RADIO EMISSION AND NATURE OF THE MOON

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1. GENERAL INFORMATION ON THE INVESTIGATION OF THE PHYSICAL CONDITIONS ON THE MOON AND ITS RADIO EMISSION

Before the 1930's, the only source of information on the physical conditions on the moon was the sunlight reflected from its surface. Naturally, it could contain information on the state of substances only on the surface itself, and more readily on its microrelief (roughness, graininess, etc.) rather than data on the nature of the substance and its properties. By now the properties of the surface as given by reflected light (reflectivity, polarization properties etc.) have been thoroughly investigated. A great contribution to these researches has been made by the French school of astronomers: Leo, Dolfus, etc.

An especially significant contribution was made by the Kharkov school of astronomers, headed by N. P. Barabashov (A. T. Chekirda, V. I. Ezerskiĭ, V. A. Fedorets, etc.), and the Leningrad school headed by V. V. Sharonov (N. N. Sytinskaya, N. S. Orlova, L. N. Radlova and others). The work of V. G. Fesenkov, A. V. Markov, A. V. Khabakov, and B. Yu. Levin is of importance. Notice should also be taken of the polarization research by V. P. Dzhapiashvili. All this exhaustive research has determined many different qualities and properties in the reflection and scattering of light by the moon's surface (see, for example [56]). However, the deductions of interest to us reduce essentially to the statement that the material on the surface is very rough or is finely crushed.

The material of the moon was found to be unlike any of the earth's rocks, which have already been investigated in their natural and crushed states, with respect to reflecting ability and polarization properties.

Only at the end of the 1920's and the beginning of the 1930's did the research of the moon in its own thermal electromagnetic radiation at infrared wavelengths of $10-15\,\mu$ begin. The measurements of Pettit and Nicholson in 1927 and 1930[5], during the time of the lunation, have made it possible to determine the surface temperature, while measurements made by the same authors during lunar eclipses[5,58], have enabled Wesselink[1] (1948) and then Jaeger[2] (1953) to determine the heat conductivity of the lunar matter, which turned out to be so small as to correspond only to thin dust in a vacuum. The measurements of Smoluchowski (1911)[65] of the heat conductivity of powders in vacuum has confirmed this well. This gave rise to the hypothesis of the continuous dust layer covering the moon. A more detailed analysis has shown that this dust covers the rocky surface and apparently its thickness is only several millimeters[59].

In 1949 Piddington and Minnet investigated for the first time in detail the moon's own thermal radio emission at 1.25 cm. They reached the conclusion that the upper cover has a double-layer dust structure and estimated the effective electric conductivity of the lunar matter at 1.25 cm. This work was significant because it led to the discovery that the radio emission of the moon is determined by a thick layer of matter and contains information concerning the physical properties of the entire layer, and not only the surface, as is the case with the reflected light waves and the intrinsic infrared radiation. However, the significance of this fact became clear only recently, when radio emission has yielded very important results which hitherto seemed unattainable.

Shortly after the first measurements, a vigorous investigation of the radio emission of the moon at different wavelengths was undertaken and ways developed to determine from these data the physical conditions on the moon, and primarily the temperature, thermal and electric properties of the substance, its structure, and nature.

The study of the moon by means of its radio emission continued abroad by many workers in many countries. A great number of investigations were carried out. The most systematic research on the moon, however, was carried out in the Soviet Union by a group of radio astronomers at the Radiophysics Research Institute (NIRFI) of Gor'kiĭ University from 1950 to the present time [3,4,8,11-14,16,24-26,28-30,34-38,40,50,52,53,63,67-70,72,76] and also a group of radio astronomers of the Physics Institute of the USSR Academy of Sciences (FIAN), under the guidance of A. E. Salmonovich, since 1955, [9,10,20-23,29,32,76] and at the Pulkovo Observatory of the USSR Academy of Sciences (GAO) under the leadership of S. E. Khaĭkin and N. L. Kaidanovskiĭ [10,71,81].

Recent studies made at NIRFI of the radio emission of the moon and of terrestrial rocks have led to many new results and to a fairly integrated and internally non-contradictory picture of the physical properties of the moon's outer cover. A lead forward in this direction was due to the development of a new precision method of measuring the radio emission from the moon, with accuracy not less than ± 1—2%. Since in what follows we shall not deal with methods of measuring the moon's radio emission, it is advantageous to stop and discuss them here. We shall first establish the definitions and concepts pertaining to the moon's radio emission.

As is well known, the moon's radio emission is thermal. The moon is not absolutely black to radio waves, so that the intensity of radio emission from an arbitrary elementary area on the moon is characterized by an effective (brightness) temperature, by which is meant the temperature of an absolutely black body which yields the observed radiation intensity. The effective temperature at radio wavelengths is more frequently called the radio temperature. The brightness radio temperature is not the same over the entire disc of the moon and its distribution over the latter corresponds to the distribution of the true temperature and the emissivity of the surface. All the methods used to measure the intensity of radio emission from the moon give some radio temperature which is averaged over the disc (weighted over the diagram), equal to [8,37]

$$\overline{T}_{\mathrm{M}}=\frac{\int\limits_{\Omega_{\mathrm{M}}} F(\Omega)\,T_{\mathrm{M}}(\Omega)\,d\Omega}{\int\limits_{\Omega_{\mathrm{M}}} F(\Omega)\,d\Omega},$$

where $\overline{T}_M$ —distribution function of the brightness radio temperature over the moon's disc, Ω_M —solid angle of the moon, and F —equation of the antenna power directivity pattern.

If the antenna pattern has a total lobe width much smaller than the angular dimensions of the moon, the measured quantity is the brightness temperature in a given direction. In the opposite case, when the directivity pattern is much larger than the moon's angular dimension, the quantity measured is in practice the radio temperature averaged over the disc

$$\overline{T}_{\mathrm{M}}=\frac{1}{\Omega_{\mathrm{M}}}\int\limits_{\Omega_{\mathrm{M}}} T_{\mathrm{M}}(\Omega)\,d\Omega.$$

To determine $\overline{T}_M$ we must measure the quantity

$$\int\limits_{\Omega_{\mathrm{M}}} FT_{\mathrm{M}}\,d\Omega,$$

which is proportional to the signal power at the antenna output, the proportionality coefficient being determined by the antenna parameters (directivity, loss, pattern). By measuring the signal power at the antenna output with the aid of radiometers and knowing the antenna parameters, it is easy to find the required value of the radio temperature. This method, which is the one customarily employed, gives rise, however, to considerable error because of the difficulties in determining the antenna prameters and to a lesser degree because of the inaccuracy with which the signal power at the antenna output is determined. The accuracy of such measurements of $\overline{T}_M$ usually does not exceed 10—20%, which makes the measurements essentially doubtful. This limits strongly the possibility of using radio data to determine the temperature and the physical parameters of the surface layer. Nevertheless, it was established by means of relative data that the surface layer of the moon has uniform properties in depth, and that it has other properties which will be discussed later on.

New results were obtained by using a precision method for radio emission measurement, developed at the NIRFI [24]. This method of measuring the moon's radio temperature is based on a comparison of its radio emission with the exactly known radio emission of an absolutely black disc, placed in the Fraunhofer zone of the antenna, at a sufficient angular height above the horizon. The signal power from the disc is proportional to a known quantity $T_d \int\limits_{\Omega_d} F\,d\Omega$ (T_d —disc temperature), which can be used readily to calibrate the entire system without resorting to measuring the power at the antenna output and without using antenna parameters which are not accurately known. This method has been named the "artificial moon" method, since the angular dimensions of the disc, as seen from the antenna, are close to those of the moon. It turned out that the most appreciable error of the method is connected with the influence of the radio emission from the earth, which is diffracted by the disc and enters the telescope, thus increasing the standard signal by an indeterminate amount. To exclude the influence of diffraction, a second standard is used in the form of an opening in a plane overlapping the principal lobe of the antenna pattern and located in the same place as the disc. The opening is exactly the same size as the disc. In this case the standard signal produced by the radiation of the disc, which is placed in the opening, is reduced by the amount of the power of the radio emission diffracted in the opening. Since the diffraction patterns of the disc and of the opening are identical (complementary screens), the values of the diffracted power will be equal. Consequently, the average value of the signals from the free disc and from the disc in the hole will be strictly equal to the known radiation of the disc.

Subsequently, by using a second standard, disc installation conditions under which the influence of the radio emission from the earth can be reduced to a negligibly small amount were found, and only a single standard disc used. The dimensions of the disc in the first measurements carried out at 3.2 cm with a 1.5 meter diameter antenna were 60 and 120 cm, and later 4—5 meters. Figure 1 shows a photograph of the set up for observation with a disc 5 meters in diameter, installed on a mountain, near the ruins of a Genovese fortress in Sudak, while Fig. 2 shows a similar installation on Mt. Kara-dag in the Crimea. Figure 3 shows a four-meter artificial moon.

As a result of the use of the first method, it was possible to determine the moon's temperature accurate to 2—3° over a wide range of wavelengths. However, this method is technically feasible only for the measurement of integral radiation, i.e., of the radio temperature averaged over the moon's disc.

In somewhat more than a decade of the observation of the radio emission of the moon, important results were obtained, which disclose the nature and the physical conditions not only of the outer cover but also deep inside the moon, and cast light on its history. The results obtained reduce briefly to the following:

1. The average temperature conditions on the moon's surface were investigated. The distribution of the temperature over the disc and the dependence of the temperature on the time were determined. The average temperature on the surface is $T_0(0) = 230°K$ at the moon's equator, and the amplitude of the first harmonic is $T_1(0) = 155°K$. There are practically no temperature fluctuations even at a depth of $1\frac{1}{2}$ meters.

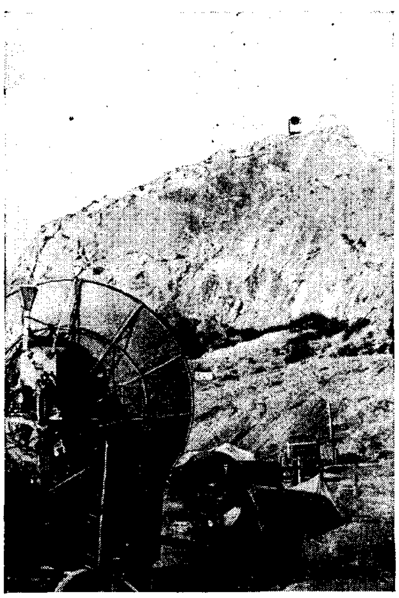

FIG. 1. Observation of radio emission from a standard disc 5 mm in diameter, mounted on a mountain near the city of Sudak.

FIG. 2. Observation of radio emission of a standard disc 4 meters in diameter, installed on Mt. Kara-dag in the Crimea.

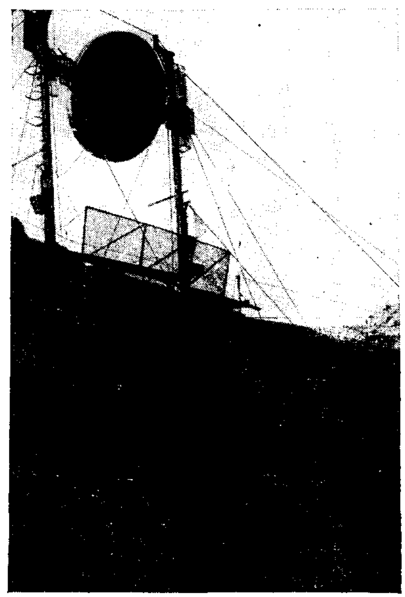

FIG. 3. "Artificial moon" 4 meters in diameter.

2. It has been established that the temperature increases on penetrating into the moon by 1.6 deg/m up to a depth of 20 meters; the heat flux from the interior of the moon is found to be the same as that of the earth, viz., 1.3×10^{-6} cal/cm^2-sec.

3. Approximate homogeneity of the properties of the outer cover of the lunar material was observed, starting from the surface to a depth of 20 meters. The density of matter in the layer is found to be close to 0.5

g/cm^3. The entire 20-meter layer of matter is in a highly porous state in the form of solidified foamy matter with a heat conductivity which is 40—60 times as small as the heat conductivity of solid terrestrial rocks.

4. The loss angle of the lunar matter at microwave frequencies (or the effective electric conductivity) was found to be 5×10^{-3} per g/cm^3, corresponding to the losses in good commercial dielectrics. Data were obtained on the chemical and mineralogical composition of the lunar material, which consists of 60—65% quartz and possibly is close to the granite group, but differs in structure.

5. The heat flux released by the moon annually was found to be 1.6×10^{19} cal/year. Assuming that this heat is radiogenic in origin, the average concentration of radioactive elements in the moon is estimated to be 5—6 times the average concentration on earth. The temperature of the lunar interior was estimated. This is the far from complete list of the results obtained.

The purpose of the present review is to present not only as complete information as possible on the physical conditions of the moon, obtained by investigating the moon's own radiation, but also to describe the methods and analysis used to determine these conditions.

2. TEMPERATURE OF THE SURFACE LAYER OF THE MOON

As is well known, the temperature of the moon's surface is determined by the heat it receives by radiation from the sun. In view of the absence of an atmosphere on the moon, it becomes possible to calculate its surface temperature accurately for a specified value and variation of the energy flux from the sun. The first to consider the thermal conditions on the moon's surface during the time of lunation, for the center of the visible disc, was Wesselink [1].

As is also well known, the character of the variation of the temperature of any body for a specified variation of the flux is determined completely by some thermal parameter $\gamma = (k\rho c)^{-1/2}$, where k is the heat conductivity, ρ the density, and c the specific heat (at constant pressure) of the material of the body. In [1] there is a theoretical calculation of the thermal conditions under the assumption that the thermal properties of the upper cover of the moon are homogeneous (k and ρ are independent of the depth), for one value of the parameter $\gamma = 920$. A more detailed calculation of the thermal conditions for the center of the disc was made by Jaeger [2]. The calculations were made under the assumption of a uniform outer layer with different hypothetical thermal properties, and also a two-layer sharply non-uniform model, according to which the lunar surface consists of a solid rock with a low thermal parameter $\gamma = (k\rho c)^{-1/2} \approx 100$, covered with a thin layer of dust with value $\gamma = 1{,}000$. To determine the variation of the surface temperature at the center of the visible disc of the moon during the lunar cycle, Jaeger solved the equation of heat conduction for a periodic heat flux from the sun and for Stefan-Boltzmann radiation [see (1) and (2)]. The solution was by numerical integration. However, the author used too low a value of the solar constant ($A_0 = 1.55$ cal/cm^2 min) and assumed that at the initial instant of time the upper layer of the moon is uniformly heated. As is well known, the solar constant is $A_0 = 2$ cal/cm^2 min.

Investigation of the radio emission from the moon has shown that the surface layer of the lunar matter has a quasi-homogeneous structure in depth, and the sharply-nonuniform model, no matter how it may agree with the experimental data, must be rejected [3]. In this connection, a more rigorous investigation was made in [4] of the temperature conditions of the moon's surface using the modern value of the solar constant and the indicated new data on the structure of the outer layer. Using the BÉSM-2 electronic computer, the steady-state values were obtained for any point of the lunar surface with selenographic coordinates φ and ψ and for values of γ equal to 20, 125, 250, 400, 500, 700, 1,000, and 1200, of the equation

$$\frac{\partial T}{\partial t} - a\frac{\partial^2 T}{\partial y^2} = 0 \qquad (1)$$

with boundary conditions

$$\left.\begin{aligned} k\frac{\partial T}{\partial y} &= E_1\sigma T^4 - A_0\cos\psi E_2\cos(\Phi-\varphi) \text{ for } |t| < \tfrac{1}{4}\tau, \\ k\frac{\partial T}{\partial y} &= E_2\sigma T^4 \text{ for } \tfrac{1}{4}\tau < t < \tfrac{3}{4}\tau. \end{aligned}\right\} \qquad (2)$$

Here $a = k/\rho c$ is the heat conductivity temperature, A = 2 cal/cm^2 min the solar constant, E_1 the emissivity in the wavelength region of the maximum of the intrinsic thermal radiation of the lunar surface, E_2 the emissivity in the range of wavelengths of the incident light flux, τ the lunation period, $\Phi = \Omega t$ the phase angle, Ω the lunation frequency, and σ the Stefan-Boltzmann constant. Since the solution was carried through to steady state, the initial conditions can be arbitrary. Figure 4 shows the dependence of the surface temperature at the center of the lunar disc on the time, referred to the lunation period. The dashed curves correspond to Jaeger's calculations for $\gamma = 20$ and 1,000. A comparison of the curves obtained with Jaeger's calculations [2] shows that the latter obtains for the surface temperature in the subsolar point a value which is almost 20° lower (374°K) than that obtained in [4]. The difference between the daytime and nighttime temperatures T_m and T_n obtained in [2] is lower by approximately the same amount. The sharper transition obtained in [4] at the points $t/\tau = 0.25$ and $t/\tau = 0.75$, corresponding to sunset and sunrise, is probably due to the fact that the subdivision of the lunation period into 20 parts, employed in [2], contributes to a smoothing of the curves at these points. Figure 5 shows the temperatures of the subsolar point

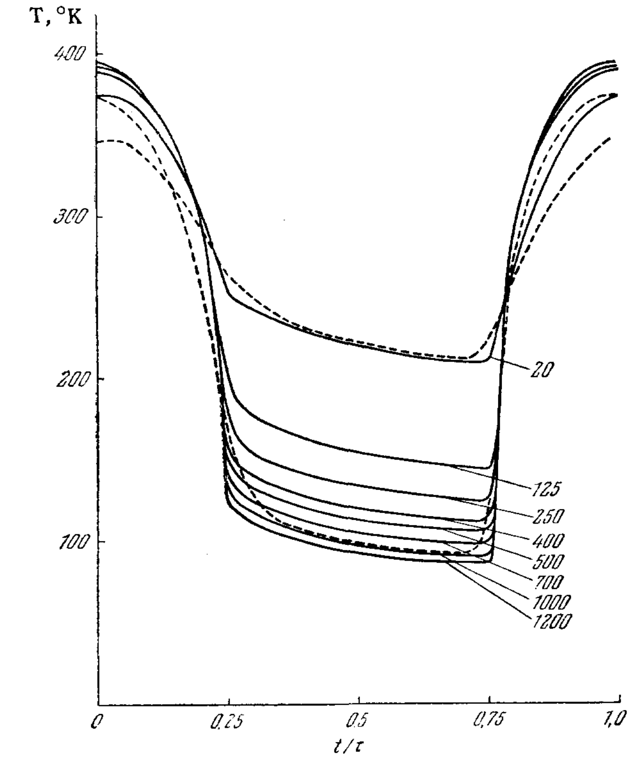

FIG. 4. Variation of the surface temperature at the center of the lunar disc as a function of the reduced lunation period for different values of the parameter γ. The dashed curves correspond to Jaeger's calculations[2] with $\gamma = 20$ and 1,000.

