IV Session: PASSIVE RADIO OBSERVATIONS OF THE MOON

Investigation of the Surfaces of the Moon and Planets by the Thermal Radiation

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In the present paper the attempt is made to summarize the numerous data, experimental and theoretical, of the investigation of the lunar and planetary surfaces based on their thermal radiation and to consider it from a common standpoint following from the physical principles discussed in this study. Accordingly, in the first part a brief theory is set forth of the methods for investigating the properties of planetary material. Secondly the results are given obtained by their application to the emission of the Moon.

1. Physical Grounds ot Studying the Material Properties and Thermal Regime of Planets' Surfaces by the Thermal Radiation

1.1. General Statements

The investigation of solid properties by the thermal radiation is based on the measurement of the radiation flux emitted by a body, usually from the surface layer of a material.

As it is known, the spectral density of a flux is equal to

$$e(\nu, T)=[1-R(\nu, r)]\int_0^\infty E(\nu, T)I(x)e^{-\tau(x)}\frac{dx}{\cos r'}\,, \tag{1}$$

where $R(\nu, r)$ is the reflection coefficient, $E(\nu, T)$ is the function of a blackbody emission at the frequency ν, $T=T(x, t)$ is the temperature at the depth x at the moment of time t, $I(x)$ is the coefficient of wave absorption, $\tau(x)=\int_0^x I(\xi)\frac{d\xi}{\cos r'}$ is an optical thickness, r' is the angle of incidence of emission out of the Moon's interior, and r is the angle of refraction (the angle between the normal to the surface and observational direction). At the stationary conditions and thermal equilibrium inside the layer, $T(x, t)=T=$constant and

$$e(\nu, T)=[1-R(\nu, r)]E(\nu, T). \tag{2}$$

For radio emission of the bodies of the solar system ordinarily $h\nu << kT$ and $E(\nu, T)=kT/\lambda^2$, then $e(\nu, T)=kTe/\lambda^2$, where

$$Te=[1-R(\nu, r)]T \tag{3}$$

is the effective temperature of radiation.

Thus, the measurement of the radiation flux $e(\nu, T)$ or the effective temperature in the case of stationary conditions enables one to estimate T, or when T is known, one may find $R(\nu, r)$.

1.2. The Dielectric Constant and Density of Material

The value $R(\nu, r)$ is determined by the medium properties and their distribution to the depth of penetration of a corresponding wave $le = 1/I$, as well as by the geometry of the surface (roughness). An estimate of $R(\nu, r)$ allows a determination of the definite properties, but at present this method is developed only for the material with a smooth surface, the reflection from which is defined by Fresnel's relations. The material of the surface is assumed to have a sufficiently small loss angle that there is no influence on $R(\nu, r)$. It is generally accepted that the permeability is equal to unity. Under these assumptions the dielectric constant of the material is evaluated, by which one can find the density of the material [Troitsky, 1961a, 1961b, 1962a].

For this, one may use the relation

$$\epsilon = e_0\left(1 - \frac{3\rho}{\frac{2\epsilon_0+1}{\epsilon_0-1}+\rho}\right), \tag{4}$$

where $\rho = 1 - \rho/\rho_0$ is a porosity value; ρ_0, ϵ are the known density and dielectric constant of a rock in a nonporous state, respectively.

An empirical formula having an accuracy of 5 to 10 percent is more suitable for practically all terrestrial silicate rocks [Krotikov, 1962a]

$$\sqrt{\epsilon} - 1 = g\rho, \tag{5}$$

where $g = 0.5\ \mathrm{cm}^3 g^{-1}$.

The spectrum of the reflection coefficient permits a determination of $\epsilon(\nu)$ which may bring out a real change of the electric properties of the material with the frequency. However, for silicate rocks, ϵ remains unchanged over a wide range of microwave frequencies. Therefore, at the smooth surface of a dielectric having small absorption, the spectra $R(\nu)$ and $\epsilon(\nu)$ indicate the inhomogeneity of the material properties in depth, particularly the density ρ, at least in the layer of the order of the depth of penetration of an electromagnetic wave.

The measurement of the spectrum $\epsilon(\nu)$ (and hence $\rho(x)$ as well) may be carried out by polarization studies of radiation by the object [Troitsky and Tseytlin, 1962].

1.3. The Variable Thermal Regime and Measurement of Thermal Parameters

In the case of the variable thermal regime of the surface, new possibilities arise for determination of properties. For the bodies of the solar system the value of energy $S_0 f(t)$ falling on the unit of the surface per unit of time is known, where S_0 is the solar constant, and $f(t)$ is the function depending on the position of a given point on a body surface. In this case the temperature $T(x, t)$ at the moment t at the depth x may be calculated from the equation for a semi-infinite body if the medium's properties, their change with depth, and temperature dependence upon the temperature and depth (a homogeneous medium) has been considered. Then

$$\frac{\partial T}{\partial t} = a^2 \frac{\partial^2 T}{\partial x^2} \tag{6a}$$

$$(1-R_i)\sigma T_s^4 - [(1-R_c)S_0 f(t)] = \mathrm{K}\left(\frac{\partial T}{\partial x}\right)_{x=0}, \tag{6b}$$

where R_i is a mean reflection coefficient or albedo in the range of reradiated waves (for the bodies of the solar system in the range of infrared waves), R_c is the reflection coefficient or albedo of light waves, $\alpha^2 = \mathrm{K}/\rho c$ is the diffusivity, K is the thermal conductivity, and c is the specific heat capacity.

For a homogeneous model the surface temperature $T_s(t)=T(0, t)$ is proved to depend more considerably on the parameter value $\gamma=(\kappa\rho c)^{-1/2}$ [Wesselink, 1948; Jaeger and Harper, 1950; Jaeger 1953].

Consequently, if the function of the surface temperature is known experimentally, one can find the value γ even with rather inaccurate data for R_c and R_i. Generally, R_c is known and the value R_i (for silicate rocks) is small enough ($R_i=0.15\pm0.15$, [Burns and Lyon, 1964] that inaccurate knowledge of it does not add error to the measurement of the infrared temperature or to the calculation [Troitsky, 1964a, b].

The insolation $f(t)$ may be periodic or nonperiodic. For the Moon both the regimes take place. The first has a period of 29.53 days, the second, during the lunar eclipse, lasts only 4 to 5 hr. The layer thickness at which the temperature variation takes place will be, obviously different for different time duration of the insolation changes. Hence, it follows that, with an inhomogeneous layer, for short-time regimes we shall obtain information about γ of the upper layers, but for slow variations we will obtain information about the lower layers.

For the determination of γ from observations of a periodic regime sometimes one may not use the function $T_s(t)$ itself but its Fourier's coefficients [Krotikov and Troitsky, 1963a]. Experimentally, the surface temperature is usually based on infrared waves, since these are emitted by solid surfaces.

1.4. The Radio Emission of the Surface of a Planet at Nonperiodic Thermal Regime

The radio emission out of a layer comparable with the depth of penetration of temperature variation enables one to measure the surface parameters. At the present time the radio emission has been considered for a homogeneous model [Piddington and Minnett, 1949; Troitsky, 1954] and for an inhomogeneous two-layer one when a thin upper layer is considered to be absolutely transparent for radio waves [Piddington and Minnett, 1949]. These cases correspond to the periodic regime of the Moon and describe the dependence of radio emission on its phase. This theory is extended to the radio emission observed of the surfaces of Venus and Mars [Troitsky, 1964a].

Only recently the radio emission of the homogeneous model has been considered in the nonperiodic regime of the temperature variation during a lunar eclipse [Troitsky, 1965].

All calculations of radio emission for the bodies of the solar system must begin with the solution of the thermal problem (eqs 6) with the corresponding forms of the insolation function $f(t)$, depending on coordinates ϕ and ψ on the surface of a planet. Then, by using the solution $T(x, t, \phi, \psi)$, one may evaluate the intensity of the thermal radiation according to (1). The solution of (1) with Plank's function $E(\nu, T)$ has not yet been obtained. Since $h\nu << KT$, $E(\nu, T)=KT(x, t)/\lambda^2$ and a flux will be proportional to the effective temperature

$$Te=(1-R)\int_0^\infty T(x, t, \phi, \psi)I(x)e^{-\tau(x)}\frac{dx}{\cos r'} \tag{7}$$

where $e(\nu, T)=KTe/\lambda^2$.

In a general case, however, an analytical form of the solution (6a) for $T(x, t, \phi, \psi)$ at the boundary conditions (6b) has not yet been found. Therefore, one uses the fact that (6) may be solved numerically, for example, on a digital computer by which it is possible to estimate the surface temperature $T_s(0, t)$ [Krotikov and Shchuko, 1963]. Utilizing $T_s(t)$ as boundary conditions in (6a) the analytical solution may be obtained.

At present the heating and radio emission are considered of an idealized planet represented as an ideal smooth sphere rotating near its axis with the angular velocity Ω_* with respect to the stars. The Sun and observer are considered to be in a plane normal to the rotation axis passing through a planet. Their visible velocities of rotation around the planet are equal to $\Omega=\frac{2\pi}{t_0}$ and Ω_*, respectively, where t_0 is the period of rotation of the planet (the period of insolation variation $f(t)$).

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The coordinate system is generally connected with the planet. One introduces the longitude ϕ read from the central meridian and the latitude ψ from the equator. In this system the position of the Sun and observer is determined by the longitude of a subsolar point $\phi_s = \Omega t$ (its latitude $\psi = 0$) and that of the planet under the observer ϕ_E (the observer is assumed to be on the Earth, though it may also be an equatorial satellite of the planet). In a common case the angular velocity of the observer is not constant; therefore, $\phi_E = \int \omega_E(t)dt$. It takes place, for example, for the earth observations of Venus.

The surface temperature in any point of the planet may be expressed in the form

$$T_s(\phi, \psi, t) = T_{s0}(\psi) + \sum T_{sn}(\psi) \cos (n\Omega t - \phi_{sn} - n\phi), \tag{8}$$

where ϕ_{sn} is the phase lag of the temperature with respect to the insolation phase.

The solution (6a) with the boundary condition (8) gives

$$T(x, t) = T_{s0} + \sum T_{sn} e^{-\beta_n x} \cos (n\Omega t - \beta_n x - \phi_{sn} - n\phi), \tag{9}$$

where $\beta_n = \frac{1}{a}\sqrt{\frac{n\pi}{t}}$ is the coefficient of harmonic attenuation of a temperature wave. If, besides, the solar heating the heat flux out of the interior takes place, it gives an additional temperature increase with the depth. Due to the smallness of this flux the temperature increase on the surface itself will approximate zero and we may write $T(x) = ax$. Adding it together with (9) and substituting into (7) one can obtain the radio temperature distribution over the planet

$$T_e(\phi, \psi, t) = [1 - R(r)] T_{s0}(\psi) + [1 - R(r)] a\, l_e \cos r' + [1 - R(r)] \sum \frac{T_{sn} \cos (n\Omega t - \phi_{sn} - \xi_n - n\phi)}{\sqrt{1 + 2\delta_n \cos r' + 2\delta_n^2 \cos^2 r'}}, \tag{10}$$

which periodically changes at each point near some constant component T_{e0}. Here

$$\delta_n = \frac{\beta_n}{I} = \frac{\sqrt{n\pi}}{Ia\sqrt{t}} \tag{11}$$

$$\xi_n = \text{arc tg } \delta_n \frac{\cos r'}{1 + \delta_n \cos r'}. \tag{12}$$

The value $1/\beta_1 = l_T$ is the depth of penetration of a temperature wave, therefore, the value $\delta_1 = l_e/l_T$ is the electrical and thermal wave-penetration ratio. For a dielectric with the loss tangent $\text{tg}\,\Delta << 1$, as known, $I = 2\pi\sqrt{\epsilon} \cdot \text{tg}\,\Delta/\lambda$ following (11)

$$\delta = \frac{1}{Ia}\sqrt{\frac{n\pi}{t_0}} = \frac{\lambda c\gamma}{b\sqrt{\epsilon}}\sqrt{\frac{n\pi}{t_0}} = m\lambda; \qquad l_e = m\lambda l_T, \tag{13}$$

where $b = \text{tg}\,\Delta/\rho$.

