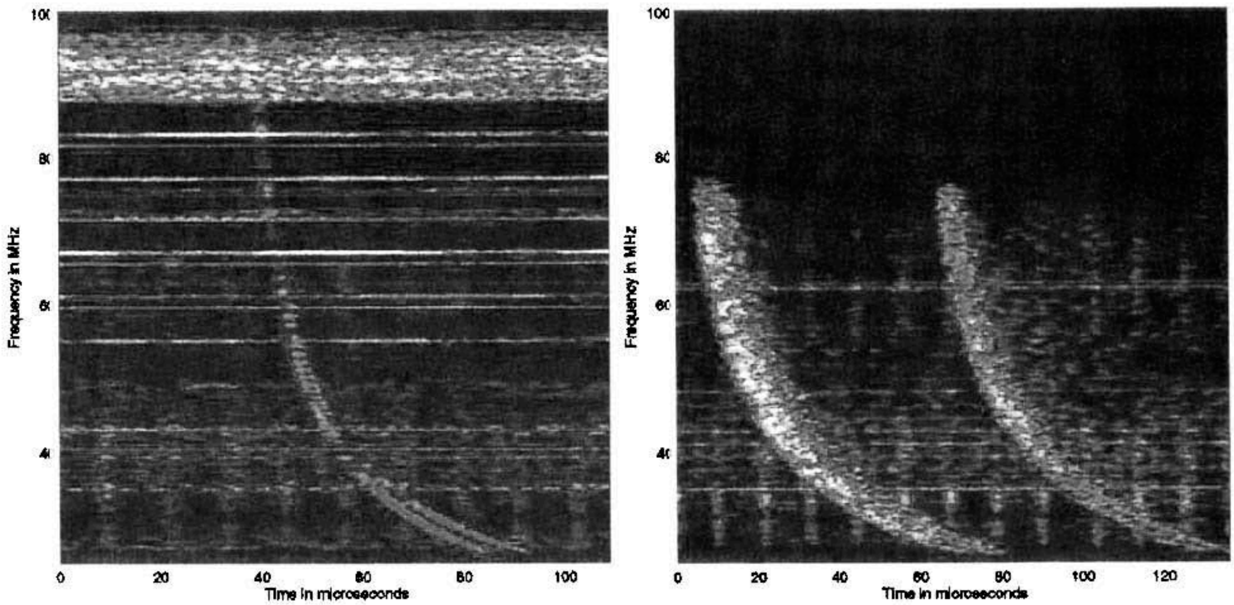

a) b)

Fig. 1: Calibration pulse from the ground (a) and transionospheric pulse pair (b) obtained at latitude 6^0 [4].

II. Diagnostics of the Plasma of the Object and the Frequency Resolution of the Equipment

The need for such a diagnostics is connected with the fact that the authors' desire [4, 5] to link the resulting dispersion picture with the influence of the ionosphere on the detected radiation is doubtful. Let us try first qualitative, and then quantitative to show that the influence of the ionosphere on the dispersion characteristic of an object is negligible. In this case, we also try to determine the electron density in the studied object. Then, we determine quantity the difference in the refractive indices of the object plasma for the ordinary and extraordinary waves at a frequency of 56 MC, where according to the spectrograms the corresponding lines merge. If for the ionosphere this difference is less than indicated, this will mean that its influence on the recorded signal is negligible. Then it will be possible to make a hypothesis for the structure of the object and determining its necessary geometric parameters and the temperature of the plasma electrons.

First of all, we will give a qualitative understanding of such a TIPP parameter as the frequency range of the process. In this case, as is customary in plasma physics, we will operate with the concept of a cyclic frequency, which is related to the frequency f by the expression $\omega=2\pi f$, and the corresponding resonant electron density n will be determined from the expression $\omega_L=(4\pi e^2 n/m)^{0.5}$, where e is the elementary charge, m - the electron mass, and ω_L-Langmuir frequency. The lower frequency boundary $f = 28$ MC will correspond to the resonant electron density $n = 9.7 \cdot 10^6$ cm^{-3}. It should be compared with the electron density in the upper F_2-layer of the ionosphere, reference data for the daily maximum of which give $n \approx 5 \cdot 10^5$ cm^{-3}, which corresponds to the critical frequency $f = 6.3$ MC. This qualitatively means that the frequency range chosen in [4, 5] assumed an almost complete passage of the investigated radiation through the ionosphere with insignificant dispersion.

