ARTICLE

THE SURFACE TEMPERATURE OF THE MOON

By R. H. Garstang

University of London Observatory

The study of the conditions on the surface of the Moon is a branch of Astronomy of continuing interest. The object of this review is to summarize the present state of our knowledge of the temperature of the lunar surface and its relation to the constitution of the outer layers of the Moon.

Observations by optical methods

The radiation which we receive from the Moon is made up of two portions, reflected solar radiation and radiation emitted by the Moon itself. The energy of the latter is of course ultimately derived from the absorption of solar radiation. When the amounts of energy received in the two portions are compared, it is found that nearly all the light and heat received in the visible and near infra-red regions of the spectrum is reflected solar radiation. Further into the infra-red conditions change. In the wavelength region from 8 to 14 microns, a region of relative transparency of the Earth's atmosphere (a so-called atmospheric window), most of the heat received is thermal radiation from the Moon. Indeed, Pettit and Nicholson[1] showed that in this 8μ–14μ region the neglect of the contribution of reflected solar radiation would lead to an error of less than one degree in the measured temperature of the Moon. The observational problem is the separation of the 8μ–14μ radiation from the remainder and the development of a method of measurement of the radiation.

The classical investigation is that of Pettit and Nicholson.[1] They separated the reflected solar radiation from the lunar radiation by the simple device of inserting a thin sheet of glass in the optical system. Glass is transparent to radiation in the visible and near infra-red regions of the spectrum, but at a wavelength of about 5μ the transparency rapidly decreases. Beyond 7μ glass is essentially opaque to radiation. The difference between the radiation received direct from the Moon and that received through a sheet of glass is the thermal radiation of the Moon itself. This property of glass is responsible for the ' greenhouse ' effect. Heat from the Sun, mainly in the visible and near infra-red regions of the spectrum, passes easily through the glass roof of a greenhouse, and is absorbed by the objects inside. Radiation from the warmed objects is mainly in the 5μ–25μ region. This does not pass through glass and is retained inside the greenhouse.

Pettit and Nicholson used the 100-inch telescope and a vacuum thermocouple as detector. The reduction of the observations was an involved process. Corrections had to be made for the loss by absorption in the Earth's atmosphere, for the loss due to tarnishing of the silver mirrors in the telescope and for the actual transparency of the glass sheet to reflected solar radiation and to lunar thermal radiation. Perhaps the most uncertain of these corrections is that for loss in the Earth's atmosphere. The sensitivity of the equipment permitted the measurement of temperatures down to 100°K; no radiation could be detected from an object appreciably cooler than 100°K.

Pettit and Nicholson first studied the variation of the heat received from different parts of the Moon's surface at full Moon. They found that the temperature of the sub-solar point was 407°K. The temperature gradually became lower towards the limb of the Moon. At 0·80 radius from the centre of the disk the temperature was about 380°K, and at 0·95 radius about 320°K. The temperatures on the disk away from the centre fall off less rapidly than might have been expected theoretically on the basis of emission by a smooth sphere exposed to parallel solar radiation. (A temperature of 355°K would be expected at 0·80 radius from the centre of the disk.) This discrepancy is almost certainly due to the roughness of the lunar surface. The temperature of the sub-solar point was measured near first quarter (the sub-solar point being at the limb) and was 358°K. This measurement gives further evidence of the effect of roughness of the surface.

This work of Pettit and Nicholson provided excellent confirmation of the early work of Rosse (1873) and Langley (1889), who showed that the lunar temperature was probably as high as that of boiling water (373°K), and is in substantial agreement with the work of Menzel.[2]

Pettit and Nicholson made one measurement of the temperature of the dark side of the Moon as near as could conveniently be obtained to the midnight meridian. They obtained a value of 120°K. This measurement was difficult, and the result must be considered tentative.

