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Abstract

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ASTRONOMY

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SOME CALCULATIONS OF THE THERMAL HISTORY OF MARS AND THE MOON

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The calculations given below are a continuation of our investigations of the thermal history of the Earth and planets, carried out with maximum allowance for the process of their formation and subsequent development. The computations were performed on the M-20 electronic computer.

I. Calculations of the heating of Mars. The content of radioactive elements in the matter of Mars (and the Moon) was estimated from their average content in meteorites. The potassium content, which is known fairly well, was taken to be $0.08 \cdot 10^{-2}$ g/g. The uranium content is apparently within the range from 1 to $3 \cdot 10^{-8}$ g/g, and the thorium content is 4 times the uranium content. The calculations were carried out for the following contents of U and Th (in g/g): $U\, n \cdot 10^{-8}$, Th $4n \cdot 10^{-8}$, where $n = 1, 2, 3$. It was assumed that at the stage of heating the content of radioactive elements per unit mass was the same throughout the entire volume.

It was assumed that the increase of density ρ toward the center follows the law

$$\rho(r) = 4.40 - 0.702 \left(\frac{r}{R}\right)^2 .$$

The age of Mars, counted from the beginning of its formation, was taken to be $4.5 \cdot 10^9$ years. The calculation began from the moment of practical completion of its formation, which lasted $\tau_0 = 0.2 \cdot 10^9$ or $0.4 \cdot 10^9$ years (for $\tau_0 = 0.2 \cdot 10^9$ years a somewhat steeper temperature drop toward the surface is obtained in the first 2.0–$2.5 \cdot 10^9$ years). The initial (at $t = \tau_0$) distribution of temperature with depth is determined mainly by the fact that the central parts of the planet, which formed first, began earlier to accumulate radiogenic heat. Since the law of growth of Mars is unknown, it was assumed that at the moment $t = \tau_0$ the temperature varied with depth according to a parabolic law. It was considered that during the time τ_0 the outflow of heat from the center was negligibly small. In addition, the increase in central temperature as a result of compression of the material under the pressure of the layers growing from outside was taken into account. The surface temperature $T(0, t)$ was assumed to be equal to 230°K at all times.

It was assumed that melting of the matter of Mars, consisting of a mixture of minerals, occurs over an interval of 200°. As the temperatures at which complete melting occurs at different depths, the melting temperatures in the Earth were used: (a) those calculated by A. F. and corrected by V. N. Zharkov, and (b) those calculated by V. N. Zharkov by another method (^{1}). After recalculation for the pressures prevailing in the interior of Mars, it turns out that down to a depth of 800 km the two melting curves coincide, while deeper the Zharkov curve lies substantially lower. According to the A. F. curve, the temperature at the beginning of melting at the center of Mars is $T_{\text{b.m.}} = 3260$°K, and according to the Zharkov curve $T_{\text{b.m.}} = 2470$°K.

The heat capacity c of both the solid and the completely molten material was taken equal to 0.25 cal/g • deg. To take into account the gradual absorption of heat over the 200-degree interval of melting temperatures, an effective heat capacity depending on temperature was introduced. Upon reaching $T_{\text{b.m.}}$, the heat capacity first increases linearly and then decreases linearly. The maximum value, $c(T) = 1.25$ cal/g • deg, corresponding to $T = T_{\text{b.m.}} + 100°$, was obtained from the condition that, when the temperature rises from $T_{\text{b.m.}}$ to $T_{\text{b.m.}} + 200°$, the complete absorption of the heat of melting of the material, equal to 100 cal/g, takes place.

The thermal conductivity was calculated from the formula:

$$\lambda = \frac{A}{T} f(p) + \frac{16}{3} \frac{n^2 \sigma T^3}{\varepsilon}, \tag{1}$$

where σ is the Stefan-Boltzmann constant, n is the refractive index ($n^2 = 3$), and ε is the absorption coefficient (taken as $\varepsilon = 10$ and 40 cm^{-1}). The function $f(p)$, obtained by Zharkov (^{2}) for the Earth, takes into account the dependence of lattice thermal conductivity on pressure. The constant A was determined from the condition that at 0°C, $\lambda = 1.2 \cdot 10^{-2}$ cal/cm · deg · s.

