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RESULTS OF INVESTIGATION OF MOON'S INTRINSIC RADIATION

by

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RESULTS OF INVESTIGATION OF MOON'S INTRINSIC RADIATION

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by V. S. Troitskiy

SUMMARY

This is a major review paper, destined to present a summary and a description of a contemporary model of structure of Moon's mantle.

The study is based in the first place on recent foreign investigations of Moon's intrinsic infrared radiation in parallel with the research conducted at the Gor'kiy Institute of Radiophysics using a wide wavelength range.

At the same time, methods are applied, which have been described in a number of papers and designed to allow us to study the properties of solid matter by its emission.

The current review is composed of four major sections, of which the third is itself subdivided in 5 sub-sections. They are :

I. EXPERIMENTAL RESULTS OF THE STUDY OF MOON'S RADIATION

2. GENERAL PRINCIPLES OF STUDY OF PROPERTIES OF MATTER MAKING UP THE MOON'S UPPER MANTLE ACCORDING TO ITS INTRINCIC RADIATION

3. PROPERTIES OF MATTER OF THE UPPER MANTLE

   1. Thermal Properties of Matter
   2. Variation of Properties with Depth
   3. Temperature Dependence of Properties of Matter
   4. Heat Flow from the Interior of the Moon. Study of Properties of Deep Layers
   5. Nature of Matter of the Upper Mantle

4. DISCUSSION OF RESULTS

The review is accompanied by no less than 81 bibliographic references.

(*) REZUL'TATY ISSLEDOVANIYA LUNY PO YEYE SOBSTVENNOMU IZLUCHENIYU

INTRODUCTION

At the present time, as a result of studies performed abroad of the Moon's intrinsic infrared radiation and of studies carried out at the Gor'kiy Radiophysical Institute (N I R F I) in a broad wavelength region ranging from submillimeter (0.87 mm) to meter (70 cm) waves, data have been obtained which allow us to make definite conclusions on the properties and structure of the mantle of the Moon. This fact made it necessary to work out methods, described in a number of papers, for studying the properties of solid matter from its radiation. A somewhat general presentation of results obtained prior to 1965 is given in references [1-3]. On the basis of recent theoretical and experimental studies; it is apparently possible to complete the basic features of development of a structural model of the Moon's mantle. We believe that it is now advisable to present a summary and description of a contemporary model of the structure of Moon's mantle, utilizing for this purpose all available experimental and theoretical results and methods developed for their interpretation.

I. EXPERIMENTAL RESULTS OF THE STUDY OF MOON'S RADIATION

The Moon's intrinsic radiation is a thermal radiation, i.e. it is determined by the temperature of matter on the Moon. This temperature varies with a period of 29.5 terrestrial days (24-hour periods), thus causing fluctuations in the intensity of Moon's intrinsic radiation. The radiation intensity in a given wave is usually characterized by the effective temperature. According to measurements and theory [4], the effective brightness temperature of any element of a surface with the selenographic coordinates ϕ and ψ is well described by the series:

$$T_e(\varphi, \psi, \lambda) = T_{e0}(\varphi, \psi, \lambda) + T_{e1}(\varphi, \psi, \lambda) \cos [\Phi - \xi_1(\varphi, \psi, \lambda)] + \\ + T_{e2}(\varphi, \psi, \lambda) \cos [2\Phi - \xi_2(\varphi, \psi, \lambda)] + \ldots, \tag{1}$$

where Φ is the local phase ($\Phi = 0$ corresponds to noon), ξ_1 is the phase lag of radiation intensity with respect to the heating phase. The upper harmonics of brightness temperature are clearly apparent only in waves shorter than 0.2-0.4 cm.

Most often measured is the radiation of the entire Moon's disk, i.e. the average effective temperature over the disk. For all waves, this temperature is well described by two terms of the series:

$$\bar{T}_e(\lambda) = \bar{T}_{e0}(\lambda) + \bar{T}_{e1}(\lambda) \cos [\Omega t - \bar{\xi}_1(\lambda)]. \tag{2}$$

The horizontal bar indicates averaging over the half-sphere, and Ωt is the phase of the Moon ($\Omega t = 0$ corresponds to fullmoon).

In the analysis of experimental data the constant component and the first harmonic are generally used, since the higher harmonics are small and so far are very difficult to measure. Even the most powerful second harmonic of brightness temperature amounts to no more than 25% of the first harmonic. This fraction does not exceed 7% of the mean radio temperature of the disk.

As may be seen from (2), the Moon's emission spectrum is a function of time. Therefore, it is appropriate to characterize it by means of the spectra of three quantities: the spectrum of the constant component, the spectrum of first harmonic's amplitude, and the spectrum of the phase lag of the first radiation harmonic. The spectrum of the constant component, obtained by using the method of precise measurements with the aid of an "artificial Moon", is shown in Figure 1, where the value of the mean effective emission temperature on the Moon's disk in the given wave is plotted along the ordinate axis [5-7]. The amplitude spectrum of the first harmonic, characterized by the ratio

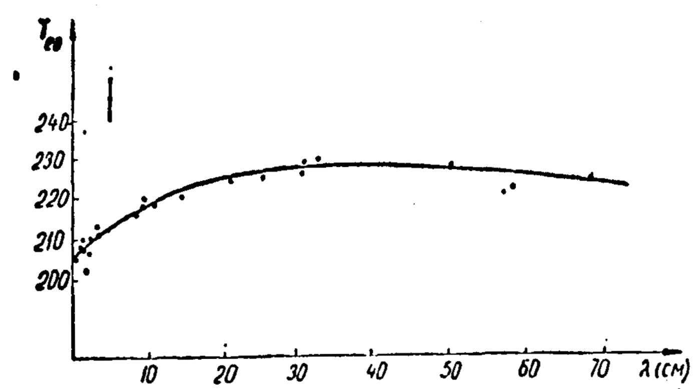

Fig.1

Spectrum of the mean constant derivative of the effective temperature, over the Moon's disk (measurements carried out in 1960-67 by the "artificial Moon" method).

$\overline{M}(\lambda) = \overline{T}_{e0}|\overline{T}_{e1}$, is shown in Figure 2 [5-39], from which one may see that the amplitude of the first harmonic decreases with increasing wavelength λ and that the fluctuations of intensity practically disappear in waves longer than 15-20 cm. Figure 3 shows the spectrum of the phase lag of the first harmonic $\xi_1(\lambda)$ [5-39].