To explain the observed dispersion of electromagnetic radiation, it is necessary to analyze the process of polarization of this radiation at the plasma boundary, which has its own characteristics in comparison with this process in the optics of solid transparent bodies. Figure 2 shows the dependence of the reflection coefficient R on the frequency ω and the angle of incidence θ, taken from [14]. In this case the waves of two polarizations are distinguished: s-polarization, or H-wave, and p-polarization, or E-wave. For the H-wave, the vector of its electric field has no projection onto the plane of incidence, but for the E-wave it has.

As shown in Fig. 2, R (ω) decreases monotonically for all frequencies, ω satisfying the condition $\omega>\omega_L/\cos\theta$, which occurs for the H-wave for any θ and for the E-wave for $\theta> 0.25\pi$. If $\theta<0.25\pi$, then for the E-wave there are two singular points $\omega_1$and ω_2. For $\omega = \omega_1$, the E-wave passes almost completely into the plasma, and the corresponding angle of incidence θ is called the Brewster angle θ_B, and $tg^2\theta_B = \varepsilon = N^2 = 1-(\omega_L / \omega)^2$. Here ε is the dielectric constant of the plasma, N is its refractive index. If θ_B is small, then the H-wave is almost completely reflected, and the E-wave passes almost completely into the plasma without reflection. This allows us to calculate the plasma frequency ω_L for such an inclusion and the electron density n in it. Assuming that the Brewster angle is $\theta_B = 6^0$, i.e., it is equal to the geographic latitude of the experiment, we obtain $\omega_L = \omega\,(1\text{-tg}^2 6^0)^{0.5} = 1.76\cdot 10^8$ s^{-1}, and $n = 1.1\cdot 10^7$ cm^{-3}. These values are close to the values of the lower boundary of the experimental frequency range [1], estimated above.

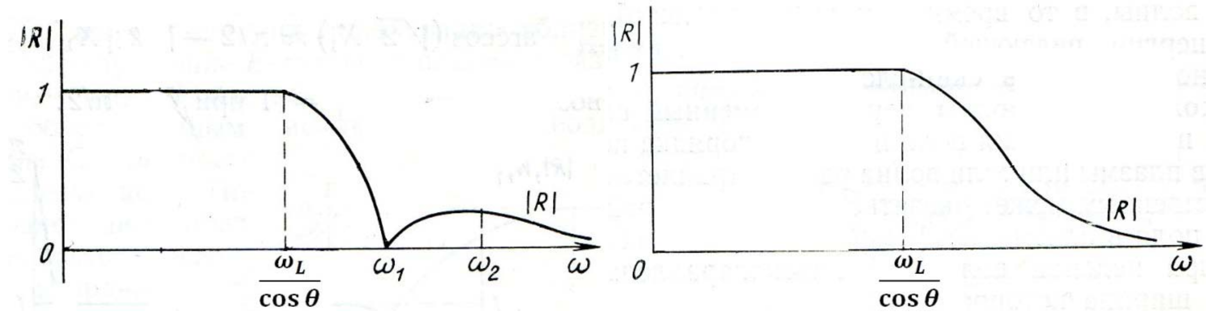

Fig. 2: The dependence of the plasma reflection coefficient on the frequency for the E-wave (a) and the H-wave (b) [14].

According to the estimate given in [1], at $n \geq 10^7$ cm^{-3}, the air at altitudes of 15 km and more becomes amplifying, since in it the temperature of the electronic subsystem is detached from the temperature of the neutral subsystem and the elastic scattering of electrons by neutral particles can provide spontaneous emission in the frequency range studied. In addition, the presence of the TIPP polarization indicates that the lower and upper horizontal boundaries of the plasma inclusion are the planes up to the wavelength at the lower boundary of the frequency range of the experiment. Finally, another consequence arising from the polarization of TIPP is the almost one-pass operation of the generator, since there is almost no reflection at the layer boundaries.