Pettit and Nicholson made a continuous series of measurements during the lunar eclipse of 1927 June 14. A point near the south limb was chosen, so as to be as near as possible to the centre of the umbra of the Earth's shadow. The temperature fell from 342°K before the eclipse to about 175° at the end of the partial phase. During totality the temperature continued to fall slowly, reaching 156°K at the end of totality, after which it recovered its original value. There was a slight lag between the phase of the eclipse and the change of lunar temperature; the smallness of the lag is a good indication that the surface materials of the Moon have low heat conductivity.

Pettit and Nicholson gave a theoretical discussion of their results, comparing the heat received by the Moon from the Sun with the reflected heat and the lunar thermal radiation. They concluded that the measured temperatures of the Moon were probably a little too high. They estimated the true value of the temperatures at the sub-solar point to be too high by about 17°. This could be explained by uncertainties in the assumed values of atmospheric transparency. It should be remembered that the temperature of 407°K for the centre of the lunar disk at full Moon refers to observations made perpendicular to the surface. Owing to the roughness of the surface the total radiation emitted by the centre of the disk in all directions (not only perpendicular to the surface) corresponds to a somewhat lower temperature, in fact to 391°K. If the above correction is applied, this 'mean spherical temperature' would be reduced to 374°K. Theoretical discussions of the absorption and reflection of solar radiation by the Moon must allow for radiation by the centre of full Moon as if it was a black body at 374°K.

In a later paper Pettit[3] extended his work to the study of the thermal radiation from the Moon as a whole. The problem had been studied by the Earl of Rosse between 1869 and 1873. Subsequent workers measured the reflected light from the Moon, but paid little attention to the lunar thermal radiation. Pettit observed the integrated thermal radiation from the whole lunar disk as a function of phase. As in the earlier work the reduction of the observations was complicated, and many corrections had to be applied. It was found that the heat received from the Moon fell off before and after full Moon more rapidly than would be expected on the basis of a smooth emitting surface. This is further confirmation of the roughness of the surface. Maximum temperature was attained at full Moon.

Pettit[4] made a further set of measurements of the temperature near the centre of the disk of the Moon during the total lunar eclipse of 1939 October 27. The temperature fell from 371°K to 200°K during the first partial phase, and slowly dropped to 175°K during totality. These results are very similar to the 1927 results; the temperatures in 1939 were rather higher than those observed in 1927, because the point observed was nearer the centre of the lunar disk. Pettit's 1939 measures have been plotted in Fig. 1.

So far as the reviewer is aware, there have been since 1939 no studies of lunar temperature variations made by techniques analagous to those of Pettit. Recently, however, Sinton[5] has extended observations of the Moon by optical techniques to the very long wavelength of 1·5 millimetres. A twenty-four-inch searchlight mirror was used and a Golay infra-red cell as detector. The observations effectively recorded the energy in a band of wavelengths from 1 to 2 mm. The observations refer to the integrated radiation from the Moon, the resolution being too small to study individual areas of the lunar surface. The apparatus was used during the total lunar eclipse on 1954 January 19. The effective (integrated) temperature of the Moon fell from 300°K before the eclipse to 170°K at the end of totality. The temperatures measured showed a substantial lag relative to the incident solar radiation; the temperature did not return to normal until some time after the Moon had left the penumbra. It will also be noticed that the maximum temperature is lower and the minimum higher than that found by Pettit and Nicholson. This significant fact will be discussed later.

Observations by Radio Techniques

War-time developments in the reception of microwaves have enabled measurements of thermal radiation from the Moon to be made by radio techniques. Microwave radiation from the Moon was first detected by Dicke and Beringer in 1946, using a wavelength of 1·25 centimetres. The first important measures were those of Piddington and Minnett,[6] also on a wave-