Thus, with increasing wavelength and hence l_e the constant component of the radio temperature [as it is seen from (10)] may increase due to temperature increase with depth of the body. For a two-layer model with the first harmonic only taken into account

$$T_e = (1 - R)T_{s0} + (1 - R)a\, l_e \cos r' + (1 - R)\frac{T_{s1} \cos (\Omega t - \phi_{s1} - \xi_r - \xi_s - \phi)}{N\sqrt{1 + 2\delta_1 \cos r' + 2\delta_1^2 \cos r'}}, \tag{14}$$

where N and ξ_s are an additional attenuation of the temperature wave and the phase lag in the upper layer with

$$N=\sqrt{1+2\delta_s+2\delta_s^2} \qquad \xi_s=\text{arc tg}\,\frac{\delta_s}{1+\delta_s},$$

where $\delta_s=\Delta x\beta s\gamma_1^2\gamma_2^2$; Δx is the thickness of the upper layer, γ_1 and γ_2 are the values of $\gamma=(\kappa\rho c)^{-1/2}$ for the upper layer and sublayer, respectively. From the relative measurements of $T_e(t)$ during the whole period of insolation (e.g., during lunation) one may find $\delta_1/\lambda=m$ or Ia.

When the observer is rotated around the planet it is possible to observe the surface radiation only for the longitudes $\phi=\phi_E\pm\tilde{\phi}$, where $0<\tilde{\phi}\leq\frac{\pi}{2}$ are the longitudes read from the point under the observer coinciding with a visible disk of the planet. For a uniform motion of the observer, $\phi_E=\Omega_E t$. By substituting it into (10) we obtain for the argument $n(\Omega-\Omega_E)t-\phi_{sn}\pm n\tilde{\phi}$. Here $(\Omega-\Omega_E)t=\Phi$ is a phase angle of the planet. But $\Omega=\Omega_*\pm\Omega_s^*$ and $\Omega_E=\Omega_*\pm\Omega_E^*$, where Ω_s^* and Ω_E^* are the angular velocities of the Sun and observer rotation among the stars (as seen from the sphere). The minus sign corresponds to a direct rotation of the sphere with respect to the Sun, and the plus sign corresponds to a retrograde rotation. Thus, the phase angle $\Phi=\phi_s-\phi_E=(\Omega-\Omega_E)t=\pm(\Omega_s^*-\Omega_E^*)t$. For a nonuniform motion of the observer, (e.g., observation of Venus from the Earth), $\Phi=\pm(\Omega_s^*t-\int\Omega_E(t)dt)$. In a general case, the expression for radio emission takes the form of

$$T_e(\phi,\ \psi,\ t)=(1-R)T_{s0}+(1-R)a\,l_e\,\cos r'+(1-R)\Sigma\,\frac{T_{sn}\cos(\pm n\Phi-\phi_{sn}-\xi_n-n\tilde{\phi})}{\sqrt{1+2\delta_n\cos r'+2\delta_n^2\cos^2 r'}}. \tag{14a}$$

When observing the Moon from the Earth, the libration being neglected, one may consider $\phi_E=0$ and $\phi=\tilde{\phi}$, $\Phi=\Omega t$ to have "+" as the directions of the proper lunar rotation and around the Sun coincide.

1.5. A Temperature Gradient to the Depth and Heat Flux Out of the Interior

Carrying out the measurement of the constant component of radio temperature for two waves λ_1 and λ_2 when observing normal to the surface of a body and using (10) and (14) [Troitsky, 1962 a, b, c] we obtain

$$\text{grad}\,T(x)=a_1=\frac{dTe}{d\lambda}\,\frac{1}{(1-R_1)ml_T}. \tag{15}$$

Multiplying it with the thermal conductivity we shall have for the heat flux density

$$qs=\frac{dTe}{d\lambda}\,\frac{\sqrt{\pi}}{(1-R_{\perp})m\gamma\sqrt{t_0}}. \tag{15a}$$

1.6. The Temperature of the Surface of a Planet

In the foregoing, temperature distribution over the planet is determined by a set of independent solutions of a plane one-dimensional thermal problem with a semi-infinite layer for the surface elements with coordinates ϕ, ψ. The effect of horizontal fluxes which may be important at the poles is not taken into consideration. Equation (6) was solved on the digital computer enabling one to find the time dependence of the surface temperature for each point of the surface ϕ, ψ in the form [Krotikov and Shchuko, 1963]:

$$T_s(\phi,\ \psi,\ t)=T_{s0}(0)\cos^{0.2}\psi+T_{si}(0)\cos^{0.33}\psi\cos(\Omega t-\phi-\phi_{s1})$$

$$+T_{s2}(0)\cos^{0.27}\psi\cos(2\Omega t-2\phi-\phi_{s2})-T_{s3}(0)\cos^{0.44}\psi\cos(3\Omega t-3\phi-\phi_{s3}). \tag{16}$$

Here T_{sn} is the amplitude of harmonics for the equator, ϕ_{sn} is the phase lag between harmonics of the temperature and those of a falling flux. The value of the amplitude T_{sn} and phase lag ϕ_{sn} depending on the value γ are cited in table 3. The mean disk surface temperature has the form of

$$\overline{T}_0 = T_{s0}(0) \cdot 0.962 + T_{s1}(0) \cdot 0.741 \cos(\Omega t - \phi_{s1}) + T_{s2}(0) \cdot 0.315 \cos(2\Omega t - \phi_{s2}). \tag{17}$$

At present there is a wide use of the distribution adopted earlier [Piddington and Minnett, 1949; Troitsky, 1954],

$$T_s(\phi, \psi, t) = T_{sn} + (T_{sm} - T_{sn})\eta(\Omega t - \phi)\eta(\psi), \tag{18}$$

where T_{sm} and T_{sn} are the temperatures of the subsolar and the antisolar point of a spherical surface. It was found [Troitsky, 1956] that $\eta(\Omega t - \phi) = \cos \frac{1}{2}(\Omega t - \phi)$ or $\eta(\psi = \cos \frac{1}{2}\psi$. Then (18) is represented as a series

$$T_s(\phi, \psi, t) = [T_{sn} + a_0(T_{sm} - T_{sn}) \cos^{\frac{1}{2}} \psi] + a_1(T_{sm} - T_{sn}) \cos^{\frac{1}{2}} \psi \cos(\Omega t - \phi), \tag{18a}$$

where $a_0 = 0.382$, $a_1 = 0.56$. Here, the first term is the constant component and the second one is the first harmonic of the temperature variations. The mean disk value of the constant component is equal to [Krotikov and Troitsky, 1962]

$$\overline{T}_{s0} = T_{sn} + (T_{sm} - T_{sn})\,(0.92)\,(0.382). \tag{19}$$

Both the distributions give similar results, but for the temperature in a polar zone the first term is zero and the second term is equal to T_{sn}. At the present time more accurate data for temperature in the polar zone are needed, which requires the solution of the thermal problem for the whole sphere (the horizontal heat fluxes being taken into account).

1.7. The Integral Radio Emission

Recently for interpretation of measurements, a theory of an integral radiation was developed [Krotikov, 1963a, 1965]. If the properties of the material of the planet's surface is homogeneous, the full radiation of the mean disk effective temperature may be expressed by that of the disk center by introducing averaging coefficients. Therefore, instead of (10) and (14a) we obtain

$$\overline{T}_e(t) = (1 - R_\perp)T_{s0}(0)\beta_0 + (1 - R_1)\Sigma \frac{T_{sn}(0)\beta_n \cos(n\Omega t - \phi_{sn} - \xi_n(0, 0) - \Delta\xi_n)}{\sqrt{1 + 2\delta_n + 2\delta_n^2}}. \tag{20}$$

Here β_0 and β_n are the averaging coefficients being approximately unity with $0.91 \leq \beta_0 \leq 0.96$ and dependent only on ϵ. In addition, β_n depends on δ, in particular, $0.75 \leq \beta_1 \leq 1$, and $0.25 \leq \beta_2 \leq 0.35$. As expected, when averaging, the second harmonic is heavily attenuated. In most cases it will be valid for the higher harmonics. Consequently, the integral radiation, in practice, is of a sinusoidal form. It is interesting that when averaging, an additional phase lag $\Delta\xi n$ occurs which for the first harmonic does not exceed 5°. For the case of an arbitrary relationship of the pattern width angular dimensions of a planet's disk the values of averaging coefficients have been calculated as well. It turns out that when the pattern width is equal to the angular dimensions of the planet, the mean disk effective temperature is actually determined.

1.8. The Radio Emission of the Surface of a Planet at the Nonperiodic Thermal Regime (the Luna Eclipse)

Now let us give briefly the results of the theory of the radio emission of the Moon during an eclipse [Troitsky, 1965]. In order to calculate the lunar emission during an eclipse it is necessary to know the function of the surface temperature variation. As it is known from the measurements during the interval $t_2 - t_1$ corresponding to the beginning and the end of penumbral stage of eclipse, the surface temperature falls almost linearly from the value T_1 to T_2. Then during the whole umbral phase up to the time t_3, the temperature slowly falls almost linearly up to T_3 and finally in the last penumbral period it linearly increases to the value $T_4 = T_1$ at the time of the end of eclipse t_4. In accordance with this a real function of the surface temperature is represented as a broken line drawn through the points t_k, T_k as

$$T_s(0, t) = \psi(t) = T_k + \alpha_k(t - t_k)$$

$$a_k = \frac{T_{k+1} - T_k}{t_{k+1} - t_k} \qquad k = 1, 2 \ . \ . \ . \ 4.$$

The initial temperature $T_s(x, t_1)$ is deduced from the solution (9) at $\Omega t = 0$ (the full Moon) for the central part of the lunar disk. First, the thermal problem of $T(x, t)$ estimation was solved, expressed by (6a), with the above boundary and initial conditions. Then the value of the effective temperature was obtained from (7) which in the interval of the penumbra is equal to

$$T_{e1}(t) = T_v(q_1) + T_1(t, q_1) \qquad t_1 \leqslant t \leqslant t_2. \tag{21}$$

During the penumbral phase

$$T_{e2}(t) = T_{e1}(t) - T_1(t, q_2) + T_2(t, q_2) \qquad t_2 \leqslant t \leqslant t_3. \tag{22}$$

During the second penumbral phase

$$T_{e3}(t) = T_{e2}(t) - T_2(t, q_3) + T_3(t, q_3) \qquad t_3 \leqslant t \leqslant t_y. \tag{23}$$