We calculate the refractive indices of the plasma for the ordinary and extraordinary waves, based on the expression [11, 12]:

$$N_{1,2}^2 = 1 - \frac{2v(1-v)}{2(1-v) - u\sin^2\alpha \pm \sqrt{u^2\sin^4\alpha + 4u(1-v)^2\cos^2\alpha}} \tag{1}$$

The upper sign in the denominator (1) corresponds to an ordinary wave, and the lower one to an extraordinary one. Here $\alpha = 0.5\pi\text{-}\Theta$, $v = (\omega_L / \omega)^2$, $u = (\omega_H / \omega)^2$, $\omega_H = eH / mc$ is the gyromagnetic rotation frequency. At the equator, with a magnetic field strength $H = 0.34$ G, $\omega_H = 5.98 \cdot 10^6 c^{-1}$ for all frequencies of the considered range and all experiments. Calculating by (1) the values of the refractive indices of the plasma with increased accuracy of calculation, we obtain:

N_1^2 (56 MC) = 0.75316, N_2^2 (56 MC) = 0.75227, $\Delta N_{1,2}$ (56 MC) = $5.1 \cdot 10^{-4}$.

N_1^2 (F_2 layer) = 0.94878, N_2^2 (F_2 layer) = 0.94844, $\Delta N_{1,2}$ (F_2 layer, 28 MC) = $1.8 \cdot 10^{-4}$.

The value $\Delta N_{1,2}$ (56 MC) reflects the threshold for detecting wave decay into ordinary and extraordinary. The value $\Delta N_{1,2}$ (F_2 layer, 28 MC) shows that the dispersion of the considered signal is not significant in the ionosphere as compared to the threshold for recording satellite equipment at 56 MC.

III. The Analysis of the Pairing of Pulses and the Scheme of the Phenomenon

We consider three models of pulse pairing, two of which were close to the models [4, 5] and were not unconditionally accepted as the basis for studies. The third model we propose is based on the NPWM [6-8], analysis of the observation of giant jets [1], and the analysis of ionosphere studies [9–12]. The basic prerequisites for these models and their brief analysis are as follows:

1. One-pulse source can migrate vertically. The second pulse is a mirror reflection of the first from the earth with a reflection coefficient close to 1. The atmosphere is neutral.

The disadvantage of this hypothesis is the need to introduce a vertical source migration process, which we added to the hypothesis [4, 5] in order to explain qualitatively the spectrum of delays between pulses. The second drawback of this hypothesis is the assumption that the momentum reflection coefficient from the earth is close to 1, which contradicts both the reference data on this issue and the presence of experimental results

[4,5], where the second pulse is more powerful than the first one.

2. A two-pulse source does not change its vertical coordinate, but changes the delay between pulses. The atmosphere is neutral. There is no reflection from the earth.

The disadvantage of this hypothesis is that two questions about the delay and the nature of the source are combined into one, which has no answer as well. Formally, such atransition is not prohibited, but it does not bring a solution to the whole problem. In addition, the radiation of such a source should have been observed from the ground, which is not confirmed by the available experimental data.

3. The source is one-pulse. Both the source and the atmosphere are piecewise ionized, that is, separated by horizontal layers and random vertical boundaries. There are no reflections from the earth, but there are reflections from individual ionized layers.

This hypothesis was expressed quite a long time ago [13] and was experimentally confirmed in [1] when analyzing the structure of a giant jet spot on the ionosphere. There, in the open resonator formed by the flat upper layer of a thundercloud and the concave surface of the lower ionosphere, a transverse structure of the jet channels appeared, similar to the transverse structure in hemispherical laser resonators. In this case, the central imprints on the ionosphere were surrounded by a wide, weak imprint. Such an imprint appears only when there are opaque scattering centers inside the resonator whose dimensions are smaller than the working wavelength, which in [1] was 300 m. In studies of the ionosphere, such areas were called sporadic and were obtained both theoretically and experimentally [9, 10,12].

The presence of such sites between the thundercloud and the ionosphere was confirmed in [1]. Our hypothesis suggests that they exist in the interval from the earth to a thundercloud. Moreover, for TIPP, the upper layers of a thundercloud represent a generator with a wide range of frequencies, and the lower layers are a set of parallel mirrors reflecting this radiation. This separation is related to the dependence of the generation threshold on the height of the plasma object, which is the case of the upper ionized layer only. The threshold for the generation of electromagnetic oscillations in air is determined in [1] by the equality of the frequencies of the elastic electron–electron interaction ν_{ee} and the effective electron-neutral interaction ($\nu_{ea}\cdot 2m/M$) in the absence of ionization, i.e. $0.5M/m\cdot\ \nu_{ee}/\nu_{ea}\geq 1$, where M is the mass of a neutral particle, atom or molecule. Substitution of air parameters into this condition and taking into account the barometric formula [1] give the condition $(1\text{-}2)\cdot 10^{-8}$ $n\exp(h/F)\geq 1$, where F = 7.5 -8 km is the reduced height and h is the height above sea level. This formula at $h\approx 2F$ = 15 km shows that at an electron density of $n\approx 10^7$ cm^{-3}, the bremsstrahlung of electrons during elastic interaction with neutral particles can enhance the electromagnetic radiation of the megahertz range, and in the presence of feedback, create lasing.