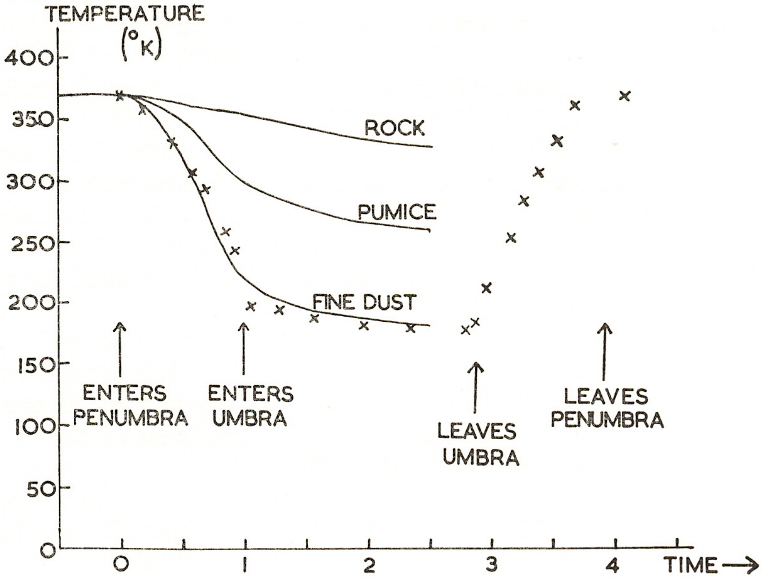

FIG. 1

Variation of temperature of the centre of the lunar disk during a total eclipse. The time scale is in units of the duration of penumbra. The theoretical curves are by Jaeger. A representative selection of the experimental measures of Pettit during the eclipse of 1939 October 27 are plotted as crosses. At this eclipse the duration of penumbra for the centre of the disk was 74 minutes.

length of 1·25 cm. The effective temperature was determined as a function of phase during three lunations. The final results were that the average temperature for the integrated disk was 239°K, and 249°K for the centre of the disk, varying by ± 40°K and ± 52°K, respectively, during the lunation. Thus, the temperature of the centre of the disk varies from 301°K to 197°K. The maximum temperatures were reached about three days after full Moon. These temperatures are apparently in disagreement with the optical observations of Pettit and Nicholson, who obtained a temperature variation of from 374°K to 120°K. The cause of this disagreement will be discussed later.

Troitsky and Zelinskaya[7] made measures of the lunar temperature as a function of phase on 70 days in 1952. Using a wavelength of 3·2 cm they found a mean temperature of 170°K. They found no certain variation with phase; the radiation received did not appear to vary by more than ± 7 per cent during a lunation.

Akabane[8] made measurements on a wavelength of 10 cm. He reported temperature variations from a minimum of 240°K to a maximum of 390°K, with probable errors of ± 50° in these values. Maximum temperature occurred a few days after full Moon.

The most recent investigation which has come to this reviewer's attention is that of Gibson.[9] He observed on a wavelength of 8·6 millimetres. After the usual laborious reductions, during which special measurements were made of atmospheric attenuation of radio waves at the wavelength in use, Gibson deduced from his results the equivalent temperature of the centre of the lunar disk as a function of phase. He found a maximum temperature of 225°K and a minimum temperature of 145°K, these occurring four to five days after full and new Moon, respectively. During this work, two total lunar eclipses (1953 January 29 and 1954 January 18) were observed. These radio observations showed no evidence of any temperature variations. This is a very different conclusion from that of Pettit and others on the basis of infra-red observations. The interpretation will be discussed later.

Summary of Observational Results

The observations described in the preceding paragraphs are summarized in Tables 1 and 2. It is clear from an inspection of Table 1 that further measures by radio techniques are needed before final conclusions can be drawn from the observations. In particular, further work at 10-cm wavelength is required to decide whether the range of temperature at this wavelength really is larger than at 8·6 mm, 1·25 cm, and 3·2 cm. Theoretical considerations to be discussed later in this review suggest that this variation is illusory, and that some substantial error has crept into the results at 10 cm. Whether theory or observation is in error can only be decided by further observation. If the observations at 10 cm are disregarded, one can suggest that the range of variation of temperature decreases with increasing wavelength. We shall discuss the interpretation of this general result, together with some of the detailed observations, in the following paragraphs.

