

## Letters

## Dust on the Moon's Surface?

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This letter was stimulated by an interesting coincidence. The publication of *Jaffe's* [1966] article in the February 15 issue of this Journal coincided closely with the news about the first 'soft landing' on the moon achieved by the unmanned Russian space probe Luna 9 on February 9, 1966. Truly close-up photographs by a camera stationed about 60 cm above the lunar surface were radioed back to earth. As an example, reference can be made to the picture reproduced on page 56 of the March 1966 issue of *Scientific American* which was accompanied by a brief summary of discussions attributed to N. Barabashov, a leading Soviet selenologist, who emphasized that the probe did not sink into the 'soil' to any substantial degree and concluded that the surface of the moon appears to be quite solid, or a sponge-like, rough-textured mass scattered with individual sharp-edged fragments of various sizes. Essentially, this agrees with independent conclusions by one of the leading United States selenologists, G. Kuiper. According to an interview published in the *Arizona Daily Star* of February 15, 1966, Kuiper says that the dust cover is entirely negligible, that the surface has the consistency of lava rather than of soft dust, and that all Luna 9 photographs show an amazingly similar texture (granulations of inch-size and below but a fairly smooth surface in the larger dimensions). Kuiper added that the surface appears to be an original lava deposit, its appreciable porosity being due to the absence of a lunar atmosphere.

In remarkable contrast, *Jaffe* [1966, p. 1103] suggests that Mare Cognitum is overlain with at least 5 m of granular material or dust. This conclusion was based on the similarity of photographs of lunar craters obtained by the U. S. space probe Ranger 7 and photographs of artificial laboratory craters overlain with various depths of granular material. It is by no means my intention to criticize *Jaffe's* experiments, which appear to be competently designed and executed.

My concern is of a more general nature. The above-named experts restricted their discussions severely by basing conclusions solely on visual impressions from photographs. Other and independent evidence appeared to be ignored. For example, significant information on the physical structure of the lunar surface can be and has been derived from measurements of thermal radiation at various wavelengths. For a brief summary, reference may be made to *Kopal* [1960]; see also *Shorthill* [1962], or others. During the last two decades, investigators in various countries have established that the lunar emission of thermal radiation differs significantly from that

of infrared radiation. For instance, in the 12.5-mm wavelength region, temperatures during the lunar cycle were found to range between a minimum of  $-70^{\circ}\text{C}$  and a maximum of  $30^{\circ}\text{C}$ , that is,  $100^{\circ}\text{C}$ , as compared with approximately  $130^{\circ}\text{C}$  for the 1- to 2-mm wavelength band and nearly  $270^{\circ}\text{C}$  for the infrared wavelength of 0.01 mm. Such reductions in amplitude of the lunar temperature cycle with increasing wavelength of radiation are associated with systematic retardation of the time of maximum phase, from a few hours to days, after the full moon.

In 1962, I summarized, using existing and available literature on lunar cycle emission data, a total of thirteen amplitude determinations, which are accompanied by phase-constant information only in four instances (a regrettably small portion). These measurements cover the wavelength range from 0.01 to 750 mm and confirm again that the upper crust of the moon, although opaque to visible and infrared light, appears to be increasingly transparent at greater wavelengths. This suggests that a series of such measurements in the domain of the microwave radiation can truly be thought of as depth soundings of the lunar crust.

Obviously, the remaining problem was the decoding, or the physical interpretation, of this information. A new solution was offered in *Lettau* [1962]. A particular solution to the thermal diffusion equation in a semi-infinite conductor was obtained in closed form, for thermal diffusivity as well as for volumetric heat capacity having lowest values at the surface and showing a continuous and asymptotic approach to conditions of homogeneity with increasing distance from the surface. In a significant extension of models derived by previous investigators, the application of the new solution to the lunar microwave emission cycle permitted a definite gaging of the depth of the porous crust of the moon; namely, with a minimum amount of ambiguity, the readily constructed empirical curve of amplitude decrement versus phase lag could be directly related to a best-fitting theoretical counterpart. The best possible interpretation of the empirical knowledge available in 1961-1962, in the light of my new model, resulted in vertical profiles of thermal parameters which are reproduced in Table 1.

The theoretical model could not be used in deciding whether the outer crust was dust or porous matter. In view of the extremely low thermal diffusivity in only the uppermost 2 cm of the lunar crust and the rapid increase from 2 to 6 cm depth to conditions of solid basalt, I concluded that the lunar crust would most likely be porous rather than covered by dust. This appears to agree quite closely with the interpretation of Luna 9 pictures by Barabashov as well as by Kuiper, quoted at the beginning of this letter. On the other hand, my results disagreed with previous estimates by other authors who

employed models of heat conduction which corresponded to a discontinuous multilayer medium. For example, *Kopal* [1960, p. 75] estimates that radiation from 10- to 100-mm wavelength will be emitted at a lunar layer as much as 1 m beneath the surface. My model predicted that this radiation should be emitted from the 2-cm level of the lunar crust.

Some advocates of a lunar 'deep-dust' hypothesis may wish to point out that the area photographed by Luna 9 cameras might not be representative of the average lunar surface. To this we can reply that the radiation data employed above are truly referring to disk averages. If agreement with photographic evidence

TABLE 1. Thermal Diffusivity ( $k$ ), Volumetric Heat Capacity ( $C$ ), and Relative Amplitude ( $a/a_0$ ) as a Function of Depth ( $z$ ) in the Lunar Crust, According to *Lettau's* [1962] Evaluation of Literature Data on Lunar Cycles of Temperature Deduced from Infrared-to-Microwave Radiation Measurements.

$z$ , cm	$k$ , $\text{cm}^2 \text{sec}^{-1}$	$C$ , $\text{cal cm}^{-3}$ $\text{deg}^{-1}$	$a/a_0$
0	0.00005	0.32	1.00
1	0.00025	0.44	0.48
2	0.00075	0.50	0.38
3	0.00135	0.53	0.35
4	0.00225	0.55	0.33
5	0.00335	0.55	0.32
6	0.00420	0.56	0.31
7	0.00470	0.56	0.30
8	0.00505	0.56	0.30
9	0.00525	0.56	0.29
10	0.00535	0.56	0.29
$\infty$	0.00540	0.56	0.00

exists at one point, it will strongly suggest agreement at most other points. Other advocates of the lunar deep-dust hypothesis may say that the visual appearance on pictures from the Luna 9 camera may be represented by a layer of cemented dust. To this we can reply that a crucial experiment would be to reproduce in such a medium the observed properties of microwave radiation, in direct response to a defined cycling of surface heat supply. Only when two independent methods agree with each other will the conclusions be reasonably safe. Obviously, there is still sufficient reason to look ahead to the results of future soft landings on the moon, involving more sophisticated unmanned probes as well as human explorers.

## REFERENCES

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