To illustrate this scheme, we take from [5] a histogram of delays between pulses, expand it vertically and put a height calibration next to the delay time calibration (see Fig.3). In this case, we will assume that the height of the upper boundary of the layer h is related to the delay τ by the relation $h = 15\text{-}0.5c\tau$, where $c = 3\cdot 10^5$ km/s. In this case the histogram can be treated as the probability of the distribution of the reflecting layers vertically with the source at its upper coordinate. It should be noted that at these altitudes there is a maximum electron density arising from cosmic radiation, which, however, would not provide the necessary electron density $n = 10^7$ cm^{-3}.

We can draw the following conclusions:

a) Reflection from the earth or from the ocean surface cannot provide differences in the difference in the path of the rays by 15 km or 100 μs, i.e., the delay between the first and second pulses in all experiments should be constant.

b) When reflecting from the ocean surface, the reflection coefficient for all frequencies of the indicated range should be close to 1. In this regard, such reflection cannot give noticeable difference in the amplitudes in individual sections of the experimentally obtained dependence. On the contrary, reflection from the earth's surface should give a significant difference in the intensity of the first and second pulses.

c) If reflection is provided by plasma inclusions, then their concentration is maximal at an altitude of 7.5 km, which corresponds to the lower boundary of the thunderstorm region for tropical latitudes, where measurements were taken.

d) The upper boundary of the graph, i.e., 15 km, practically coincides with the upper boundary of a thundercloud participating in the formation of the transverse mode structure of a giant jet, as described in [1], for tropical latitudes as well.

e) In [4, 5] it was shown that the energy of the first pulse is almost always greater than the energy of the second pulse, and only in some cases the energy of the second pulse exceeded the energy of the first pulse. In the framework of the model under consideration, this means that the electron concentration in plasma inclusions is nonzero and lower than 15 km, but remains below the generation threshold. This suggests that the second reflected pulse can pass with amplification only through the upper layer. The ratio of the powers of the first and second pulses is determined by the reflection coefficient of the lower mirror and the gain of the upper plasma layer, and depending of the fact whether the reflected pulse passed through a medium with an inversion weakened by the first pulse.

f) In [5], rare (~ 1%) recordings of single pulses were also reported, which is consistent with the proposed model, assuming that the reflected pulse did not encounter plasma inclusions on its way to the ground, where it had been absorbed or scattered.

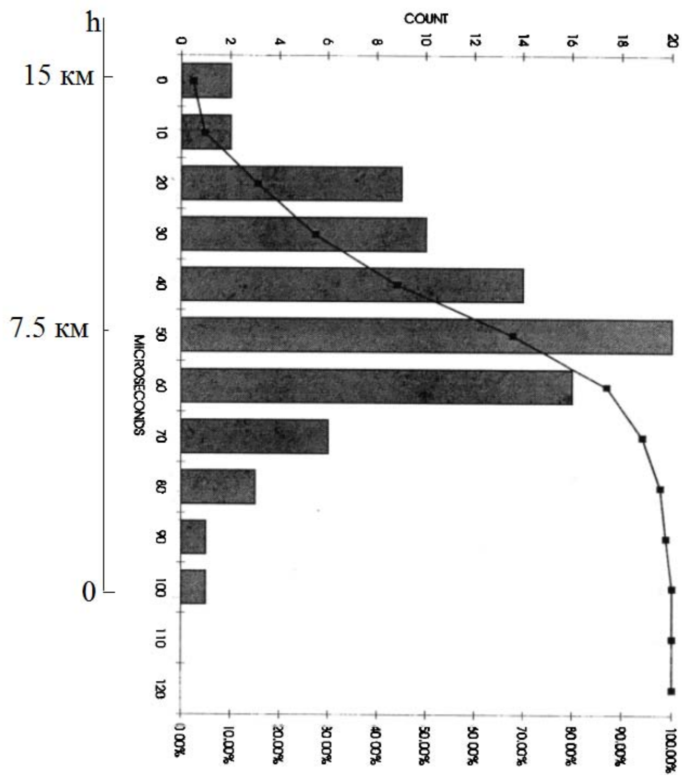

Fig. 3: The probability of vertical distribution of the reflecting plasma planes

In our model, it is assumed that the TIPP radiation is close to parallel, similar to the one emanating from the laser, which can explain qualitatively the increased TIPP intensity at the antenna of the satellite receiving device.