Data on the variation of emission intensity during lunar eclipses constitute an important characteristic of Moon's radiation [47-56]. These data are given for a number of wavelengths in Figure 4, where the quantity $\overline{M}_3 = \overline{T}_{em}|\Delta\overline{T}_e$, is plotted along the ordinate axis; this quantity is equal to the reciprocal of the maximum relative intensity drop characteristic for the end zone of the shadow phase in the eclipse of the center of the

Moon's disk. It may be seen in Figure 4, that in waves longer than 1.5 cm. there is practically no change in intensity during eclipse.

Another important characteristic of the intrinsic radiation is its polarization. However, the amount of data obtained in this field is still small [57-61] By using the results of polarization measurements and Fresnel's reflection factors, it is possible to determine the reflection factor and the dielectric constant of the emitting layer.

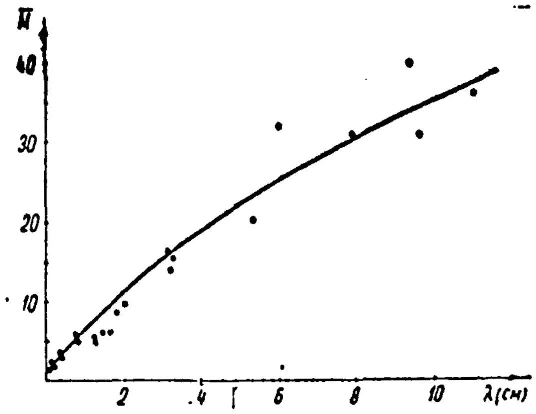

Fig.2
Spectrum of the ratio of the constant derivative to the amplitude of the first harmonic of fluctuations of Moon's effective temperature (mean value over the Moon's disk). Measurement error ± 10%.

The spectrum of the reflection factor is a rather important characteristic of the surface layer. The results of measurements of the reflection factor are known, and these were obtained both by radar [62-66] and radioastronomy methods, measuring certain characteristics of intrinsic radioemission, including measurements of its polarization [67-70]. Further in this paper we shall utilize the values of radar reflection coefficients, substantially reduced by us. The fact is that radar experiments yield the quantity $gR_{\perp}$, where $R_{\perp}$ is the reflection factor in the case of perpendicular incidence, while g is a factor which taken surface roughness into account. For an ideal sphere $g = 1$, and this was generally assumed. At the same time, model experiments [46] have shown that for the surface roughness, characteristic of the Moon, $g = 1.6$ in centimeter waves and $g = 1.06$ in decimeter waves. In Fig. 5, dots represent the values of radar reflection factor, reduced according to the above-mentioned values of g. In the same figure, small crosses represent data obtained mainly from measurements of the polarization of radioemission (see, for example, [61]).

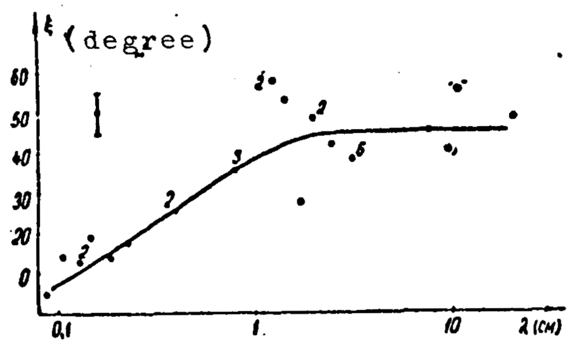

Fig.3
Spectrum of the phase lag of the first harmonic of temperature fluctuations of Moon's radioemission relative to the phase of surface temperature fluctuations.

It should be noted that radar measurements of $R_{\perp}$ can yield erroneous values not only on account of inaccurate knowledge of g

but also as a result of body shape deviation from spherical shape in the reflection region. For example, the presence of flattenings or even concave surfaces caused by mountains can greatly increase the reflected power and, consequently, the value of $R_{\perp}$.

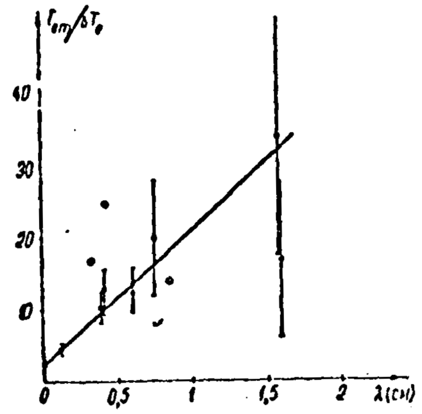

Fig.4

Spectrum of the receiprocal value of the maximum relative drop of Moon's effective emission temperature during its eclipse.

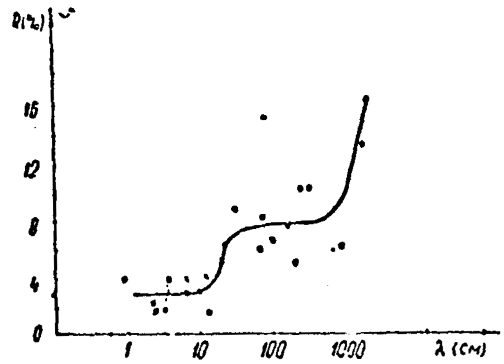

Fig.5

Spectrum of the reflection factor of radio waves by the Moon's surface. Dots correspond to radar data (reduced); measurement error +100% or −50%; small crosses correspon to radioastronomy data on the polarization of intrinsic radiation measurement error ±20%.

2. GENERAL PRINCIPLES OF STUDY OF PROPERTIES OF MATTER MAKING UP THE MOON'S UPPER MANTLE ACCORDING TO ITS INTRINSIC RADIATION

As is well known, the proper radiation of any medium can be described by an equation of radiant energy transfer. For the dense matter of the Moon, this equation can be simplified since we may utilize the principle of partial local thermodynamic equilibrium, according to which kinetic equilibrium in mantle takes place, although in a general case it is possible that no equilibrium takes place between the matter and the surrounding radiation. If the above said is taken into account, the equation of radiation transfer in the frequency ν has the form:

$$\frac{d}{\alpha_\nu dl}\left(\frac{I_\nu}{n^2}\right) = -\frac{I_\nu}{n^2} + \frac{B_\nu}{n^2}, \qquad (3)$$

$$B_\nu = \tilde{\lambda}\int I_\nu f(\chi)\frac{d\omega'}{4\pi} + (1-\tilde{\lambda})\, n^2 B_{\nu 0}.$$

Here α_ν and $n = \sqrt{\varepsilon}$ are respectively the damping factor and refraction index of waves in the medium, ε is the dielectric constant, $\tilde{\lambda}$ is a factor characterizing the scattering, $f(\gamma)$ is the scattering indicatrix, $B_{\nu 0} = B(\nu, T)$ is a Planck's function for the radiation flux of the medium into vacuum. As is well known, the damping factor α_ν is equal to the sum of the damping factor on account of wave $\tilde{\lambda}\alpha_\nu$ scattering and by the true absorption $\chi_\nu = (1 - \tilde{\lambda})\alpha_\nu$. The medium's radiation into vacuum is determined by solving the first equation in (3) and, as is known, in the case of a sufficiently homogeneous medium (in the wavelength scale, is equal to:

$$I_\nu = (1 - R) \int_0^\infty B_\nu \exp\left(-\int_0^l \alpha_\nu dl\right) \alpha_\nu dl, \tag{4}$$

where R is the reflection factor of radiation of a given polarization from the interface, while B_ν is an unknown function which can be determined by the solution of (3). If the surface is sufficiently smooth, then R is linked with ε by Fresnel's formulas; if the surface has a very rough texture, then R must be recognized as the albedo of the surface.