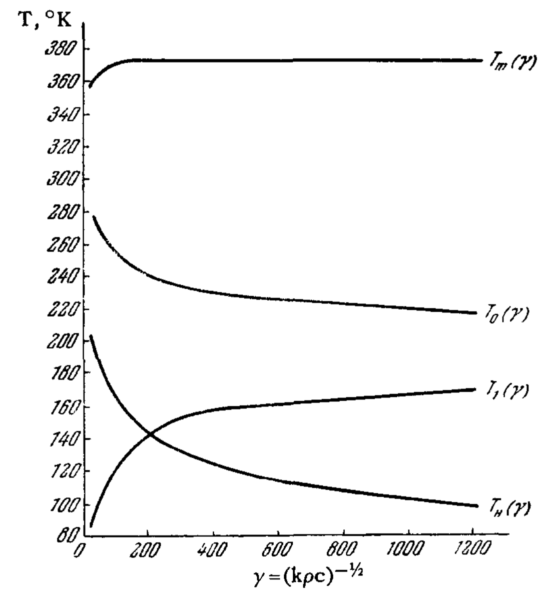

FIG. 5. Dependence of the temperature of the subsolar point T_m, the steady component T_0, the amplitude of the first harmonic T_1, and the nighttime temperature T_n on the parameter $\gamma = (k\rho c)^{-1/2}$.

T_m, the steady component T_0, the amplitude of the first harmonic T_1, and the nighttime temperature T_n obtained as functions of the parameter γ on the basis of this calculation for the center of the moon's disc.

The surface temperature at the subsolar point is completely determined by the incident light flux, and is therefore practically independent of the parameter γ, whereas the nighttime temperature does depend on it considerably. The larger γ, the more is the moon's surface cooled and the lower the nighttime temperature. This leads to a decrease in the steady component and to an increase in the amplitude of the first harmonic. A solution of the thermal problem for emissivity values in the range $0.9 \le E_1$, $E_2 \le 1$ has shown that the surface temperature changes in this case by 2%.

The effect of the solar constant on the temperature of the subsolar point and the nighttime temperature is shown in Fig. 6. Variation of the solar constant over a wide range exerts an appreciable influence on the temperature of the subsolar point and barely affects the nighttime temperature. The slight change in the variation of the solar constant due to the eccentricity of the earth's orbit has practically no effect on the temperature of the lunar surface.

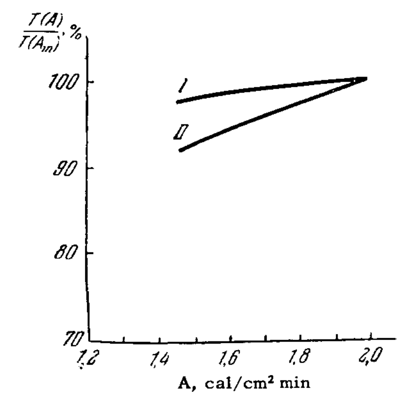

FIG. 6. Relative temperature of the subsolar point (curve II) and relative nighttime temperature (curve I) as functions of the solar constant.

In calculations of the radio emission from the moon it is advisable to obtain an analytic expression for the intensity of the radio emission. To this end it is necessary to know the analytic expression for the depth distribution of the temperature. It is obtained by solving the equation of heat conduction, provided the temperature on the surface is known. The most convenient form in which to specify the surface temperature is to use a function in the form of a Fourier series. Therefore the results of the calculation of the surface temperature are presented in the form [4]

$$T(\varphi, \psi, t) = T_0(\psi) + \sum_{n=1}^{4} (-1)^{\alpha_n} T_n(\psi) \cos(n\Phi - n\varphi - \varphi_n), \quad (3)$$

where φ is the longitude and ψ the latitude of the position, and φ_n the phase shift for the n-th harmonic of the variation of the surface temperature relative to the phase shift of the incident flux. The sign of the first four harmonics is determined by the exponent

Table I. Numerical values of the elements of the Fourier expansion of the surface temperature at the center of the moon's disk as a function of γ

γ	$T_0(0)$, °K	$T_1(0)$, °K	φ_1, deg	$T_2(0)$, °K	$-\varphi_2$, deg	$T_3(0)$, °K	φ_3, deg	$T_4(0)$, °K	$-\varphi_4$
125	247	132	5	34	6	19	11	13	7
250	237	146	4	35	7	23	6	14	9
400	230	156	3	36	7	26	6	15	9
500	227	159	3	36	7	28	5	15	9
700	223	165	3	36	7	30	4	15	9
1000	219	170	2	36	6	31	3	15	9
1200	217	173	2	36	6	32	3	15	8

$$\alpha_n = \frac{(n-1)(n-2)}{2}.$$

As was shown in [4], the first five values of $T_n(\psi)$ are well approximated by the expressions

$$\left.\begin{aligned} &T_0(\psi)=T_0(0)\cos^{0.2}\psi, \quad T_3(\psi)=T_3(0)\cos^{0.44}\psi,\\ &T_1(\psi)=T_1(0)\cos^{0.33}\psi, \quad T_4(\psi)=T_4(0)\cos^{0.3}\psi.\\ &T_2(\psi)=T_2(0)\cos^{0.27}\psi, \end{aligned}\right\} \tag{4}$$

Here $T_n(0)$ are the values of the corresponding harmonics of the temperature at the center of the moon's disc.

The expressions (4) obtained for the distribution of the different components over the disc are practically independent of the parameter γ as the latter varies in the range $125 \le \gamma \le 1200$. The numerical values of the constant component $T_0(0)$ and of the amplitudes of the harmonics $T_n(0)$, and the corresponding phase shifts φ_n, are listed in Table I as functions of γ. The solution of the problem with the aid of a computer gives also the distribution of the temperature with the depth y at any point (φ, ψ). Knowing the function of the temperature distribution over the lunar surface (3) enables us to solve the heat conduction equation (1) with boundary conditions specified in the form of a harmonic series (3). As a result we obtain for any point (φ, ψ) of the moon's surface a depth temperature distribution in the form

$$T(y, \varphi, \psi, t)=T_0(\psi)+\sum_{n=1}^{4}(-1)^{\alpha_n}T_n(\psi)e^{-y\sqrt{\frac{n\Omega}{2a}}} \times\cos\left(n\Phi-n\varphi-\varphi_n-y\sqrt{\frac{n\Omega}{2a}}\right). \tag{5}$$

It is clear therefore that the temperature at any depth is made up of a time-independent temperature, called the steady component, and an alternating component, made up of the sum of harmonics with periods that are multiples of the lunation period (τ = 29.53 days). Each harmonic attenuates with depth, and at a depth

$$l_{tn}=\sqrt{\frac{2a}{n\Omega}}$$

the amplitude of the temperature fluctuations decreases to 1/e of the value on the surface. This depth will henceforth be called the depth of penetration of the temperature wave, and for the first harmonic its value is

$$l_t=\sqrt{\frac{2a}{\Omega}}=\sqrt{\frac{2k}{\varrho c\Omega}}. \tag{6}$$

At a depth of three or four times l_t, there are practically no temperature fluctuations. The value of l_t, characterizes the thickness of the rock layer heated by the sun during the lunar day.

The law governing the surface temperature variation with latitude ψ was used in [7] and [8] for an analysis of the radio emission from the moon. Piddington and Minnet [7] proposed that the steady component of the surface temperature depends on the latitude in accordance with

$$T_0=T_0(0)\cos^{1/4}\psi. \tag{7}$$

It was assumed in [8] that the temperature at any point of the moon's surface is in the general form equal to

$$T(\varphi, \psi, t)=T_n+(T_m-T_n)\eta(\Phi-\varphi)\eta(\psi), \tag{8}$$

where $\eta(\Phi-\varphi)$ and $\eta(\psi)$ are the distributions of the temperature in excess of the nighttime temperature, T_m is the temperature of the subsolar point, and T_n is the nighttime temperature. On the basis of Jaeger's curves for the changes in temperature during the time of lunation, it was found [14] that $\eta(\psi) = \cos^{1/2}\psi$ and $\eta = (\Phi-\varphi) = \cos^{1/2}(\Phi-\varphi)$. Expansion of (8) in a time-dependent Fourier series gives the following expression for the steady component:

$$T_0=T_n+a_0(T_m-T_n)\cos^{1/2}\psi, \tag{9}$$

where a_0 = 0.387 is the coefficient for the Fourier expansion of the variation of the surface temperature. The distribution (9)—(8), adopted in [8] and used to the present day, practically coincides with the exact distribution (3)—(4). A noticeable difference is observed only near the pole. Let us compare the obtained distributions of the temperatures and their magnitudes with those obtained by experiment.

The first measurements of the infrared temperature were made by Pettit and Nicolson [5]. They obtained at the subsolar point a temperature T_m = 391°K. Subsequently Sinton et al [6] obtained T_m = 389°K. These figures are in good agreement with the temperature obtained in [4] for the subsolar point. However, in literature published outside the USSR, the value $T_m = 374°K$, obtained by Pettit and Nicolson from theoretical calculations, is still being used. It is shown in [5] that the temperature distribution function in terms of the ray incidence angle r deviates from the $\cos^{1/4} r$, which corresponds to a smooth surface. The actually observed law is

$$T(r) = T_m \cos^{1/6} r \tag{10}$$

Naturally, the distribution calculated in [4] will give a somewhat smaller value of the temperature near the moon's limb than is given by (10). Incidentally, this difference sets in when $r > 45-50°$, i.e., within 3–4 angular minutes near the moon's limb. The deviation of the temperature distribution from the theoretical $\cos^{1/4} r$ law is attributed by the authors of the paper to the great degree of roughness.

Measurements of the distribution of the moon's radio brightness at wavelengths 0.8 and 2 cm with the 22 meter telescope of the Physics Institute of the Academy of Sciences [9] have made it possible, using the procedure proposed by N. L. Kaĭdanovskiĭ and A. E. Salomonovich [10], to determine the function $\eta(\psi)$ and to find that it is close to $\eta(\psi) = \cos^{1/2} \psi$.

3. THEORY OF RADIO EMISSION FROM THE MOON

The radio emission from the moon has a thermal character and its main features are determined by the conditions under which the surface layer becomes heated and cooled during the course of the lunation.

The first theory of the moon's radio emission was presented by Piddington and Minnet in 1949 [7] in connection with an explanation of the phase variation of the moon's radio emission which they observed at 1.25 cm. In the calculations it was assumed that the moon's material is a dielectric which can support propagating waves that have a certain degree of damping. The radio emission of such a material comes essentially from a layer whose optical thickness is equal to unity. This layer, obviously, has a lower limit at a depth l_e, from which the radio emission emerges to the outside attenuated by a factor $e = 2.73$. All the features of the phase dependence of the radio emission of the moon, as shown in [7], are determined by the relation between the thickness l_e of the emitting layer and the thickness l_t of the layer of rock heated by the sun. Thus, the character of the dependence of the moon's radio emission on its phases is determined both by the electric (loss angle) and thermal (thermal conductivity, density, specific heat) properties of its material.

A detailed examination of the theory of radio emission from the moon was made in [8]. It was assumed there that the surface of the moon is sufficiently smooth with respect to radio waves and that Fresnel's formulas for the reflection coefficient are valid. In addition, it was assumed that the matter in the outer layer is uniform in depth with respect to its thermal and electrical properties, i.e., that it has everywhere a constant density up to a certain depth. According to [8], the effective radio emission temperature of an element of the moon's surface with coordinates φ and ψ is equal to

$$T_e = [1 - R(\varphi, \psi)] \int_0^\infty T(y, \varphi, \psi, t)\, \varkappa \sec r' \cdot e^{-y\varkappa \sec r'} dy, \tag{11}$$

where $T(y, \varphi, \psi, t)$ is the true temperature of the lunar matter at a depth y at the instant of time t, given by expression (5), and $R(\varphi, \psi)$ is the reflection coefficient corresponding to the vertical or horizontal polarization, while κ is the coefficient of electromagnetic wave absorption, which does not depend on y for the case under consideration where the structure of the outer layer of the moon is assumed homogeneous, and r' is the angle between the direction of the outward radiation and the normal to the element of the surface where the radiation emerges. After substituting in (11) the depth distribution of the temperature in the form (5), different from that used in [8], we obtain the following expression for the effective temperature of an element of the moon's surface

$$T_e(\varphi, \psi, t) = [1 - R(\varphi, \psi)] \Big\{ T_0(\psi) + \sum_{n=1}^{4} (-1)^{\alpha_n} T_n(\psi) \int_0^\infty \varkappa \sec r' \cdot e^{-y\left(\sqrt{\frac{n\Omega}{2a}} + \varkappa \sec r'\right)} \times \cos\left(n\Phi - n\varphi - \varphi_n - y\sqrt{\frac{n\Omega}{2a}}\right) dy \Big\}. \tag{12}$$

From this we obtain, in accordance with [8],

$$T_e(\varphi, \psi, t) = [1 - R(\varphi, \psi)] \Big\{ T_0(\psi) + \sum_{n=1}^{4} (-1)^{\alpha_n} \frac{T_n(\psi)}{\sqrt{1 + 2\delta_n \cos r' + 2\delta_n^2 \cos^2 r'}} \times \cos(n\Phi - n\varphi - \varphi_n - \xi_n(\varphi, \psi)) \Big\}, \tag{13}$$

where

$$\delta_n = \frac{\sqrt{\frac{n\Omega}{2a}}}{\varkappa}$$

is the ratio of the depth of penetration of the electromagnetic wave $l_e = 1/\kappa$ to the depth of penetration of the n-th harmonic of the thermal wave

$$l_{nt} = \sqrt{\frac{2a}{n\Omega}}, \quad \cos r' = \frac{1}{\sqrt{\varepsilon}} \sqrt{\varepsilon - \sin^2 r},$$

r is the angle between the normal to the surface and the direction at the point of reception,*

$$\xi_n(\varphi, \psi) = \operatorname{arctg} \frac{\delta_n \cos r'}{1 + \delta_n \cos r'}$$

is the phase shift for the n-th harmonic of the effec-

*arctg = $\tan^{-1}$.

tive temperature relative to the phase of the surface temperature. The functions $T_n(\psi)$ are given by relations (4). It is seen from this expression that the intensity of the radio emission from the moon fluctuates periodically within the lunar cycles about some average quantity, usually called the constant component of the temperature.

Equation (13) gives the distribution of the brightness over the moon's disc for any phase angle Φ. Figure 7a shows a two-dimensional distribution of the effective temperature at 0.8 cm, calculated by formula (13) for a phase angle $\Phi = 133°$. Figure 7b corresponds to an analogous distribution, obtained experimentally by A. E. Salomonovich [9] using a high-resolution radio telescope. A qualitative agreement between the two distributions and a decrease in the effective temperature towards the edge of the moon's disc, due to the increase in the reflection coefficient in the case of tangential emergence of the radiation, can be seen. The theoretical curves of the moon's radio brightness distribution, plotted in [8] along the equator and the meridian for the constant component, show a noticeable decrease in the intensity only towards the edge of the disc, in a ring comprising 2–3 minutes of angle, whereas along the meridian the radio temperature decreases, more rapidly, owing to the latitudinal distribution of the surface temperature.

In one particular case, for the center of the visible moon's disc, expression (13) simplifies greatly to

$$T_e(0,0,t) = (1-R_\perp)\left\{T_0(0) + \sum_{n=1}^{4} \frac{(-1)^{\alpha_n} T_n(0)}{\sqrt{1+2\delta_n+2\delta_n^2}} \cos(n\Phi - \varphi_n - \xi_n)\right\}, \tag{14}$$

where

$$R_\perp = \left(\frac{\sqrt{\varepsilon}-1}{\sqrt{\varepsilon}+1}\right)^2$$

is the coefficient of reflection for perpendicular incidence, and

$$\xi_n = \operatorname{arctg} \frac{\delta_n}{1+\delta_n}.$$

The harmonic amplitudes above the first harmonic constitute a relatively small fraction of the first harmonic and can be discarded in many cases to some degree of approximation. Then the oscillations of the radio emission of the center of the moon's disc are expressed approximately by the very simple relationship:

$$T_e(0,0,t) \approx (1-R_\perp)\left\{T_0(0) + \frac{T_1(0)}{\sqrt{1+2\delta_1+\delta_1^2}} \cos(\Phi - \varphi_1 - \xi_1)\right\} \tag{15}$$

with a sinusoidal alternating component. It is clearly seen that the maximum of radio emission from the moon lags behind the full moon. The lag angle, equal to ξ_1, depends on the ratio $\delta = l_e/l_t$ of the depths of penetration of the electromagnetic wave (or thickness of the radio emission layer) and the penetration of the temperature wave. As $\delta \to \infty$ we have $\xi_1 \to 45°$, and the amplitude of the alternating component tends to zero. This is quite obvious physically. The larger the thickness of the radio emitting layer, the smaller the fraction of the radiation comes from its heated part which is proportional to l_t. This leads to a decrease in the amplitude of the radio temperature oscillations, due to the radiation from the layer l_t. The delay is also increased as a result of the increasing delay in the heating of the lower layers. If the radio emission were to come from the surface itself, as is the case for infrared waves ($\delta \approx 0$), then the oscillation amplitude of the first harmonic of the radio temperature would differ from the amplitude of the true temperature on the surface $T_1(0)$ only in a factor equal to the radiating ability $1 - R_t$. If the width of the diagram is such that the radio reception comes from the entire disc of the moon, then in order to interpret the results of these measurements it is necessary to establish general relationships between the distribution of the brightness radio temperature and the measured radio temperature, averaged over the disc. In [7] the experiments yielding the radio temperature averaged over the disc were interpreted by using the relationships for the brightness radio temperature, which leads to errors. Approximate relations for the integral radio emission of the moon were derived in [8], how-

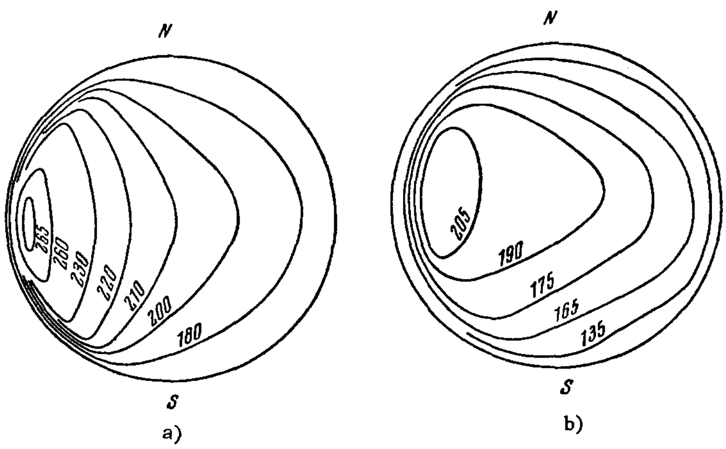

FIG. 7. a) Distribution of the effective temperature over the moon's disc, calculated by formula (13) for 0.8 cm. b) Analogous distribution obtained experimentally by A. E. Salomonovich[9]. Phase angle $\Phi = 133°$; $\Phi = 0$ corresponds to full moon.

ever, their accuracy is insufficient for the interpretation and reduction of precision measurements. Exact solutions were obtained in [11] for the integral radiation from the moon, and are in keeping with the increasing measurement accuracy.