The mass and dimensions of Mars are such that the discrepancy between the melting-temperature curves obtained by Uffen and Zharkov introduces a large uncertainty into the thermal history of its interior. Nevertheless, it can be stated with confidence that at least the greater part of the Martian interior must have melted completely or partially. This should have led to physicochemical and gravitational differentiation of Mars, to the formation of a sialic crust with an increased content of radioactive elements, and, in the presence of inclusions of metallic iron, to the formation of an iron core. In the present calculations differentiation was not taken into account, and they have been carried through purely formally to the present time.

The calculations show that melting of the Martian interior begins at depths of

400-700 km, 1.7-2.5 $\cdot 10^9$ years after the beginning of formation (depending on the content of U and Th), and then spreads toward the center. The values of the heat flux through the surface of Mars at the present time, obtained in different variants of the calculations, lie within the limits 0.28-0.41 $\cdot 10^{-6}$ cal/cm$^2 \cdot$ s.

In the scheme considered, the flux through the surface remains much lower than the heat generation up to the present time. However, the process of differentiation during the last 2.0-2.5 $\cdot 10^9$ years could substantially increase the flux, so that the heating of Mars may in fact already have been replaced by cooling.

For $n = 2$ and 3 it was found that almost the entire interior of Mars below 300 km, even assuming Uffen' s melting curve, is at the present time in a state of partial or complete melting. For $n = 1$, 50% of the volume of Mars is in a molten state, while the central parts remain solid.

II. **Calculations of the heating of the Moon.** Earlier calculations of the heating of the Moon (^{3},^{4}) showed that 2.5-3.0 billion years ago its interior must have melted down to the center. This should have led to differentiation of the material, to the formation of a crust with an increased content of radioactive elements, and to the transition from heating of the Moon to cooling. As already noted, the upward transport from below, in the process of differentiation, of hot light melts should have enhanced melting of the outer solid layer (^{3},^{4}). To take account of this additional transfer of heat, new calculations were made in which an effective thermal conductivity was introduced, increasing as the temperature rose above the temperature at which melting begins. If it is assumed that upon reaching the temperature of complete melting the effective thermal conductivity increases by approximately a factor of 4, and the calculations are carried through to the present time, then for $n = 2$ and 3 the thickness of the solid crust decreases by 50 km (in comparison with calculations without the introduction of an effective thermal conductivity), while for $n = 1$ it remains practically unchanged.

III. **Calculations of the cooling of the Moon.** In the calculations of the cooling of the Moon, a two-layer model of the Moon was considered, consisting of a crust enriched in radioactive elements brought out from the remaining volume of the Moon, and the remaining volume of the Moon (the interior), with a reduced content of radioactive elements. For both the crust and the interior a density of 3.3 g/cm^3 was assumed.

The calculations were made for the average content of radioactive elements in the Moon, corresponding to $n = 1$ and 2. It was assumed that after the forma-

of radioactive-enriched crust in the interior of the Moon there remained approximately a dunite content of radioactive elements. The potassium content was taken as $0.025 \cdot 10^{-2}$ g/g (⌒5), and the uranium content from $0.2 \cdot 10^{-8}$ to $0.8 \cdot 10^{-8}$ g/g (n = 0.2—0.8). With a crustal thickness of 15 km, the potassium content in the crust is found to be 2.14 $\cdot 10^{-2}$ g/g, while the U content (expressed in units of 10^{-8} g/g) varies from n = 8.8 to n = 71.7, depending on the adopted values of n and n . The Th content was taken equal to $4n$. The age of the Moon was taken to be $4.5 \cdot 10^9$ years.