In the case of a substantially inhomogeneous medium (for a given wavelength) the coefficient of radiation transfer through the surface (1 - R) depends on the depth l and must be introduced under the integral sign. The quantity R itself is determined in this case by Ricatti's differential equation [71]. We may see from (4) that the radiation intensity depends upon the distribution of the temperature in the layer along the beam. For the Moon, the temperature of the layer is determined only by heating under the action of solar rays, by thermal properties of matter and by the heat flow from the sub-surface. At a given moment of time t at the depth x below the surface the temperature is determined by the heat conductivity equation with corresponding boundary and initial conditions:

$$\frac{\partial}{\partial x}\left[k(x, T)\frac{\partial T}{\partial x}\right] = \rho(x) c(x, T) \frac{\partial T}{\partial x},$$

$$(1 - R_c) S_0 f(t) - (1 - R_u) \sigma [T(0, t)]^4 - \left[k \frac{\partial T}{\partial x}\right]_{x=0} - q = 0, \tag{5}$$

where, $k(x, T) = k_0 + k_p$ is the total heat conductivity, equal to the sum of the molecular, k_0, and radiation, k_p, heat conductivity; $\rho(\chi)$ is the density; $c(\chi, T)$ is the heat capacity of matter; R_u and R_c are respectively the infrared and light albedo of the surface; so is the solar energy flux; $f(t)$ is a function of flux variation in time, which depends on the spot of the lunar sphere whose radiation is being investigated and which is a periodic function for lunations and a pulse function for eclipses.

In boundary conditions the first term represents the surface-absorbed solar energy, the second term the energy loss on surface emission into vacuum, the third term - the loss on heating the body, and the fourth - the heat flux from the interior of the Moon. In the case of computation of lunation regime the initial conditions are arbitrary since steady-state "forced" periodic solution is being sought. In the case of eclipse, the initial conditions are assigned by temperature distribution at the commencement of the eclipse, which is obtained from the solution of the lunation problem at fullmoon time, which is the only time when lunar eclipses take place. The combination of Eqs. (3) - (5) fully determines the Moon's intrinsic radiation. Consequently, it is possible at least in principle, to determine by using various radiation characteristics all the parameters of matter entering into these equations, namely $k(x, T)$, $c(x, T)$, $\rho(x)$, $\varepsilon(x)$, $x_v(x, T)$, q, $T(x, t)$, $\lambda(x)$, $f(\chi)$, R_H, R_c and the roughness. The knowledge of these parameters permits us to draw a conclusion on the nature of matter (mineralogical composition type of rocks) and also on the type of structure (hard compact, hard-porous, friable) and on the microstructure (dimensions of particles and pores), etc.

As is well known, comparison of the observed phenomenon with its theory is a general method of studying the properties of an object. In particular, the determination of Moon's layer parameters amounts to finding the parameters of Eqs. (3)-(5), satisfying the solution I_ν known from experiments, i.e. to solving the inverse problem. However, the inverse solution of differential and integro-differential equations, which are the types of equations we are dealing with here, involves great difficulties. Usually, a direct solution is sought for a set (family) of parameter values, which are then found by comparing calculated and experimental data. In practice this is possible when the solution is determined only by one parameter, However, we are confronted with about ten unknown parameters, every one of which is a function of depth in the general case, while some of these parameters are also function of temperature. On the strength of the above-said, the method of analysis must consist in selecting such radiation characteristics which are defined mainly by a single parameter; other parameters either exert no effect whatsoever on these characteristics or exert so small an effect that it can be disregarded in a first approximation. In order to explain the selected phenomenon or a group of phenomena, an appropriate partial model is built. Assortment of partial models, which explain the entire available experimental material, makes it possible to build a general model that satisfies best all the data available. This approach was used in the study of the Moon.

It should be noted that in our study of the Moon based on its intrinsic radiation we start from quite specific original data, known from other sources. Eqs. (3)-(5) themselves point out these original concepts. The equations are valid when we consider that the Moon has no atmosphere and that the matter making up its upper mantle is solid. These facts are derived from visual astronomical observations.

At the present stage of the study of the Moon's radiation it is assumed that for radio waves $\lambda = 0$. Then, in (3) and (4) B_ν is equal to the well-known function $B_\nu = n^2 B_{\nu 0}$, $\alpha_\nu = \varkappa_\nu$, and the solution is considerably simplified. Apparently, scattering in lunar matter will be substantial only for waves shorter than millimeter waves.

3. PROPERTIES OF MATTER OF THE UPPER MANTLE

The obtained spectrum of the oscillation amplitude of Moon's radiation (Fig.2) shows that the intensity fluctuations decrease with increasing wavelength. The amplitude of fluctuations reaches a maximum in infrared. This can be explained only by the fact that emission in the infrared originates from the surface itself and, consequently, the value of temperature is also obtained for the surface. On longer waves, radiation originated from a layer of finite thickness, and the greater this layer the longer the wave. Its thickness is comparable with that of the layer in which temperature fluctuations take place. Thus, a process, similar in depth sounding of the layer, takes place with the variation of received radiation wave. The amplitude of the variable part of the radiation will be inversely proportional to the ratio between the penetration depth of the electromagnetic wave $l_\nu = 1/\varkappa_\nu$ to the penetration depth of the temperature wave l_T. The penetration depth of the electromagnetic wave characterizes the effective thickness of the emitting layer. The greater the thickness of the emitting layer, l_ν as compared with l_T, the smaller the fluctuation amplitude of the intensity. Consequently, the spectrum $\overline{M}(\lambda)$ characterizes the value of the ratio l_ν/l_T. A similar relation between electric and thermal parameters is characterized by the eclipse spectrum $\overline{M}_3(\lambda)$. However, in this case the relation thus obtained will characterize a thinner upper layer of matter.