TABLE I

Variation of the temperature of the Moon with phase

Wavelength	Region	Temperature		Reference
		Maximum	Minimum	
8μ—14μ	Centre of disk	374°K	120°K	1
8·6 mm	Centre of disk	225°K	145°K	9
1·25 cm	Centre of disk	301°K	197°K	6
3·2 cm	Whole disk	170°K	170°K	7
10 cm	Whole disk	390°K	240°K	8

TABLE 2

Variation of the temperature of the Moon during total eclipse

Wavelength	Region	Temperature		Reference
		Maximum	Minimum	
8μ—14μ	Centre of disk	371°K	175°K	4
1·5 mm	Whole disk	300°K	170°K	5
8·6 mm	Whole disk	225°K	225°K	9

Theoretical Interpretation of Optical Infra-Red Observations

The physical processes involved are the absorption of solar heat by the lunar surface, the conduction of heat into or out of the outer layers of the Moon, and the radiation of heat from the surface into space. The problems involved were studied in an early paper of Epstein,[10] and extensive studies have been published by Wesselink[11] and Jaeger.[12, 13]

It is convenient to assume as a working hypothesis that the surface layers of the Moon are homogeneous (e.g. a uniform solid, or dust with properties the same at different depths). The theoretical investigations show that the variation of surface temperature of the Moon for given incident solar radiation depends on only one parameter $(K\rho c)^{-\frac{1}{2}}$. K is the thermal conductivity of the material, ρ its density, and c its specific heat per unit mass. The importance of a parameter of this kind can be seen without entering into the details of the calculations. If K is small, the lunar material being a poor conductor of heat, the solar radiation which is absorbed will not be conducted very far into the Moon. The solar radiation will therefore affect only a thin layer of the Moon, and the temperature of this layer will show a large and rapid increase. Later in the lunation, when no solar radiation is incident on the Moon, the surface temperature will show a large and rapid fall. If K is large, the heat will be conducted to greater depths, and the rise and fall of the surface temperature will be much smaller. A large capacity for absorbing heat (i.e. a large value of ρc) has a similar effect to that of a large K; a large heat capacity implies a small rise in temperature when a given amount of heat is absorbed. Combining these considerations, it can be seen that when $(K\rho c)^{-\frac{1}{2}}$ is small the surface temperature undergoes relatively small changes, and if $(K\rho c)^{-\frac{1}{2}}$ is large, the temperature changes are relatively large.

The theoretical approach to the problem may be made in several ways. Wesselink[11] showed that, if some simplifying assumptions were made, it was possible to deduce a value of $(K\rho c)^{-\frac{1}{2}}$ for the Moon from the observed maximum and minimum temperatures during a lunation, and it is possible to proceed in a similar manner by analyzing eclipse observations. Alternatively, one might estimate the value of $(K\rho c)^{-\frac{1}{2}}$ from laboratory data for substances which could conceivably form the lunar surface, and, having computed the temperature variations for each substance, compare with observations to see what substances would agree with observation. This method is essentially that adopted by Jaeger.[12, 13] In this review space does not permit the detailed description of both approaches, and we shall use some of Jaeger's results to illustrate our discussion.

The physical properties[14] of a few selected materials are shown in Table 3, together with the values of the parameter $(K\rho c)^{-\frac{1}{2}}$. The values for rock are typical for most kinds of igneous materials. The values for powders are of especial interest. The leading investigations on the conductivity of powders are those of Smoluchowski[15] (quoted in the *International Critical Tables*,[14] Volume II, page 315). Under laboratory conditions a loose powder has a considerable admixture of air, and the latter contributes substantially to the conductivity. If the air pressure is reduced the conductivity is reduced. Smoluchowski studied powders of different materials and with grain sizes in the range 0·003 to 0·26 millimetres, and air pressures from atmospheric (760 mm mercury) down to 0·05 mm mercury. He found that at the latter pressure most powders had thermal conductivities in the neighbourhood of

3×10^{-6} cal/cm²/sec/(°K/cm). A more recent investigation by Kannuluik and Martin[16] suggests a value of 1×10^{-5} for powders in vacuum. Both values have been used in Table 3.