According to [8], the effective temperature averaged over the disc is

$$\overline{T}_e = \frac{1}{\pi}\int\int_{-\pi/2}^{+\pi/2} [1 - R(\varphi, \psi)]\, T_e(\varphi, \psi, t)\cos^2\psi\cos\varphi\, d\varphi\, d\psi. \quad (16)$$

It is advantageous to represent it in terms of the radiation of the center of the disc, by introducing the required conversion coefficients.

From (14) and (16) we can obtain after transformation and integration an expression for the effective temperature averaged over the disc in terms of the temperature of the center of the disc, in the form

$$\overline{T}_e = (1 - R_\perp)\,\beta_0 T_0(0) + (1 - R_\perp)\sum_{n=1}^{4}(-1)^{\alpha_n}\frac{T_n(0)\,\beta_n}{\sqrt{1 + 2\delta_n + 2\delta_n^2}} \times \cos(n\Phi - \varphi_n - \xi_n - \Delta\xi_n), \quad (17)$$

where

$$(1 - R_\perp)\,\beta_0 T_0(0) = \overline{T}_{e0}$$

is the constant component of the effective temperature averaged over the coordinates*,

$$\frac{T_n(0)\,\beta_n}{\sqrt{1 + 2\delta_n + 2\delta_n^2}}$$

is the n-th harmonic of the effective temperature averaged over the disc, β_0 and β_n are the corresponding averaging coefficients, and $\Delta\xi_n$ is the additional phase shift resulting from the averaging.

The quantities β_0 and β_n are expressed in rather complicated fashion in terms of integrals which depend on ϵ and δ of the moon's surface. An analytic calculation of these quantities is impossible, and therefore an electronic computer was used in [11] for a wide range of variation of ϵ and δ. Figure 8 shows the dependence of the coefficient β_0 on ϵ. Figures 9—10 show the coefficients β_1 and β_2 as functions of δ_1 for different values of ϵ.

As can be seen from Fig. 9, when δ_1 is constant, the coefficient β_1 increases with decreasing ϵ. This is due to the increase in the amplitude of the radio temperature oscillations towards the edge of the moon's disc, owing to the fact that the radio emission emerges from the surface tangentially. Indeed, the depth from which the radio emission emerges at a given point of the moon's surface is equal to

$$l = l_e\frac{1}{\sqrt{\varepsilon}}\sqrt{\varepsilon - \sin^2 r},$$

i.e., it decreases towards the edge of the disc. Therefore, with decreasing ϵ, the contribution to the total radio emission from regions located near the moon's limb increases. The coefficients β_1 and β_2 remain practically constant with variation of δ_1 when $\delta_1 > 10$. Analysis in [11] has shown that the high harmonics of the effective temperature averaged over the disc are appreciably attenuated compared with the corresponding harmonics of the effective temperature at the disc's center. Thus, at 0.4 cm the amplitude of second harmonic of the temperature averaged over the disc is 8%, while that of the third is less than 1% of the amplitude of the first harmonic for the center of the disc, whereas the corresponding quantities for the center of the disc are 20 and 13% respectively. For longer waves, and consequently for larger δ_n, the higher harmonics of the integral radio emission from the

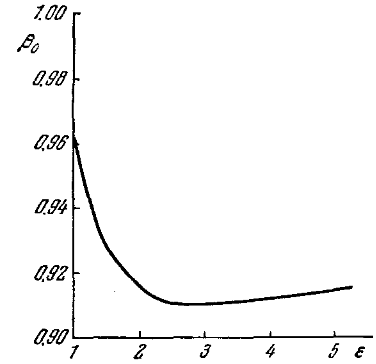

FIG. 8. Dependence of the coefficient β_0 on ϵ.

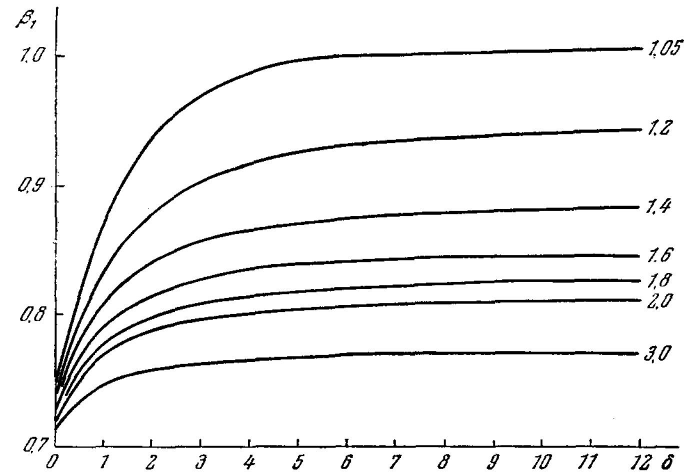

FIG. 9. Dependence of the coefficient β_1 on δ_1 for different values of ϵ.

*$\overline{T}_{e_0}$ can also be represented in terms of the mean-spherical emissivity $1 - \overline{R} = (1 - R_\perp)\alpha$ and the steady component of the surface temperature averaged over the disc, $\overline{T}_0 = 0.964\, T_0(0)$, in the following fashion: $\overline{T}_{e0} = (1 - R_\perp)\alpha \times 0.964\, T_0(0)$, where 0.964 is the averaging coefficient, and α is the normalized mean-spherical emissivity, normalized to the center of the disc

$$\alpha = 1/\pi\,(1 - R_\perp)\int\int_{-\pi/2}^{+\pi/2}[1 - R(\varphi, \psi)]\cos^2\psi\cos\varphi\, d\varphi\, d\psi.$$

The dependence of α on the dielectric constant is given in[12].

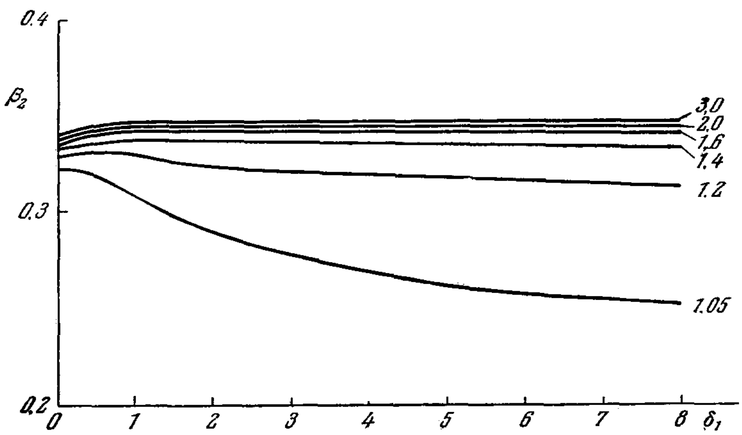

FIG. 10. Dependence of the coefficient β_2 on δ_1($\delta_2 = \sqrt{2}\delta_1$) for different values of ϵ.

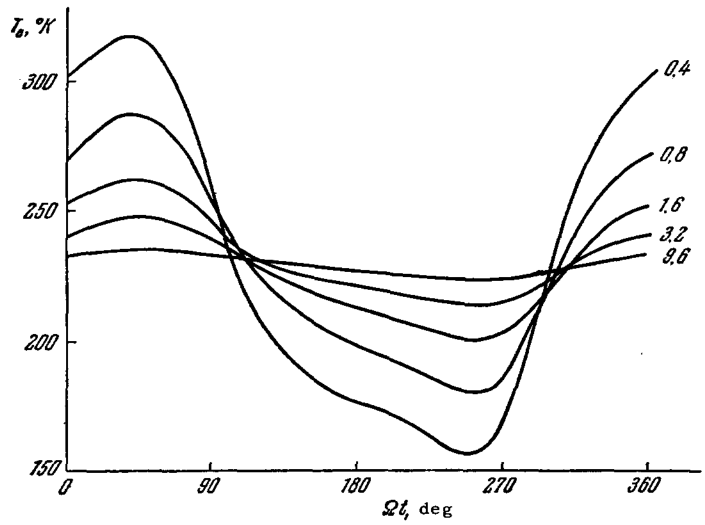

FIG. 11. Phase dependence of the effective temperature of the moon's center for different values of λ.

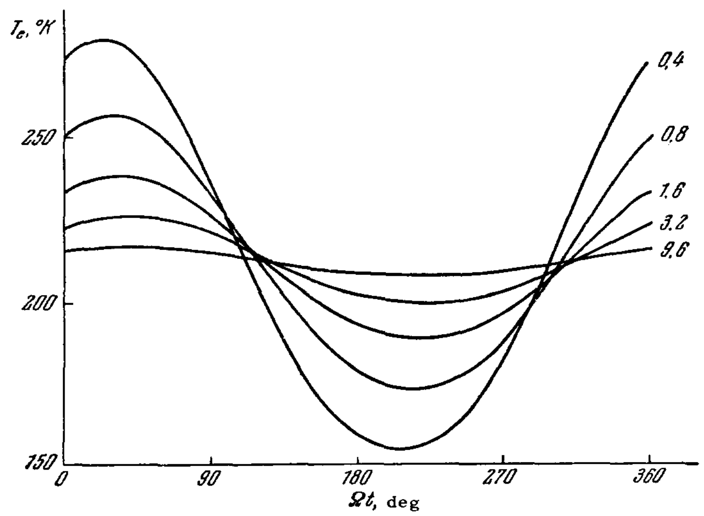

FIG. 12. Phase dependence of the effective temperature of the moon averaged over the disc for different values of λ.

moon will be attenuated even more. This means that the oscillation of the radio temperature averaged over the disc is well described by the first harmonic alone, as is confirmed by the results of the measurements of the integral radio emission from the moon at different wavelengths.

Figures 11 and 12 show the phase dependences of the effective temperature at wavelengths 0.4, 0.8, 1.6, 3.2, and 9.6 cm, calculated from (14) and (17), for the center and for the entire lunar disc[11]; these show clearly the smoothing effect resulting from spatial averaging. The values obtained for the transfer coefficient β_n for the conversion from the integral radiation to the radiation of the center of the disc or vice versa

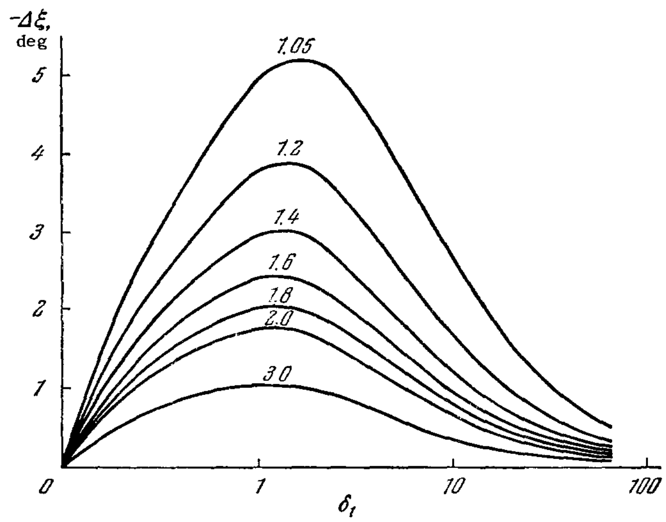

FIG. 13. Dependence of the additional phase shift on δ_1 for different values of ϵ.

enable us to reduce all the experimental data to one of the indicated characteristics.

Figure 13 shows the dependence of the additional phase shift $\Delta\xi$ on δ_1 for the first harmonic of the integral radiation. When ϵ varies over a wide range, the maximum value of $\Delta\xi$ does not exceed $-5°$. Consequently, the phase of the integral radiation leads somewhat the phase of the center of the disc. This is apparently connected with the influence of the asymmetry in the heating of the lunar surface. There is practically no analogous phase shift for the second harmonic of the integral radiation.

As is known from the experimental data, at wavelengths up to 10 cm, the ratio of the constant component to the amplitude of the first harmonic is given sufficiently accurately by

$$M_{\text{expt}} = \frac{\overline{T}_e}{\overline{T}_{1e}}. \qquad (18)$$

A comparison of this ratio with the theoretical value, which according to [11] is equal to*

$$M_{\text{theor}} = \frac{T_0(0)}{T_1(0)} \frac{\beta_0}{\beta_1} \sqrt{1+2\delta_1+2\delta_1^2}, \qquad (19)$$

enables us to determine δ from data on the integral radio emission.

In [7] is considered the radio emission of the moon for a non-homogeneous model of its upper layer, in which the density and the thermal properties vary with depth. Inasmuch as the calculation of the radio emission from such a model is in general a complicated matter, a simplified sharply non-homogeneous model was assumed, according to which the continuous thick layer of matter with parameter $\gamma \sim 100-200$ is covered with a layer of thin dust merely a few millimeters thick, having $\gamma \approx 1{,}000$. In addition, it is assumed that this layer is absolutely transparent to the centimeter and millimeter radio wavelengths, i.e., that the radio emission is due to the dense substrate. It is obvious that in this case all the formulas obtained for the radio emission (13), (14), and (15) remain in force, except that the amplitudes of the temperature harmonics at the surface itself (i.e., on the dust layer) must be replaced by the temperature amplitudes on the surface of the substrates. The dust layer acts as a thermal resistance, decreasing the amplitude of the temperature fluctuations behind it by a certain factor m. In addition, this layer causes a certain lag ξ_s in the phase of the temperature oscillations on the substrate as compared with the phase of the oscillations of the surface temperature.

The radio emission of such a model at the center of the disc, neglecting the higher harmonics, is described by the relationship

$$T_e = (1-R_\perp) T_0(0) + (1-R_\perp) \frac{T_1(0)}{m\sqrt{1+2\delta_1+2\delta_1^2}} \cos(\Phi - \varphi_1 - \xi_1 - \xi_s). \qquad (20)$$

The attenuation m and the phase shift ξ_s of the temperature waves in the dust layer depend on the thickness and heat conduction of this layer. Both quantities are interrelated by

$$m = \sqrt{1+2\delta_s+2\delta_s^2} \text{ and } \xi_s = \operatorname{arctg} \frac{\delta_s}{1+\delta_s},$$

where δ_s is some auxiliary quantity, connected with the parameters of the dust layer by the relation

$$\delta_s = \frac{k}{k'} \frac{\Delta y}{l_t}.$$

Here k′ and Δy are the heat conduction and the thickness of the dust layer, l_t the depth of penetration of the heat wave in the substrate. It is more convenient to express this quantity in terms of the parameters γ and γ' of the substrate and of the dust

$$\delta_s = \left(\frac{\gamma'}{\gamma}\right)^2 \frac{\Delta y}{l_t}.$$

The dust layer attenuating the amplitude of the temperature wave by m = 1.4 or 5 times has $\delta_s = 0.4$; assuming as usual $\gamma' = 1{,}000$ and $\gamma = 100$, and also $l_t \approx 25$ cm (see below), we obtain for the thickness of the dust layer $\Delta y = 1$ mm. It was indicated in [13,14] that if the lunar matter is similar in chemical composition to earth rocks, then the depth of penetration of the electromagnetic wave (or the thickness of the radio emitting layer) is proportional to the wavelength in vacuum, i.e.,

$$l_e = \tilde{a}\lambda, \qquad (21)$$

where $\tilde{a}$ is the proportionality coefficient and depends on the properties of the substance. Indeed, for terrestrial dielectrics, if the tangent of the loss angle is much smaller than unity, we have

$$l_e = \frac{v\sqrt{\varepsilon}}{4\pi\sigma} = \frac{\lambda}{2\pi\sqrt{\varepsilon}\,\operatorname{tg}\Delta}, \qquad (22)^*$$

*$\beta_0/\beta_1 = 1$ for the center of the moon's disc.

*tg = tan.

where σ is the effective electric conductivity at a given frequency

$$\operatorname{tg} \Delta = \frac{2\sigma}{\varepsilon f}$$

is the loss angle, f the frequency of the wave, and v the velocity of light in vacuum. As will be clear from what follows, relationship (21) is valid also for lunar rocks [3,13,14,34]. Thus, the greater the wavelength of the received radiation, the greater the depth from which it originates.

In this connection, if the temperature in the interior of the moon is higher, as it is on earth, owing to the flow of heat from the inside, then the constant component of the radio emission should increase with the wavelength. In [15,16] there is a theoretical analysis of the influence of the internal heat flux on the radio temperature of the moon.