1. <u>Thermal Properties of Matter</u>. It may be easily seen that the fluctuations of the Moon's effective temperature, measured in infrared, do not depend on medium's absorption ($\varkappa_\nu$), but rather on the thermal parameters k, c and density. Indeed, as the wave becomes shorter the value of l_ν decreases and we measure the temperature values at smaller and smaller depths. When l_ν becomes much smaller than the scale of temperature in depth, i.e. smaller than the value of l_T, further shortening of the wave will not change the value of the radiation temperature, and therefore, for waves in this band we may postulate $l_\nu = 0$ ($\varkappa_\nu = \infty$). Hence, according to (4), $I_\nu = (1 - R)\,[B_{\nu 0}]_{x=0}$, i.e., the entire radiation is determined only by the temperature of the surface itself, which is the solution of Eq.(5) and a function of thermal parameters only. Consequently, the infrared and submillimeter portions of the spectrum can be used for the determination of thermal parameters. However, for this purpose it is necessary to adopt some kind of structure model of the upper layer, to calculate its thermal regime if, according to (5) and to compare with the experiment. The only solution available in this case is the use of the method of consecutive approximations.

As a first approximation a homogeneous model is adopted, in which the properties do not depend on x. It is also assumed that the properties do not depend on the temperature. We find in this case that for a know flux and albedo the surface temperature depends only on the single parameter $\gamma = (k\rho c)^{-1/2}$. In the second approximation, a homogeneous model is adopted whose heat conductivity and heat capacity are temperature-dependent. According to the first-approximation model, lunar rocks are found to consist of highly porous silicates for which the heat capacity value and its temperature dependence are well known. We may also estimate the degree of temperature dependence of the heat conductivity arising as a result of the radiative energy transfer in the porous matter (substance). It was found that at T = 300°K the radiative heat conductivity amounts to only 20-30% of molecular heat conductivity [80] and therefore it influences very little the phase dependence of the intrinsic radiation both in the infrared and radiowave range [76,78]. It is known at present from measurements that the midnight temperature of the surface is equal to T_N = 100°K [42], the noon temperature T_D = 395°K, the ratio of the constant derivative to the amplitude of the first harmonic T_0/T_1 = 1,3, and the relative temperature drop during an eclipse T_E/T_D= = 0.52. In the homogeneous model approximation and taking into account the temperature dependence of heat capacity inherent to this leads to values

$$\begin{aligned} \gamma_1(300) &= 10^3\ \mathrm{cal}^{-1}.\mathrm{cm}^2.\mathrm{sec}^{1/2}.\mathrm{degree} \\ \gamma_2(300) &= 600\ \mathrm{cal}^{-1}.\mathrm{cm}^2.\mathrm{sec}^{1/2}.\mathrm{degree} \end{aligned} \qquad (6)$$

respectively for eclipses and lunations.*

The close values of γ for eclipse and lunation processes speak in favor of the existence of an approximate uniformity of properties in depth. Indeed, the eclipse process lasts only 4-5 hours and during this time only the uppermost layer about 1-2 cm thick succeeds in cooling off. During a period of 29.5 days (lunar 24-hour periods), the process of temperature variation encompasses the deeper layers of matter. The depth ratio is proportional to the square root of the process time ratio, i.e. is equal to 10. Accordingly, the eclipse values of γ refer to the uppermost layer, while lunation values are related to a layer ten times thicker.

Analysis of the spectrum (Fig.2) has shown that it agrees well with a homogeneous model layer [72,73] and does not correspond to all to the sharply inhomogeneous model, which assumes the existence of a dust layer several millimeters thick covering compact rocks. The uniform distribution in depth of matter's thermal properties is demonstrated particularly clearly by the existence of a limit phase retardation ξ_1, equal to 45°, with increasing wavelength (Fig.3). This is precisely the value obtained in the theory of a homogeneous model [4]. Every significant inhomogeneity in depth, and particularly a dust layer, results in a sharp increase of the limiting retardation

* Previously, the values T_N = 120°K and T_0/T_1 = 1.5 were obtained, which gave γ_2 = 350 [1,43] for lunations.

Thus, a homogeneous model agrees rather well with the intrinsic radiation spectrum. In addition, as calculations of the Moon's thermal regime show, the character of propagation of a heat wave is not greatly affected by the introduction of temperature dependence of properties, which is characteristic lunar matter [78], i.e. the theory of lunar radiation developed for a homogeneous (uniform) model with temperature-independent properties is applicable with sufficient approximation to the case of temperature dependence. This fact makes it possible, by using the developed theory of radiation of a homogeneous model, to determine in a second approximation a number of parameters of matter. It was found that, in the wave range of 0.1 cm to 15 cm.*

$$l_\nu/l_T \simeq 2{,}2\lambda, \qquad \sqrt{\frac{\Omega}{2}}\frac{c\gamma}{b\sqrt{\varepsilon}} \simeq 2{,}2, \tag{7}$$

where b = tgΔ/ρ, and tgΔ is the angle of lunar matter losses.

The obtained spectrum of the quantity $l_\nu = 2{,}2\,l_T\lambda$, as in the case of the first-approximation model, indicates the dielectric nature of lunar matter. It is most probable that rocks, similar to those found on Earth, i,e, silicates, are constituted of such a dielectric material. This provides us immediately value for the heat capacity, which for all silicates on the average (with a precision up to 10%) is equal at T = 300° to c(300) = 0.19 cal. degree^{-1}.gr^{-1}.

The further determination Of parameters such as the density of the matter and heat conductivity is possible by making use of new and independent measurements. An independent measurement of density may involve the measurement of the dielectric constant which is known to be dependent on the degree of porosity and which for silicate rocks, is rather precisely linked with the density ρ by the relation [74]

$$\sqrt{\varepsilon} = 1 + \tilde{a}\rho, \tag{8}$$

where $\tilde{a}$ = 0.5.

Several methods for measuring ε of matter making up the upper mantle of the Moon have been proposed [67, 69, 70], which are based on the fact that the Moon's surface is so smooth for radio waves, as shown in radar studies, that Fresnel's formula for the reflection factor is valid in the wavelength range > 0.8 cm. Hence it is possible to determine ε from the polarization of intrinsic radiation [69], from the distribution of brightness temperature along the lunar disk [67], which yields the function R(ϕ, ψ) and finally from direct radar measurements of the reflection [62-66] and by other methods [70].

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* According to a first-approximation model, the value $l_\nu/l_T = 2$ was previously given. The new value for $T_0/T_1 = 1{,}3$ (instead of 1.5) leads to (7)).

