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Temperature Distribution of the Moon

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New techniques and instrumentation have been developed for the measurement of lunar surface temperatures. The infrared pyrometer has a resolution of about 10 seconds of arc. Special computing methods permit precise determination of the spots being measured on the lunar surface.

A theoretical study has enabled the lunar surface temperature and its variation to be predicted during a lunation and during total eclipses of the Moon for a number of models. These include surfaces of solid rock, porous rock, dust, rubble, and various surfaces overlaid with different depths of dust. Certain areas, like the crater Tycho, appear to have no appreciable insulating layer of dust, although the environs may have some dust cover of indefinite thickness.

Looking further to the future, we have calculated the temperature of the lunar surface during and immediately after the landing of the manned vehicle known as the Lunar Excursion Module, or LEM. High temperatures will result from the exhaust flame of the retro-rocket, of some 1500 to 1600 °K immediately below the LEM. However, the cooling will be rapid and the astronauts could safely leave the craft 5 or 10 min after set-down.

Working under a grant from N.A.S.A., Harvard astronomers have developed techniques and instrumentation for the measurement of lunar infrared radiation (Ingrao, Young & Linsky 1965 *a*, *b*). The pyrometer has a resolution of the order of 10 seconds of arc. In order to find the precise location of the receiver on the lunar surface we have had to develop special methods. Motion pictures, taken through a photographic channel of the equipment, provide the basic information. A computer converts the raw data into positions on the lunar surface, with an accuracy of about 1·5 seconds of arc for a given scan. Total lunar eclipses—especially dark ones—pose additional problems. But even here, high-speed films or image converters provide adequate identification.

Our studies of the lunar eclipse of 18–19 December 1964 have already been published, together with a theoretical analysis of the problem. The Infrared Group at Harvard set up an elaborate computer program for solving the problem of lunar heat flow under a variety of special conditions, including those of eclipse. Various models of the lunar surface were investigated.

First, we have investigated a series of homogeneous models consisting of rocks having various thermal parameters, $\gamma = (K\rho c)^{-\frac{1}{2}}$, where K is the effective conductivity, ρ the density, and c the specific heat. We considered the various types of rock likely to occur on the Moon, some with porous or vesiculated structure. We then considered crushed or powdered rock, such as basalt, for which it was necessary to introduce the dependence of the conductivity on temperature. Finally we studied composite models consisting of two layers, for example one of dust of different thickness on top of a layer of rock.

We solved a number of time-dependent problems, of which the temperature variation during a total lunar eclipse was particularly interesting. The insulating power of a layer of dust is clearly evident and consistent with the physics of the situation. The dust has a very low heat content as well, so that the wave does not penetrate far into the solid rock beneath. A dust layer only 7 mm thick, for example, will vary in temperature during an eclipse practically independent of the character of the underlying rock. On the other hand, a thickness of only 0·6 mm will show widely divergent temperature variation, according to the thermal properties of the lower layer (figure 1).

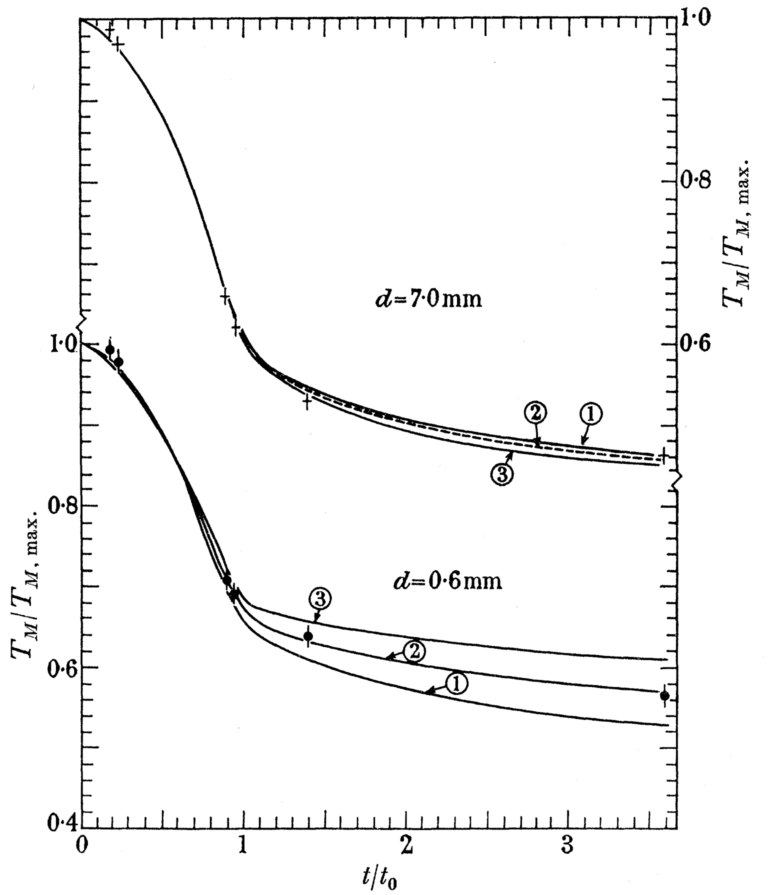

Figure 1. Theoretical eclipse cooling curves for lower layers with different thermal parameters γ and and for two different upper layer depths d. The plotted data pertain to Tycho (•) and its environs (+) and were obtained during the lunar eclipse of 18–19 December 1964.