When numerical values of $(K\rho c)^{-\frac{1}{2}}$ have been determined (or assumed), the calculations on the variation of temperature can be performed. In Fig. 1 we have plotted some of Jaeger's results[13] for the variation of temperature during a lunar eclipse. The time scale has been chosen to make the theoretical curves comparable with Pettit's measurements.[4] The curves correspond to values of $(K\rho c)^{-\frac{1}{2}}$ of 20 (rock), 140 (pumice) and 1000 (fine dust). It is clear by inspection of Fig. 1 that the surface of the Moon cannot be bare rock, nor can it be a layer of solid pumice, or similar cellular substance. This seems to dispose of the oft-repeated suggestion that solid volcanic lava forms the surface of the Moon.

TABLE 3

Material	K	ρ	c	$(K\rho c)^{-\frac{1}{2}}$
Units	cal/cm²/sec/(°K/cm)	gm/cm³	cal/gm	
Copper	0·9	9	0·09	1
Rock	5×10^{-3}	3	0·2	20
Pumice	3×10^{-4}	0·6	0·2	170
Powder in vacuum	1×10^{-5}	2	0·2	500
Powder in vacuum	3×10^{-6}	2	0·2	900

Jaeger[13] has studied the properties of a layer of dust lying on solid rock. At present the observations do not suffice to distinguish between a very deep covering of dust and a thin layer of dust, but a covering of at least several millimetres seems absolutely essential to fit the observations.

Wesselink[11] was the first to demonstrate the high value of $(K\rho c)^{-\frac{1}{2}}$ needed to explain the observations. His paper contains much other interesting information. He showed that at lunar mid-day, when the surface temperature is about 370°K, only about one per cent of the heat of the Sun is conducted through the surface layers of the Moon: the remainder is immediately radiated into space by the warmed surface. Wesselink also determined the reflectivity of the Moon, and showed that about 20 per cent of the solar heat is reflected into space, and hence does not contribute to the heating of the surface.

Wesselink[11] and Jaeger[12, 13] both studied the variation of temperature during a lunation. Some of Jaeger's results have been plotted in Fig. 2. The measure of Pettit and Nicholson[1] of the temperature on the dark side of the Moon is shown. This measure is rather uncertain, and as no other measures have been made on the dark side temperatures it is hardly possible to draw firm conclusions from Fig. 2. The suggestion made on the basis of eclipse observations that the surface is dust-covered is supported by the additional evidence in Fig. 2. The decline in temperature from 140°K to 90°K during the 14-day lunar night is very slow because of the low rate of radiation of heat into space by such a cold surface.

The extent to which variations of temperature at the surface penetrate into the lunar interior was investigated by Wesselink.[11] He showed that the thermal effects of a lunar eclipse are negligible below a depth of about 7 millimetres, and the effects during a lunation are inappreciable below about 10 centimetres, provided the dust is at least as deep as this. If there was a thin layer of dust overlying solid rock, the temperature variations during a lunation might be expected to penetrate to a depth of two or three metres.