For theoretical verification of the proposed model and for its subsequent experimental verification, it is necessary to make several estimates that can be refined after additional experimental information. In this case, the main attention will be paid to the operation of the generator located at an altitude of 15 km, since the work of the reflecting layers is trivial. Firstly, it is necessary to make another frequency estimate for the frequency of electron-atom collisions ν_{ea}. A standard calculation of this value at an altitude of 15 km is $\nu_{ea} = 4.7 \cdot 10^{10} s^{-1}$. In order to obtain the effective energy frequency of electron-atom collisions, which ensures the process of pumping the medium, the obtained value should be divided by 2m/M. Then we get $\nu_{ea}^{eff} = 4.4 \cdot 10^{5} s^{-1}$. The inverse value will give a characteristic pump time $\tau^{eff} = 2.3 \cdot 10^{-6}$ s, which is close to the average TIPP pulse duration. Thus, the estimates showed that the electromagnetic radiation of the frequency range selected in [4, 5] freely passes through the generator layer, and the duration of a single pulse is almost equal to the duration of pumping by the radiation of electrons from the medium. You can also specify the number of passes of radiation in the generator as from one to four passes.

In optical generator circuits, there are two restrictions diffraction and geometric for divergence of the received radiation, diffraction and geometric. The diffraction restriction is reduced to the condition $\lambda_{max} \leq d$, where $\lambda_{max} = 11$ m is the maximum wavelength for radiation of the frequency range under consideration, d is the transverse horizontal dimension of the plasma inclusion. The geometric divergence is d/L, where L is the distance between the plasma mirrors in the plasma generator. For generators with a small number of passes, the maximum quality factor of the wave in the generator will be achieved when the diffraction divergence is approximately equal to the geometric divergence, i.e., $\lambda_{max} / d \approx d / L$. From here we can estimate the horizontal size of the plasma inclusion as $d \approx (\lambda_{max} \cdot L)^{0.5}$. Assuming $\lambda_{max} = 11$ m, and from the delay histogram estimating $L \approx 750$ m, we obtain $d \approx 90$ m.

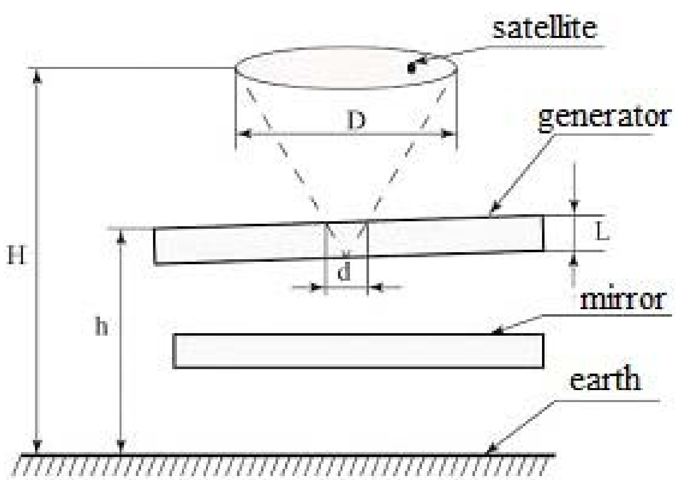

Fig. 4: The geometric design of the experiment

In order to estimate the temperature of the electron of the generator, we consider the geometric scheme of the experiment (see Fig.4). If the satellite is at a height H, and the upper end of the generator at a height h, then the ratio of the spot diameters on the satellite D and the diameter of the generator end face d will be D / d = (H-h + L) / L≈H / L. Then for further estimates, you can take D ≈ 100km.

The histogram of received energy at the satellite's antenna presented in [5] can be interpreted as the shape of the radiation spot in the plane of the satellite's passage, scanned by the satellite's antenna in various experiments, and therefore it can be approximated as a spot in the far zone of the generator through a dependence of the type $F(r) = A\exp[-(r/a)^2]$. Such an approximation at parameter values $A = 40{\cdot}10^{-9}$nJ / m and a = 40 km gives a satisfactory coincidence with the histogram. Integrating F (r) over the radius and azimuth, we can obtain the total energy in the spot $W_H = 4$ m J.