Thus, knowing ε and using (8), we find $\rho_1 = \left(0{,}6 \begin{matrix} +0{,}2 \\ -0{,}1 \end{matrix}\right)$ gr.cm^{-3}, which together with (6) gives us a value of $k \simeq 10^{-5}$cal.cm^{-1}.sec^{-1}.degree^{-1}, and hence $l_T \simeq (2k/\rho c\Omega)^{1/2} \simeq 7{,}5$ cm., finally according to (7), $l_* = 17\lambda$, etc.

2. Variation of Properties with Depth. Data are available which indicate a somewhat weak nonuniformity of properties of lunar matter in depth. This fact does not contradict the above assertion that the spectra of the amplitude and phase lag correspond to an homogeneous model. The point is that these spectra are not very sensitive to small inhomogeneities. A weak inhomogeneity, in which properties change insignificantly with depth (1.5 to 2 times with regard to density) and smoothly, as calculations show, does not greatly affect the character of spectra (their variations lie within the limits of measurement precision. Therefore, the spectrum obtained allows the existence of a certain inhomogeneity.

In order to clarify the nature of this inhomogeneity, we must find the parameters sensitive to this inhomogeneity and measurable. Such parameters are the wave reflection factor, the radiation polarization, and also the data on the "obscured" and night temperatures of the lunar surface. An increase of the reflection factor in the $\sim$ 15-20 cm. wavelength range (Fig.5) may indicate either a true frequency dependence of the dielectric constant of lunar matter or the existence of a nonuniformity of dielectric properties in depth. The first assumption must be rejected since the observed and sufficiently sharp increase of ε with increasing wavelength must, according to Kramers-Kronig's theorem, be accompanied by an increase of the angle of lunar matter losses in this wavelength range, which would have affected the spectrum of $M(\lambda)$. This has not been observed sofar, so that, apparently, the second case takes place. Indeed, if the upper layer has a lower density it must have a smaller dielectric constant. The waves incident upon the surface, whose length is much smaller than the thickness of the upper layer, will be reflected from the interface between medium and the vacuum. As a result of small variations in properties over the wavelength, part of wave energy which passed through this interface will pass into the dense layer without being reflected by it and will be attenuated. On the contrary, for waves whose length is much greater than the thickness of the inhomogeneous layer, the latter does not seem to exist and these waves are reflected from the lower and denser layer.

Thus, the reflection factor for such a medium will vary in a certain frequency range from its value at the surface to that of its substrate.

The presently available calculation of the reflection factor for an exponential density variation with depth:

$$\rho(x) = \rho_2 - (\rho_2 - \rho_1)\exp(-x/x_0), \qquad (9)$$

where $\rho = \rho(0)$, $\rho_2 = \rho(\infty)$, has shown that the wavelength near which change of the reflection factor takes place is $\lambda_1 = 20\ \chi_0$ [75]. As may be seen from Fig.5, this value is $\sim$ 30 cm. Consequently, the characteristic dimension of the layer is $\chi_0 = 1.5$ cm. The dimension of the layer is approximately $d_1 = (3-4)$ cm. The following data satisfy the observed spectrum $R(\lambda)$: $\rho_1 = 0.6\ g.cm^{-3}$ when $\rho_2/\rho_1 = (1.5 - 2)$ and $\chi_0 = 1.5$ cm. As we have seen, the same degree of inhomogeneity is also obtained by calculating γ by surface temperatures during eclipses and lunations provided the temperature dependence of heat capacity is taken into account. The difference between γ_1 and γ_2 in (6) points to density increase of matter in depth.

Thus, phenomena such as the surface temperature during eclipse and the lunar night, the spectrum of the reflection factor, the spectrum of the amplitude and phase lag are all in agreement with an approximately homogeneous model in which properties do not vary over a distance of 3-4 cm. by more than 1.5-2 times. At the same time the density at the surface is $\left(0{,}6^{+0{,}2}_{-0{,}1}\right)$ $g.cm^{-3}$ while at the depth of 3-4 cm and more it is $(0.9 \div 1.2) g.cm^{-3}$.

Studies of heat conductivity of porous silicate materials in vacuum show that it is proportional to the density for a given "structure" of the porous body, i.e.

$$k = \alpha\rho. \tag{10}$$

The quantity α depends on the type of porous body (hard-porous, loose). Relation (10) is valid for $\rho \leqslant 1.5\ g.cm^{-3}$ and must also be applicable to lunar matter. Consequently, the heat conductivity varies in depth to the same extent as ρ. Using the above data γ_1, γ_2 and ρ_1, ρ_2 we find that for lunite $\alpha_{\text{л}} \simeq 10^{-5}\ cal.cm^2.sec^{-1}.deg^{-1}\ X^1 g^{-1}$. This value corresponds best to a hard-porous body with open pores.

3. Temperature Dependence of the Properties of Matter. The heat conductivity of porous bodies must a priori depend on temperature on account of radiative heat transfer through pores. In the "lunar" temperature range, radiant heat transfer takes place by means of emission in infrared waves whose length corresponds to Planck's maximum $\lambda = 0.38/T \simeq (10 - 30)$ microns. For a porous body, in which the effective size of pores is equal to l_p and the actual substance (matter) is impervious to infrared waves, the magnitude of radiative heat conductivity k_p, is

$$k_{p\text{п}} = \frac{R_\text{п}}{2 - R_\text{п}} 4\sigma l_\text{п} T^3. \tag{11}$$

Here, σ is a Stefan-Boltzmann's constant. It may be shown that for lunar temperatures the radiative heat conductivity is much smaller than the molecular provided the size of the pores does not exceed 1/10 of a millimiter.

As is well known, the matter itself can be permeable to infrared waves; then $k_p = \frac{16}{3}\sigma\varepsilon_i \bar{l}_r T^3$, where $\bar{l}_r$ is Roseland's mean penetration depth of radiation into the matter and ε_i is the dielectric constant of matter for infrared waves. Calculations show that, when the dependence $l_r = a\lambda$ holds (this dependence follows from radio measurements and the heory of nonresonant wave absorption in matter), $\bar{l}_r = 0{,}365\ a/T$. Hence [80], we have

$$k_p = 2\varepsilon_i a\sigma T^2. \qquad (12)$$

Frequent attempts have been made to discover the effect of radiation transfer on the Moon's radioemission. Attempts involving a theoretical analysis of this effect [78] have led to the conclusion that the phase dependence of intrinsic radiation both in the infrared and radiowave range is not sensitive to the existence of radiative transfer. Experimental data agree with a wide range of models having thermal properties which are both dependent on and independent of the temperature. In order to estimate the role of radiation transfer, it is necessary to find phenomena which are determind to a sufficiently great extent by temperature dependence of heat conductivity. Such a phenomenon, as was found later, does exist.