Finally, after the end of eclipse

$$T_{e4}(t) = T_{e3}(t) - T_3(t, q_4) + T_4(t, q_4) \qquad t_4 \leqslant t \leqslant \infty, \tag{24}$$

where $T_v(q_1) = T_{s0}[1 - \Phi(z_1)]e^{z_1^2} + \dfrac{T_{s1}}{2} A_-[1 - \Phi(y)]e^{y^2} + \dfrac{T_{s1}}{2} A_+[1 - \Phi(Z_1)]e^{z_1^2} \cos 2yz_1$

$$\frac{-T_{s1}}{\sqrt{\pi}} D + y \cos 2yz_1 + \frac{T_{s1}}{2} D_-[1 - \Phi(z_1)]e^{z_1^2} \sin 2yz_1, \tag{25}$$

and $\dfrac{T_k(t, q'')}{1-R} = \left\{T_k + \alpha_k(t - t_k) + \dfrac{\alpha_k}{I^2 a^2}\right\} \{1 - e^{z_n^2}[1 - \Phi(z_n)]\}$

$$-\frac{2}{\sqrt{\pi}} \alpha_k(t - t_n) z_n^{-1} + \alpha_k(t - t_n) e^{z_n^2}[1 - \Phi(z_n)]. \tag{26}$$

Here $q_n = 1/2a\sqrt{t - t_n}$ is analogous to the coefficient of the thermal-wave attenuation during the eclipse and $z_n = I2q_n = Ia\sqrt{t - t_n}$ is the ratio of electrical and thermal-wave attenuations,

$$\Phi(z_n) = \frac{2}{\sqrt{\pi}} \int_0^{z_n} e^{-\xi^2 d\xi}, \ y = \beta/2q_1;\ A_- = \frac{1+\delta}{B} - \frac{1-\delta}{B_1};\ A_+ = \frac{1+\delta}{B} + \frac{1-\delta}{B_1};\ D_+ = \frac{\delta}{B} + \frac{\delta}{B_1};$$

$$D_- = \frac{\delta}{B} - \frac{\delta}{B_1};\ B = 1 + 2\delta + 2\delta^2; \qquad B_1 = 1 - 2\delta^2;\ \delta = \beta/I.$$

As one can see that the temperature variations during the eclipse are determined by the values z_n and y, i.e., by the value Ia. For waves longer than $\lambda=0.1$ cm the value Ia is very small, z_n and y being small as well. It permits one to use the relations (25) and (26) in a series expansion over these parameters. By restricting with the second approximation over Ia we obtain for each k interval of the eclipse

$$T_{ek}(t)=T_{em}+(1-R)\frac{4Ia}{3\sqrt{\pi}}\sum_{1}^{k} n(\alpha_n-\alpha_{n-1})\,(t-t_n)^{3/2}$$

$$-(1-R)\frac{I^2a^2}{2}\sum_{1}^{k} n(\alpha_n-\alpha_{n-1})(t-t_n)^2 \qquad k=1,2\,.\,.\,.\,4, \tag{27}$$

with $\alpha_0=\alpha_y=0$.

The value of the initial effective temperature is equal to

$$T_{em}=\left(T_{s0}+T_{s1}\frac{1+\delta}{B}\right)(1-R)$$

and coincides with that which follows from (10) for the full Moon. In practice, the maximum radio temperature variation appears exactly at the moment t_3. According to (27) it is equal to

$$\frac{1}{M(\lambda)}=\frac{\Delta T}{T_{em}}=-(1-R)\frac{4Ia}{3\sqrt{\pi}T_{em}}\{\alpha_1(t_3-t_1)^{3/2}+(\alpha_2-\alpha_1)\,(t_3-t_2)^{3/2}\}$$

$$+(1-R)\frac{I^2a^2}{2T_{em}}\{\alpha_1(t_3-t_1)^2+(\alpha_2-\alpha_1)\,(t_3-t_2)^2\}. \tag{28}$$

From (25) to (28) one can see that the measurements of relative changes of the radio emission intensity permit an estimation of the value Ia both during eclipse and lunation,

$$Ia=\frac{1}{\lambda}\cdot\frac{b\sqrt{\epsilon}}{c\gamma}. \tag{29}$$

For the measurements during eclipse this value characterizes the upper layer of the material and for those during lunation it characterizes a layer approximately 10 times deeper. On figure 1 the families of curves for the radio eclipse of 30 December 1963 are given calculated in accordance with the formulae (21) to (26) at different values of $\gamma/b\sqrt{\epsilon}$. From (27) and (29) it is obvious that a reciprocal value of maximum relative changes of radiation $M(\lambda)$ is almost a linear function versus the wavelength. The spectrum incidence is defined by the value $c\gamma/b\sqrt{\epsilon}$. Consequently, the experimental study of the spectrum of radio-temperature fall during the eclipse as well as for a periodic case may give only the relation $c\gamma/b\sqrt{\epsilon}$. On figure 2 the spectrum $M(\lambda)$ is shown calculated from (21) to (26) for the eclipse of 30 December 1963 and the experimental points are plotted.

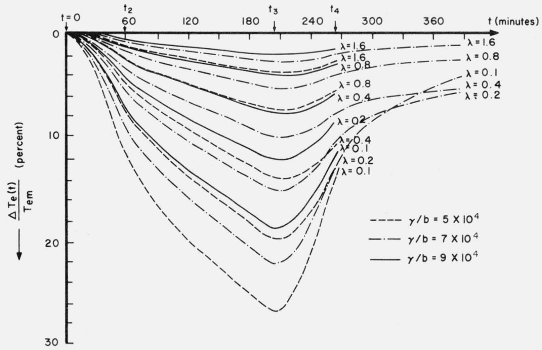

FIGURE 1. *The families of curves for the radio eclipse 30 December 1963 at different values* γ/b.

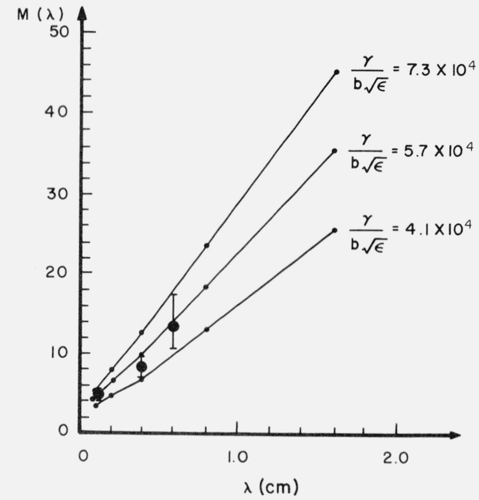

FIGURE 2. *The spectrum* M(λ) *for the eclipse 30 Dec. 1963 at different* $\gamma/b\sqrt{\epsilon}$.
The dots correspond to the experimental data.

1.9. Investigation of Material Microstructure of a Layer

The conclusions concerning the microstructure may be derived from the value of the volumetric density ρ, because when ρ_0 is known, one can estimate the degree of body porosity. However, two bodies, one of powder and the other solid-porous, may have an identical overall apparent porosity. Apparently, these cases may be distinguished when comparing the value κ with ρ. The value of thermal conductivity of one and the same material may considerably differ at the equal volumetric density ρ (and porosity), either for a powder or solid-porous state of a body in vacuum. Otherwise the function of κ dependence upon ρ must be different for these media and besides may be dependent on a grain size or pores.

It was shown [Troitsky, 1962a] that, in the air, for all porous solid and powder silicate materials the following relation may be used with an accuracy of 10 to 20 percent:

$$\kappa = \alpha\rho = 0.6 \times 10^{-3}\rho \qquad 0.4 \leq \rho \leq 1.5. \tag{30}$$

This relation of κ and ρ, as was shown be experimental investigations, also holds in a high vacuum, but for the fine powder materials with grains of about several microns, the value α turns out to be 50 times less [Bernett, Wood, Jaffe, and Martens, 1963]

$$\kappa_c = \alpha_c\rho \simeq 10^{-5}\rho \qquad 0.2 \leq \rho \leq 1.5. \tag{31}$$

For a solid-porous body the accurate measurements have not yet been made. Probably, one may expect [Woodside and Messmer, 1961] that

$$\kappa_r = \alpha_r\rho \simeq 5 \times 10^{-5}\rho. \tag{32}$$

There are data of the influence of gas composition filling the pores [Woodside and Messmer, 1961].

Therefore, a knowledge of κ and ρ and the use of κ/ρ permits us to draw a conclusion about the structure of the material and, perhaps, about the nature of gas filling the pores and its pressure. The latter is especially valuable for the investigation of Venus and Mars. The dependence between κ and ρ is discussed in the same way as in Halajian's work [1964]. It should be noted that for different dispersity and pore sizes the question of the dependence between κ and ρ has not yet been studied, either theoretically or experimentally.

1.10. The Nature of Material: Mineralogical Composition

The investigation of a chemical composition is based on the comparison with the Earth's rocks for the definite parameters. Neither density nor thermal conductivity are suitable for this purpose. The attempts are made to identify the material by the loss angle at the superhigh frequencies, which, as known, is mainly determined by the chemical material composition. However, there is no full identification of the relation between the loss angle and chemical composition. One and the same loss angle may correspond to rather different natural materials. But if we take a definite group of materials (e.g., silicate rocks) such a comparison will be not so hopeless. However, the value $tg\Delta$ by itself depends not only on a rock type but also on its density ρ. Therefore, for identification a value invariant from the density is suggested for use [Troitsky, 1961a]. Theoretically such a value is the specific tangent of the loss angle:

$$b = \frac{tg\Delta}{\rho}.$$

The independence of this value to within ± 15 percent on the density has been shown experimentally when $0.1 \leqslant \rho \leqslant 1.5$ for different Earth rocks [Krotikov, 1962a]. This justifies the introduction of it in the expressions for δ and la as a basic electric characteristic of the material.

1.11. Main Conclusions

Let us draw some conclusions from which we shall be able to learn about the properties of a body by its radiation, assuming that, for simplicity, the layer of material is homogeneous, the surface is smooth and the material is a dielectric. As a result of measurements we have three known relations, $\epsilon = \epsilon(\epsilon_0, \rho)$, $\gamma = (\kappa \rho c)^{-1/2}$, and $c\gamma / b\sqrt{\epsilon}$ between six unknowns, ϵ_0, ρ_0, κ, ρ, c, and b. Three of them are immediately determined in practice if the rocks are considered to belong to a silicate group. Then $c = 0.2$, $\epsilon = \epsilon(\rho)$, but κ, ρ, and b remain unknown being connected with three known equations. In the case of a density change with depth, for example, one more unknown is added that is a characteristic scale of inhomogeneity. Therefore, a measurement of new independent relations of parameters is required. The radar investigations of the spectrum of the reflection coefficient may give the important data of the degree of inhomogeneity of properties with depth.

2. Investigation Results of Properties of the Surface Cover and Its Temperature Regime

In this section the experimental data of the lunar investigation on infrared and radiowaves are considered. A theoretical interpretation is given of experimental data obtained in accordance with the above methods in order to obtain information about the material parameters of the upper layer.

The order of analysis corresponds to the general scheme of investigation mentioned in the first section.