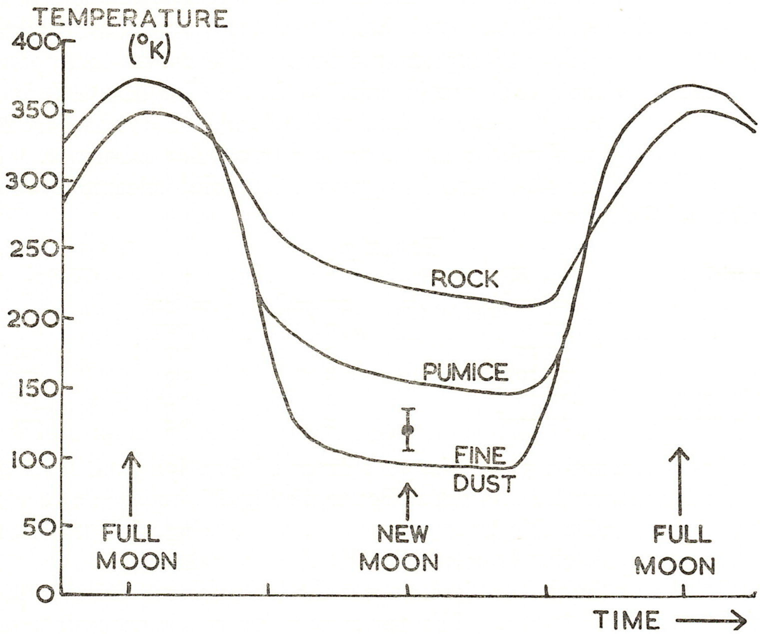

FIG. 2

Variation of temperature of the centre of the lunar disk with phase throughout a lunation. The theoretical curves are by Jaeger. The lunar midnight temperature measured by Pettit and Nicholson is marked as a dot, with the possible error of the observation shown.

The conclusion from all this work is that the surface of the Moon is covered with dust, but that no information is forthcoming on the depth of the dust layer. The extremely low values of the thermal conductivity provide yet another confirmation of the absence of any appreciable lunar atmosphere. The dusty nature of the surface is in agreement with conclusions from studies on the variation with phase of reflected moonlight.

Theoretical Interpretation of Microwave Observations

The chief remaining problem in the subject is to explain the provisional conclusion that the range of variation of temperature decreases with increasing wavelength. An explanation has been put forward. Solids which are poor electrical conductors (e.g. rocks) are partially transparent to microwave radiation, even if they are opaque to visible or infra-red radiation. It follows that the microwave thermal radiation from the Moon does not originate at the surface, but in a region below the surface. The temperatures which are observed are an average of the real physical temperatures in the layers through which the radiation has passed before leaving the Moon. It has been mentioned earlier (in connection with Wesselink's work) that the surface temperature variations only penetrate short distances below the surface. It is clear that when the temperatures are averaged over the depth of penetration of the microwaves, the resulting observed temperature will show smaller variations than the surface temperature. This is exactly as observed.

Detailed calculations have been carried out by Piddington and Minnett,[6] Jaeger,[13] Troitsky,[18] and Pawsey and Bracewell.[20] It is found that the observed temperatures depend on two parameters, $(K\rho c)^{-\frac{1}{2}}$ (as before), and a new parameter $C = \alpha(KP/\rho c)^{\frac{1}{2}}$, where P is the length of the lunar month and α is a constant connected with the depth to which microwave radiation penetrates the lunar material. A large value of α (and C) implies little penetration; a