	γ (upper layer) / γ (lower layer)	$T'_{M,\max.}$ (°K)	$T_{M,\max.}$ (°K)
①	1000/350	355·1	355·4
②	1000/250	354·8	353·6
③	1000/150	354·2	352·7

For $\bar{\epsilon}_M = 0·93$, $\zeta = -0·685$, $\eta = -0·140$

In all of these studies, the thermal content and conductivity of the upper layer have dominant effects on the temperature. A layer without insulation or with only 0·6 mm of dust stays warm much longer than does the surface of a dust layer 7 mm or more in thickness. Our measures of the crater Tycho and its environs, made during a total lunar eclipse, illustrate the effect. The fact that the crater interior remains much warmer than the exterior as the eclipse progresses, suggests that Tycho itself is practically dust free, but that the environs are covered with a layer of dust at least 7 mm thick. However, a wide variety of different models exhibit very similar cooling curves and no unique conclusions can be drawn from them concerning the character of the lunar surface.

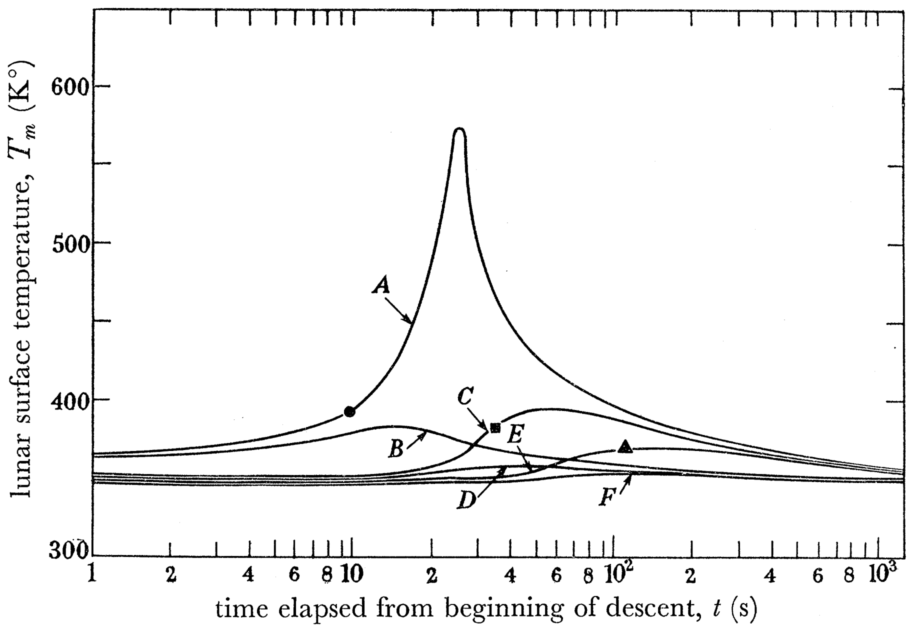

FIGURE 2. Variation of surface and subsurface temperature with time (plots based on computer output). Model 2, homogeneous vesicular material.

curve	distance from point of touchdown, *d* ft.	depth cm
A	5	0·0
B	20	0·0
C	5	0·5
D	20	0·5
E	5	1·0
F	20	1·0

Maximum temperature at lunation: ▲, 368 °K; ■, 381 °K; ●, 394 °K.

We recently completed a temperature analysis of quite a different kind (Holland & Ingrao 1966). Future plans in N.A.S.A. include the soft landing of the Lunar Excursion Module known as LEM as part of the Apollo program. The Apollo spacecraft, powered by a three-stage Saturn V, will go into lunar orbit. LEM will then separate from the orbiting vehicle and soft-land on the Moon. There the astronauts will carry out their mission. The LEM will then return to orbit, dock with the parent craft, and finally return to Earth.

The question of the temperature of the Moon during and after the landing manoeuvre is of great importance. As the LEM comes in for landing, the retro-rockets will fire vertically downwards. The flames from these jets will heat up the surface of the Moon. A heat wave will warm the subsurface layers, expand, and finally die out. The question is, how will this temperature vary with time and with distance from the module?

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We have carried out a variety of analyses, with eight different kinds of surface layers. The surfaces studied include: homogeneous particulate matter, homogeneous vesicular matter, homogeneous solid material, dust over a substratum of vesicular material, dust over solid matter, vesicular surface over solid matter, dust over rubble, homogeneous rubble.

The curves vary as expected for the different kinds of surfaces. I shall show just one, for vesicular matter, such as pumice. Figure 2 shows the change of temperature with time at three depths, 0, 0·5 and 1·0 cm. There are curves for the temperature variation 5 and 20 ft from the point of touch-down. Time is the horizontal axis. The surface temperature attains a maximum at the surface, near the point of touchdown. The temperature for 20 ft. away from the module reaches a maximum before that just under the module, because of the divergence of the exhaust flame. At lower levels the maximum occurs after that on the surface, because it takes time for the heat wave to penetrate. The decay is rapid and begins to revert to the initial value after 1000 s or so. However, it should be safe for the astronauts to emerge from the LEM after an elapse of some 5 or 10 min. The temperature directly below the axis of the craft attains the very high value of 1490 °K. For other models, a dust surface with its low heat content and low conductivity is still hotter than a vesicular surface. A surface composed of homogeneous solid matter is substantially cooler than one composed of dust.

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