2.1. The Temperature of the Lunar Surface

The surface temperature of the Moon is ordinarily measured on infrared waves in the atmosphere window 8 to 12μ. At present, the temperature measurement for different regions and details of the Moon have been carried out both during lunations and eclipses. An estimate of the temperature of a subsolar point T_{sm} by many authors is in rather good agreement, being equal to 407 °K [Pettit and Nicolson, 1930] or 389 °K [Geoffrion et al., 1960]. The recent measurements on the wavelength 4μ gave 400 ± 10 °K [Moroz, 1965]. The measurements on this wavelength are especially important for $h\nu = 15kT$, and an error because of the infrared albedo not taken into consideration, even if the latter is equal to 20 to 30 percent, affects the result less than 2 percent. The absence of difference in the measurements on 4μ and 10μ suggests a small infrared albedo of the Moon's surface which, apparently, is not more than the optical albedo. A theoretical value of the temperature of the subsolar point is equaled $T_{sm} = 395$ °K, the optical and infrared albedo being equal. Thus, one may take

$$T_{sm} = 400 \pm 10\,°\mathrm{K}.$$

The situation is much worse when measuring the temperature at an antisolar point. According to Pettit and Nicolson's measurements [1930] and Geoffrion et al. [1960], $T_{sn} = 120 \pm 2$ °K. Recently Murrey and Wildey [1964] have obtained $T_{sn} = 106$ °K and Saari and Shorthill [1964] have obtained $T_{sn} = 100$ °K. It should be noted that such a low night temperature leads to a value of the constant component that appears to be equal to or far less than that of the radio temperature, an impossibility. Below we shall take some mean value

$$T_{sn} = 115\ °\mathrm{K}.$$

In accordance with the measurements [Pettit and Nicolson, 1930], [Saari and Shorthill, 1962] the temperature during the eclipses in different parts of the disk with the exception of crater bottoms has, in the average, a similar relative change. So $T_2/T_1 = 0.53$, $T_3/T_1 = 0.46$ that gives $T_1 = 400$ °K, $T_2 = 210$ °K, and $T_3 = 185$ °K for the central part of the disk. Recently Saari and Shorthill [1965] have discovered that during the umbra the sea Humorum is warmer than others and that over the entire disk there are about a hundred observable warm points. Some of them are identified with small rayed craters. The distribution of the surface temperature over the disk is estimated only for the full Moon along the equator [Pettit and Nicolson, 1930]. Instead of the expected law $\cos^{1/4} r$ which is attributed to the distribution (16) as well, one obtains $T = T_{sm} \cos^{1/6} r$. It is explained by the roughness influence not taken into account in the theory. The distribution measurements of the surface temperature on radio waves confirmed the correctness of the distribution (18a) [Kaydanovsky and Salomonovich, 1961; Saari and Shorthill, 1962]. But more valuable measurements of isotherms for a night Moon have not yet been made.

2.2. Experimental Data of Radio Emission of the Moon

At the present time the radio emission of the Moon has been studied in the range of waves 0.13 cm and 168 cm, both during lunations and eclipses. The dependence of radio emission intensity on phase cannot be measured on a wavelength of 20 cm or longer, and the eclipse changes are not noticeable even on the waves 2 cm and longer. All the experimental dependences of radio temperature upon the lunar phases are approximated rather well by a sum of a constant component and a sinusoidal one, thus, $T_e = T_{e0} + T_{e1} \cos(\Omega t - \xi_1)$. In table 1 the measurement results have been cited during a phase cycle of the Moon, and in table 2 during the eclipses.

In table 1 the values of a constant component T_{e0}, the amplitude of the first harmonic T_{e1}, the phase lag ξ_1, the beam width of the radiotelescope and the accuracy of measurements are given. In table 2 the maximum values are given of the relative temperature variations at the moment of the end of the umbral phase of the corresponding eclipse. It is interesting to note that in a set of measurements carried out by the usual methods (table 1) the difference of values given by different authors exceeds twice the error of the measurement and is equal to 30 percent. In a set of precision measurements made by the method of the "artificial Moon" the difference on each wavelength is far less than the error of each measurement, i.e., not more than 1 to 2 percent.

TABLE 1. *The list of experimental results of the radio emission of the Moon during lunations*

	λ *cm*	T_{e0} °*K*	T_{e1} °*K*	ξ *Degrees*	Error of measurement $\pm$ %	Half beam width θ	References
1	0.13	219	120	16	15	10′	Fedoseyev 1963.
2	.18	240	115	14	20	6′	Naumov 1963.
3	.40	230	73	24	10	25′	Kislyakov 1961.
4	.40	228	85	27	15	1′.6	Kislyakov, Salomonovich 1963.
5	.40	204	56	23	4	36′	Kislyakov, Plechkov 1964.
6	.8	197	32	40	10	18′	Salomonovich 1958.
7	.8	211	40	30	15	2′	Salomonovich, Losovsky 1962.
8	.86	180	35	35	15	12′	Gibson 1958.
9	1.25	215	36	45	10	45′	Piddington, Minnett 1949.
10	1.63	224	36	40	10–15	26′	Zelinskaya et al., 1959.
11	1.63	208	37	30	3	44′	Kamenskaya et al., 1962.
12	1.63	207	32	10	3	44′	Dmitrenko et al., 1964.
13	2.0	190	20	40	7.5	4′	Salomonovich, Koshchenko 1961.
14	2.3			35		2 × 40′	Kaydanovsky et al., 1961.
15	3.15	195	12	44	15	9′	Mayer et al., 1961.
16	3.2	223	17	45	15	6′	Koshchenko et al., 1961.
17	3.2	245	16	41	15	40′	Strezhnyova, Troitsky 1961.
18	3.2	210	13.5	55	2.5	1°12′	Krotikov et al., 1961.
19	3.2	213	14	26	2	1°27′	Bondar' et al., 1962.
20	3.2	216	16	15	3	40′	Bondar' et al., 1962.
21	9.4	220	5.5	5	5	2°20′	Medd, Broten 1961.
22	9.6	230			15	19′	Koshchenko et al., 1961.
23	9.6	218	7	40	2.5	1°40′	Krotikov 1962b.
24	10.3	207			15	18.05′	Sloanaker 1962.
25	11	214			12	17′	Mezger, Strassl 1960.
26	14.2	221			3.5	2°	Krotikov et al., 1965.
27	20.8	205	5			36′	Waak 1961.
28	21	250	5		15	35′	Mezger, Strassal 1959.
29	22	270			20	15′	Davies, Jenisson 1960.
30	22	270					Westerhout 1958.
31	23	254	6.5		15	38′	Castelli 1961.
32	32.3	233			2.5	3°00′	Razin, Fyedorov 1963.
33	33	208					Denisse
34	35	236			4	3°06′	LeRoix.
35	36	237			3	3°10′	Krotikov, Porfiryev 1963.
36	50	241			5	4°40′	Krotikov 1963b.
37	70.16	17			8	1°30′	Krotikov et al., 1964.
38	75	185			20	2°00′	Seeger et al., 1957.
39	168	233			4	13.6 × 4°	Baldwin 1961.

TABLE 2. *The list of the experimental measurement results of the radio emission of the eclipsed moon*

λ cm	$\frac{\Delta T_e}{T_{em}}$ %	$\overline{T}_{em}$	$\Delta\zeta$	$(\gamma/b\sqrt{\epsilon}).10^{-4}$		Date of eclipse	$t_2 - t_1$		$t_3 - t_1$		References
				Center	Disk		Center	Disk	Center	Disk	
0.12	17	315	7	6,2		6–7/7/63	85		175_{min}		Kamenskaya et al., 1965.
.12	22.5±2	315	7	4.7		30/12/63	60		204		Do.
.21	[a]8	300	10	10.0		6–7/7/63	85		175		Do.
.32	6 ± 2	277	2.9	10.5		30/12/63	60		204		Jacobs et al., 1964.
.4	8 ± 2	270	20	8.3	9.7	6–7/7/63	85	75	175	255	Kamenskaya et al., 1965.
.4	12 ± 2	270	20	4,5		30/12/63	60		204		Do.
.4	10 ± 2	270	20	4.5		19/12/64	60		194		Plechkov, Porfirjev 1965.
.43	4 ± 1	268		12.9		26/8/61	63		182		Tolbert et al., 1962.
.6	8 ± 2	257	35	4.5		30/12/63	60		204		Kamenskaya et al., 1965.
.75	5 ± 2	253	36	7.5	8.7	6–7/7/63	85	75	175		Do.
.86	7	247		3.9		5/9/60	60		211		Gibson 1961.
1.6	3 ± 2	235	44	6.4	7.5	6–7/7/63	85	75	175		Kamenskaya et al., 1965.
1.6	6 ± 3	235	44	3.3		25/6/64	71		239		Plechkov 1965.
2.2	1	228	58	15.6		19/12/64	60		194		Plechkov, Porfirjev 1965.

[a] The value of radiotemperature drop in 60 min after the beginning of the umbral eclipse of the center of disk.

The important first detailed observations of radio emission of the Moon during lunations and eclipses on wavelengths of 0.2 and 0.13 cm, was carried out by Naumov [1963], and Fedoseyev [1963]. Since the main results of the lunar properties have been obtained from the precision measurements, we shall consider the method in more detail.

This method is based on the comparison of the radio emission of the Moon or planets with etalon radiation of an absolutely black disk placed in the Fraunhoffer zone of an antenna at a sufficient elevation. This method was called the method of the "artificial Moon," as the disk is arranged to have the same angular dimensions as the Moon viewed from the radiotelescope.

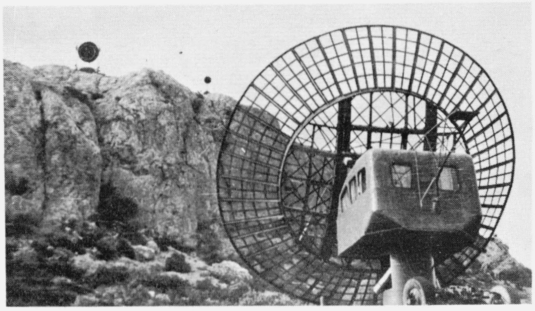

FIGURE 3. *Artificial Moon installed on the mountain Khara-Dag in the Crimea, viewed from the antenna.*

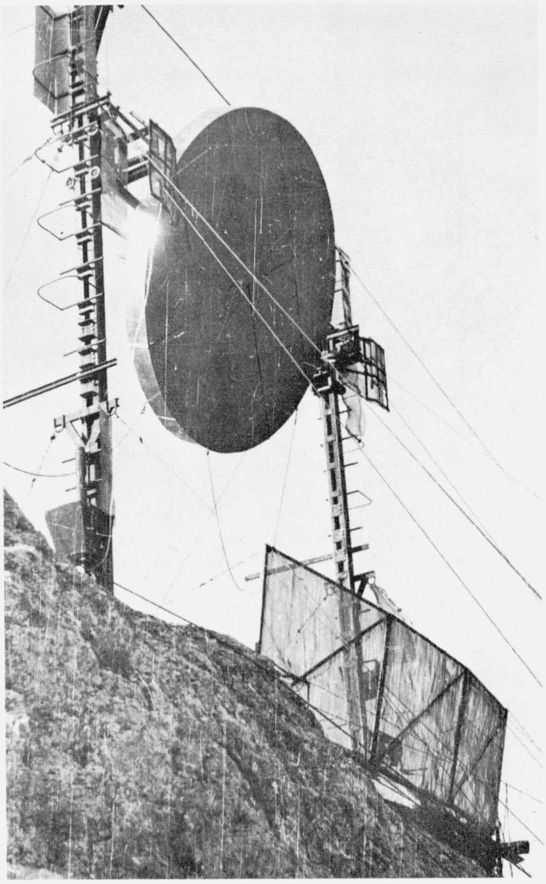

FIGURE 4. *Closeup of artificial Moon and mounting.*

In order to eliminate the diffraction of the radio emission of the Earth around the disk, which is contributing some power to the antenna, a second pattern was used in a shape of an opening in the plane that covers the main lobe of the polar diagram of the antenna and is inserted into the same place formerly occupied by the disk. The opening repeats strictly the dimensions of the disk. In this case, the signal pattern formed with emission of the disk inserted into the opening appears to be weakened by the magnitude of power of the earth emission (diffraction powers are equal in value). Consequently, the mean signal value from a free disk and from that in the opening will be strictly equal to the known black-disk emission [Krotikov, Porfiryev, and Troitsky, 1961]. Later, by applying the second disk, the conditions of the disk model were found under which the diffraction effect for the given wave and disk diameter could be disregarded. Finally, the diffraction error was computed theoretically [Tseytlin, 1963]. Figures 3 and 4 show the model of an artificial Moon installed on the mountain Khara-Dag in the Crimea.