This allows a rough estimate of the electron temperature. At the same time, it must be remembered that the concept of temperature is strictly applicable to equilibrium systems only obeying the Planck distribution. That is why, in the presence of an experimental amplitude-frequency characteristic of radiation, comparing it with the Planck distribution, one can rigorously determine the temperature of plasma electrons. Since the experiment [4, 5] does not give such a characteristic, the electron temperature introduced below is only an estimated measure of the generator energy and the generation process.

The balance of energy in the generator's volume, provided that the energy at the generator's end face and the energy in the spot in the region of the satellite's span $W_H = W_h$ is written as $0.25\pi\eta nLd^2 1.5k(Te-T_0) = W_H$, where T_0=200K is the temperature of the neutral component, k is the Boltzmann constant, and η is the generator efficiency. Hence, the electron temperature T_e will be determined from the condition:

$$T_e - T_0 = \frac{8W_H}{3\pi\eta knLd^2} \tag{2}$$

Calculations by (2) give T_e-T_0 = 1 / η·4.1 K. The sharp leading edge of each pulse in the pair, as well as the shape of the spot in the far zone of the generator, suggests that the radiation from the generator should be coherent. Such radiation can be obtained only with the help of a wave developing in the volume of the generator. The closest analogue of such a device is a traveling wave maser [15].

According to [16], masers have η in the range from 0.01 to 0.1, depending on the level of their technical optimization. Moreover, the lower value of η corresponds to the inversion threshold. That is why, as the first very rough estimate of the electron temperature in the layer under consideration, we can take η = 0.01, T_e-T_0 = 400 K, and T_e = 600 K. A detailed discussion of the wave transformation in a plasma generator goes far beyond the scope of this work, and therefore we only mention that in the ionosphere at lower n the electron temperature can reach 1000–2000 K [9, 10]. This is also an estimate by analogy, which at best gives an upper bound on the electron temperature in the generator in question.

Another estimate can be taken from a consideration of the evolution of plasma in a tube of diameter d and length L [17]. If the condition L >> d is satisfied, then the diffusion of all plasma elements in the tube is radial in nature, then in the stationary state the condition is satisfied:

$$\frac{T_e}{E_i} = \left[\ln\left(\frac{\Lambda^2}{\lambda_{ea}\lambda_{ia}}\cdot\frac{M_i}{m}\cdot\frac{\nu_{ia}}{\nu_{ea}}\right)\right]^{-1} \tag{3}$$

Here, λ_{ea} and λ_{ia} are the mean free path in electron-atom collisions and the characteristic ionization length, ν_{ia} and ν_{ea} are the collision frequencies in ion-atom and electron-atom collisions, M_i / m is the ratio of the mass of the ion to the mass of the electron, Λ is the diffusion length, which is determined from ratios Λ = 0.5d / 2.405, E_i is the ionization potential of the neutral component. In the calculations, we take $\Lambda = 2.7{\cdot}10^3$ cm, $\lambda_{ea} = 6.9{\cdot}10^{-9}$ cm, $\lambda_{ia} = 2.4{\cdot}10^{-2}$ cm, $\nu_{ea} = 4.7{\cdot}10^{10}$ s $^{-1}$, $\nu_{ia} = 1.2{\cdot}10^{9}$ s $^{-1}$, M_i / m = $5.5{\cdot}10^{4}$. In this case, we obtain T_e / E_i = 0.023, which, taking into account the dispersion of air components in ionization potentials, will give T_e from 3000 K to 3500 K. These values may seem overestimated in comparison with the T_e ionosphere. However, it should be kept in mind that the radiation of the sun and cosmic radiation are the sources of ionization of the ionosphere. Here, an additional action of the electric field and the corresponding currents are assumed.

IV. Conclusion

The analysis allows us to explain the TIPP phenomenon on the basis of the generation of a plasma layer located at an altitude of 15 km, a thickness of 750 m, a diameter of 90 m with an electron density of 10^7 cm^{-3} in the electron temperature range from 600 K to 3000 K and the energy of a pair of pulses is about 4 mJ. In addition, as follows from experiment [4, 5], the frequency range of the detected radiation is from 28 MC to 80 MC. In this case, the lower limit of this range is determined not by the physics of the phenomenon, but by the characteristics features of the experiment.

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