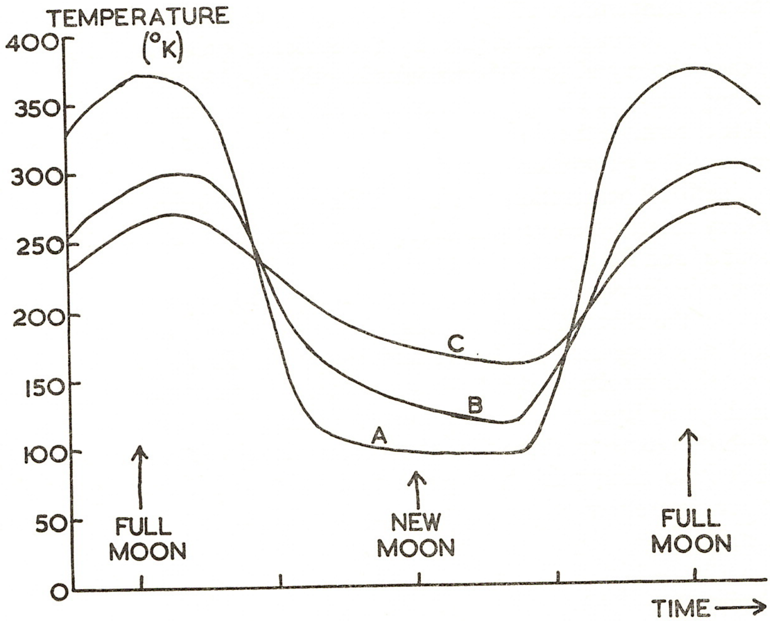

FIG. 3

Variation of the microwave temperature of the centre of the lunar disk with phase throughout a lunation. The curves are by Jaeger. All refer to a surface consisting of fine dust. Curve A is the same as the 'fine dust' curve in Fig. 2, and refers to waves which do not appreciably penetrate the surface. Curve B refers to waves which penetrate to an average depth of about one centimetre and curve C to waves penetrating to about three centimetres

small value of α (and C) implies penetration to relatively large depths. $1/\alpha$ is the average depth of emission of the observed radiation. The theoretical results of Jaeger[13] on the microwave temperature of the Moon are illustrated in Fig. 3. The curves refer to a value of $(K\rho c)^{-\frac{1}{2}} = 1000$, as deduced from optical observations, and three different values of C. The curves illustrate the lower temperature variations expected for waves which penetrate the lunar surface, and show that for these penetrating waves the maximum temperatures occur a few days after Full Moon.

The measures of Gibson[9] are probably the best available up to the present time. His observed temperatures, on a wavelength of 8·6 millimetres, are in excellent agreement with Jaeger's theory if we take $C = 1{\cdot}25$, curve C in Fig 3. [Gibson reduced Jaeger's temperatures somewhat before making the comparison to allow for an emissivity of the surface of 0·85.] This gives $\alpha = 0{\cdot}3$ per centimetre; the radiation comes from an average depth of about 3 centimetres. The measures of Piddington and Minnett[6] on 1·25 cm give a similar value of α. The measures of Troitsky and Zelinskaya[7] on 3·2 cm wavelength indicate a value of α of about 0·1; the radiation comes from a mean depth of 10 centimetres.

The observation of Gibson[9] that there was no measurable change in the microwave temperature of the Moon during an eclipse is easily explained by the theory. A rough calculation by the reviewer suggests that a change of more than about 5°K (on 8·6-mm wavelength) should not occur.

Sinton[5] analysed his measures on a lunar eclipse made at 1·5 mm wavelength to determine the absorption coefficient of the lunar material. Expressed in terms of the parameter α used in this review, his result was $\alpha = 6$. The mean depth of penetration was 1·7 millimetres. Sinton made a series of laboratory measures on various substances. For basalt he found a value of α of about 4, and for a meteorite a value of roughly 20.

Some calculations have been performed by Piddington and Minnett[6] and Jaeger[13] on the effect of a thin dust layer overlying solid volcanic rock. Such a model was suggested by Jaeger and Harper.[17] Piddington and Minnett analyzed their results on this basis, and obtained a fit of theory and observation if the dust layer was a few millimetres thick. The later work by Jaeger and Gibson seems to show that the observational data so far available are insufficient to distinguish between a thin layer and a deep layer of dust. More accurate observations are urgently needed to enable further progress to be made.

Conclusion

The main conclusion reached is the very low thermal conductivity of the lunar surface, entirely consistent with its being a layer of dust. The determination of the depth of the dust may eventually be possible when more accurate microwave observations become available. Little further progress is likely in this field until such observations are made.

Addendum

After the above article had gone to press, a note appeared by Seeger, Westerhout and Conway.[21] They report that on 75 cm wavelength no variation of the temperature of the Moon was observed during a lunation. They also refer to unpublished work on 33 cm wavelength by Denisse and Le Roux, in which no variation during a lunation was found.

The article by Gibson[9] has now been published.[22]

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