As a result of adopting the above method, measurements of the radio temperatures of the Moon are possible with an error not exceeding 2 to 3 percent, in a wide range of wavelengths.

2.3. Investigation of the Distribution of Material Properties With Depth Using the Spectrum of Periodic Variations of the Radio-Emission Intensity

The data obtained for the spectrum of the variable part of the radio emission of the Moon enables one to explore the character of the distribution of material properties with depth. At present, the experimental results are compared with two extreme idealizations of the distribution of properties: a homogeneous model and sharply inhomogeneous one with a nonabsorbing upper

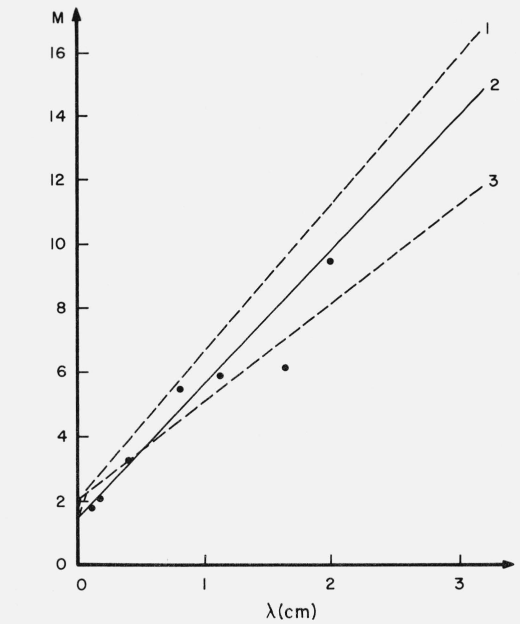

FIGURE 5. *The dependence of* M *on* λ.
Curve 2 corresponds to a homogeneous model ($m=1.0$, $\delta_1=2\lambda$). Curve 1 corresponds to a two-layer model ($m=1.5$, $\delta=1.5\lambda$), Curve 3, to a model with $m=1.5$, $\delta=\lambda$.

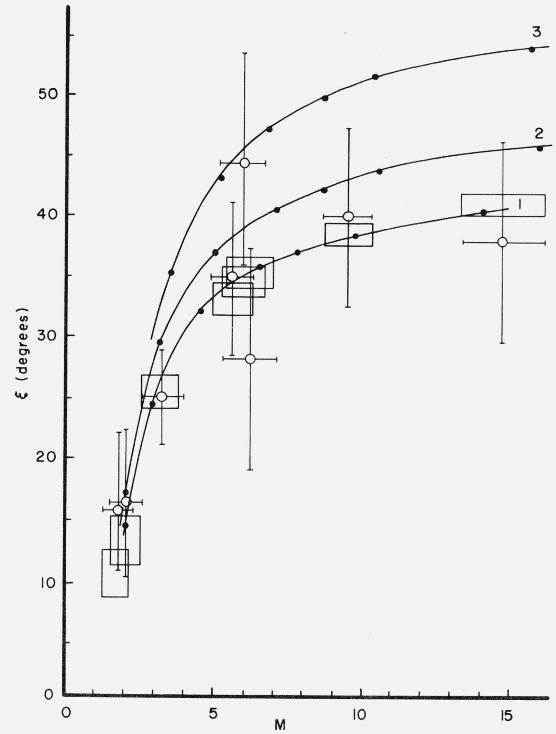

FIGURE 6. *Theoretical dependence of the phase lag of the first harmonic of the radio emission of the Moon on the ratio of the constant component to the amplitude of the first harmonic of the emission for a cycle: 1. Homogeneous structure of the surface* ($m=1.0$, $\xi=0$, $\delta=2\lambda$), 2–3.
Two-layer-dust ($m=1.0$, $\xi=5°$, $\delta=2\lambda$) and $m=1.4$, $\xi=15°$, $\delta=1.5\lambda$ respectively). Black dots are theoretical values for wavelengths 0.13, 0.4, 0.8, 1.25, 1.63, 2.0, and 3.2 cm. The circles are the experimental values plotted with indication of errors on ξ and M.

layer [Troitsky, 1961a, 1962a, 1964b]. Figures 5 and 6 present the results of this comparison. On figure 5 are plotted the theoretical curves of dependence of the inverse magnitude $M(\lambda)=T_{e0}/T_{e1}$ of relative variations of the radio temperature, in the function λ, equal, in accordance with (20) and (14) to

$$M_1(\lambda)=N\frac{T_{s0}(0)}{T_{s1}(0)}\frac{\beta_0}{\beta_1}\sqrt{1+2\delta_1+2\delta_1^2};\qquad \delta_1=m\lambda \tag{32a}$$

curve 2 corresponds to the single-layer model, and curves 1 and 3 to the two-layer model by the $N=1.5$, $\delta_1=1.5\lambda$, and $N=1.5$, $\delta_1=\lambda$. The circles indicate the experimental points which lie on a straight line for the homogeneous model ($N=1$) plotted for $\delta/\lambda=m=2$. The value M and the retardation ξ are functions of the model. Figure 6 gives the theoretical dependence between M and ξ for the assumed models and presents the experimental points. Curve 1 corresponds to the homogeneous model ($N=1, \xi=0$); curve 2 corresponds to the two-layer model with a very thin upper dust layer giving $N=1.1$ and $\xi_s=5°$. At the thickening of the layer when $N=1.4$ and $\xi_s=15°$, one obtains curve 3. Experimental points for the wavelengths 0.13, 0.2, 0.4, 0.8, 1.25, 1.6, and 3.2 cm are marked by circles with indication of the limits of the possible error in ξ and M. As is seen from figure 6, the experimental points correspond to the single-layer model, and all of them cannot be made to agree simultaneously with the two-layer model having even a very thin layer of dust. By rectangles are marked the values M and ξ when M is derived from the experiment, and ξ is computed from the value δ_1 (found by value M) by the formula for the homogeneous model. If the model were inhomogeneous, these values would not fall on the curve which corresponds to the homogeneous model. Thus, in the limits of the investigated spectrum of the value M, the upper layer behaves as a homogeneous medium in radio emission. This enables one to draw a conclusion of a quasi-homogeneity of layer properties with depth. The result obtained does not contradict the assumption of a smooth, slight inhomogeneity which does not become apparent either due to inaccuracy of measurements, or due to insufficient coverage of the spectrum.

Investigation of the model of the superficial cover structure by the spectrum of a variable part of the radio emission of the Moon is, for the present, unique. Often, in the works on the measurements at one wavelength the conclusions are drawn about the model, but, as shown by analysis, the data at one wavelength may be interpreted loosely enough. This is not surprising, as only the spectrum of radio emission values satisfies the exploration of different depths. In most works the statements about the model are simply drawn without any analysis [Garatang, 1958; Giraud, 1962].

It should be noted that the generally adopted two-layer model is self-contradictory [Troitsky, 1964b]. Generally the layer in this model has $\gamma_1=1000$, and the lower $\gamma_2=100$, the density being admitted an equal to $\rho_1=\rho_2$. Therefore it turns out that thermal conductivities differ from each other by $\kappa_2/\kappa_1=\gamma_1^2/\gamma_2^2=100$ times! Taking into consideration $\kappa=\alpha\rho$, we find that the model with given values γ_1, γ_2 cannot have the arbitrary relationships of thermal conductivity and density; it must have the following correct relations of parameters:

$$\kappa_2/\kappa_1=\gamma_1\sqrt{\alpha_2}/\gamma_2\sqrt{\alpha_1};\ \rho_2/\rho_1=\gamma_1\sqrt{\alpha_1}/\gamma_2\sqrt{\alpha_2}.$$

In the case of the identical structure type ($\alpha_1=\alpha_2$), the relation of thermal conductivites and densitites in the adopted model ought to be identical and equal to 10. By different structures of the sublayer and of the upper layer, as for example when the sublayer is solid, somewhat porous, and the upper layer, thin dust,

$$\alpha_2\simeq 4\alpha_1 \text{ and } \kappa_2/\kappa_1=20 \text{ and } \rho_2/\rho_1=5.$$

2.4. Spectrum of Reflection Coefficient. Dielectric Constant and Density of Material of the Upper Layer. Model of Layer

Four methods are offered for measuring the relection coefficient and dielectric constant of the planet material. (1) Measurements of the constant component of radio temperature [Krotikov and Troitsky, 1962]; (2) measurement of the polarization of radio emission [Troitsky, 1954; Troitsky and Tseytlin, 1960]; (3) measurements of distribution of radio brightness at the disk [Salomonovich, 1962a]; (4) measurements of the amplitude distribution and phase lag of variations of radio temperature on the equator of the Moon [Troitsky, 1961a].