In the calculations of [16] it was assumed that in a thick layer matter can become denser with increasing depth, and consequently, the heat conductivity can depend on y. However, in order to simplify the calculation, the attenuation of the electromagnetic wave was assumed to be independent of y.

The constant component of the temperature at a depth y, in the presence of internal heat flux, is a function of y and in the general case, it is equal to

$$T_0(\varphi, \psi, y) = T_0(\varphi, \psi) + t(y), \tag{23}$$

where $T_0(\varphi, \psi)$ is the constant component of the temperature, due to the heating by the sun, which was determined in Sec. 2 above, and $t(y)$ is the additional temperature, determined by the density of heat flux q_s from the interior of the moon and by the heat conductivity $k(y)$, with $t(0) = 0$,

$$t(y) = q_s \int_0^y \frac{dy}{k(y)}. \tag{24}$$

It was assumed in [16] that $T(y, \varphi, \psi)$ differs little from a linear function in y

$$T(y, \varphi, \psi) = T_0(\varphi, \psi) + by + gy^2. \tag{25}$$

From (11) and (25) we obtain the following expression for the constant component of the effective temperature of the surface element:

$$\begin{aligned} T_{e\lambda}(\varphi, \psi) &= [1 - R(\varphi, \psi)] \int_0^\infty [T_0(\varphi, \psi) \\ &+ by + gy^2] \varkappa \sec r' e^{-y\varkappa \sec r'} dy \\ &= [1 - R(\varphi, \psi)] (T_0(\varphi, \psi) + bl_э \cos r' + 2gl_э^2 \cos^2 r'). \end{aligned} \tag{26}$$

For the center of the disc $\cos r' = 1$ and

$$T_{e\lambda}(0, 0) = (1 - R_\perp)(T_0(0, 0) + bl_e + 2gl_e^2). \tag{27}$$

As can be seen from (21) and from the expression obtained, an increase in the radio brightness of the central part of the disc should be observed with increasing wavelength, whereas the edge of the disc, where $\cos r' \approx 0$, has a constant radio brightness. Neglecting the quadratic term and assuming for the moon a coefficient [3] $\tilde{a} = 2l_t^3$, we obtain the following expression for the temperature gradient inside the moon in terms of the constant components of the effective temperature measured at two wavelengths

$$\operatorname{grad} T = \frac{T_{e\lambda_2} - T_{e\lambda_1}}{(1 - R_\perp) 2l_t (\lambda_2 - \lambda_1)}. \tag{28}$$

Multiplying (28) by the heat conduction coefficient and transforming, we obtain for the heat flux

$$q = \frac{(T_{e\lambda_2} - T_{e\lambda_1}) \sqrt{\frac{\Omega}{2}}}{(1 - R_\perp) 2\gamma (\lambda_2 - \lambda_1)}. \tag{29}$$

Relationships (28) and (29), determined in [16], enable us to calculate the temperature gradient in the heat flux from the experimental data.

The polarization of the radio emission from the moon is of interest. The polarization of the radiation from a surface element is connected with the different emissivity of the surface for the horizontal and vertical polarized radiation, and it can be calculated in an elementary fashion. A more complicated question is that of the polarization of the integral radiation. In [8] are presented the corresponding calculations and it is shown that the integral radiation is polarized only as a result of the latitudinal variation of the moon's surface temperature. The degree of polarization depends on the dielectric constant and does not exceed 1 or 2%. The possible influence of roughness on the intensity of the radio emission is discussed in [8] qualitatively in the geometrical optics approximation. At the present time this question should be solved accurately. Particularly urgent is an investigation of the influence of roughness on the polarization of radio emission, both for surface elements and for the entire lunar disc.

4. EXPERIMENTAL DATA ON THE RADIO EMISSION FROM THE MOON

The radio emission of the moon was first measured by Dicke and Beringer in 1946 at 1.25 cm [18]. They made only one measurement near full moon (phase angle +18°). The first systematic observations of the radio emission from the moon over an entire lunar cycle were made at 1.25 cm by Piddington and Minnet [7] in 1949. They observed that the effective temperature of the moon averaged over the disc varies at this wavelength approximately sinusoidally, like $T_e = 215° + 36 \cos(\Phi - 45°)$. An interesting feature of the results is that the amplitude of this variation is practically one quarter of the amplitude obtained in the infrared, and the maximal of the radio emission lags behind the optical phase by 45° (there is practically no delay for infrared radiation). The authors have explained this correctly by showing that the radio waves originate also in layers lying under the surface, where the temperature variation is smaller than on the surface, and where the temperature wave has a phase delay. In 1952 the radio emission of the moon was measured at the NIRFI at 3.2 cm [13]. In this investigation, only the upper limit of the relative change in effective temperature was established to be $\leq 7\%$, at a mean value of 170°K. Later measurements, carried out in 1959–1961 at 3.2 cm [22,37], have disclosed that the radio emission from the moon has a phase dependence at this wavelength.

In 1958 A. E. Salomonovich observed a phase variation in the radio temperature at 8 mm [32]. Even the first experiments have shown that the alternating part of the moon's radio emission depends significantly on the wavelength, and this has made it possible to establish the correctness of (21) for the moon in [13,14].

Table II. Summary of results of the measurement of the Moon's radio emission

No.	λ, cm	Mirror diameter, d, m	Half width of diagram	T_{e0}, °K	T_1, °K	ξ, deg	Measurement error	$M=\frac{T_{e0}}{T_1}$	δ_1	$\frac{\delta_1}{\lambda}$	Year of publication	Author	Remarks
1	0,13	0.42	10′	219	120	16°	±15	1.82	0.22	1.7	1963	L.N. Fedoseev (NIRFI)[25]	Single measurements using optical techniques
2	0.15										1955	W.M. Sinton[27]	
3	0,18	1	6′	240	115	14	±20	2.08	0.34	1.9	1963	A.I. Naumov (NIRFI)[26]	
4	0.40	0.95	25′	230	73	24	±10	3.15	0.9	2.20	1961	A.G. Kislyakov (NIRFI)[28]	
5	0,40	22	1′.6	228	85	27	±15	2.7	0.76	1.7	1963	A.G. Kislyakov, A.E. Salomovich (NIRFI, FIAN)[29]	
6	0.40	0.5	36′	204	56	23	±4	3.8	0,95	2.3	1963	A.G. Kislyakov, V.M. Plechkov (NIRFI)[30]	
7	0.43	3.5	6′.3				±20				1958	R.J. Coates[31]	Three measurements for phases 77, 126, and 280° (Φ = 0 corresponds to new moon). T_e is respectively equal to 182, 243, and 245°K
8	0,8	2	18′	197	32	40	±10	6,16	1.84	2.3	1958	A.E. Salomonovich (FIAN)[32]	
9	0,8	22	2′	211	40	30	±15	5.28	1,95	2.4	1962	A.E. Salomonivich, B. Ya Losovskiĭ (FIAN)[20]	
10	0.86		12′	180	35	35	±15	5.14	1.88	2.18	1958	R.H. Dicke, R. Beringer[18]	Angle measurement: phase +18°, T_e = 270°K
11	1,25												
12	1.25	1.12	45′	215	36	45	±10	6	2.1	1,7	1949	J.H. Piddington, H.C. Minnet[7]	
13	1.63	4	26′	224	36	40	±10—15	6,22	2.4	1.5	1959	M.R. Zelinskaya, V.S. Troitskiĭ, L.N. Fedoseev (NIRFI)[34]	
14	1.63	1.5	44′	208	37	30	±3	5.6	2.2	1.3	1962	S.A. Kamenskaya, B.I. Semenov, V.S. Troitskiĭ, V.M. Plechkov (MIRFI)[35]	
15	1.63	1.5	44′	207	32	10	±3	6,62	2.25	1,4	1963	D.A. Dmitrienko, S.A. Kamenskaya (NIRFI)[25]	
16	2.0	22	4′	190	20	40	±75	9.5	4.0	2.0	1961	A.E. Salomonovich[20], V.I. Koshchenko (FIAN)	
17	2.3		2′×40′			35					1961	N.L. Kaĭdanovskiĭ, V.N. Iskhanova, G.P. Apushinskiĭ, O.N. Shivris (Main Astron. Obs.–GAO)[81]	Phase variation obtained for the shift in the center of gravity of the emission
18	3,2	22	6′	223	17	45	±15	13,1	5.3	1.7	1961	V.N. Koshchenko, B.Ya. Losovskiĭ, A.E. Salomonovich (FIAN)[22]	
19	3.15	15	9′	195	12	44	±15	16.2	6.6	2.1		C.H. Mayer, R.M. McCullough, R.M. Sloanaker[19]	
20	3.2	4	35′	170	12		±15	14	60	1,9	1955	M.R. Zelinskaya, V.S. Troitskiĭ (NIRFI)[13]	
21	3.2	4	40′	255	16	50	±15	15.9	6,43	2,05	1961	K.M. Strezhneva, V.S. Troitskiĭ (NIRFI)[37]	
22	3,2	1,5	1°12′	210	13,5	55	±2,5	15,55	6.35	2,0	1961	V.D. Krotikov, V.A. Porfir'ev, V.S. Troitskiĭ (NIRFI)[24]	
23	3.2	1.5	1°27′	213	14	26	±2	15.2	6.2	1.95	1962	L.I. Bondar', M.R. Zelinskaya, V.A. Porfir'ev, K.M. Strezhneva (NIRFI)[38]	
24	3.2	4	40′	216	16	15	±3	13.5	5.4	1,7	1962		
25	9.4	3.5	2°20′	220	5.5	—	±5	40	19.5	2	1961	W.I. Medd, N.W. Broten[39]	Data recalculated for center of visible disc

Table II (cont'd)

No.	λ, cm	Mirror diameter, d, m	Half width of diagram	T_{e0}, °K	T_1, °K	ξ, deg	Measurement error	$M=\frac{T_{e0}}{T_1}$	δ_1	$\frac{\delta_1}{\lambda}$	Year of publication	Author	Remarks
26	9.6	22	19′	230			±15	46	21	2.3	1961	V.N. Koshchenko, A.D. Kuz'min, A.K. Salomonovich (FIAN)[23]	
27	9.6	4	1°40′	218	7	40	±2.5	31	13.4	1.4	1961	V.D. Krotikov (NIRFI)[40]	
28	10			215							1951	J.H. Piddington, H.C. Minnet[17]	Single measurement
29	10			130							1956	N.L. Kaĭdanovskiĭ, M.T. Tursubekov, S.É. Khaĭkin (GAO)[41]	
30	10	10		315	75						1955	K. Acabane[42]	
31	10.0	25	18′	256			±15				1960	I. Castelly, C.P. Ferioli, J. Aarons[43]	Observation during 1 day (50 readings of the moon)
32	10.3										1961	J.A. Waak[45]	Reports observation of phase variation ~2.5%, no numerical data cited
33	10.3	25	18′,5	207			±15					R.M. Sloanaker[44]	Unpublished, referred to in[77]
34	11	25	17′	214			±12				1960	P.G. Messger, H. Strassl[46]	Some change of temperature observed near new moon
35	20.8	25	36′	205	5						1961	J.A. Waak[45]	Reports observation of 2.5% phase variation
36	21	25	35′	250	⩽5		±15				1959	P.G. Messger, H. Strassl[47]	
37	22	76	15′	270			±20				1960	R.D. Davies, R.C. Jennisson[48]	
38	22			270							1958	G. Westerhout[49]	
39	23	25	38′	254	⩽6,5		±15				1960	J.P. Castelly, C.P. Ferioli, J. Aarons[43]	
40	32.3	8	3°	233			±2.5				1963	V.A. Razin, V.T. Fedorov (NIRFI)[50]	
41	33			208								J.F. Dennisse, E. deRoux[51]	Unpublished, cited in[54]
42	35	8	3°6′	236			±4				1963	V.D. Krotikov, V.A. Porfir'ev (NIRFI)[52]	
43	36	8	3°10′	237			±3				1963		
44	50	8	4°40′	241			±5					V.D. Krotikov (NIRFI)[53]	
45	75	25	2°	185			±20				1957	S.L. Seeger, G. Westerhout, R.G. Convway[54]	
46	168		13′,6× ×4,6°	233			±4				1961	J.E. Baldwin[15]	

By now, extensive experimental material on the moon's radio emission has been accumulated in the wavelength range from 0.13 to 168 cm. The results of the measurements are listed in Table II. The first column indicates the wavelength, the second the antenna diameter, the third the width of the directivity pattern, and finally the fourth, fifth, and sixth give the values obtained by the authors for the constant component T_{0e}, the amplitude of the first harmonic of the oscillations of the radio temperature T_{1e}, and the phase lag ξ_1, respectively. This, almost all the experimental data (with the exception of the data obtained at millimeter wavelengths at large radio telescope resolution) are approximated by

$$T_e = T_{0e} + T_{1e}\cos(\Phi - \xi_1).$$

In Table II are listed the values of the measurement errors cited by the authors of the papers, and also the values of δ_1 and δ_1/λ calculated from the tabulated data; the table contains both the measurements performed by the usual procedure, which is accurate to $\pm 10 - \pm 20°$, as well as measurements with $\pm 2-3\%$ accuracy. The former constitute essentially the group of relative measurements, and the latter are absolute. In the relative-measurement group the discrepancies between data obtained by different workers, even at one wavelength (if we discard the patently erroneous measurements of [41,42]) reach double the value of the error cited by each author, i.e., 30%. In the precision measurement group, the discrepancies at each wavelength are considerably smaller than the cited error of each measurement.

Of interest to the relative measurements of the intensity fluctuations are measurements made at different wavelengths by a single procedure and by the same workers. In this connection, notice should be taken of the results obtained in 1959—1961 by a group of radio astronomers at the Physics Institute of the Academy of Sciences, at wavelengths 0.8, 2.0, 3.2, and 9.6 cm using the 22-meter radio telescope[20-23]. The high resolution of the radio telescope has enabled the authors to obtain at wavelengths 0.8, 2.0, and 3.2 cm the two-dimensional distribution of the radio brightness over the moon's disc as a function of its phase, and to observe the theoretically predicted[8] darkening towards the edge of the lunar disc, due to the difference in the emissivity. The precision measurement group includes data obtained at the NIRFI by the "artificial moon" method at wavelengths 0.4, 1.6, 3.2, 9.6, 32.3, 35, 36, and 50 cm[24,30,35,36,38,40,50,52,53]. These measurements have made it possible to determine the thermal parameters of the material of the surface cover of the moon, its density and dielectric constant, and also the systematic increase in the moon's temperature with wavelength. The phase dependence of the radio emission at 9.6 cm was first observed. Particular notice must also be taken of the importance of the first detailed measurements of the moon's radio emission at 0.13 and 0.18 cm, made at the NIRFI by L. N. Fedoseev[25] and A. I. Naumov[26]. No such measurements were made until recently, if we disregard the isolated measurements of Sinton at 0.15 cm using optical techniques[27].

5. STRUCTURE OF THE OUTER COVER OF THE MOON

At the present time there are various hypotheses concerning the structure of the outer cover of the moon. An hypothesis which is widespread, particularly outside the USSR, is Gold's hypothesis[55] of the solid dust cover. According to this hypothesis, the ultraviolet and corpuscular radiation from the sun destroys the crystalline lattice of the minerals, and meteor impacts pulverize and mix the lunar bedrock, as a result of which a fine dust layer arises, the thickness of which can reach several kilometers. This continuous dust layer does not remain at its point of origin, but shifts from the high-lying sections to the lowlands.

In very many papers where the nature of the moon's surface is discussed there is expressed the thought that inasmuch as there are no erosion processes on the moon, the lunar surface is the fresh unchanging surface of magmatic rock (see, for example,[56]).

An approach to the question of the nature and structure of the material of the lunar surface on the basis of a comparison of the optical characteristics (reflection coefficient, scattering indicatrix, color, etc.) of the lunar surface and terrestrial rocks has led to the conclusion that the moon's surface is not made up of fresh continuous rock. The comparison indicates that the surface is slag-like; consequently N. N. Sytinskaya advanced the so-called meteor-slag hypothesis of the formation of the outer cover of the moon[57]. According to this hypothesis, the outer cover of the moon, up to a depth of perhaps several meters, is the result of modification by meteors, which crush, mix, and evaporate the rock. The condensation of the vapor and the cooling of the molten matter under vacuum conditions leads to the occurrence of porous slag-like formations.

The foregoing hypotheses regard, in one manner or another, the moon's surface as being homogeneous in depth and having no radical changes in the structure near the surface. When Wesselink[1] interpreted the experimental results of Pettit[58] on the measurement of the moon's surface temperature during an eclipse, he also used the notion that the lunar surface has a homogeneous structure. Wesselink has shown that the experimental curve showing the temperature variation of the moon's surface during the eclipse coincides with the theoretical one, calculated for a homogeneous model with $\gamma = (k\rho c)^{-1/2} \approx 1{,}000$. Later, however, Piddington and Minnet[7], in an explanation of the experimental results on radio emission from the moon, reached the conclusion that there exists on the lunar surface a thin layer of dust (several millimeters thick), which is transparent to radio waves, but which greatly attenuates the thermal wave. The presence of such a dust layer explained well the presence of a considerably larger phase shift in the radio emission relative to the heating phase, larger than would follow from the notion that the moon's surface has a homogeneous structure.

Jaeger and Harper[59], in an interpretation of Pettit's results, indicated that the experimental curve for the cooling of the lunar surface during the time of full shadow is somewhat less steep than would follow from the notion of the homogeneous structure of the lunar surface. On the basis of the foregoing calculations, they reached the conclusion that the two-layer model of the lunar surface, according to which there exists a non heat conducting layer of dust 2—3 mm thick having a thermal parameter $\gamma = 1{,}000$, lying over a solid substrate with $\gamma = 100$, gives better agreement with experiment than the homogeneous model. This gave rise to the notion of the two-layer structure of the lunar surface. What is the structure, can we assume the outer cover to be homogeneous, or does it have a sharply inhomogeneous two-layer structure?