The calculations began from the time $\tau_0 = 1.5$ or 2.0 billion years. It was assumed that the differentiation of the lunar interior had been completely completed and that the Moon was in the solid state. As the temperature distribution, one was chosen which, deeper than 300—600 km, coincides with the distribution of the temperature at the onset of melting of the material, while at smaller depths it drops toward the surface to the temperature $T(0,t)$. The calculations were carried out for $T(0,t) = 230$°K, and also, in order to take into account the difference in temperatures in the equatorial and polar regions of the Moon, for $T(0,t) = 90$ and 160°K*. Calculations made for $\tau_0 = 1.5 \cdot 10^9$ and $2.0 \cdot 10^9$ years show that differences in τ_0 have practically no effect on the present-day temperature distribution. It is assumed that, as a result of differentiation, denser and consequently more refractory minerals are found at greater depths, and therefore at the surface the temperature of the onset of melting is taken as 200°, and at the center as 100° below the melting temperature of dunite (the latter, as in (^3, ^4), was calculated from Wolf' s formula (^6), which gives the dependence of the melting temperature of dunite on pressure). It is assumed that complete melting of the differentiated lunar material occurs within a temperature interval of 100°. For solid material the heat capacity is $c = 0.25$ cal/g • deg, and for the variation of the effective heat capacity in the 100-degree melting interval a law was adopted analogous to that used in the case of Mars. The thermal conductivity was calculated from formula (1), but in the lunar interior, owing to the small pressure, $f(p) = 1$. The calculations were carried out with $\varepsilon = 10$ and 40 cm^{-1}.

In all the calculations performed, cooling of the outer layers of the Moon and heating and partial melting of the deeper interior are obtained (the latter shows that the initial temperature distribution adopted in these calculations is incorrect). During the entire time considered, the total heat release in the Moon proves to be less than the total heat flux through the whole surface of the Moon**.

Different total contents of U and Th in the lunar material, leading after differentiation to different contents of them in the crust, affect only the magnitude of the flux through the surface. The values of the fluxes q for the present moment of time, obtained in the calculations (for $T(0,t) = 230$°K), are given in Table 1 (in the last two columns is given the flux which would occur if the thermal regime were stationary).

Table 1

n	0.2	0.2	0.2	0.2	0.8	0.8	0.8	0.8	Stationary thermal regime	Stationary thermal regime
ε, cm^{-1}	10	10	40	40	10	10	40	40		
n	1	2	1	2	1	2	1	2	1	2
q, 10^{-6} $\frac{\text{cal}}{\text{cm}^2 \cdot \text{sec}}$	0.37,	0.46	0.35	0.45	0.34	0.44	0.32	0.41	0.23	0.33

When the surface temperature is lowered to 90°K, the flux increases by approximately 10%, because the lattice thermal conductivity is inversely proportional to temperature.

* Since the horizontal temperature gradients are much smaller than the vertical ones, calculations for a spherically symmetric problem are legitimate.

** In the calculations published in (^3, ^4), made with the aid of a hydrointegrator, an error was made (apparently in the rate of inflow of water simulating heat release), as a result of which a value of the surface flux that was too low was obtained. Calculations carried out on the electronic calculating machine M-20 according to the scheme considered in this article, for $n = 5.2$ ($n = 0.2$ and 0.8) gave a flux of 0.76 and $0.72 \cdot 10^{-6}$ cal/cm^2 • sec.

The temperature of the interiors is determined practically by the assumed content of radioactive elements in them and by the thermal conductivity. At $n = 0.8$, the temperature at depths of 300-500 km is 70-100° higher than the temperature at $n = 0.2$, which in the second case leads to a thickness of the solid surface layer 50-150 km greater (depending on the thermal conductivity) than in the first. The distribution of temperature with depth and the thickness of the solid outer layer depend especially strongly on the thermal conductivity. The dependence of the present thickness of the solid outer layer Δl on various parameters for the most probable value $n = 2$ is shown in Table 2.

Table 2

n	n	n	n	n	n	n	n
0.2	0.2	0.2	0.2	0.8	0.8	0.8	0.8
ε, cm^{-1}	ε, cm^{-1}	ε, cm^{-1}	ε, cm^{-1}	ε, cm^{-1}	ε, cm^{-1}	ε, cm^{-1}	ε, cm^{-1}
10	10	40	40	10	10	40	40
$T(0,t)$, °K	$T(0,t)$, °K	$T(0,t)$, °K	$T(0,t)$, °K	$T(0,t)$, °K	$T(0,t)$, °K	$T(0,t)$, °K	$T(0,t)$, °K
90	230	90	230	90	230	90	230
Δl, km	Δl, km	Δl, km	Δl, km	Δl, km	Δl, km	Δl, km	Δl, km
800	700	600	500	650	600	550	450

The calculations carried out indicate that the outer parts of the Moon down to depths of 500–800 km (which amounts to 60–80% of its volume) are at present solid. The central regions of the Moon still remain partially molten.

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Note: Figure translations are in progress. See original paper for figures.

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