The precision measurements of radio emission enable one to determine the constant component of the mean effective temperature on the disk. Measurements at a number of centimeter wavelengths, which will be described below, with gradient correction, give the following value for the constant component:

$$T_{e0}=207\pm 2\ ^\circ\text{K}.$$

Simultaneously, the mean value of the temperature on the surface is equal to $\overline{T}_{e0}=(1-\overline{R})\overline{T}_{s0}$, for the above adopted values of the subsolar and antisolar temperatures. In accordance with (19), we obtain $\overline{T}_{s0}=T_{sn}+(T_{sm}-T_{sn})a_0\beta=216\ ^\circ\text{K}$, hence the mean hemisphere reflection coefficient

$\bar{R}=0.04\pm\pm 0.02$. This gives [Krotikov and Troitsky, 1962]

$$R_{\perp}\approx 1 \text{ percent} \qquad \epsilon=1.5\pm 0.3.$$

Polarization measurements carried out at the wavelengths 3.2 cm and 2.05 cm [Soboleva, 1962; Baars, Mezger et al., 1963] give the value for dielectric constant

$$\epsilon=1.5.$$

In both works the roughness of the surface was taken into account, in the second case the value $\pm 15°$ was taken for the slopes as the closest to that derived from the radar. For distribution of radio brightness, one value only is obtained: $1\leqslant\epsilon\leqslant 2$ [Salomonovich, 1962]. Thus, by means of radio astronomic methods, $\epsilon=1.5\pm 0.3$ and $R\approx 1$ percent were obtained for the centimeter wavelengths. Knowing the dielectric constant and assuming the silicate structure of rocks, the density of the material on the Moon surface layer, in accordance with (5), is equal to $\rho=0.5\pm 0.3$. Meanwhile, the radar investigations give, at the same wavelengths, the average from all the existing measurements, $R_1=4$ percent and $\epsilon=2.25$. The difference is probably associated with roughness leading to the formation of sufficiently plane reflection surfaces creating a similarity to a polyhedron inscribed into the sphere of the Moon. On radio emission where the phase relationships play no part, such a form of the surface will have no influence. It is interesting that the same radar measurements give for the $\lambda=30-75$ cm the average reflection coefficient value, for all the data, twice as much, i.e., $R_1=8$ percent and $\epsilon=3.2$. Of course, the spectrum of the reflection coefficient is not associated with a real changing of ϵ with the frequency, and appears as a result of inhomogeneity of the properties with depth. This problem was considered in one of the works [Matvejev, Suchkin, and Troitsky, 1965], the results of which are reduced to the following: As for initial data, one may safely adopt the values R and ϵ at the centimeter waves, measured radioastronomically, and at the decimeter waves, the value 2.5, i.e.,

$$\begin{array}{llll} R_1=1.7 \text{ percent} & \epsilon_1=1.7 & \rho_1=0.6 & 0.8\leqslant\lambda\leqslant 12 \text{ cm} \\ R_2=4 \text{ percent} & \epsilon_2=2.25 & \rho_2=1.0 & 33\leqslant\lambda\leqslant 784 \text{ cm} \end{array} \tag{33}$$

(values R_1 and R_2 correspond to the normal incidence of waves).

The range, where the transition from one series of values to another one is being achieved, makes up about 15 to 50 cm. The medium-frequency wave in this range, $\lambda_m=30-35$ cm, is not determined with certainty.

The most probable explanation of the dependence $R(\lambda)$ consists in assumption of the changing of density and ϵ with depth. Here two cases may be noted: the change occurs at the depth of the order of wave penetration [Gold, 1963], or the density is changing on the surface itself. In both cases one should assume that the properties of the layer are varying for the length which presents portions of the length of the wave λ_m. The first version should be excepted as it does not explain the difference between the eclipse and lunation values of γ (see below). The second case is probable. Therefore, if the properties vary smoothly from the surface to the depth l, then for $\lambda>>l$ the lower dense layer of the material will mainly reflect, and for $\lambda<<l$ the boundary of the upper layer for this wave will become deeper as λ increases.

The following law of density variation with depth was adopted:

$$\rho(x)=\rho_2-(\rho_2-\rho_1)e^{-x/x_0}, \tag{34}$$

where ρ_1 and ρ_2 are the density values of lunar material at surface and at the depth x, respectively. At the depth $l=2.5x_0$, later called the thickness of an inhomogeneous layer, the density attains its limiting value, ρ_2.

In the case of one-dimensional inhomogeneity, the coefficient of reflection is determined, as is known by the Ricatti equation. Its solution under conditions (33), (34) was carried out on a digital computer. As a result, it turned out that the experimentally known medium-frequency wave of the transition range depends on the thickness of inhomogeneity, in the following way:

$$l = \frac{\lambda_m}{8}.$$

Taking into account the experimental value of $\lambda_m = 30$ cm, we find that the observed spectrum of the reflection coefficient will take place if the thickness of the inhomogeneous layer is

$$l = 4 \text{ cm} \qquad x_0 = 1.5 \text{ cm}.$$

Thus, the radio-astronomic and radar investigations of the reflection coefficient lead to the conclusion about density changing of the material to the depth by 1.5–2 as much for the distance of 3 to 4 cm. The thermal conductivity probably varies in the same proportion, as well (if $\alpha(x) = \alpha = \text{Const.}$).

A final judgement still necessitates the accurate measurement of the spectrum of reflection in the range of 10 to 50 cm, both by radar and radio-astronomic methods.

2.5. Thermal Properties of the Surface Cover

Let us apply the above-considered methods of determining the value γ. Let us first consider the eclipse regime. To determine γ, the different curves of temperature falls obtained at the time of the eclipses in 1927 and 1939 were used [Pettit and Nicolson, 1930; Pettit, 1940]. Comparison with the computation for the homogeneous model [Wesselink, 1948; Jaeger and Harper, 1950] leads us to the value

$$\gamma_1 = 1000.$$

However, the optimum coincidence of the theoretical curve in the zone of shade is obtained, for the two-layer-dust model [Jaeger, Harper, 1950] considered above. Recently, for the eclipse on 5 September 1960, the measurements of cooling curves and of the γ of five radiant craters, with their environment, were carried out [Saari and Shorthill, 1962]. On the average, with the exception of the bottoms of craters, $\gamma = 1000$. However, the extreme need of more precise and reliable measurements of temperature slope at the time of the eclipses for different formations should be noted. The case is somewhat worse with the measurement of the γ_2 in the lunation regime. Here the complete cycle does not yet exist. Theoretical curves for the homogeneous model are presented on figure 7 [Krotikov and Shchuko, 1963]. As can be seen from this figure, the most effective measurements to determine the γ_2 are measurements by the transition from day to night. Recently such measurements were carried out [Murray and Wildey, 1964], giving the value $\gamma_2 = 700$. The periodic regime permits another method of determinating γ_2 – not by the curve of the surface temperature, but by its Fourier components. This method has the advantage that we can use the data on radio measurements which do not give the absolute values of the surface temperatures, but allow its Fourier components to be found out without requiring a knowledge of electrical properties of the model. For such a determination, the related values T_{sn}, $T_{s0}(0)$, $T_{s0}(0)/T_1(0)$ in the function γ_2 are given in table 3 for the homogeneous model [Krotikov and Shchuko, 1963]. Disposing of experimentally known values T_{s0}, T_{s0}/T_{s1}, and T_{sn}, one finds the value of γ_2 [Krotikov and Troitsky, 1963a]. Here we present the value γ corrected according to more precise initial data. Plotting curve $M(\lambda)$, according to the measurements of radio emission, one can find that by letting $\lambda \to 0$, then $T_{s0}/T_{s1} = 1.35 \pm 0.1$. This gives, in accordance with the table 3, $400 \leqslant \gamma_2 \leqslant 800$. The value of the night temperature $T_{sn} = 115 \pm 5°$ leads to the same value. For the constant component of

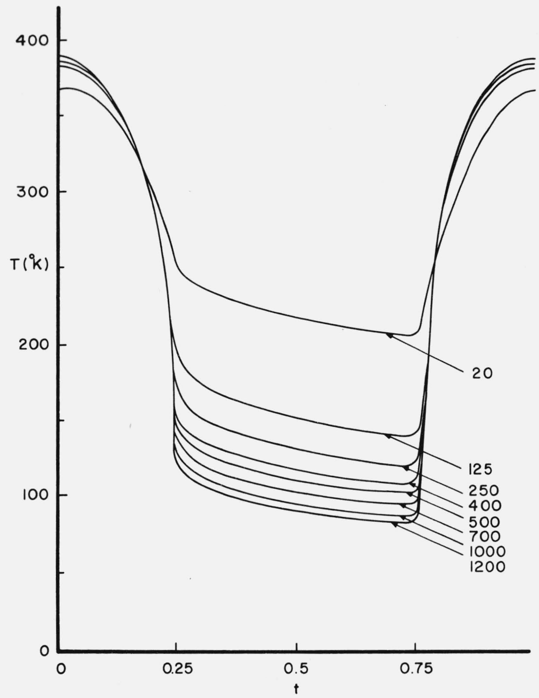

FIGURE 7. *The surface temperature measurement in the center of the lunar disk in the dependence of the given lunation period for different values of the parameter γ.*

the center at the disk, according to the measurements of mean radio temperature for the disk and after a corresponding recomputation, one obtains $T_{s0}(0)=226°\pm5°$, which gives $\gamma_2=600\text{–}800$. Thus, the present data lead to the value

$$\gamma_2=600\pm200.$$

TABLE 3. *Numerical values of the terms of Fourier-expansion of the surface temperature in the center of the lunar disk and ζ as a function of γ.*

γ	T_{sm}	T_{sn}	T_{s0}	T_{s1}	T_{s2}	ζ^0_{s1}	ζ^0_{s2}	T_{s0}/T_{s1}	T_{s0}/T_{s2}
125	390	158	247	132	34	5	−7	1.86	7.27
250	391	136	237	146	35	4	−7	1.62	6.77
400	392	123	230	156	36	3	−7	1.48	6.40
500	392	117	227	159	36	3	−7	1.42	6.30
700	393	109	223	165	36	3	−6	1.35	6.20
1000	393	100	219	170	36	2	−6	1.29	6.10
1200	393	96	217	173	36	2	−6	1.26	6.03

This difference between the eclipse and lunation values is naturally explained by inhomogeneity of the density of the material in the superficial layer. Realizable dependency of the material properties on temperature [Buettner, 1963], as computations show [Aljeshina and Krotikov, 1965], cannot explain the observed difference. The assumption of a linear dependence of κ and c on the temperature, made by Munsey [1958] seems to us to be very unlikely. It should be noted that, in the case of an existing inhomogeneity and with the adoption for the determination of γ the theory of a homogeneous model, we can obtain an overestimation of γ_2 lying between that at the surface and the true value at a depth. Using the values for defined parameters at the surface $\gamma_1=1000$ and $\rho_1=0.5$, we obtain for the thermal conductivity

$$\kappa_1=(1\pm0.5)\times10^{-5}\text{ cal/cm degree sec.}$$

The structural parameter is equal

$$\alpha_1 = \kappa_1/\rho_1 = (2 \pm 1) \times 10^{-5} \text{ cal cm}^2/\text{sec degree}.$$

At the depth of 3–4 cm or more, $\gamma_2 = 600$ and $\rho_2 = 1$; hence $\kappa_2 = (1.7 \pm 1) \times 10^{-5}$ for the same structural parameters. It remains to evaluate the depth of the penetration of a temperature wave. As for both media $\kappa = \alpha\rho$, the value $l_T = \sqrt{\frac{\kappa}{c\rho} \cdot \frac{t_0}{\pi}}$ should be identical for both media too. But in the case of the inhomogeneous layer composed of those media, this expression is now unjust for the l_T. However, a small inhomogeneity will not change substantially the value l_T, and it will be

$$l_T = \sqrt{\frac{\alpha t_0}{c\pi}} = (10 \pm 5) \text{ cm}.$$

For the eclipse, a similar value at the moment of the end of the umbral phase is equal to $l_{ec} = \sqrt{\frac{\alpha}{c}} (t_3 - t_1)$, where $t_3 - t_1$ is a time-interval from the beginning of the eclipse up to the umbral phase; this time interval is equal to about 3 hr. Hence,

$$l_{ec}/l_T = \sqrt{\frac{(t_3 - t_1)\pi}{t_0}} \simeq 0.1 \text{ and } lec \simeq 1 \text{ cm}.$$

2.6. Absorption Spectrum of Electromagnetic Waves in the Material of the Moon

In order to determine the absorption spectrum, it is necessary to determine δ_1 from the experimental data. The best way is to compare the experimental value M with the theoretical one (32a) for the homogeneous model. It is apparently safe to use the theory of the homogeneous model in spite of the existence of some inhomogeneity; as we have seen, the experiment satisfies this model to within the measurement accuracy. Determination of δ at the wavelengths of 0.13 to 3.2 cm has shown that it is changing in proportion to the wavelength λ [Troitsky and Zelinskaja, 1955; Zelinskaja, Troitsky, and Fedosejev, 1959; Krotikov and Troitsky, 1963b]

$$\delta = m\lambda \qquad 0.1 \leq \lambda \leq 3.2 \text{ cm}.$$

The value of the coefficient of proportionality is found to be equal to $m = 2$. Figure 8 shows the spectrum $\delta/\lambda = m$ including all available data. Some deviation from a linear dependence takes place in the vicinity of $\lambda = 1.6$ cm, which can be interpreted as absorption in the lunar material near that wavelength. Taking the value of $l_T = 10$ cm, we obtain depth of the penetration of electromagnetic wave of

$$l_e = (20 \pm 10)\lambda.$$

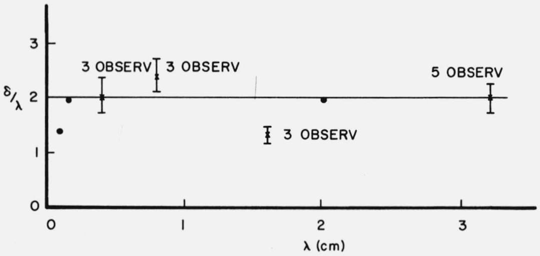

FIGURE 8. *The dependence of δ/λ on wavelength λ.* Black dots correspond to the experimental data.