The answer to this question is the subject of [3], in which there are analyzed special measurements made at the NIRFI on the radio emission from the moon in the wavelength range 0.4—3.2 cm, and in which use is made of data in reports by others.

The analysis is based on a comparison of the experimental data concerning the dependence of the characteristics of the moon's radio emission [the quantities $M(\lambda)$ and $\xi(\lambda)$] on the wavelength with the theoretical data for the homogeneous and the two-layer model of construction, in accordance with the formulas of Sec. 3. The possibility of observing sharp inhomogeneity of the layer (a double layer) by comparison of data obtained at different wavelengths is physically connected, on the one hand, with the variable heat conditions, and on the other with the fact that data obtained at different wavelengths correspond to measurements of the temperature at different depths. Any radical variation of the properties of the outer cover with depth leads to a change in the temperature distribution and can be observed in the radio emission. In the case of a temperature which does not change with time or with depth, no non-homogeneities can appear in the radio emission. Therefore an investigation of the outer layer of the moon's surface (in the absence of a heat flux from the inside) can be extended only to a depth comparable with the depth where temperature fluctuations still exist, to $(3-4)\, l_t$. We shall show later, however, that owing to the considerable heat flux from the inside of the moon, it becomes possible to investigate a layer that extends to considerable depths. In virtue of the fact that the temperature gradients due to the heat flux are large in a layer of thickness $(3-4)\, l_t$, this layer is the most accessible for study.

From the main characteristics of the radio emission from the moon indicated above, the quantity most accurately determined is the relative amplitude of the radio temperature fluctuations. In the case of a homogeneous layer, the radio emission is determined by a thinner and thinner layer with reduction of wavelength, and in the limit as $\lambda \to 0$ the radiation comes from the surface. The amplitude of the oscillation of the radio temperature (in the case of an absolutely black surface) will in the limit equal the amplitude of the fluctuation of the temperature on the surface itself, i.e., approximately 155°. For the two-layer structure it is obvious that the amplitude of the fluctuations of the radio temperature will tend, with decreasing wavelength, to the amplitude of the temperature oscillations under the dust layer, as the dust layer becomes transparent, i.e., it will tend to a value which is m times as small as for the homogeneous layer. This enables us to observe the sharp non-homogeneity produced in the two-layer model by the layer of dust which does not absorb radio waves. In the cited paper [3], there was plotted for this purpose an experimental curve of the ratio $M(\lambda)$ of the steady component to the amplitude of the alternating component against λ. The ratio $M(\lambda)$ is determined most accurately, because it is independent of the accuracy of the absolute measurements and of the radiating ability of the moon. Figure 14 shows this curve (dots), supplemented with the results of the latest measurements at $\lambda = 0.13$ cm and $\lambda = 0.18$ cm.

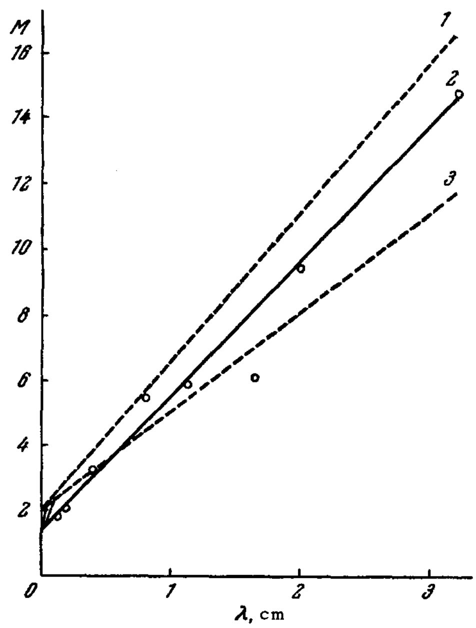

FIG. 14. Dependence of M on λ. Curve 2—one-layer model with $m_s = 1$, $\delta_1 = 2\lambda$. Curve 1—two-layer model with $m_s = 1.5$, $\delta_1 = 1.5\lambda$. Curve 3—with $m_s = 1.5$, $\delta = \lambda$.

It is clearly seen that extrapolation of the curve to $\lambda \to 0$ gives the ratio of the constant component of the surface temperature to the amplitude of the first harmonic on the surface

$$M(0) \cong \frac{T_0(0)}{T_1(0)}.$$

This ratio is found to be

$$\frac{T_0}{T_1} = 1.5. \qquad (30)$$

The theoretical $M(\lambda)$ curve for the two-layer model has in accordance with (20) the form

$$\left. \begin{aligned} M(\lambda) &= m\frac{T_0(0)}{T_1(0)}\sqrt{1+2\delta_1+2\delta_1^2}, \\ l_e &= a\lambda. \end{aligned} \right\} \qquad (31)$$

When $m = 1$ we obtain the function for the single-layer model. The theoretical function $M(\lambda)$ (solid straight line) passes through the experimental points only for $m = 1$ and $\delta = 2\lambda$, i.e., for the one-layer model. Figure 14 shows also the theoretical (dashed) curves for the two-layer model with a dust layer which attenuates the amplitude of the temperature oscillations under the layer by a factor m = 1.5. Upon extrapolation to $\lambda \to 0$, these curves, in accordance with the foregoing, should tend to a larger value of M(0), equal to $\frac{T_0(0)}{T_1(0)}$ m. The two theoretical curves correspond to different values of the coefficient $\tilde{a}$, i.e., to different electrical properties of the medium. It must be noted that actually, no matter how transparent the dust layer, it becomes opaque just the same for some wavelength. This should manifest itself in the fact that starting with this wavelength the curves $M(\lambda)$ for $\lambda \to 0$ will converge to the point $m_S = 1$, shown in Fig. 14 by the dotted part of the dashed lines. In general, for any two-layer model with given m and with different assumptions concerning the value of $\tilde{a}$, there will be obtained a pencil of straight lines which appear to emerge from the point m $\frac{T_0(0)}{T_1(0)}$ on the $M(\lambda)$ axis. As can be seen from Fig. 14, it is possible to choose a theoretical straight line corresponding to the double-layer model, which would agree with the experimental results at one wavelength or at close wavelengths, but the experimental points obtained will lie on straight lines corresponding to different values of the coefficient $\tilde{a}$. This means that the electrical properties of the moon's surface depend on the wavelength in an explicably complicated manner.

Thus, an analysis of the dependence of the amplitude of the oscillations of the radio temperature on the wavelength offers unambiguous evidence in favor of the homogeneous model of the crust. In [3], in order to determine this model, the experimental data were also analyzed on the basis of the dependence of the phase lag of the radio emission ξ on the value of M. The quantities ξ and M are related and depend on the wavelength. The character of their relation is determined by the structure of the moon's surface. To ascertain the surface structure to which the experimental data correspond, it is necessary to plot $\xi(M)$ curves corresponding to both models, and to place the experimental points on these plots. The theoretical value of $M(\lambda)$ is given by (31), and the corresponding phase shift angle is

$$\xi = \operatorname{arctg} \frac{\delta_1}{1+\delta_1} + \xi_s, \tag{32}$$

where ξ_S is the phase shift produced in the dust layer ($\xi_S = 0$ for the homogeneous surface structure). The theoretical relation $\xi(M)$ is obtained by eliminating δ_1 from (31) and (32), and has in accordance with [3] the form

$$\xi(M) = \operatorname{arctg} \frac{-\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{1}{2}\left\{\left[\frac{M}{m_s}\frac{T_1(0)}{T_0(0)}\right]^2 - 1\right\}}}{\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{1}{2}\left\{\left[\frac{M}{m_s}\frac{T_1(0)}{T_0(0)}\right]^2 - 1\right\}}} + \xi_s. \tag{33}$$

Figure 15 shows curves calculated in accordance with (33), assuming

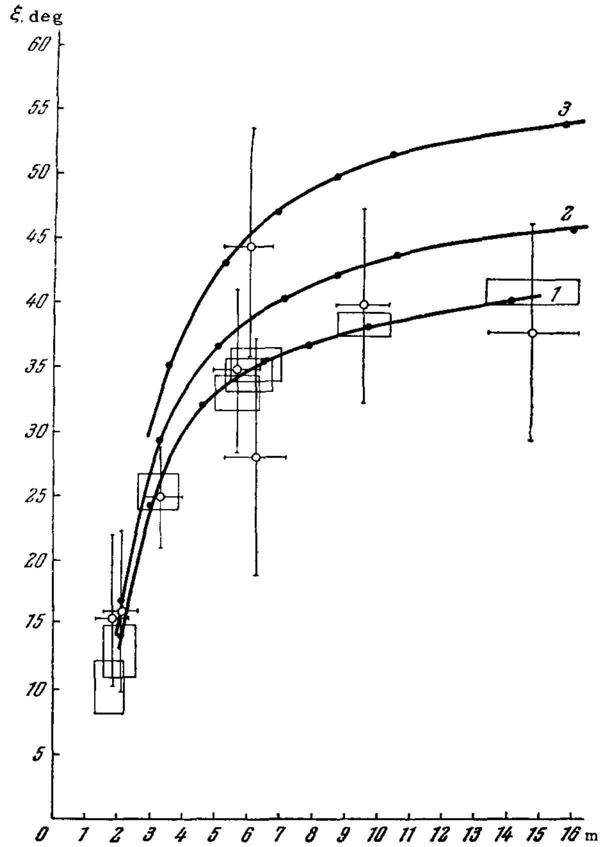

FIG. 15. Theoretical dependence of the phase lag of the first harmonic of the moon's radio emission on the ratio of the steady component to the amplitude of the first harmonic. 1 – Homogeneous surface structure ($m_S = 1$, $\xi_S = 0$, $\delta = 2\lambda$), 2 and 3 – two-layer dust model ($m_S = 1.1$, $\xi_S = 5°$, $\delta = 2\lambda$, and $m_S = 1.4$; $\xi_S = 15°$, $\delta = 1.5\lambda$). Full circles – theoretical for wavelengths 0.13, 0.4, 0.8, 1.25, 1.63, 2.0, and 3.2 cm. Light circles– experimental points with the errors in ξ and M indicated. The rectangles correspond to the errors for ξ and M if ξ is calculated from the value of δ_1 determined from the experimental data.

$$\frac{T_0(0)}{T_1(0)} = 1{,}5,$$

as follows from the experimental data. Curve 1 corresponds to the homogeneous structure of the moon's surface with $m_S = 1$ and $\xi_S = 0$. Curve 2 corresponds to the double-layer model with a very thin dust layer, $m_S = 1.1$ and $\xi_S = 5°$. When the thickness of the layer is increased to $m_S = 1.4$ and $\xi_S = 15°$, we obtain curve 3. The experimental points are shown by circles, with the limits of the possible errors in ξ and M indicated. Each point corresponds to the average values of ξ and M, obtained for each wavelength on the basis of Table II.

As can be seen from Fig. 15, the experimental points* correspond all together to the curve 1, calculated for the single-layer model, and they cannot be

*In comparison with the figure of[3], experimental points are presented for recent measurements made at $\lambda = 0.13$ cm[25] and 0.18 cm[26].

simultaneously reconciled with the two-layer model, with a very thin dust layer (curve 2). Indeed, whereas the point corresponding to the measurement at 1.25 cm can be reconciled with the two-layer model (Fig. 3), the data for the remaining wavelengths do not lie in this curve at all. Whereas at 3.2 cm the theoretical value of the phase $\xi = 45°$ for the two-layer model with a very thin dust layer lies within the limits of possible errors, at 0.4 and 1.6 cm the theoretical value of the phase differs from the experimental ones. It is possible to choose parameters for the two-layer model so as to satisfy the experimental data at one wavelength or close wavelengths, but this cannot be done at all over the entire wavelength interval. In order to reconcile the experimental data with the theoretical relation for the two-layer model it becomes necessary to decrease the layer, even compared with curve 2, meaning that there exists no dust layer that is transparent for the employed waves on the surface of the moon.

The result is the unambiguous statement that up to a depth to which the 3.2 cm wave penetrates, i.e., 1—2 meters, the outer crust of the moon is approximately a homogeneous structure, and the two-layer dust model, which is also highly non-homogeneous, does not correspond to reality.* Therefore, we can use in lieu of the quantity ξ_{exp}, which is not measured with sufficient accuracy, the theoretical value obtained from the experimentally determined value of M. In Fig. 15 these values (rectangles) all fit accurately the curve corresponding to the homogeneous structure of the moon's surface. Another important result of the analysis in [3] is the establishment of a quantitative relation between the wavelength λ and the quantity l_e [see formula (21)]

$$\delta = 2\lambda, \quad l_e = 2\lambda l_t, \tag{34}$$

which is valid, when the new data are included, in the range from 0.1 to 3.2 cm. Figure 16 shows the values of δ/λ as functions of λ, averaged for each wavelength over all the available data. Some deviation from the indicated dependences is obtained in the vicinity of 1.63 cm. It can be interpreted, in particular, as the presence of an absorption line in the lunar matter at this wavelength. Other explanations can also be offered, but to clarify the nature of this effect it is necessary to carry out additional measurements at wavelengths close to the line.

The investigation of the model of the structure of the upper layer against the character of the moon's radio emission spectrum, carried out in [2] is so far the only one, but in papers which are devoted for the most part to the analysis of data at some one particular wavelength, some conclusions are drawn also on the model of the structure. In Soviet papers it is in-

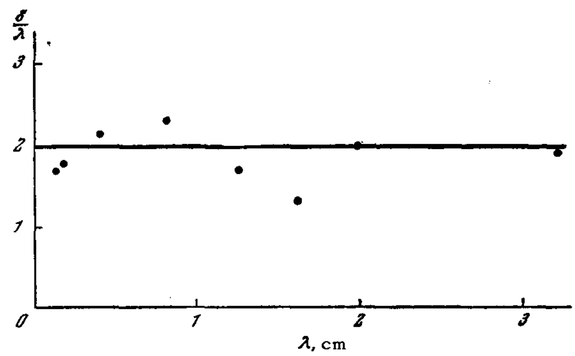

FIG. 16. Dependence of the ratio δ/λ on the wavelength λ. The black dots correspond to the experimental data.

dicated most frequently that the single-layer model is correct, citing the correspondence between the amplitude of the alternating part and the phase lag, which is characteristic of the single-layer model (see, for example, [9,32]).

Papers of similar character published outside the USSR, on the contrary, frequently contain statements of agreement with the thin-layer-dust model (see, for example [60]). However, no analysis of the radio emission in a wide range of wavelengths, i.e., a spectrum, is presented.

In [61] the experimental work on the radio emission and radar sounding of the moon is discussed within the framework of the homogeneous model. The author assumes the lunar surface to be covered with a layer of a dustlike material, the thickness of which can be different in the valleys and in the high points. No new quantitative data are cited, however.

Somewhat more definite opinions concerning the structure of the outer cover are made in the paper by Gibson [62] on the data of investigations of the radio emission from the moon at $\lambda = 0.86$ cm during an eclipse. The author observed no decrease in intensity larger than the fluctuation of the input signal, which amounted to 1°. Knowing the depth of the layer which has cooled during the time of the eclipse, and taking the drop in radio temperature per degree, Gibson obtained the absorption coefficient of the material of the cooling layer, which was found to be one tenth the absorption coefficient obtained by measuring the radio emission during the time of lunation at the same wavelength. This discrepancy is attributed by the author to the presence of two layers on the moon's surface. The first layer has a low thermal conductivity ($\gamma = 1000$) and is responsible for the variation of the radio emission at 0.86 cm during the eclipse, being made of matter similar to dry sand. The radio emission at 0.86 cm, not being appreciably absorbed in the outer layer, comes predominantly from the substrate layer, which consists of a pumice type material, the thermal conductivity of which is calculated by the authors to be 16 times that of the upper layer ($\gamma \approx 250$). Since the temperature of the substrate does not remain constant during the time of the lunation, as during the eclipse,

*In Sec. 9 we show, on the basis of an analysis of the dependence of the steady component of the radio temperature on the wavelength, that the outer cover of the moon is approximately homogeneous to a depth 15 – 20 meters.

the alternation of the radio emission during the lunar cycle yields information on the absorption by precisely this layer. The author indicates, however, that this two-layer model cannot be reconciled with the results of the measurements at longer wavelengths ($\lambda \approx 3.2$ cm) during the time of lunation, since the presence of the outer layer should lead, in his opinion, to larger values of the amplitude of the effective temperature than are actually observed.* In order to eliminate this contradiction, it is concluded that the lunar surface has a three-layer structure. It is assumed here that the second layer has a thickness which is approximately equal to the depth of penetration of the wave, 1 cm. The third layer has a thermal conductivity larger than the second layer, and is made up of materials analogous to the terrestrial rocks. These considerations, although physically correct, cannot withstand quantitative tests, since they are based, on the one hand on old data concerning the density and dielectric constant (he uses $\rho = 2$ and $\epsilon = 5$), and on the other hand ρ and k are assumed to be independent. In addition, the observation of the integral radiation during the eclipse leads in itself to a smoothing of the curve showing the drop of the radio temperature. This is not taken account by the author. By virtue of the foregoing, Gibson's model is not sufficiently well justified, although apparently some decrease in the density of matter towards the surface is to be expected (see also [9,32]).

Thus, the variable thermal regime caused by the sun has made it possible to establish, by measuring the amplitude of the alternating part of the radio emission, the properties of the layer up to a depth $l_e = 2\lambda$, $l_t \cong 150$ cm. Deeper sounding at longer wavelengths no longer yields reliable values of the alternating component, and consequently cannot yield any information concerning these layers.

It turned out, at the same time, that owing to the presence of heat flux from the interior of the moon, there is a considerable temperature gradient inside the moon, as established by the authors of this review in [63]. This uncovers the possibility of investigating the parameters of the layer by determining the character of the depth distribution of the temperature, measured determining the wavelength dependence of the studied component of the radio emission (see Section 3).

Owing to the use of the precision method of measuring radio temperatures, it became possible to observe and measure the temperature gradient inside the moon in a layer up to 20 meters. It turned out to be practically constant throughout, thus providing evidence that the material is uniform to a depth of 15—20 meters.