It has been pointed out that the presence of weak temperature dependence of heat conductivity results in a qualitatively new effect [77] consisting in an increase in depth of the constant component in a layer of the order l_T. This effect was later computed quantitatively by means of Eq.(3) for different laws of temperature dependence [78, 79]. It was found that the temperature accretion ΔT_{max} depends on γ and the quantity k_p/k_o. It has been shown in [79] that the constant component of the true temperature increases in depth according to the law $T_0(x) = T_0 + \Delta T_{max}[1 - \exp(-2x/l_T)]$. This results in a growth of the constant component of radio temperature with increasing wave length, However, this growth must cease on waves emanating from a depth greater than (2-4) l_T. Calculations show that the constant component of radioemission's brightness temperature depends on the wave according to the relation $T_{e0} \simeq T_0 + \Delta T_{max}\frac{4{,}4\lambda}{1+4{,}4\lambda}$.

Hence, it may be seen that the constant component reaches its value $T_{e0} = T_0 + \Delta T_{max}$ as early as in wavelengths $\sim$ 2-3 cm. Thus, by measuring in infrared the temperature on the surface and in depth (on waves with $\lambda \simeq$ 2-3 cm) we can find the temperature accretion ΔT_{max} and determine k_p/k_o. Such a determination became possible owing to precise measurements of radio temperature by the "artificial Moon" method. It has been shown in [80] that the existing difference of 10-15° in the constant components obtained from infrared and radiowave measurements can be explained by this effect. By comparing with theory it was found that, if the lunar matter is impervious to infrared waves and has $\gamma_2 \approx 600$ cal^{-1}.cm^2.sec$^{1/2}$.degree (this value of γ_2 is taken at T = 300°K), then the relative share of radiation transfer through pores at T = 300°K is equal to $k_{pp}(300)/$ $/k_o$ = 0.25. In the case of permeable matter, $k_p(300)/k_o$ = 0.4. Substantially larger (greater) shares were found by way of comparison of the calculated surface temperature variation during sunset with the experimental results [76]. Homogeneous models were used in all these calculations, since inhomogeneity of properties does not result in the above-mentioned effect of constant component growth with depth, although it does affect the value of ΔT_{max}.

Setting $k_o \approx 0.6 \cdot 10^{-5}$ cal.cm^{-1}.sec^{-1}.deg^{-1}, we will obtain $k_{pp}(300) = (0.15 - 0.25) \cdot 10^{-5}$ cal.cm^{-1}.sec^{-1}.deg^{-1} and k_p (300) = $(0.25 - 0.4) \cdot 10^{-5}$ ca .cm^{-1}.sec^{-1}.deg^{-1}. From the obtained value of k_{pp}, we shall find with the aid of (11) that the effective size of pores constitutes 170-350 μ. Since the porosity of matter is close to 50%, the pore dimensions must be approxim tely equal to the dimensions of particles. If the matter is assumed to be permeable to infrared waves, then, according to (12) and to the value of k_p, we find that a = 6-12 and, consequently, for infrared waves $l_* = (6 - 12)\lambda$. As we have seen, for waves longer than 1000 μ, $l_* = 17\lambda$. It seems to be most probable to us that the matter is permeable to infrared waves. Then, to render this heat transfer through pores insignificant, the latter and, consequently, the particles of matter, also must be many times smaller than the path length of an infrared quantum, equal to $l_* = (60 - 120)$ μ. Apparently, these may be particles having a size ranging from 1/10 to several tenths of micron. As is shown by calculations of [81], the low value of heat conductivity requires that the contact area of such particles be approximately 10^4-10^5 times smaller than the cross-section area of the particle itself. Thus, the heat conductivity of lunar matter is equal to

$$k(T) = k_0(x)\,[1 + 0{,}4 \cdot 10^{-5} T^2], \qquad (13)$$

where k_o is given by the values obtained above.

An essential possibility of studying the properties of the uppermost layer consists in the study of the radioemission of the Moon during its eclipse. Since temperature variations during eclipse are 1.5 times smaller than those during lunations, the effects of all possible temperature dependences $c(T)$, $k(T)$, and $\varkappa(T)$ are considerably weaker.

As is shown by calculations of [79], the presence of temperature dependence of heat capacity to the degree observed for silicates does not cause any substantial variation in the value of T_e whatsoever. By virtue of the above-said, we may use for the analysis of an eclipse the calculation of a model with a temperature-independent heat conductivity and heat capacity with a good approximation. Besides the shallow depth encompassed by the cooling process allows us to utilize for the study of an eclipse a uniform model with good reason. Accordingly, an emission theory has been developed for an eclipsed Moon [47] in the approximation of an homogeneous model with temperature-independent properties. Comparison of the spectrum of intensity variation with the above theory makes it possible to determine for the first centimeter of the layer the value

$$c\gamma_1/\sqrt{\varepsilon_1}\; b_1 = (11{,}4 \pm 3)\, 10^3. \tag{14}$$

According to (7) the same value, determined from lunation measurements in the approximation of an homogeneous temperature-independent model, is:

$$c\gamma_2/\sqrt{\varepsilon_2}\; b_2 = 11{,}2\cdot 10^3. \tag{15}$$

When the temperature dependence of properties and the weak inhomogeneity are taken into account, this relation, generally speaking, is not accurate. However, as already stated above, in view of the small temperature and depth parameter variations the homogeneous model theory gives a sufficiently good approximation. Calculations taking all these factors into account can be performed only on an electronic computer; these calculations will show the precision of approximation at a later date.

Considering the fact that $\gamma_1 = 10^3$ cal^{-1}.cm^2.sec$^{1/2}$.deg, $\varepsilon_1 =$ $= 1{,}7$ and $\gamma_2(300) = 600$ cal^{-1}.cm^2.sec$^{1/2}$.deg, $\sqrt{\varepsilon_2} = 1.5$, we obtain from (14) and (15) $b_1 = (13 \pm 4)^{-3}$, $b_2 = \left(7^{+2}_{-1}\right) 10^{-3}$. An explanation of the higher value of tg $\Delta/_\rho$ in a layer 3-4 cm-thick is beset with certain difficulties. We may admit that the upper layer undergoes great losses either as a result of the external action of the flux of particles and ionizing radiations, or because the chemical composition of this layer is different from the underlying one; the latter may also be associated with proton fluxes. Usually terrestrial basic rocks and, in particular, stone meteorites have greater losses. However, it is difficult to assume that the upper layer consists of more basic rocks than the lower layer. It is possible that the difference is connected with some effects still unaccounted for in theory and that in reality there is no such difference. In particular if one assumes a strictly homogeneous model ($\varepsilon_1 = \varepsilon_2$, $\gamma_1 = \gamma_2$) no difference in the values of tg$\Delta/_\rho$ will be observed. These problems require further clarification.

