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Abstract

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ASTRONOMY

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SOME CALCULATIONS OF THE THERMAL HISTORY OF THE MOON

(Presented by Academician V. A. Ambartsumian, 12 III 1960)

In calculations of the thermal history of the Moon, as in analogous calculations for the Earth, it is necessary to consider various models of these bodies, i.e., simplified schemes of their structure and evolution. In the calculations given below, the authors sought, as far as possible, to reflect more accurately the evolution of the Moon formed by the accumulation of cold bodies.

1. Initial data. Owing to the smallness of the Moon's mass, heating by impacts of the bodies that formed it, as well as the increase in the temperature of the interior as a result of compression by the growing outer layers, was, in contrast to the Earth, negligibly small. Therefore the initial temperature distribution, established by the time of the practical completion of the Moon's growth, was determined by the fact that the central parts were formed and began accumulating radiogenic heat earlier than the peripheral ones. "Initial" temperature distributions were used, calculated for two variants of the content of radioactive elements (see below) under the assumption that the formation of the Moon lasted $0.23 \cdot 10^9$ years and proceeded according to the law obtained by V. S. Safronov ⁽¹⁾ for the Earth. The surface temperature was assumed throughout to be equal to 0° , which approximately corresponds to conditions in the equatorial zone of the Moon.

The mean content of radioactive elements in the Moon was taken to be the same as in meteorites. Analyses of meteorites performed in recent years by various authors, although they give values for the contents of U and Th differing by an order of magnitude, nevertheless show a general tendency toward decrease. Therefore, along with the mean content according to the summary ⁽²⁾, denoted as variant C, calculations were carried out for variant $C_{1/2}$, in which half the content of U and Th was adopted with the same content of K. Variant C (in g/g): U $5.2 \cdot 10^{-8}$, Th $21 \cdot 10^{-8}$, K $0.7 \cdot 10^{-3}$; variant $C_{1/2}$ (in g/g): U $2.6 \cdot 10^{-8}$, Th $10.5 \cdot 10^{-8}$, K $0.7 \cdot 10^{-3}$. In variant $C_{1/2}$, the content is very close to that

adopted by A. P. Vinogradov ⁽³⁾. MacDonald ⁽⁴⁾ assumes a still twice smaller content of U and Th; he bases this on the results of meteorite analyses carried out by the neutron-activation method, which gives systematically lower values than other methods. The age of the Moon, counted from the beginning of its formation, was taken to be $5 \cdot 10^9$ years.

The thermal conductivity was taken in the form of the sum of molecular and radiative conductivities,

$$\lambda = A/T + \frac{16}{3} n^2 \sigma T^3 / \varepsilon,$$

where T is the absolute temperature; σ is the Stefan-Boltzmann constant; n is the index of refraction (taken as $n^2 = 3$); ε is the absorption coefficient (taken as $\varepsilon = 10 \text{ cm}^{-1}$ and $\varepsilon = 40 \text{ cm}^{-1}$). The constant A was determined from the condition that at 0°C , when radiative thermal conductivity is negligible, $\lambda = 1.2 \cdot 10^{-2} \text{ cal/cm} \cdot \text{sec} \cdot \text{deg}$ (dunite). The heat capacity was taken equal to $0.2 \text{ cal/g} \cdot \text{deg}$.

The calculations given below were carried out on a hydointegrator designed by V. S. Lukyanov at the Central Scientific Research Institute of Construction of the Ministry of Transport Construction.

2. Calculations of the heating of the Moon. The Moon was considered homogeneous in density ($\rho = 3.3 \text{ g/cm}^3$), with a uniform distribution of radioactive elements. The calculation began from the time of practical completion of the Moon's growth, i.e., from the time $t = 0.23 \cdot 10^9$ years (time t is counted

from the beginning of the formation of the Moon). In both variants of the content of radioactive elements (C and $C_{1/2}$), melting of the material is obtained, beginning from the center. Stony material, consisting of various minerals, melts gradually over some range of temperatures. It was assumed that the melting of lunar material occurs within an interval of 200° and is completed entirely upon reaching the melting temperature of dunite. For the latter, Wolf's melting curve was taken ⁽⁵⁾, i.e., the dependence on pressure p was taken according to the formula $t_{\text{melt}} = s_0 + ap + bp^2$. The constants $s_0 = 1250^\circ$, $a = 0.005$, $b = -0.020 \cdot 10^{-6}$ were obtained from measurements at comparatively low pressures. According to this formula, it follows that the melting temperature of dunite (and, according to the assumptions indicated above, also the temperature at the beginning of melting) at the center of the Moon is 190° higher than at the surface.