We see that the foregoing analysis has established only the basic character of the layer—its approximate homogeneity—but it could not and cannot answer the question concerning the physical parameters of the layer and the microstructure of the matter in it (dust, solid, etc.). These answers are obtained by analyzing the absolute values of the radio temperatures themselves, as well as other data, as will be considered below.

*Actually, the presence of a layer that does not conduct heat leads to a decrease in the amplitude of the oscillation; see Sec. 3, formula (20).

6. THERMAL PROPERTIES OF THE MATERIAL OF THE MOON'S CRUST

In 1930, Pettit and Nicholson[5] indicated, on the basis of experimental data which they obtained during the lunar eclipse of 1927, that the sharp decrease in the temperature of the lunar surface during the passage of the penumbra is due to the low thermal conductivity of the material of the lunar surface. Analyzing the results of this eclipse, Epstein[64] reached the conclusion that the parameter γ for lunar matter is close to 120. Inasmuch as this quantity is characteristic of porous terrestrial rocks such as pumice, the lunar surface is consequently covered with porous material. However, Epstein's calculations turned out to be in error. A rigorous calculation, as indicated by Wesselink[1] and by Jaeger and Harper[59], whose work was mentioned in Section 2 above, leads to a much larger value of the parameter γ for the lunar surface, equal to 1,000 according to their calculations. Assuming for the lunar surface $\rho = 2\text{g/cm}^2$ and $c = 0.2$, they found that a value $\gamma = 1{,}000$ corresponds to a thermal conductivity coefficient $k = 2.5 \times 10^{-6}$ cal/cm-sec-deg. Such a low value of thermal conductivity is possessed, according to Smoluchowski[65], by thin dust in vacuum.

Jaeger[2] undertook an attempt to determine the parameter γ from the calculated curves showing the variation of the temperature during the lunar cycle, by comparison with the surface temperature during lunar midnight as measured by Pettit and Nicholson ($T_n = 120°\text{K} \pm 15°$). However, lack of an exact value of T_m made it only possible to establish that this temperature corresponds to a value of γ ranging between 200 and 1,000.

Fremlin in [82] gives for the lunar craters a depth dependence of the thermal conductivity coefficient $k(y) = 7 \times 10^{-7}\sqrt{y}$. For the surface of the crater he assumes the value of k at a depth of 1 cm, i.e., $k_{sur} = 7 \times 10^{-7}$ cal/cm-sec-deg. However, as indicated by Jaeger, this value is unjustifiably low and contradicts both the results of Pettit[58], and the recently obtained data of Saari and Shorthill[83], who cite results and measurements of individual lunar craters during the time of the eclipse in the infrared range.

A more accurate value of the nighttime temperature was determined quite recently by Sinton[66]: $T_m = 122 \pm 3°\text{K}$; the latter, corresponds, according to [66] to $\gamma = 430$. Jaeger has indicated that an exact knowledge of the variation of the radio temperature during the lunar cycle can be used to determine the value of thermal parameter γ [2].

In [3], by comparison of the electric characteristics of the lunar surface obtained from an analysis of the data on the moon's radio emission with the electrical characteristics of terrestrial rocks, it is established that the density of the outer cover of the moon is of the order of 0.5 g/cm^3. On the basis of the obtained density and the value $\gamma = 1{,}000$ customarily assumed at that time, the thermal conductivity coefficient was estimated at $k = 10^{-5}$. This is one order of magnitude lower than the value obtained in [1,2], corresponding more readily to porous pumice-like material than to dust in vacuum.

Attempts to determine the thermal properties of the lunar surface from data on the radio emission of the moon were undertaken by A. E. Salomonovich [9]. He compared the experimental phase variation of the radio temperature of the moon at different wavelengths with the theoretical phase variation obtained on the basis of corrected calculations [2] for the higher temperature of the subsolar point. However, in view of the low accuracy of the absolute values of the radio temperature, the experimental data satisfied, as in Jaeger's case, a parameter γ lying in the range $300 < \gamma < 1000$.

Following the development of a method for precision measurements of radio emission from the moon [24], it became possible to determine with sufficient accuracy the thermal properties of the moon's surface, something of which was done in a paper by the present author [67]. To this end they made the already cited special calculation [4] of the thermal regime for a homogeneous structure and for temperature-independent thermal properties of the outer cover of the moon.

Figure 5 shows the temperature of the subsolar point T_m, the steady component $T_0(0)$, the first harmonic T_1, and the nighttime temperature T_n for the center of the lunar disc, as functions of the parameter γ, obtained in [4].

In [67] the thermal parameters of the lunar matter were determined using these calculations and the results of the precision measurements of the moon's radio temperature.

Owing to the appreciable increase in the accuracy of the absolute radio measurements, the steady component of the effective moon temperature, averaged over the disc, has by now been reliably established for different wavelengths. Neglecting the slight wavelength dependence, due to the presence of heat flow from the interior of the moon, a value $T_{e0} = 211 \pm 2$°K, measured at 3.2 cm, has been obtained for the effective temperature averaged over the disc.* Using the dependence $\beta_0(\epsilon)$ (see Fig. 8) and relation (18), let us recalculate the steady component of the effective temperature, $\overline{T}_{e0}$ averaged over the disc to the corresponding temperature $T_{e0}(0)$ of the center of the disc. The recalculation leads to a value $T_{e0} = 227 \pm 5$°K. Recognizing that even in accordance with the extreme estimates the emissivity of the moon's surface for particular incidence of the wave lies in the range $0.96 \leq 1 - R_1 \leq 0.99$, we find that the steady component of the true surface temperature is $229°\mathrm{K} \leq T_0(0) \leq 236°\mathrm{K}$. According to Fig. 5, this corresponds to $250 \leq \gamma \leq 450$.

*This value has been found as the average of two precision measurements, listed in Table II.

Another value of γ is obtained in [67] from the ratio T_0/T_1. The theoretical dependence of T_0/T_1 on γ is shown in Fig. 17. The ratio T_0/T_1 can be determined without knowing the emissivity, and is gotten from relative measurements of the intensity of the moon's radio emission in a broad interval of wavelengths, as the limit of the ratio of the steady component of the radio emission to the amplitude of the alternating component as $\lambda \to 0$. According to [3] we have

$$\frac{T_0(0)}{T_1(0)} = 1.5 \pm 0.1.$$

This value of the ratio $T_0(0)/T_1(0)$ corresponds (from Fig. 17) to $270 \leq \gamma \leq 550$. Finally, γ was determined in [67] by measuring the temperature at infrared wavelengths during the time of lunar midnight.

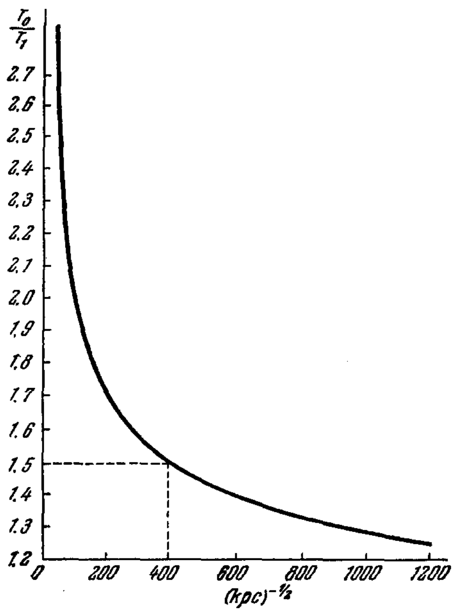

FIG. 17. Dependence of the ratio of the steady component to the first harmonic of the surface temperature at the center of the moon's disk on the parameter $\gamma = (k\rho c)^{-1/2}$.

Comparison of the value recently obtained by Sinton for the nighttime temperature $T_n = 122 \pm 3$°K [66] with the $T_n(\gamma)$ of Fig. 5 yields $350 \leq \gamma \leq 430$. Thus, one relative and two absolute perfectly independent measurements of different characteristics of the thermal process lead practically to the same interval of values of γ. Consequently we can state with a great degree of reliability that the most probable value of γ, with accuracy not worse than ±20%, is $\gamma = 350$.

With the rock density $\rho = 0.5$ g/cm^3 and with c

= 0.2 we obtain for the thermal conductivity coefficient a value

$$k = (1 \pm 0.5)\,10^{-4}\ \text{cal/cm-sec-deg}.$$

The value of k obtained is practically 50 times the value determined in [1,2] and corresponds most readily to porous pumice-like and not to a dust-like outer crust of the moon. Using the obtained value of the thermal conductivity coefficient let us estimate the depth of penetration of the thermal wave:

$$l_t = \sqrt{\frac{k\tau}{\varrho c\pi}} \approx 25\ \text{cm}. \qquad (35)$$

What is striking is the disparity between the values of γ determined from the temperature variation during the time of the eclipse ($\gamma \approx 1{,}000$)[1,2] and during the time of lunation ($\gamma = 350-400$)[66,67], which exceeds all possible measurement errors.

Taking into account the approximate homogeneity of the layer in depth, which will be established below, this disparity cannot be attributed to the presence of a two-layer-dust structure. It is possible that it is connected with the dependence of the properties of the moon's crust on the temperature or with the nevertheless existing gradual decrease in the density near the surface. It must be noted that an attempt to take into account the dependence of the properties on the temperature was undertaken in [84]. Assuming that k and c vary linearly with the temperature and comparing the steady components of the temperature on the surface as obtained by Pettit and Nicholson [5] and Piddington and Minnet [7], the author estimates the parameter γ at $\gamma \approx 200-300$.

Inasmuch as the analysis of [84] is confined only to the steady component and to an approximate temperature dependence of k and c, further improvement in the accuracy of γ and k calls for a rigorous solution of the problem of the thermal regime with exact account of the temperature dependence of k and c.

7. DENSITY AND DIELECTRIC CONSTANT OF THE ROCKS IN THE MOON'S OUTER CRUST

In spite of the fact that the investigations of the radio emission are now in their second decade, only recently were methods proposed for the measurement or determination of the density and dielectric constant of its outer crust. In studies outside the USSR the density and dielectric constant until recently were assumed, by analogy with the density and dielectric constant of the terrestrial rocks[15,33,60,62,66], to be $\rho = 2$ and $\epsilon \approx 4-5$.

It must be specially emphasized that foreign authors who consider a sharply non-homogeneous two-layer model, assume the density to be the same even for layers having greatly differing thermal conductivity [15,62]. Actually, as is known from the theory of heat conduction, the value of the thermal conductivity for any material depends on the degree of its porosity P, which is equal to the ratio of the volume of the voids to the total volume. The porosity determines the average density of the material ρ, or, in other words, its specific gravity, and is equal to

$$P = 1 - \frac{\varrho}{\varrho_0},$$

where ρ_0 is the density of the matter in the non-porous state. Thus, the thermal conductivity of any material is represented by the functions k(P) or $k(\rho)$. This circumstance was pointed out by one of the authors of this review in [68] and the use of the dependence $k(\rho)$ was proposed for the determination of the density of lunar matter from the measured value of the thermal parameter γ.

The method is based on the following considerations. For any rock or combination of rocks, including the rocks forming the outer crust of the moon, $\gamma = (k\rho c)^{-1/2}$ should be a single-valued function of the density ρ, since the thermal conductivity depends on ρ and c —the heat capacity per gram of matter—does not depend on the density. As a result we get

$$\gamma(\varrho) = (k(\varrho)\varrho c)^{-\frac{1}{2}}.$$

For the moon γ is known from direct measurements. Therefore, if we know the function $k(\rho)$ for lunar matter in vacuum, we can readily obtain from it the density ρ. It is possible that for different structures, say a solid foamy or grainy friable material, the functions $k(\rho)$ will be different and depend also on the dimensions of the pores or grains. Thus, generally speaking, we must distinguish between the functions $k_1(\rho)$ and $k_2(\rho)$ for foamy and friable structures.

The probem of determining the density reduces consequently to the problem of determining the functions $k(\rho)$ for lunar matter. In this connection, it is indicated in the cited work that inasmuch as lunar matter consists of ordinary silicate materials, such as in terrestrial rocks, the function $k(\rho)$ for the material of the moon's surface is the same as for terrestrial rocks. In this connection, according to the available published data on the thermal conductivity of rocks and silicate materials in air, it has been shown that for both foamy and friable materials the thermal conductivity, in the density interval $0.4 \le \rho \le 1.5$, is given by

$$k(\varrho) = \alpha\varrho = 0.6\cdot 10^{-3}\varrho,$$

which is a universal function for the silicate group. At a density $\rho > 1.5$, the value of k can also be approximated by a straight line, although with a larger slope. From the obtained law for the thermal conductivity in air, conclusions can be drawn for vacuum. It is assumed that the thermal conductivity remains linear in ρ, and only the proportionality coefficient α changes. The value of α_{vac} was determined from isolated published data on the thermal conductivity of silicate materials in vacuum. It was found that for foamy materials the thermal conductivity, for a porosity exceeding 30%, decreases in the mean by a factor of 3, and

$$k_1 = 2 \cdot 10^{-4} \varrho, \qquad 0.2 \leqslant \varrho \leqslant 1.5.$$

For friable materials, the decrease in thermal conductivity compared with the value in air reaches a factor of 10–20 and depends on the particle dimensions. For grains that are not too small we get

$$k_2 = 5 \cdot 10^{-5} \varrho, \qquad 0.2 \leqslant \varrho \leqslant 1.5.$$

These expressions, obtained for terrestrial rocks, are assumed to apply also to lunar rocks. By substituting the functions k_1 and k_2 into the expression for γ and using the obtained value $\gamma = 350$, we get for the density of a foamy structure

$$\varrho_1 = \frac{160}{\gamma} = (0.4 \pm 0.1)\ \mathrm{g/cm^3}. \qquad (36)$$

For the density of a friable structure we have

$$\varrho_2 = \frac{320}{\gamma} = (0.9 \pm 0.2)\ \mathrm{g/cm^3}. \qquad (37)$$

To determine the dielectric constant, several methods were proposed. Measurements were made in accordance with some of the methods. It is shown in [3] that knowledge of the dielectric constant of lunar matter at radio frequencies is an important factor in the determination of its structure, and also of the state of the surface itself. In fact, the dielectric constant of any sample of material, at radio wavelengths, depends, like the thermal conductivity, on its porosity P or specific gravity ρ. The same substance, but with a different degree of porosity, will have different dielectric constants. The larger the porosity the smaller the dielectric constant of the given sample. In the limit, when the amount of material in the volume is very small, the dielectric constant approaches unity, the value for vacuum. Thus, $\epsilon = \epsilon(P\epsilon_0)$, where ϵ_0 is the dielectric constant of the non-porous sample. The formula usually employed is

$$\varepsilon = \varepsilon_0 \left(1 - \frac{3P}{\frac{2\varepsilon_0 + 1}{\varepsilon_0 - 1} - P}\right). \qquad (38)$$

This formula has been investigated quite thoroughly theoretically and experimentally, and enables us to determine the porosity by measuring ϵ and knowing ϵ_0, and to determine the density of the rock ρ by knowing ρ_0. It turns out that at microwave frequencies ϵ_0 is practically the same for all silicate rocks [69]. Therefore, to determine ρ it is necessary to know only ϵ and ρ_0. Thus, a complete analogy with the measurement of ρ from the value of γ is observed here.

In order to determine the dependence of ϵ on ρ more precisely, numerous measurements were made at the NIRFI of the dielectric constant of various dry terrestrial rocks, for which an empirical relation was obtained [69]

$$\sqrt{\varepsilon} - 1 = c\varrho, \qquad (39)$$

with $c \approx 0.5\ \mathrm{cm^3/g}$. This formula gives results that are close to the theoretical ones but is preferable, since it has been obtained for terrestrial rocks which are close apparently in composition to lunar rocks.

But how are we to measure the dielectric constant of lunar rocks? To answer this question we must obviously analyze the influence of the dielectric constant on the phenomena observed with the aid of the radio telescope. Many possibilities and methods arise. The first of the proposed and realized methods consists in comparing the measured radio temperature with the true temperature of the observed section of the lunar surface. As can be seen from (14), by measuring the steady component of the radio temperature at the center of the disc

$$T_{e0} = (1 - R_\perp)\, T_0(0)$$

and knowing the steady component of the true temperature $T_0(0)$, we can obtain the emissivity $1 - R_\perp$ and ϵ from the Fresnel formula, if we assume that the moon's surface is smooth for the given wavelength.

Obviously, the same can be done also using the alternating component. However, the method under consideration calls for very precise measurement of the radio temperature, something that can be done only for the steady component by using the artificial moon method. In this case it becomes necessary to use the steady component for the integral radiation, which is equal to [see the footnote following Eq. (17)]

$$\overline{T}_{e0} = (1 - R_\perp)\, \alpha \cdot 0.964\, T_0(0),$$

where $(1 - R_\perp)\alpha$ is the average spherical emissivity, and $0.964\, T_0(0) = \overline{T}_0$ is the steady component averaged over the disc. From precision measurements at $\lambda = 3.2$ cm we get $\overline{T}_{e0} = 211 \pm 2$°K. The value of T_0 is known from infrared measurements and from thermal calculations, with $T_0 = 0.964\, T_0(0) = 218$°K. The authors have obtained [12] for the mean spherical emissivity

$$(1 - R_\perp)\, \alpha = 0.96.$$

Hence, using a value of α calculated with an electronic computer, we get

$$R_\perp \approx 2\%,$$

so that the dielectric constant is

$$\varepsilon \approx 1.5.$$

Another method, described in [20,22], consists of a direct measurement of the distribution of the radio brightness over the moon's disc, i.e., a function of the emissivity $1 - R(r\epsilon)$. The character of this function is determined entirely by ϵ. This method has advantages over the former in view of the fact that the measurements are relative, but it does call for the use of very sharply directional antennas. The results of the measurements of the distribution of the steady component of the radio brightness show that the observed course of the emissivity curve corresponds to a value of ϵ in the range

$$1 \leqslant \varepsilon \leqslant 2.$$

A third method has been proposed [70] and is based on measurement of the degree of polarization of the radiation from some section of the moon's surface. In fact, if the temperature of this section is T_0, then for vertically and horizontally polarized radiation its radio brightness will be, respectively,

$$T_{ev} = T_0 (1 - R_v) \text{ and } T_{eh} = T_0 (1 - R_h).$$

The degree of polarization, expressed in terms of the measured values of T_{ev} and T_{eh}, will be

$$\frac{T_{eh} - T_{ev}}{T_{eh} + T_{ev}} \approx \frac{R_v - R_h}{2}.$$

For a smooth surface, R_v and R_h are known and their difference depends on ϵ, so that we can obtain ϵ. We can use also the ratio of T_{eh} and T_{ev}. Measurements of the polarization are also relative, but call for the application of sufficiently sharp directivity. It is easy to see that for the observed small values of ϵ, the largest polarization will occur near the edge of the moon's disc, where the angle of incidence r to the surface is close to the Brewster angle, which is approximately equal to 30–45°. This corresponds to a distance between the section and the edge of the disc of approximately 4–5 angular minutes. This determines also the width of the required antenna directivity pattern.