All the data examined above are based on a study of radiation's phase dependences, are related to a layer (4-5) $l_T = 40$ cm thick, in which temperature fluctuations are still taking place. A wavelength $\lambda \sim 2$-25 cm corresponds to this depth of 40 cm. Investigation of greater depths by this method (i.e. according to the phase course on longer waves) is impossible in principle, although such a study no doubt yields the damping value of the same upper layer in longer waves.

Another possibility of studying great depths was found, which is based on temperature increase in depth as a result of heat flow from the interior of the Moon.

4. Heat Flow from the Interior of the Moon. Study of Properties of Deep Layers. Measurements by the "artificial Moon" method have made it possible to detect an increase of the constant component of the Moon's temperature with wavelength, which is equivalent to the detection of temperature increase in depth. The corresponding spectrum is shown in Fig.1. A number of important conclusions can be drawn on the basis of this spectrum First, the almost linear increase of the effective temperature up to wavelengths $\lambda \simeq 15\text{-}20$ cm points to approximate invariability of heat conductivity in the layer down to a depth corresponding to these waves, i.e. about 4 m. Secondly, the ceasing of temperature accretion points to the presence of compact rock formations at greater depths.

Calculation of radioemission for such a two-layer medium is in good agreement with the obtained spectrum of the constant radioemission component for a layer thickness of $d_2 = 4$ m and a thermal flow $q = 0.85 \cdot 10^{-6}$ cal.cm^{-2}.sec^{-1}. The theory gives the following expression for the dependence $T_{e0}(\lambda)$ when $\lambda \gtrsim 3$ cm and in the presence of thermal flow from the interior with a density q(cal.cm^{-2}.sec^{-1}):

$$\bar{T}_{e0}(\lambda) = \bar{T}_{e0}(300) + (1 - R_{\perp}) A_1 2{,}2 \sqrt{\Omega/2}\, q\gamma_2 [1 - \exp(-d_2/17\lambda)]\lambda \tag{16}$$

Here, $A_1 = 0.8$ is a coefficient appearing when averaging over the Moon's disk is performed. The temperature gradient dT/dx and q can be expressed from (16) by means of the value of the derivative $dT_{e0}/d\lambda$ at λ, when $d_2 \gg 17\lambda$, i.e. for a wave with λ = 3-10 cm:

$$\frac{dT}{dx} = \frac{dT_{e0}}{d\lambda} \frac{1}{A_1(1-R_{\perp})\, 2{,}2 l_T},$$

$$q_s = k\frac{dT}{dx} = \frac{dT_{e0}}{d\lambda} \sqrt{\frac{\Omega}{2}} \frac{1}{A_1(1-R_{\perp})\, 2{,}2\gamma_2} \tag{17}$$

The quantity $d\bar{T}_{e0}/d\lambda$ is determined from Fig.1 and in the range λ = 3-15cm it is equal to 1 deg.cm^{-1}. The penetration depth of the thermal wave is l_T = 7-8 cm; accordingly, from (17) the temperature gradient caused by the heat flow from the interior of the Moon is equal to 6-7 deg.m^{-1} in the entire 4-m-thick layer. Parameter γ_2 must be taken for the basic layer at temperature T = 250°K, corresponding to this layer.

We obtained $\gamma_2(300)$ = 600 cal^{-1}.cm^2.sec$^{1/2}$.deg. For both laws of radiation heat conductivity, $\gamma_2(250) = 700\ cal^{-1}.cm^2.sec^{1/2}.deg.$ Hence, $\underline{q} = (0.85 \pm 0.2)\cdot 10^{-6}\ cal.cm^{-2}.sec^{-1}$. In Fig. 1, the solid curve coincides with the theoretical curve of the constant component for the above-mentioned flow and thickness of the porous layer. It should be noted that in [78], on the basis of our data for $T_{e0}(\lambda)$, a considerably smaller value of $\underline{q}$ was found, namely $q = 0.34\cdot 10^{-6} cal.$ $.cm^{-2}.sec^{-1}$. The reason for this is that a too high value $\gamma_2(250) =$ $= 1300\ cal^{-1}.cm^2.sec^{1/2}.deg.$ was taken in [78], as well as an underrated value of $dT_{e0}/d\lambda$, determined from the mean inclination of the curve in Fig.1, in the range of λ = 3-35 cm.

5. Nature of Matter of the Upper Mantle. Sofar the only possible and somewhat reliable way of determining the chemical composition and the principal rocks forming the upper mantle of the Moon is the use of the centimeter waves by lunar matter. As previous studies have shown [74], the specific angle of losses of various terrestrial rocks, $\underline{b} = tg\ \Delta/_\rho$, is practically independent of ρ and depends only on the type of rock and, apparently, on the conditions leading to its formation. It was found that the group of rocks corresponding to the lunar value of the specific loss angle can be determined by comparing the values of $\underline{b}$ obtained for various terrestrial rocks with the value of $\underline{b}$ obtained for the Moon. The values of $tg\ \Delta/_\rho$ of different rocks as a function of the amount of SiO_2 are shown in Fig.6. The shaded areas correspond to lunar rocks. The upper band corresponds to the

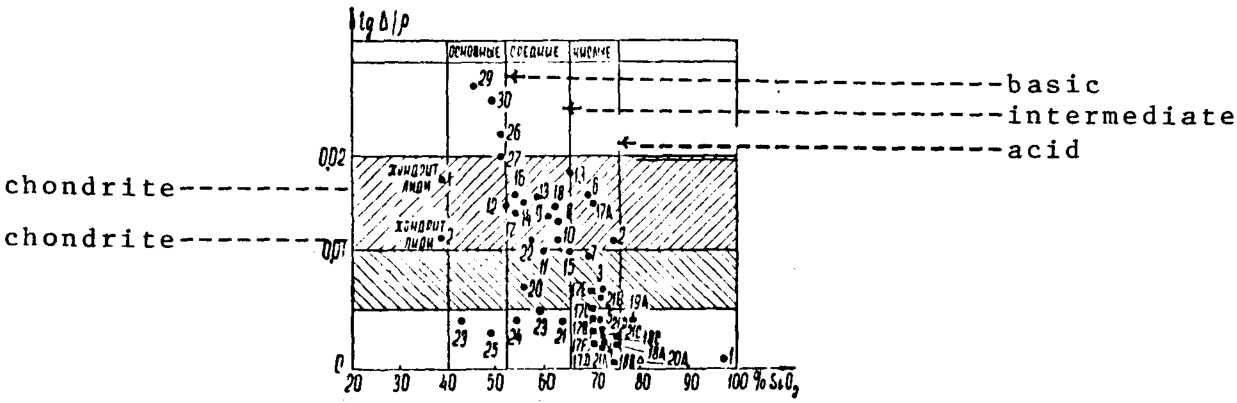

Fig. 6

Diagram of the spheric tangent of the angle of losses for various terrestrial rocks and lunar matter.