The heat of melting was taken to be 100 cal/g . It was assumed that its absorption occurs uniformly over the adopted melting interval. Melting of the material at the center began at the time $t = 0.5 \cdot 10^9$ years in variant C and at the time $t = 0.7 \cdot 10^9$ years in variant $C_{1/2}$. Let us note that melting at the center is also obtained for an even smaller content of radioactive elements, but only it occurs still later ⁽⁴⁾.

3. Qualitative picture of the processes occurring during melting.

Since the pressure in the Moon's interior is small, the melting of its material meant not only a transition from the crystalline state to an amorphous one, but also a transition into a liquid flowing state. In the course of heating, the most fusible materials and eutectics should have begun to melt first. As a rule, they are less dense; moreover, melting itself reduced their density. Therefore the melts should have tended upward, seeping between the particles that remained solid, while these solid, denser particles should have tended downward, squeezing the melts upward. Differentiation by density and chemical composition resulted. (In addition, large-scale vertical movements could have occurred, associated with the fact that large volumes of material must have acquired somewhat different densities owing to fluctuations in the composition and structure of the accumulated bodies.) Since the temperature gradient was many times greater than the adiabatic one, vertical movements of material meant the transfer of an enormous amount of heat, equivalent in some measure to a significant increase in thermal conductivity.

The oxides of radioactive elements are impurities that lower the melting temperatures of silicate material⁽³⁾. Therefore they enter the light melts and are carried upward together with them. In the course of the Moon's heating, this process should have intensified the melting of the outer solid layer and weakened the heating of the inner regions of the Moon, in which the content of radioactive elements decreased. In the central part of the Moon, as a result of gravitational differentiation, an iron core grew, containing very few radioactive elements.

Idealizing the further course of the Moon's heating, let us assume that the melting of the outer solid layer continued until it became so thin that it could transmit through itself all the heat being released in the interior. If a constant thermal conductivity, independent of temperature, is assigned to the outer layer, then its thickness D can be calculated from the condition that the heat flux through the surface $4\pi R^2\lambda(-\partial T/\partial r)$ is equal to the heat being released, $^{4/3}\pi R^3 H(t)$ ($H(t)$ is the heat release per unit volume). Neglecting the heat release within the layer under consideration, one may take $-\partial T/\partial r = T_{\text{melt}}/D$. With the aid of the obtained curves of the temperature distribution with depth, one can approximately calculate the time of maximum melting t_m , and then, knowing $H(t_m)$, find D . For $\lambda = 0.4 \cdot 10^{-2}$, for variant $C_{1/2}$, $t_m \approx 1.3 \cdot 10^9$, $D \approx 40$ km, and for variant C , $t_m \approx 0.9 \cdot 10^9$, $D \approx 20$ km.

Such thin solid shells, denser than the underlying mol-

molten matter, could not have existed. This calculation shows that, at some stage of melting of the outer layer, owing to inhomogeneities of structure and density, fractures must have arisen in it, and the lumps that formed must have sunk and melted, undergoing the same differentiation as the rest of the lunar material. The observed molten matter, on solidifying, also sank, and new lava outpourings took its place. How and when this process came to a halt in the

course of the Moon's further cooling depends essentially on the degree and nature of the differentiation of lunar matter. The transition itself from heating and melting to cooling and solidification was connected both with a decrease in the total amount of radioactive elements as a result of their decay and with their removal to the surface in the course of differentiation of the interior.