The polarization method of determining ϵ was used by N. S. Soboleva [71]. The measurements were carried out at 3.2 cm with the large Pulkovo radio telescope, which has a knife-like directivity pattern. This yielded the average value of the polarization in a strip cutting through the moon's disc vertically. As a result of the data reduction, the dielectric constant was found to be

$$\varepsilon \approx 1.65 \pm 0.05.$$

A fourth method of measuring ϵ is proposed in [72]. This method is based on determining the lag of the phase of the radio emission from sections of the disc located at different longitudes along the moon's equator, as compared with the phase of heating of the corresponding sections of the surface.

From all the obtained values of ϵ, equal in the mean to 1.5, and from (38) and (39), it follows that the average density of the lunar surface rocks in a layer not thicker than the depth of penetration for a wave with $\lambda = 3$ cm, i.e., about $1\frac{1}{2}$ meters, is equal to

$$\varrho \approx 0.5 \text{ g/cm}^3.$$

Comparing the obtained value of ρ with the value independently determined from thermal measurements (from the value of γ), we see that agreement is obtained for a foamy material. We shall demonstrate below experimentally that this density of matter prevails also at a depth up to 20 meters. This possibly offers evidence once more that the matter is not in the state of dust, and is not a deep layer of thin mobile shifting dust, as is proposed in Gold's hypothesis [55].

8. NATURE OF THE MATERIAL OF THE OUTER COVER OF THE MOON

To investigate the properties of the outer cover of the moon in the optical wavelength range, some optical characteristics of the lunar surface (luminosity, color, scattering indicatrix, polarization) are compared with the corresponding characteristics of terrestrial rocks of volcanic origin. Much experimental material has been accumulated in this field, on the basis of which conclusions are drawn concerning the probable composition and structure of the lunar surface [73]. However, optical methods of comparison give information only for a thin surface layer, the properties of which can differ appreciably from those of the deeper layer. In addition, these methods are not fully adequate for the determination of the nature of substances. It is well known that many identical rocks encountered in nature have different colors and different reflectivities (black and white pumice, modifications of quartz having a great variety of colors, etc.), which depend frequently on a negligible amount of impurities. Even less representative of the chemical nature of material are characteristics such as scattering and polarization of light upon reflection, since these characteristics depend essentially not on the composition but on the geometry of the surface, the character of the irregularities, and the degree of pitting.

With the development of radio astronomical methods, a new possibility was uncovered for the investigation of the nature of the outer cover of the moon by comparison of the electric characteristics of the lunar surface (ϵ and $\tan \Delta$) with the electric characteristics of the rocks and minerals encountered under terrestrial conditions).

On the basis of an investigation of the radio emission from the moon it has been proved that its surface is a good dielectric ($\tan \Delta \ll 1$), for which $\tan \Delta$ is practically independent of the wavelength over a broad wavelength interval (from 0.4 to 3.2 cm) [3]. This was demonstrated recently down to $\lambda = 0.13$ cm (see Table II). Under terrestrial conditions, analogous properties are possessed by inorganic dielectrics with alumosilicate base.

Attempts at comparing terrestrial rocks and the material of the lunar surface by determining the dielectric constant and the electric conductivity (or $\tan \Delta$) were made by several workers [62,74]. This comparison was made, however, without account of the dependence of ϵ or $\tan \Delta$ on the density of the material. Yet the dielectric constant and the electric conductivity depend essentially on the density of the material, so that such a comparison is possible only if use is made of characteristics that do not depend on the density. It is shown in [3] that such a characteristic is the ratio $\tan\Delta/\rho$. This quantity is invariant with respect to the density ρ and depends essentially on the chemical composition of the material. From relation (34) of [3], an expression was obtained relating the electric and thermal parameters of the material of the lunar surface: $(\sqrt{\epsilon}\tan\Delta)/\rho = 88\times10^{-6}\,c\gamma$. Assuming $c = 0.2$, $\epsilon = 1.5 \pm 0.3$, and $\gamma = 350 \pm 75$ [67], a value $\tan\Delta/\rho = (0.5 \pm 0.3)\times10^{-3}$ was obtained for the material of the lunar surface. Measurement of $\tan\Delta/\rho$ for terrestrial rocks makes it possible to determine a group of rocks which has the same value of the invariant and probably corresponds to the rocks comprising the outer crust of the moon.

There are presently relatively few experimental investigations devoted to the electric parameters of terrestrial rocks. In [74], for an interpretation of the radar reflection characteristics of the moon, measurements were made of the dielectric constant and permeability as well as the dielectric losses for a large number of specimens of terrestrial rocks, meteorites, and tectites. The authors of [74] investigated also the influence of the degree of crumbling of the material on the dielectric constant. But the dielectric characteristics of terrestrial mineral rocks have been measured only at audio frequencies, and therefore the use of the data obtained by these authors for comparison with the characteristics of the material of the lunar surface, measured at microwave frequencies, is impossible. In the same paper are given the results of measurements of ϵ and $\tan\Delta$ in the frequency range from 420 to 1800 Mcs for two samples of stone meteorites of the chondrite type.

Detailed results of measurements of electrical characteristics of tectites at 60 cm wavelengths are given in [75], where 15 samples of tectites, observed in different places on earth and usually named after their original location, have been investigated. These include five autralites, three indochinites, one moldavite, four phillipinites, and one sample of silica glass from the Lybian desert. The measurement results are listed in Table III. The dielectric constant determined for the naturally dense state (ρ_0 for all sample measurements lies in the range $2.4 \le \rho_0 \le 2.5$) for different samples varies quite insignificantly ($6.0 \le \epsilon_0 \le 7.4$), and the dielectric losses are quite small and vary over a considerable range ($0.43\times10^{-3} \le \tan\Delta \le 3.4\times10^{-3}$). Using the results of [75] we calculated with the aid of the Odolevskiĭ-Levin formula the dielectric constant for the porous state $\rho \approx 0.5$ g/cm^3 and the specific dielectric loss angle tangent. The results of these calculations are also given in Table III.

A large number of mineral rock samples with a great variety of chemical compositions (from acid to base) were measured at the NIRFI [69]. The samples were measured at wavelengths 0.8, 3.2, and 10 cm both in the natural and in the crushed state, making it possible to ascertain how the dielectric constant and the loss angle tangent depend on the wavelength and on the density ρ. To eliminate the adsorbed moisture, the samples were first dried for several hours at 200—250°C. It was observed as a result that for all rocks the value of $\tan\Delta$ remains approximately constant in the indicated wavelength range.

On the basis of measurements of samples with dif-

Table III. Dielectric constant and loss angle tangent of tectites at a wavelength of 60 cm

Name	Australites						Indochinites	
Av. pct. SiO_2	70,0						73,3	
№	17 *A*	17 *B*	17 *C*	17 *D*	17 *E*	17 *F*	18 *A*	18 *B*
ϱ	2.42	2.43	2.45	2.45	2.41	2.46	2.40	2.37
ε	6.53	6.41	6.65	6.39	6.58	7,2	6.29	6.85
$\varepsilon_{0,5}$	1.73	1,73	1.75	1.73	1.74	1.80	1.73	1,80
tg Δ	$34\cdot10^{-3}$	$7.5\cdot10^{-3}$	$12.0\cdot10^{-3}$	$4.9\cdot10^{-3}$	$16.0\cdot10^{-3}$	$7.8\cdot10^{-3}$	$4.7\cdot10^{-3}$	$0,43\cdot10^{-3}$
tg Δ/ϱ	$14.05\cdot10^{-3}$	$3.9\cdot10^{-3}$	$4.9\cdot10^{-3}$	$2.0\cdot10^{-3}$	$6.64\cdot10^{-3}$	$3.17\cdot10^{-3}$	$1.96\cdot10^{-3}$	$0,18\cdot10^{-3}$

Name	Indo-chinites	Moldavite	Silica glass	Phillipinites			
Av. pct. SiO_2	73,3	78,0	97,6	71,64			
№	18 *C*	19 *A*	20 *A*	21 *A*	21 *B*	21 *C*	21 *D*
ϱ	2.40	2.35	2.20	2.44	2.42	2.49	2.44
ε	6.00	6.09	4.16	6.09	7.41	6.76	7.11
$\varepsilon_{0,5}$	1,70	1.72	1.53	1.72	1.84	1.75	1,81
tg Δ	$5,3\cdot10^{-3}$	$9.1\cdot10^{-3}$	$0.46\cdot10^{-3}$	$4,4\cdot10^{-3}$	$17\cdot10^{-3}$	$6,5\cdot10^{-3}$	$6.7\cdot10^{-3}$
tg Δ/ϱ	$2,21\cdot10^{-3}$	$3.87\cdot10^{-3}$	$0.21\cdot10^{-3}$	$1.8\cdot10^{-3}$	$7.02\cdot10^{-3}$	$2.61\cdot10^{-3}$	$2.75\cdot10^{-3}$

Table IV. Dielectric constant and specific loss angle tangent of terrestrial mineral rocks at 3.2 cm

Name	Density interval	% SiO_2	$\frac{\sqrt{\varepsilon}-1}{\varrho}$	$\frac{\tan\Delta}{\varrho}$	$\varepsilon\ (\varrho=0.5)$
1. Quartz sand	1.24	98	0.4	0.001	1.44
2. Obsidian	1.18—2.26	74.9	0.57	0.011	1.65
3. Ignimbrite	0.9—1.15	72.9	0.50	0.0066	1.56
4. Liparite	11.8—2.35	72.7	0.47	0.0024	1.53
5. Granite	1.2—2.48	71.2	0.46	0.004	1.51
6. White pumice	0.42—0.7	69.2	0.68	0.015	1.8
7. Black pumice	0.3—0.7	68.54	0.64	0.01	1.74
8. Tuff 1	0.57—1.2	62.5	0.64	0.0126	1.74
9. Tuff 2	0.65—1.24	60.5	0.57	0.013	1.65
10. Tuff 3	0.9—1.85	62.7	0.61	0.011	1.72
11. Trachyte lava	1.18—13	60.1	0.52	0.01	1.59
12. Volcanic ash 1	0.93	52.0	0.60	0.013	1.69
13. Volcanic ash 2	0.77	65.2	0.62	0.015	1.72
14. Volcanic ash 3	1.34	62.0	0.55	0.013	1.63
15. Volcanic ash 4	1.69	64.0	0.48	0.01	1.54
16. Volcanic ash 5	1.32	52.5	0.5	0.015	1.56
17. Volcanic ash 6	1.43	53.4	0.55	0.013	1.63
18. Volcanic ash 7	1.2	55.0	0.53	0.014	1.60
19. Volcanic ash 8	1.05	56	0.53	0.014	1.60
20. Quartz syenite	1.24—1.38	64	0.51	0.004	1.58
21. Syenite	1.25—2.5	56.9	0.51	0.007	1.58
22. Andesite-basalt	1.23—2.36	58.4	0.52	0.013	1.59
23. Diorite	1.2—2.53	58.9	0.47	0.006	1.53
24. Gabbro 1	1.3—1.5	54.4	0.50	0.003	1.56
25. Gabbro 2	1.26—1.36	48.2	0.53	0.003	1.60
26. Basalt 1	1.34—2.55	49.1	0.52	0.017	1.59
27. Basalt 2	1.3—2.55	49.0	0.53	0.018	1.60
28. Ijolite	1.3—1.54	42.8	0.53	0.005	1.60
29. Dunite	1.26—2.56	40.5	0.52	0.02	1.59
30. Dolerite	1.26—1.42	48.0	0.54	0.023	1.61

Recalculation to the density 0.5 g/cm³ is by means of the formula $(\sqrt{\epsilon}-1)/\rho=\alpha$.

ferent fractions, it was established that the ratio $\tan\Delta/\rho$ is independent of the density ρ within $\pm 15\%$.

It was found that the quantity

$$\frac{\sqrt{\varepsilon}-1}{\varrho}$$

is likewise independent of the density, accurate to $\pm 5-7\%$, and varies very insignificantly for different rocks. The results of the measurements of [69] are listed in Table IV, which shows also the values of ϵ, calculated for a density $\rho = 0.5$ by means of formula (39). The information obtained in [69,74,75] on the electric characteristics of mineral rocks, meteorites, and tectites enables us, by carrying out the comparison in accordance with [3], to establish the substances encountered under terrestrial conditions, which have the same value of $\tan\Delta/\rho$ as the material of the moon's surface, and apparently correspond to the substance comprising the outer cover of the moon.

Figure 18 shows the values of $\tan\Delta/\rho$ obtained in [69] and also determined from the data of [74,75] for different terrestrial rocks, meteorites, and tectites, as functions of the percentage content of SiO_2, which characterizes the basicity of the material*.

*Inasmuch as the chemical composition of the measured samples is not given in [74,75], we used on the diagram the average values of the SiO_2 content, known from the literature.

The shaded area corresponds to $\tan\Delta/\rho = (0.5\pm0.3)\times10^{-2}$, which has been determined for the material of the moon's surface. This region includes terrestrial rocks of different alkalinity: acid (liparite, granite, ignimbrite), medium (syenite, diorite), and base (ijolite, gabbro). It is quite interesting that almost all the tectites measured in [75] have the same specific loss as the material of the lunar surface. In our opinion this is evidence in favor of the hypothesis of lunar origin of the tectites.

Such terrestrial rocks as basalt, dunite, volcanic ash and tuff, and also meteoritic stones such as chondrites, have specific losses which are much larger ($\tan\Delta/\rho \approx (1.5-2)\times 2^{-2}$) than the lunar surface material, and therefore do not fall in the "lunar" region. This means that even if these substances are contained in the moon's surface, their percentage is such that their influence on the dielectric properties of the outer cross of the moon cannot be decisive.

Figure 18 shows quite clearly the characteristic mineralogical and chemical composition of the lunar matter. It is most probable that this matter consists of 60—65% quartz, 15—28% aluminum oxide, and the remaining 20% oxides of potassium, sodium, calcium, iron, and magnesium. However, as we have seen, rocks or mixtures of minerals forming the outer cover

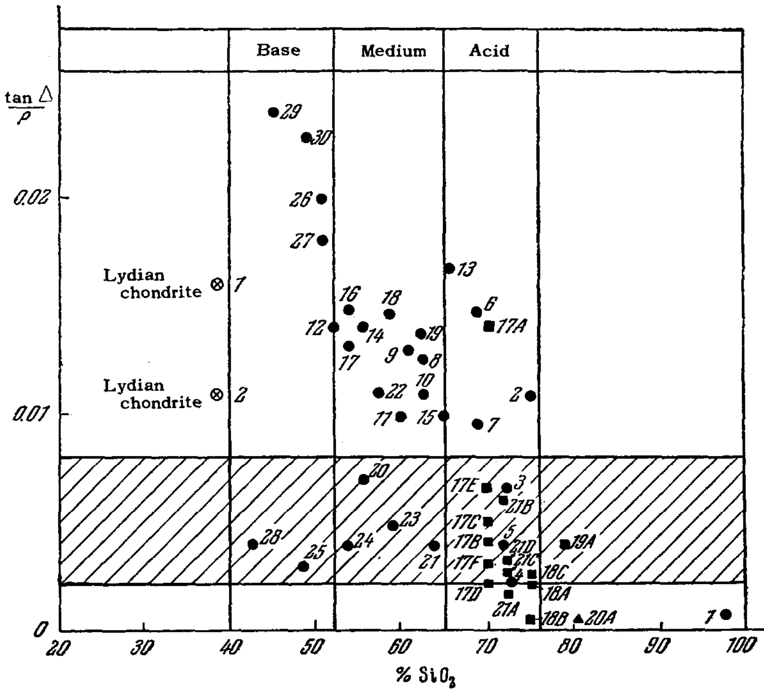

FIG. 18. Dependence of tan Δ/ρ on the percentage content of SiO_2 for different mineral rocks, meteorites, and tectites. The numbers correspond to the number of the sample in Table III or IV.

of the moon should be in a highly porous state and in this sense they are not similar to the usual dense terrestrial rocks.

There are many other subtle differences, which manifest themselves in the optical characteristics. All this suggests that a new name be given to the material of the outer cover of the moon, a suggestion occurring more and more frequently in the literature. In our research we now call it lunite.

It must be noted that the values given for the specific losses are averages for the entire lunar surface, so that they indicate only the average mineralogical or chemical composition. In this connection, it is suggested that different parts of the moon's surface may consist of different rocks.

There are hypotheses, according to which the lunar "seas" are made up of basic rocks of the type of basalt and the continents are made of acid rocks of the type of granite. If this is so, then by investigating the radio emission from these formations we can readily observe a difference between the rocks comprising the lunar "seas" and "continents."

At the present time, no measurements specially set up for this purpose have been made. However, the measurements of the distribution of the intensity of radio emission over the moon's disc, carried out in [20] at 0.8 cm, indicate more readily the absence of noticeable effects in the difference of the lunar rocks. Recently, using a radio telescope with high resolution, more specialized measurements of the radio emission from the "seas" and "continents" were made at 0.4 and 0.8 cm [76]. It was found that a section located in the region of the lunar "sea" has an effective temperature several degrees higher than a section located in the region of the "continents." The difference obtained may offer evidence in favor of some difference between the thermal properties of the "seas" and "continents." However, the measurements of the phase variation of the radio emission, carried out at the same time for different equatorial regions at 0.4 cm [29], showed no noticeable differences in the amplitude or phase of the oscillation.