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This dependence between l_e and λ confirms the dielectric nature of the Moon material. The unknown relationship of the heat and electric parameters is equal to

$$\frac{c\gamma_2\text{-}}{b_2\sqrt{\epsilon_2}} = 5.6\times 10^3 m = 11.2\times 10^3,$$

where the points indicate parameters most likely to concern the layers deeper than 3 to 4 cm ($3 \leq l_e \leq 60$ cm). Contrary to this, the eclipse measurements give the value for the parameters of the upper layer and are marked by the x's. All present data on the magnitude of a relative of a relative drop in radiation temperature at the time of the eclipse are given in the table 2.

In the same table are presented the values $\frac{\gamma_1}{b_1\sqrt{\epsilon_1}}$ computed in accordance with the above theory [Troitsky, 1965].

Figure 5 gives the theoretical curves $M(\lambda)$ for the eclipse of December 30, 1963, with different values for $\gamma/b\sqrt{\epsilon}$, computed by exact formulas, together with the experimental points. According to the data presented in the table 2 (except the data on the partial eclipse of February 7, 1963), one may take

$$\frac{c\gamma_1}{b_1\sqrt{\epsilon_1}} = (11.4\pm 3)10^3.$$

This value concerns the layer less than $l_{ec} \simeq 2-3$ cm. In accordance with this it is necessary to adopt the values ϵ and γ for the corresponding depths, for the determination of b_1 and b_2; i.e., $\epsilon_1 = 1.5$, $\gamma_1 = 1000$; and $\epsilon_2 = 2.25$, $\gamma_2 = 600$. As a result we obtain

$$b_2 = (7.5\pm 1.5)\times 10^{-3} \qquad b_1 = (14\pm 4)\times 10^{-3}.$$

A comparison of these data suggests that, together with a certain inhomogeneity as to the density of the material, apparently there takes place an inhomogeneity with depth of the electrical properties, i.e., of the nature of the material. The increase in a specific loss angle to the surface may be associated with saturation of the surface layer by meteoric material having the $b \simeq 2\times 10^{-2}$.

2.7. Spectrum of the Constant Component and Heat Flux From the Depths of the Moon

As shown above, the constant component of radio emission is determined by a constant portion of the layer temperature at the depth of the penetration of the wave. The repeated attempts to discover the anticipated systematic rise of the constant component with the wavelength turned out to be unsuccessful due to poor precision of usual radio measurements. In order to discover the effect, the special measurements of radio emission were carried out at the 168-cm wavelength [Baldwin, 1961]. However, neither precision of measurements, nor assumptions made by working out the results (linear rise in temperature up to the wavelength 168 cm) allowed the gradient and flux to be determined with sufficient safety. One has estimated the flux, $q_s = 0.25\times 10^{-6}$ cal/cm^2 sec, that coincides with the theoretical values [Jaeger, 1959; McDonald, 1959; Levin and Majeva, 1960; Majeva, 1964]. As a result of using the precision method of measurements, the growth of the constant component of radio temperature of the Moon was soundly established [Krotikov and Troitsky, 1963c]. Figure 9 presents the spectrum $\overline{T}_{e0}(\lambda)$, obtained by the above measurements of the wavelengths 0.4 cm, 1.6 cm, 9.6 cm, 14 cm, 32.5 cm, 35 cm, 50 cm, carried out in the Research Institute of Radio Physics in 1961–1964. The observed effect cannot be explained by any overlooked errors of measurements or such causes as roughness or reflection by the Moon of galactic and solar radiation. Reflected by the Moon, the galaxy radiation appears at those wavelengths

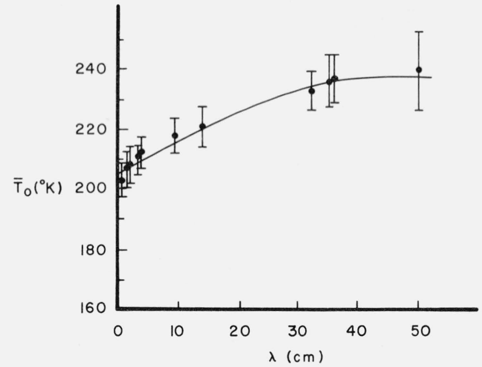

FIGURE 9. *The dependence of the mean disk constant component of the effective temperature on wavelength, from the data of precision measurements of lunar radio emission.*

so small that it may be disregarded [Starodubtsev, 1964]. The only way to explain the observed effect is to admit a real rise in the deep temperature due to flux of internal heat. However, the question of the origin of such a flux remains. In principle, two possibilities exist. Either the flux is of a solar origin, or, just as the Earth, it is caused by dissociation of radioactive elements, contained in all of its rocks. The first assumption requires very unnatural suppositions about light penetrating to depths of up to 10 m, and so on. The least contradictory explanation is that the flux of heat comes from great depths. Figure 9 shows the almost linear rise in radio temperature of the Moon with wavelength up to $\lambda = 30$ cm, which suggests an approximately constant thermal conductivity to the depth of penetration of each wavelength. There are far more dense layers at greater depth with thermal conductivity close to the terrestrial value (100 times greater than the lunar), giving, therefore, a temperature rise with depth hundreds of times smaller. Thus, the thick porous layer of the material lies, apparently, on a dense rock base. The thickness of this layer may be evaluated. As the thermal conductivity in the layer is equal throughout, the density is equal as well. If the parameter b is not changed, the value of electromagnetic wave attenuation is equal in the total layer, as well as in its upper part $l_e = 20\lambda$. Consequently, the thickness of the porous layer, corresponding to depth of penetration of waves of $\lambda = 30$ cm, is equal approximately to

$$l_{\text{por}} \simeq (3 \text{ to } 10) \text{ m}.$$

As seen from figure 9, $dT_{e0}/d\lambda \simeq 1$ deg/m. Hence, from the above theoretical computations, where $l_T = (10 \pm 5)$, we obtain for the gradient of temperature in the 6-m layer,

$$\text{grad } T(x) = (4 \text{ to } 2) \text{ deg/m}.$$

Accepting $\gamma_2 = 600$, the density of the flux, according to (15), turns out to be equal to

$$q_s = (1 \pm 0.3) \times 10^{-6} \text{ cal/cm}^2 \text{ sec}.$$

As we have seen, the theoretical values for the flux density give a value 4 to 5 times less.

The total heat flux from the depths of the Moon is

$$Q = (1 \pm 0.3) \times 10^{19} \text{ cal/deg}.$$

If a heat equilibrium is set up, then it follows from the value Q that per 1 g of the lunar material there is educed per year

$$q_v = 1.7 \times 10^{-7} \text{ cal/g year}$$

of radiogenic heat.

This value is 4 to 5 times greater than that for the Earth, and suggests that the mean concentration of radioactive elements in the Moon material is much higher than their mean concentration for the Earth. This fact will require the radical revision of existing ideas about the heat history of the Moon, based on low content of radioactive elements.

2.8. Microstructure: Nature of the Material

The microstructure of the obtained porous layer is still very obscure. In the main, one has to choose between a fine dispersed dry (dust) and a solid porous structure. However, the parameter α_L appears for the Moon not so well determined for this purpose. Its value, as we have seen, for both parts of the layer is approximately $\alpha_L \simeq 2.10^{-5}$. This value lies between the values α for the dust and the solid porous medium in vacuum, which are composed of terrestrial rocks. Unreliability of the latter numbers, and of the value α_L, too, for the Moon makes the conclusion about the microstructure very tentative. It is possible that the vicinity of α_L to the value for the dust points to the character of origin of the upper porous layer by means of cohesion and adhesion of dust particles arising by meteoric bombardment of loose enough structures. This gives an intermediate structure between a solid-porous and a dry-dust structures, when the heat contacts are weaker than in the first one, and stronger than in the second, as the pores are opened. A similar structure was investigated at optical wavelengths, and was found to be corresponding as to the scattering, to the superficial layer of the Moon [Hapke and Van Horn, 1963].

To draw some conclusions about the nature of the material, according to the above method, on figure 10 gives values of tg Δ/ρ for various rocks. In the diagram are plotted two shaded bands corresponding to likely lunar values of parameters. The upper band corresponds to the measurements to the time of the eclipse b_1 that give a value for the layer at adepth of the order of 1 to 2 cm. The lower band corresponds to the values b_2 derived from the lunar measurements for lunar lying depths. As seen from figure 10 and table 4, the upper layer of the material may be a volcanic slag, meteoric material and tuff, the lower layers, tuff, pumice, ashes, etc.

2.9. Distribution of Properties on the Surface of the Moon

A number of investigators repeatedly affirm a considerable difference in properties of the material over the lunar surface. Thus, for example, the maria have been claimed to be formed of basalt, and the continents of granite.

Quantitative investigation of different characteristics of reflected light (polarization, index of reflection, albedo, color) lead, as is known, to the conclusion of a high photometric homogeneity

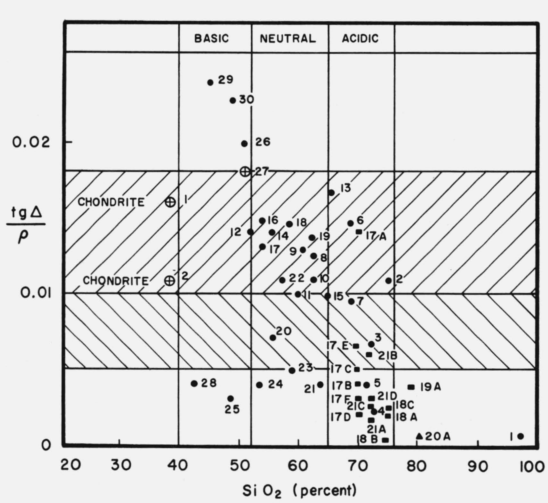

FIGURE 10. *The dependence* tg Δ/ρ *on the percent content* SiO_2 *for different rocks, meteorites, and tectites.*

of the Moon surface [Barabashov et al., 1959]. However, this does not give sufficient arguments in favor of the homogeneity of such properties as density, thermal conductivity, and chemical and mineral composition.