4. Calculations of the cooling of the Moon. Despite the uncertainty introduced by the stage of development described above, it is possible, by calculations of the cooling of the Moon, to estimate the present distribution of temperature in its interior. During the 3–3½ billion years that have elapsed after the transition from heating to cooling, the influence of the “initial” (for this calculation) temperature distribution is largely erased, and the present temperature distribution depends mainly on the distribution of radioactive elements, as well as on the thermal conductivity.

The cooling calculations were carried out for the following layered model of the Moon: the Moon is assumed to be divided into an iron core with a mass of 1/7 of the total mass (radius 685 km), a mantle, and a crust. The content of radioactive elements in the core is the same as in iron meteorites according to A. G. Starkova (²), namely (in g/g): U $0.5 \cdot 10^{-8}$, Th $2 \cdot 10^{-8}$, K 0; in the mantle—similar to dunites, namely U $1.2 \cdot 10^{-8}$, Th $5.2 \cdot 10^{-8}$, K $6 \cdot 10^{-5}$; in the crust—similar to a mixture of 1/3 (by volume) granite and 2/3 basalt, namely U $1.6 \cdot 10^{-6}$, Th $6.6 \cdot 10^{-6}$, K $3 \cdot 10^{-2}$.

For variant C the thickness of the crust enriched in radioactive elements is found to be 17 km, and for variant C_{1/2}, 10 km.

As a **conditional** “initial” temperature distribution, the iron melting curve at high pressure (⁶) was taken in the core, and in the mantle (the presence of a thin crust was not taken into account) the curve of the beginning of melting obtained as follows. Although the same content of radioactive elements is adopted for the whole mantle, it is assumed that it is somewhat differentiated and that denser, more refractory minerals are concentrated below. Therefore, at the surface the temperature of the beginning of melting was taken as 200° below the melting temperature of dunite, and at the core boundary as 100° below. It was assumed that complete melting occurs within a temperature interval of 100°. Such a temperature distribution was adopted for the moment $1.5 \cdot 10^9$ years, from which the calculation of cooling began.

In this model it was found that the outer layers cool rapidly, while the lower parts of the mantle heat up and partially melt (see Fig. 1). Cooling gradually propagates inward, and by the present time the thickness of the solid layer reaches 500–700 km. The lower layers of the mantle are still continuing to heat up slowly, without, however, reaching complete melting. If radiative thermal conductivity plays a moderate role ($\varepsilon = 40$, solid curves), then the iron core also partially melts (by no more than 15%); if, however, radiative thermal conductivity is large ($\varepsilon = 10$, dashed curves), then it cools by approximately 50°.

Fig. 1

Figure 1: Fig. 1

The layered models considered by us for variants C and $C_{1/2}$ differ only in the thickness of the crust, and therefore the temperature distribution in the interior is practically the same for them. Only at the surface is the temperature gradient, and together with it the heat flux, in variant C 15–20% greater than in variant $C_{1/2}$. These fluxes amount to $0.2\text{--}0.25 \cdot 10^{-6}$ cal/cm² · sec. A calculation for the case of a surface temperature of -150° C, which corresponds to the polar regions of the Moon, gave a present heat flux 12% greater and a present thickness of the solid outer

layer is 70 km greater than the calculation for a zero surface temperature. The increase in the temperature of the interior obtained in the calculation, relative to the “initial” temperature we adopted, shows that with the given content and distribution of radioactive elements such an “initial”

Fig. 1

temperature distribution could not have existed—the lower parts of the shell would have had to remain partially molten. However, it is enough to reduce somewhat the assumed content of radioactive elements in the shell, at least in its lower part—which is quite likely—for cooling to occur, i.e., for the entire shell and core of the Moon to be solid. Since the conditional “initial” temperature distribution has little effect on the present-day temperature distribution, which depends mainly on the content of radioactive elements, and since the content adopted in our calculations may be considered maximal, it follows that the Moon is now solid down to a depth of at least 500–700 km. Under conditions of almost complete gravitational differentiation, one should not expect the existence in the lunar interior of light molten masses that could break through this layer and pour out onto the surface.

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