From the presently available incomplete data we can only conclude that the thermal properties and the composition of the entire lunar surface are highly homogeneous.

9. HEAT FLUX FROM THE INTERIOR OF THE MOON. THERMAL STATE OF THE LUNAR INTERIOR

As was shown in Sec. 3, the steady component of the radio emission of the moon is determined by the temperature of the layer at the depth penetration l_e of the electromagnetic wave. It was established in Section 5 that for lunar rocks, as well as for terrestrial ones, l_e increases linearly with increasing wavelength λ [formula (34)]. In this connection, it becomes possible to determine the variation of the temperature in the interior of the moon.

As can be seen from Table II, by now many data have been published on the lunar temperature at wavelengths ranging from millimeters to meters, characterizing the values of the temperature at different depths under the moon's surface. However, attempts to use these data to disclose the expected systematic increase of temperature with increasing wavelength, undertaken by Messger [46] and Mayer (see [77]) were without success. As can be seen from Table II, the scatter and the values of the steady components of the moon's temperature, given by the different authors (with the exception of the data obtained by the "artificial moon" method), reaches ±40–50°K, and no systematic increase could be observed against this background.

In order to observe and measure the temperature gradient inside the moon, Baldwin[15] undertook special measurements of the radio emission of the moon at 168 cm. The measurement method consisted of comparing the radio emission from the moon with the background of cosmic radiation which is screened by the moon. What was actually measured was a small difference between the effective temperature of the moon and the background screened by it. Because of this, the errors in the measurements of the small difference, connected as usual with inaccuracy of the calibration and lack of knowledge of the antenna parameters, influenced the result little. However, to determine the radio temperature of the moon it was necessary to know the radio temperature of the screening background. According to the statement of the author of that paper, the background was known with a considerably higher accuracy than ± 10%, as is now customarily assumed. As a result, a value $\bar{T}_M = 233 \pm 8°K$, which is accurate to ± 3%, is given for the radio temperature averaged over the disc at 168 cm. To describe the accuracy of the measurements themselves, it must be noted that this quantity has been obtained from two measurements, which gave the minimum temperature in a series of eight measurements. The scatter in the moon's temperature in the entire series was 100°K.

Baldwin did not know the exact value of the radio temperature at shorter wavelengths, and therefore had to assume for further calculations the theoretical value of the steady component of the surface temperature, $T_0 = 222°K$[2]. The author assumes that the increment in the temperature at 168 cm does not exceed 25% and attributes it to heat flow from the interior of the moon. Assuming a homogeneous model for the construction of the layer up to the proposed depth of penetration of the 168 cm wave (approximately 60 meters), he obtained for the heat flux density $q_S \leq 0.25 \times 10^{-6}$ cal/cm-sec, which agreed with the theoretical estimate[78-80]. Leaving aside the question of the estimate of the measurement accuracy, which apparently is considerably exaggerated, we note that, first, the value obtained for the temperature increment itself, namely 25°, is only slightly larger than even the 8° measurement error which was underestimated by the author. This makes the flux estimates unreliable. Second, one can hardly assume a 60 meter layer to be homogeneous in density. It is natural to assume that the lower layers may be denser. This will make the depth of penetration of the 168 cm wave actually smaller and the estimate of the heat flux should be considerably increased by taking this circumstance into account.

As a result of the development of a method that ensures a high degree of accuracy in the measurement of the radio emission fluxes, it became possible to undertake and solve the problem of determining the heat flux from the interior of the moon.

In [16] estimates were given of the heat flux on the basis of precision measurements of the radio emission from the moon in the centimeter wavelength band. However, the small wavelength interval, and consequently also the small increment in the radio temperature, comparable with the measurement error, only gave an estimate of the upper limit of the heat flux density, $q_S \leq 4 \times 10^{-6}$ cal/cm^2 sec.

The question of the heat flux was discussed by the authors of the present review in [63], where an analysis is presented of the results of precision measurements of the radio emission of the moon at wavelengths 0.4, 1.6, 3.2, 9.6, 32.3, 35, and 50 cm, listed in Table II and performed in 1961–1962[24,30,35,36,38,40,50,52,53]. Figure 19 gives the dependence of the steady component of the radio temperature as a function of the wavelength as obtained from the indicated measurements. In the paper cited[63], particular attention is paid to an analysis of the possible error in the measurements, resulting from the influence of the ionosphere, cosmic-ray background blocked by the moon and by the disc, and other factors which manifest themselves with increasing wavelength.

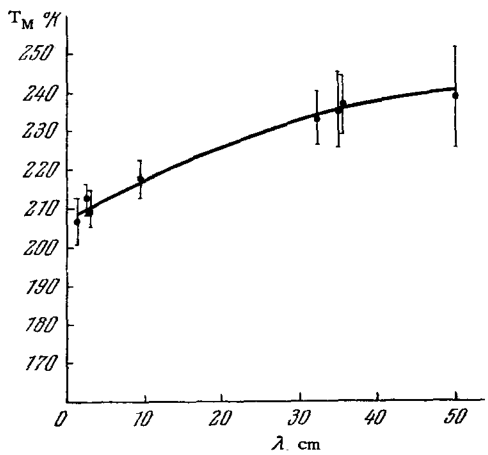

FIG. 19. Dependence of effective temperature, averaged over the disc, on the wavelength. Obtained from precision measurements of the moon's radio emission.

Although it may be doubted that the observed effect is due to an increase in the moon's radio temperature, it must be admitted that there exists a considerable background of cosmic radio emission, the difference of which in the directions of the disc and of the moon should reach 25–30° at wavelengths 35–50 cm and at high galactic latitudes. This explanation, which is not confirmed by direct measurements of the background, would necessitate a radical review of the theory of the origin of cosmic radio emission and possibly would affect the main notions concerning the properties of the cosmic medium.

This raises the question of whether the explanation of the observed increase in radio temperature as a consequence of the heat flux from the interior of the moon is the only one possible. Generally speaking, several other causes can be suggested: the reflection of radio emission from the sun by the moon, of cosmic radio emission, or of sources situated on earth; the dependence of the thermal properties of the moon on the temperature (nonlinearity of the heat conduction equations), and finally an increase in the emissivity of the moon's surface with increasing wavelength. Calculation has shown that with a reflection coefficient $R = 2\%$, the increase in radio temperature due to reflection of solar radio emission is $\Delta T = 10^{-7}\ T_{\odot}$, where $T_{\odot}$ is the radio temperature of the sun for the given wavelength. We see therefore that even at meter wavelengths ($T_{\odot} \approx 10^6\,°K$), the increment of the radio temperature is negligible. The increment due to the reflection of the cosmic radio emission at wavelength $\lambda = 50$ cm is of the order of $\Delta T \approx 0.05°K$. The effect of the emission of radio stations on the earth in the 10—60 cm band is also negligible, although at meter wavelengths, by using television, as indicated by Shklovskiĭ, the radio brightness of the earth may be quite appreciable, and this in turn can cause "brightening up" of the moon in analogy with brightening due to the solar radio emission.

The nonlinearity of the heat conduction equations for the lunar matter is connected essentially with the dependence of the specific heat on the temperature. The steady component of the solar-heating temperature will then depend on the amplitude of the temperature fluctuations. Since the latter varies with depth, the steady component will depend on the depth, and consequently also on the wavelength. It is clear that this dependence will occur at depths not larger than $(3-4)\,l_t \approx 100$ cm, and deeper than this the steady component will be constant. Thus, the entire change of the steady component can be observed only in the wavelength interval from several millimeters to 3—4 cm. However, the main increase in the radio temperature is observed at wavelengths longer than 3 cm; the nonlinearity of the medium can change only the initial course of the radio temperature vs. wavelength curve.

The assumption that the degree of blackness increases with the wavelength can likewise not be fitted within the framework of the known concepts. By virtue of the roughness, an improvement in the reflecting ability of the moon at longer wavelengths is to be expected, and this should decrease the effective temperature with increasing wavelength.

Thus, the only possibility of explaining the observed effect is to assume that heat flows from the interior of the moon. The nearly linear increase in the radio temperature of the moon with wavelength, from $\lambda = 0.4$ cm to $\lambda = 35$ cm, indicated in Fig. 19, shows that the heat conductivity is approximately constant with depth from the very surface to the penetration depth of the $\lambda = 35$ cm wave. This means in turn that according to the established connection between the thermal conductivity and the density of matter (Sec. 7) the density of matter in the entire layer is approximately constant and equal to the density of the surface layer as determined above. Consequently, for the entire layer in which the 35 cm wave penetrates, relation (34) holds true:

$$l_e = 2\lambda l_t, \qquad 0.1\text{ cm} \leqslant \lambda \leqslant 35\text{ cm},$$

According to this, the depth of penetration of the 35 cm wave is equal to approximately $l_e = 20$ meters. Some deviation from the moon's radio temperature at $\lambda = 50$ cm from the value corresponding to the linear increase may indicate that the lunar matter becomes denser at depths exceeding 20 meters. In Fig. 19 the average slope of the curve is $(T_{\lambda 2} - T_{\lambda 1})/(\lambda_2 - \lambda_1) = 0.8$ deg/cm; according to (28) we find for $l_t = 25$ cm that the temperature gradient in the 20-meter layer is

$$\operatorname{grad} T(y) = 1.6\ \text{deg/m}.$$

From (29), assuming $\gamma = 350$, the density of the heat flux from the interior of the moon is

$$q_s = 1.3\cdot 10^{-6}\ \text{cal/cm}^2\ \text{sec}.$$

The total heat flux from the interior of the moon will be

$$Q = 1.6\cdot 10^{19}\ \text{cal/deg}.$$

The obtained value of the heat flux density for the moon is practically equal to the heat flux density from the interior of the earth.*

Theoretical estimates of the possible heat flux from the moon, made by McDonald[80], Levin[79], and Jaeger[78], starting from the assumption that the lunar rocks have a chondrite composition, leads to a considerably smaller value $q_s = (0.2-0.3)\times 10^{-6}$ cal/cm^2 sec. The value we obtained for the flux density is 4—6 times larger than the theoretical estimates presented. From the determined total heat flux of the moon it follows that the number of radiogenic calories released by one gram of lunar matter in one year is

$$q_v = 2.2\cdot 10^{-7}\ \text{cal/g-yr}.$$

*The question arises of the interpretation of this undoubtedly existing heat flux. It seems to us that in principle there can only be two possible explanations: either this flux is of solar origin, or, as on earth, it is due to the decay of radioactive elements (for the most part uranium, potassium-40, and thorium) contained in all the rocks. The former explanation calls for rather far fetched assumptions involving the penetration of at least one thousandth of the solar radiation to a depth of several meters. In this case, however, there should be observed at decimeter wavelengths an appreciable phase variation of the radio emission, something not observed so far. There is only one non-contradictory explanation left, namely that the heat flux comes from the deep interior and has, as on earth, radiogenic origin.

The radioactive elements contained in meteoritic stones generate, according to various recent researches, from 0.4×10^{-7} to 1×10^{-7} cal/g-yr. For the earth, the volume density of the generated radiogenic heat is merely

$$q_v = 0.35 \cdot 10^{-7} \text{ cal/g-yr}.$$

This low value is connected with a large amount of iron inside the earth, in which the content of radioactive elements is one order of magnitude lower than in meteoritic stones. The values of q_s and q_v are reduced to $\frac{1}{2}$ if we assume $\gamma = 700$, a value close to that which follows from infrared measurements during the time of a lunar eclipse.

The high value obtained for the radiogenic heat contradicts the hypothesis that the moon was formed of meteoritic substance of the chondrite type, and calls for a radical review of the present notions concerning the thermal history of the moon, starting from the foregoing low-values of the content of radioactive elements in the lunar matter.

In [63], the following conclusions are drawn:

1. The high temperature gradient in the surface layer (at least up to 20 m thickness) is due to the low thermal conductivity of the substance in this entire layer. By virtue of the homogeneity of the layer, the thermal conductivity in it is approximately the same throughout and is equal to the value obtained previously for the one-meter layer. Thus, one of the new conclusions is the statement that the substance is highly porous even at depths of several dozen meters. It is consequently obvious that this substance cannot be in the form of dust. The low density and low thermal conductivity may be retained at these depths if the material is sufficiently strong and not made more dense by pressure of the layers above it.

2. As applied to the moon, the thermal conductivity of its exterior rocks is determined by the degree of their porosity or density. At some depth, the rocks will have the density corresponding to the non-porous state and will have the same thermal conductivity as on earth. Consequently, the thermal conductivity of rocks should increase at large depths by a factor 40—60 compared with the thermal conductivity in the outer layer under consideration. The temperature gradient, as can be readily calculated, will at these depths be equal to the temperature gradient on earth, i.e., $\frac{1}{30}$ of a degree per meter of depth, which apparently will occur even at a depth of several hundred meters.

To estimate the possible temperature in the interior of the moon, it is necessary to know the distribution of the radioactive elements in depth. Minimum estimates of the temperature can be obtained if all the radioactive elements are assumed to be concentrated in the surface layer. We shall assume that it consists of granite—the most radioactive rock, one gram of which releases 7×10^{-6} calories of heat annually. It is easy to find that a 20 km layer of granite provides the experimentally obtained total flux. Apparently, like on earth, the outer radioactive layer consists of granite which is on a basalt base. If we assume, as on earth, that the equivalent thickness of the layer is approximately 60 km and assume that at a depth of 60 km the heat flux drops to zero, we can easily find that at this depth the temperature should be approximately

$$\frac{1}{2} \cdot \frac{1}{30} \cdot 6 \cdot 10^4 \approx 1000^\circ \text{K}.$$

The temperature will obviously not vary deeper than this. The more uniform the distribution chosen, the higher the temperature of the deep interior.

10. SOME PROBLEMS IN THE INVESTIGATION OF THE MOON BY USING ITS RADIO EMISSION. CONCLUSION

Among the various problems, we have noted only those which must be solved immediately after those which have already been solved, and which are included in the questions detailed above. These include primarily the problems of more precise and detailed investigation of the physical and structural parameters of the outer layer, and particularly an investigation of the variation of the parameters (density, thermal conductivity) of the layer as functions of the depth. This problem calls for theoretical research on the radio emission from the moon for a non-homogeneous outer layer. The difficulty of the problem lies in the fact that all the thermal equations and the integrals for the radio emission can be solved only numerically, using an electronic computer. The result of the calculations should be the spectra of the principal experimentally observed characteristics of the moon's radio emission: the amplitude of the oscillation intensity and the phase lag, etc. When we take into account the influence of the possible non-homogeneity of the layer on the character of the radio emission, the problem arises of taking into account the dependence of the thermal and characteristic properties of the moon on the temperature. In the lunar interval of temperatures, the heat capacity, for example, can vary by a factor of several times, and the loss angle can also have a noticeable variation. All this can greatly change the spectrum of the radio emission characteristics as compared with the spectrum for the homogeneous model, if the properties are independent of the temperature. Actually, the results described above, which pertain to the simplest case, are only a first and possibly crude approximation.

To disclose the foregoing properties of the outer layer (some density non-homogeneity, temperature dependence of the thermal and electric properties) further measurements are needed on the radio emission in the almost continuous wavelength band from infrared to decimeter lengths. In addition, precision measurements of the steady component are necessary. Special work must be done on the properties of the layer below a depth where the fluctuations of the temperature are still noticeable (depth exceeding $l_t \sim 100$ cm). The properties of this layer can be investigated as a result of the observed heat flux from the interior of the moon. The main problem here is experimental. Accurate measurements must be made of the radio emission from the moon at wavelengths 1.5—2 meters, which perhaps will permit penetration to a depth of 100—140 meters and determine the character of the variation of the thermal conductivity and density in this layer. Exact measurements in this band are quite difficult and call primarily for the organization of exact absolute measurements of the cosmic radio emission background.

To construct a model of the layer, agreeing with all the radio emission data, it is necessary to carry out laboratory research on the thermal conductivity and loss angle of rock specimens in a wide range of wavelengths. This raises the difficult and still unsolved heat-physics problem of determining the dependence of the thermal conductivity in vacuum of rocks (or silicate materials) on the degree of porosity, pore dimensions, or grain size and temperature.

There are still not enough data on the electric conductivity of terrestrial rocks at microwave frequencies, especially at low temperatures. In particular, the invariance of $\tan \Delta/\rho$ for densities larger than 1.5—2 g/cm^3 has not yet been sufficiently well verified.

However, all the foregoing problems can be actually solved only for the entire hemisphere of the moon, and will yield an average characteristic, which in many cases differs from the characteristics of the individual sections of the moon's surface. In this connection the question arises of investigating the degree of nonhomogeneity of the properties of the cover over the moon's disc and for individual formations, something which is possible only by using large radio telescopes. In particular, a feasible task is to determine the electric properties (loss angle) of the matter constituting the lunar seas and continents, so as to establish their nature or at least to answer the question of whether they are made up of identical or different rocks. This can resolve, finally, the ancient dispute between different hypotheses with respect to the nature of the seas and the continents. The existing small research material obtained with the aid of high resolution telescopes (up to 2—3 minutes) offers evidence for the time being in favor of the homogeneity of the properties of the outer cover over the entire lunar disc. It is barely possible to make appreciable progress in the investigation of the minor details by using radio emission, owing to the fact that any satisfactory resolution can be obtained at the present time only for shorter than centimeter wavelengths, the depth of penetration of which does not exceed half a meter. Thus, individual details of the lunar relief can be sounded with modern means, using observations from the earth, only from the surface itself to this depth. There can be no thought of sounding individual sections at depths of several dozen meters. The technical difficulties in the investigation of individual features of the lunar relief by radio emission are quite large.

In this connection, an important field of research on the physical conditions in the details of lunar reliefs (volcanos, craters, etc.) may be the measurement of the moon's own submillimeter and infrared radiation. However, the investigation of the details of lunar reliefs and of their physical characteristics will more readily be turned over to the astronauts, who, we hope, soon will set foot on the moon's surface

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