Reports of the Academy of Sciences of the USSR

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1962

SovietRxiv

Abstract

Full Text

Reports of the Academy of Sciences of the USSR

1962. Volume 146, No. 3

Geophysics

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INVESTIGATION OF THE LOWER IONOSPHERE BY MEANS OF LONG RADIO WAVES AND LOW-FREQUENCY RADIOSONDES INSTALLED ON A ROCKET. DETECTION OF A NEW IONOSPHERIC LAYER

(Presented by Academician I. M. Vinogradov on 1 VI 1962)

Because of the unsuitability of the pulse radiosounding method and radio-interference methods for measuring small electron concentrations, the ionosphere at altitudes 50 km $< h <$ 90 km until recently remained the least investigated part of the Earth' s atmosphere. Although after rocket studies of solar radiation (^{1}, ^{2}) it has been possible to understand the nature of the ionization of the lower ionosphere, aeronomic theories of the ionosphere are still very far from the state in which they will be able to give sufficiently accurate profiles of the concentrations of electrons $N_e(h)$ and ions $N^+(h)$, $N^-(h)$. This situation compelled us, during 1950–1960, to work on new methods for investigating the lower ionosphere.

As a result, the following two methods were developed and used at MIT.

The first method, described in (^{3}), consisted in reconciling all data on the field of long and superlong radio waves and data on the propagation medium with the aid of theoretical functional relations obtained from the solution of a boundary-value problem for Maxwell' s equations. As a result, new information on the lower ionosphere was obtained, partially published in (^{3}), and a new layer was also detected, named at the colloquium of the Computing Center of the Academy of Sciences of the USSR on 17 III 1960 layer C.

The second method consisted in measuring the impedance of a small antenna (a whip and a T-shaped antenna) placed on the side surface of a vertically flying rocket. Such a device is a capacitor filled with an anisotropic semiconducting medium. The effective conductivity $\sigma_\perp$ and the real part of the dielectric con-

Fig. 1

Figure 1: Fig. 1

stant $\varepsilon'_{\perp}$ were measured directly in the Earth' s magnetic field H_0, nearly normal to the antenna field. With the aid of the known formulas

$$\varepsilon'_{\perp} = 1 - \frac{V(s^2+1-u^2)}{(s^2+1+u^2)^2-4u^2};$$

$$\sigma_{\perp} = \frac{\omega V s(s^2+1+u^2)}{4\pi(s^2+1+u^2)^2-4u^2}\, 10^6\, \frac{\mu\mho}{\text{m}}, \tag{1}$$

where $V = 4\pi e^2 N_e/m\omega^2$; $s = \nu_{eff}/\omega$; $u = -eH_0/mc\omega$; $\omega = 2\pi f$, from the measured $\sigma_{\perp}(h)$ and $\varepsilon'_{\perp}(h)$ the quantities $N_e(h)$ and the effective collision frequency $\nu_{eff}(h)$ were determined. In 1959 the probe method was applied in the works (4), but the frequency used by the authors, $f = 7.75$ MHz, was too high to detect ionization below 90-100 km. In our case $f = 50$ kHz, which makes it possible to measure concentrations down to 20 el/cm^3 (at $h = 60$ km).

Fig. 1 gives preliminary results of measurements of $N_e(h)$ and $\nu_{\text{eff}}(h)$, obtained from two launches: A–2 VIII 1958 at 09 h 47 min, and B–2 VII 1959 at 07 h 40 min local time in the middle latitudes of the northern hemisphere, at solar angles $\chi = 41^\circ$ (A) and $\chi = 57^\circ$ (B). According to observatory data, the sun during experiments A and B was quiet. The same figure gives averaged results obtained by the first method during the period of maximum solar activity: N_e^{∂} [1] and N_e^{∂} [3] refer to noon in middle latitudes for summer and winter, N_e^{n} to night, and N_e^{∂} [3] to noon in the equatorial zone. A characteristic feature of N_e^{∂} [1] and N_e^{∂} [3] is the "tail," located in the height interval 57-67 km for summer and 57-80 km for winter, called in [3] the C layer. It does not depend on the time of day or season, being determined only by the latitude of the site. Comparison of N_e^{∂} [1] with N_e^{∂} [3] shows that it is absent in the equatorial zone. Arising with the first ray of the sun, which contains no ionizing radiation but is capable of destroying O_2^-, layer C advances in the form of a wedge, as shown in Fig. 1 by the curves $C_1, C_2, \ldots$ with the speed of this ray. Twenty to thirty minutes after