The author [Troitsky, 1964c] considered in his work the methods to determine the variations of values γ, ρ, and b on the disk of the Moon. Briefly the results are reduced to the following:

One can determine variations of the value γ on the disk of the Moon by spatial distribution of the temperature of the night Moon or at the time of an eclipse. Fluctuations of temperature can be determined by deviation of observed isotherms from the ideal ones. Approximately, the relationship connecting the variations γ with those of the night temperature, has a form

$$\frac{\Delta T_{sn}}{T_{sn}}=\frac{1}{16}\frac{\Delta\bar{\gamma}^2}{\gamma^2}+\frac{1}{16}\frac{\Delta\bar{R}_i^2}{(1-R_i)^2}.$$

Spatial distributions of infrared temperature in the sunlit zone, when the incidence angle of Sun's rays is $i \leqslant 70$–$80°$, are equal to

$$\frac{\Delta\bar{T}^2}{T^2}=\frac{1}{16}\,tg^2 i\Delta\bar{i}^2+\frac{1}{16}\frac{\Delta\bar{R}_0}{(1-R_0)^2}+\frac{1}{16}\frac{\Delta\bar{R}_i^2}{(1-R_i)^2}.$$

The fluctuations of temperature in the subsolar zone ($i=0$), as one can see from the expression, allow a determination of the sum of mean squares of relative fluctuations of an optical and infrared albedo. Measurements at low angles of the Sun determines the fluctuations of surface slopes. The investigation of infrared isotherms for the sunlit zone using a resolution of about 20 km [Saari and Shorthill, 1962] have shown that for the subsolar point, variations of $\sqrt{\Delta\bar{T}^2}=\pm(1-1.5)$. This corresponds to albedo variation of the order of $\sqrt{\Delta\bar{R}_0^2}=\sqrt{\Delta\bar{R}_i^2}\simeq 10^{-2}$. Variations of the value γ at present can be evaluated only roughly, as a map of the night isotherms of the Moon does not yet exist. Individual measurements of the night temperature all along the trajectory [Murray and Wildey, 1964; Saari and Shorthill, 1964] prove that its variations do not exceed, apparently, $\pm 15°$, i.e., about $1/20$ of the average value. Hence we obtain

$$\frac{\Delta\gamma_s}{\gamma_s}=\pm 0.25; \qquad 750\leqslant\gamma_1\leqslant 1250.$$

The direct measurements of γ_1 for different points on the Moon's disk (with the exception of the bottom of radiating craters) show the same scattering [Saari and Shorthill, 1962]. Thus, we come to the conclusion that thermal conductivity and density of the lunar material, when averaging over a region of about 20 km, are varying on the surface (except bottoms of craters) hardly more than by 1.5 to 2 times. Notice that the depth of the penetration of heat wave will be identical, independent of the value of ρ. By measuring the radio emission with a sharp beam, the possibility arises of evaluating the distribution of values of $\gamma/b\sqrt{\epsilon}$ on the disk. The measurements carried out at 0.4 cm [Kisljakov and Salomonovich, 1963] testify to a considerable constancy of that value in the equatorial zone when averaging over a region having a linear dimension of the order of 150 km. No difference was observed in this value for maria and continents. This indicates the unchanging nature of the material that forms the lunar superficial layer. At least, the data definitely deny the hypothesis of basalt rock for the material of maria and that of granite for continents. The measurements of radio emission at the $\lambda=3.2$ mm at the time of the eclipse were recently carried out for different points, including the bottoms of craters, as well [Jacobs et al., 1964]. The analysis carried out by us shows that the value $\gamma/c\sqrt{\epsilon}$ turns out to be in the limits of precision of measurements (± 20 percent) identical for all of those formations. Thus, besides the photometric homogeneity, there exists the radiometric homogeneity of the material of the first decimeter of the lunar surface, associated with a high degree of the homogeneity of thermal and electric properties of the material on the Moon surface.

2.10. Properties of the Venus Surface

The radar investigations have shown that for Venus, $R_{\perp} \simeq 0.1$. This gives $\epsilon = 4$, and, if the material of the surface is composed, just as at the Earth, of silicate rocks, then the density $\rho = 2$ g/cm^3. The dependence of radio emission on the phase, according to measurements at $\lambda = 3.2$ cm and 10 cm, respectively, has a form $T_{e1} = 621 + 73 \cos(\Phi - 12)$ and $T_{e1} = 622 + 39 \cos(\Phi - 17)$. This phase dependence proves that the axis of rotation of the Venus does not lie in the plane of its orbit, and the rotation is retrograde. We assume for the material of the Venus, as well as for all the silicate dielectrics, that $\delta = m\lambda$. Equating the relations $M(3) = 621/73$ and $M(10) = 622/39$ with their theoretical value (32a) for integral flows and solving the equations with two unknown quantities by the $\beta_0 = 0.92$, $\beta_1 = 0.73$, we obtain [Troitsky, 1964]

$$\delta = 0.14\lambda, \; T_{s0}(0)/T_{s1}(0) = 4, \; T_{s1}(0) = 150\ ^{\circ}\mathrm{K}.$$

$$\frac{\gamma c}{b\sqrt{\epsilon}} = 2m\sqrt{\pi t_0}.$$

The duration of a solar day, according to radar measurements, is of the order of 100 days. Accepting $c = 0.2$, we have $\frac{\gamma}{b} = 1.5 \times 10^4$. Accepting, as for terrestrial rocks, the mean value $b = (1 \pm 0.5) \times 10^{-2}$, we obtain

$$\gamma = 150.$$

This value is too high, and by $\rho = 2$ leads to the value $\alpha = 0.6 \times 10^{-4}$ which is by one order less than the value for porous rocks in the atmosphere of the Earth. If to solve the problem of determination of a period, adopting the $\gamma/b = 50/10^{-2} = 5 \times 10^3$ as an initial value close to the terrestrial one, we obtain $t_0 \simeq 10$ days. It is necessary to carry out more precise measurements of phase dependence of radio temperature of the Venus.

3. Conclusions

As the above considerations show, the investigation of the proper thermal radiation from solid bodies, particularly by existing variable thermal regimes of different periodicity and duration, allow us to obtain the substantial information on physical parameters of the layer and the temperature regime. However, the experimental initial data obtained for the Moon are still not sufficiently complete and precise. There continues to be considerable uncertainty in our knowledge of the parameters of the Moon layer material. Essentially, at present we have the values but for those magnitudes. For a more precise determination of parameters of the Moon layer, further investigations on infrared radiation and radio emission of the Moon are needed in both thermal regimes; the lunation and the eclipse. Precise measurements of the night infrared temperature are particularly needed; the absolute measurements of surface temperatures depending on time for different formations on the Moon, are also necessary. The relative measurements of temperature distribution on the Moon disk at night and at the time of the total phase of the eclipse are needed.

At present, the radio experiments are more advanced, perhaps, than in the infrared field. In any case, the quantity and precision of radio data on integral emission do not limit the possibility of drawing conclusions. However, at present, it is clearly necessary to measure the radio emission at short millimeter waves in order to determine the inhomogeneity of the layer with depth. Especially advisable is the measurement of the polarization spectrum in the range from millimeter up to decimeter wavelengths. Practically speaking, only the first steps have been made here. Finally, a large remaining field is the investigation at the radio waves of separate zones of the Moon. It is extremely advisable here to use wavelengths in the decimeter range. However, here one meets with difficulties in obtaining sufficient resolving power. Possibly such investigations can be made from the satellites placed around the Moon.

At the present, the working of experimental data necessitates an elaboration of theoretical problem relative to the radiation of layers of the material with a variable thermal regime and different distribution of properties with depths, the elaboration of the theory of radiation of the rough Moon, etc. Strict and precise computations are needed, as the precision measurements allow one to observe even the slightest effects.

Especially, we should like to point out that the research of the thermal radiation of the Moon from the Earth gives objective characteristics which are added to the basic constants characterizing the Moon. They have their original value, irrespective of very limited possibilities of interpretation.

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Discussion Following Troitsky's Paper

F. D. Drake: Are there difficulties in your measurements with the "artificial Moon" being in the near or Fresnel zone?

A. E. Salomonovich: The use of the method of the "artificial Moon" requires, generally speaking, its placement in the Fraunhofer zone and against the sky background (with not too large zenith distances when the atmospheric radiation is considerable). Prof. Troitsky uses this method for relatively small antennas (3–8 m), when the distance to the "artificial Moon" is not great, and the disk diameter required to cover the main lobe (or its largest part) is 4–6 m. With larger sizes of antennas where a large number of wavelengths (10^3 and more) are included within its diameter it is necessary to either correspondingly increase the size of the disk, which is extremely inconvenient, or else to change the method. A method of calibration within the Fresnel region has been developed that makes use of extraterrestrial sources of large angular dimensions. In this method the radiator (feed) is displaced from the focus a certain distance, and the aerial diagram is obtained with the use of a transmitter located in the Fresnel zone. According to the known distribution of brightness across the lunar disk and the measured diagram, it is possible to calculate the effective area of the radio-telescope antenna. An analogous method in which the "artificial Moon" is used was recently proposed by Dr. N. M. Tseitlin.

A. Boischot: With what accuracy can you know the brightness of the "artificial Moon"?

A. E. Salomonovich: The emissivity of the absorbing disk material can be measured in the laboratory to an accuracy better than 1 percent. The physical temperature of the disk surface also can be measured with high accuracy with the aid of a thermocouple, or a system of thermocouples. The principal source of error in such measurements is the additional radiation due to diffraction of Earth radiation by the disk. These effects have been considered in the papers cited in the review paper of Prof. Troitsky.

C. Sagan: How does Prof. Troitsky determine the imaginary part of the dielectric constant? This value depends greatly on impurities in the material. A large number of substances could give the values you quoted.

A. E. Salomonovich: In radio-astronomy observations of the Moon (during eclipses and lunations), under certain assumptions one finally determines the value of tan Δ/ρ, which does not depend on the porosity of the substance but does depend on the chemical and mineralogical composition. Of course, the impurities do affect this value. A comparison with terrestrial ores helps in selecting materials most similar in composition. It is possible that this choice is not quite unique.

(69D12–603)

Polarization of Thermal Radiation of the Moon at 14.5 Gc/s

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A summary of this work has been given in Astronomical Journal **70,** 132 [1965]. Comparison of measured polarization with calculated results for smooth and rough spheres indicated the best agreement for the central lunar disk is obtained with $\epsilon = 1.8$, while the region near the limb corresponds to $\epsilon = 1.5$. It was concluded that dielectric constant decreases with increasing frequency.

Discussion Following Mezger's Paper

G. H. Pettingill: You do not include radar determinations of dielectric constant in the comparison.

C. Sagan: I believe that Prof. Troitsky explained the increase of dielectric constant with wavelength as being due to longer wavelengths penetrating to the deeper, more compacted layer of porous material.

It seems you neglect the influence of the temperature distribution on the polarization.

A. Giraud: These results agree with the work of N. S. Soboleva at 3.2 cm, with the large Pulkovo telescope [Astron. Zhur. **39,** 1124, 1962].

(Paper 69D12–604)