Upper band - specific angle of losses of the first lunar layer
Lower band - same for the second layer

first layer of 3-4 cm thickness. The lower band corresponds to the lower layer of matter extending to a depth of several meters. It may be seen from this diagram that in the upper layer the matter has a greater basicity than that in lower layers, which corresponds to intermediate rocks.

6. Surface Uniformity of Properties. With the exception of data for γ, the data obtained above are data which are averaged over the entire hemisphere of the Moon. Therefore the question naturally arises as to the extent to which these data correspond to local values. According to studies performed in infrared, and except for the bottoms of radiant craters, the thermal properties over the lunar disk vary very little and by no more than $\pm(20\text{-}25)$ % [40]. These variations are practically within the limits of measurement precision. A high degree of uniformity of radioemission characteristics such as $M(\lambda)$ and ξ_1, along the lunar disk has also been observed when averaging over areas ranging from several tens to hundreds of kilometers [34-40]. For this reason, we may talk about the existence of radiometric uniformity, similar to the well-known photometric uniformity [41] associated with that of the characteristics of reflected light. This radiometric homogeneity points to uniformity of electric properties of matter making up the upper mantle of the lunar surface in a layer at least 10 cm-thick. Hence follows the approximate homogeneity in the chemical nature of lunar matter. In particular, it was found that the matter of the surface of lunar maria and continents is practically identical [40]. The hypothesis that the upper rocks of continents are granite and those of maria are basalts is thus in complete disagreement with the radiation characteristics.

Since the properties of the upper mantle are highly uniform in horizontal direction, the characteristics obtained represent the true properties of matter at every spot. The high uniformity of properties is confirmed by the results obtained from "Luna-9", "Surveyor-1" and "Luna-13"

4. DISCUSSION OF RESULTS

The data obtained allow us to draw certain conclusions in regard to the history of the development and structure of the Moon.

The extremely fine-grained structure of the porous matter, with grains having a size of up to tens of microns, is evidence of the existence of an extensive grinding and reworking stage. The mean hemispheric layer depth of 4 m indicates the very high efficiency of these factors. Apparently, as was noted in [44], a processing (reworking) of lunar matter took place here under the action of intense meteoritic impacts.

If we assume that, as in the case of the Earth, the heat flow from the interior of the Moon is associated with the decay of radioactive unarium, thorium and potassium and that the thermal process has reached at present a stationary state, then all heat lost by the Moon is equal to the heat of radioactive decay. The total heat generated in one year is equal to $Q = 10^{19}$ cal/year^{-1}, which gives per gram of matter $q_m = 1.35 \cdot 10^{-7}$cal.g^{-1}.year^{-1}. As is easy to compute, this generation density, is 4 times greater than for terrestrial matter.

Hence, it follows that the concentration of radioactive elements in lunar matter is 4 times greater than in terrestrial matter. The thermal flow found, $q = 0.85 \cdot 10^{-6}$cal.cm^{-2}.sec^{-1}, is about 4 times greater than the previously assumed heat flow from the interior of the Moon, based on the analogy with the Earth and on the radioactivity of stony meteorites. This fact changes essentially our conception of the thermal history of the Moon. Corresponding calculations were made in [45] and showed that a nearly complete melting of lunar matter is attained only for this high concentration; consequently, the most complete differentiation of the Moon's interior mass and a migration of radioactive elements to the surface are assumed. This results in an earlier cessation of heating and, consequently, in the current hardening of the melted mass at great depths. As calculations show, in the case of a high concentration of radioactive elements, the thickness of the hard lunar crust may reach at the present time 600-700 km, while in the case of a low concentration of radioactive elements corresponding to that found on Earth, this thickness may reach 300-400 km. At such concentrations, the fusion process takes a longer time and the interior mass of the Moon does not have enough time to cool down.

According to present data, the shape of the Moon is not equilibrium, i.e. basically solid or the hard crust extends at least to a depth of about 1000 km. As we have seen and as paradoxical as it may seem, hardening to a sufficiently great depth can take place only in the case of a sufficiently high concentration of radioactive elements.

If we assume that the upper spherical layer of lunar matter consists of terrestrial granites with their inherent high concentration of radioactive elements, then in order to explain the heat flow observed, the granite layer must have a thickness of 10 km. If we assume that the layer consists of basalts, then its thickness must be equal to 40 km. In order that radioactive elements be deposited in such a thin upper layer, fusion must be practically complete.

The temperature at the depth of 40 km must be equal to about

$$T = 300 + \frac{q}{k}\int_0^d \left(1 - \frac{x}{d}\right) dx = 300 + \frac{0{,}8 \cdot 10^{-6}}{6 \cdot 10^{-3}} \frac{d}{2} \simeq 600^\circ\mathrm{K}. \qquad (18)$$

The high degree of radioactivity of lunar matter can best be reconciled with the hypotheses on Moon's formation either as the result of mass breaking away from the Earth when the upper layer of the latter was already enriched by radioactive elements, or on account of capture of the Moon. In principle, the high radioactivity can also be correlated with the generally accepted hypothesis of the simultaneous formation of the Earth and the Moon from protoplanetary matter, but sofar such an hypothesis is confronted with certain difficulties.

The general model thus obtained represents essentially the sum of specific models in which variations of properties in depth, the temperature dependence of these properties, and the effect of surface roughness were taken into account. The accuracy of the obtained parameter data is characterized by an error $\geqslant$ 20-25%. It is doubtful that more accurate qualitative data can be obtained by establishing a radiation theory for an outright complete model and taking all factors into account. Apparently, the multiplicity of parameters and their mutually compensating effects do not allow us to obtain substantially more accurate results. The only thing that can be convincing is that the general model obtained corresponds to all initial facts. New data will become available with further progress in direct investigations of the Moon's surface by space navigation methods. Numerous important conclusions may be derived if only by a single comparison of results obtained by different methods, but only the entire complex of investigations will provide us with the possibility of establishing a more reliable information on the Moon and, in particular, on the properties of its upper mantle.

In conclusion, I wish to express my thanks to A.B. Burov for his help in compiling this review.

* * * THE END * * *

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