Fig. 1

sunrise it reaches heights of 57-58 km and stabilizes. Further deformation of the profile $N_e(h)$ is due to changes only in the middle part of $N_e(h)$, which depends on the solar zenith angle χ according to a law $\simeq \log\sec\chi$. This part is naturally identified with layer D, which, according to Nicolet [5], is caused by ionization of NO by the L_α line. Layers C and D are partially overlapped. The degree of overlap varies with time of day and with season. In winter, because of the high position of layer D (larger χ), layer C is almost completely exposed. From our investigations by method I it follows that the maximum of layer D is masked by the tail of layer E, and only a bend of the curve $N_e(h)$ is possible, not detected by the first method because of the great width of the uncertainty band (shaded region). However, the absence of corresponding bends on curves A and B also cannot be regarded as a reliable fact, since processing the experimental $\sigma_\perp(h)$ and $\varepsilon_\perp(h)$ by formulas (1) gives somewhat overestimated N_e for $h > 80$ km because of the violation of the perpendicularity of H_0 to the electric field of the antenna. Let us note that the layers D_α and D_β introduced earlier in ([6]) have no direct relation to the layers D and C considered here. Thus, for example, the sharp increase in the reflection of long waves at an angle of incidence of 45–55° does not require, for its explanation, the introduction of the layers D_α and D_β (see ([3],[7])) and is also observed in the case when only one layer D exists. But without the layer C, too small attenuation coefficients β are obtained for the wave TH_1, which determines the long-range field of long waves ([3]), something observed only in the equatorial belt, where there is no layer C. Only in order to explain large $\beta(TH_1)$ in the middle belt does one have to introduce the layer C, which plays the role of an absorbing "cushion." Unfortunately, the layer C was not investigated by method II because of regularly observed disturbances of the radiotelemetric communication channel with the rocket when it entered the layer C.

It follows from ([1],[2]) that none of the usually observed solar radiations penetrates into the altitude region 57–67 km. This fact, and the unusual behavior of the layer C during the day and as a function of latitude, make it possible to suppose that it is produced by radiation not of solar origin. It is very probable that it is caused by primary cosmic radiation. Calculations of N_e in the lower ionosphere with allowance for primary cosmic rays were published in May 1960 in papers ([8],[9]); they are presented in Fig. 1 by the curves N. A. and M. for latitude $\varphi = 60°$. Both curves N. A. and M. lie outside the uncertainty band of the curve $N_e^o[\lambda]$, which is caused by the inaccuracy of the aeronomic data and by the uncertainty of the recombination scheme used in ([8],[9]). In the layer D, the curves N. A. and M. are close to $N_e^o[\lambda]$ and to the curve H obtained in ([10]). Our curve $\nu_{\text{eff}}(h)$ for 80 km $\leq h \leq$ 90 km is a smooth continuation of $\nu_{\text{eff}}(K)$, obtained by Kane ([11]) by the method of differential attenuation of ordinary and extraordinary radio waves with $f = 7.75$ MHz at the moment of a polar blackout, when $N_e(h = 60 \text{ km}) = 2\cdot 10^5$. For $h > 90$ km, $\nu_{\text{eff}}(h)$ is overestimated because of collisions of electrons with ions. Let us note that (1) follows from a more exact expression of kinetic theory:

$$\varepsilon_\perp = 1 + i\,\frac{8V}{3\sqrt{\pi}}\int_0^\infty \frac{(s_{\text{tr}} - i)w^4 e^{-w^2}\,dw}{(s_{\text{tr}} - i)^2 + u^2},$$

$$s_{\text{tr}} = \frac{\nu_{\text{tr}}}{\omega} = \frac{nAv}{\omega}, \tag{2}$$

where $A(v)$ is the transport cross section for collisions of electrons with molecules at electron velocity v; $\bar{v} = \sqrt{2kT/m}$ is the most probable electron velocity for a Maxwellian velocity distribution; $w = v/\bar{v}$; n is the number of molecules in 1 cm^3, if one assumes that $A \sim v^{-1}$. Then $\nu_{\text{tr}} = \nu_{\text{eff}}$ does not depend on v. An analogous hypothesis underlies the Appleton–Hartree formula used in ([11]). However, from laboratory experiments ([12,13]) on the mobility, diffusion, and drift velocity of thermal electrons (80–500°K) in molecular nitrogen, as well as from microwave experiments, it follows that $A = a_0 v$, where $a_0 = 3.29 \cdot 10^{-23}$. Therefore the concept ν_{eff} is not adequate to the physical processes of radio-wave energy dissipation in the lower ionosphere, and agreement between laboratory and ionospheric data must be made on the basis of formula (2). Recalculation of our data for $\operatorname{Re}\varepsilon_\perp$ and $\operatorname{Im}\varepsilon_\perp$ with the aid of (2) and under the condition $A = av$ gives, for the most probable transport collision frequency, $\bar{\nu}_{\text{tr}} = nav^2$, the curve shown in Fig. 1 by the dash-dot line. It is a continuation of the corrected

$\bar{\nu}_{\text{tr}}(K)$ (13). As a result, $\bar{\nu}_{\text{tr}}(h)$ from ionospheric data in the altitude interval 60-90 km proves to be close to $\bar{\nu}_{\text{tr}}(h) = 1.2 \cdot 10^8 P$, where P is the pressure in millimeters of mercury, obtained from laboratory data (12). The difference between ν_{eff} and $\bar{\nu}_{\text{tr}}$ does not have an appreciable effect on N_e; therefore curves A and B were not corrected.

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Received
31 V 1962

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