OBSERVATION OF A LUNAR ECLIPSE AT 1.5 MM

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ABSTRACT

Observations were made of a total lunar eclipse in a band of wave lengths at approximately 1 5 mm. It was found that the lunar emission decreased during the eclipse but that this decrease lagged about 1 hour behind the visual eclipse. To account for this lag, the 1.5-mm radiation is interpreted as arising from levels beneath the surface of the moon. From this interpretation a mass-absorption coefficient of 2.9 cm^2 gm^{-1} has been determined for the surface of the moon. Measurements of the mass-absorption coefficient of pumice, basalt, obsidian, and a stony meteorite are reported and compared to that of the moon.

It is well known from the work of Pettit and Nicholson (1930) and Pettit (1940) that the temperature of the surface of the moon drops rapidly during a total eclipse and recovers almost immediately at the end of the eclipse. Theoretical treatments of this phenomenon (Epstein 1929; Wesselink 1948; Jaeger 1953*a*) show that the surface of the moon consists of a material with an extremely low thermal conductivity. The theory shows that the sudden drop in temperature is propagated into the surface but is progressively attenuated beneath the surface and lags behind the surface variation.

Wesselink and Jaeger have shown that the surface temperature varies through a lunation from about 100° to 370° K. However, observations by Piddington and Minnett (1949), at 12.5 mm, of the temperature of the moon throughout a lunation show only a 104° K variation in the temperature and a 45° phase lag. This smaller variation and the phase lag demonstrate that the moon's surface is partially transparent to this wave length, so that radiation beneath the surface is observed. Layers of such depth are observed at 12.5 mm that the apparent temperature variation during an eclipse is attenuated to negligible amplitudes. On the other hand, there is sufficient absorption at wave lengths near 1 mm that a temperature change is observed during an eclipse, although delayed and of reduced amplitude.

Observations of the sun and the moon at approximately 1.5 mm have been made by the author by optical techniques (Sinton 1952, 1955). A 24-inch searchlight mirror is used as a telescope, and a Golay infrared cell is used as the detector. Removal of all the radiation shorter than 1 mm is accomplished by filters of black paper and expanded vinylite and by the water vapor of the earth's atmosphere. The long-wave-length limit is established by the tail of the black-body-curve of the sun and the moon. A band of approximately 1–2 mm is thus detected. The field of the telescope is set partly by the 3-mm aperture of the Golay detector and partly by diffraction by the 24-inch mirror. The field is approximately the same as the apparent disks of the sun and the moon.

The temperature of the moon is determined from the ratio of the moon's to the sun's deflections, corrected to the same zenith distance. The apparent solar temperature has not been measured at 1.5 mm. J. P. Hagen (1951) has found an apparent temperature of 6840° K ± 10 per cent at 8.5-mm wave length, while Piddington and Minnett, as quoted by Pawsey and Yabsley (1949), found a temperature of 10,000° K ± 10 per cent at 12.5 mm. For the purpose of reducing the lunar data to temperatures, an apparent temperature of 7000° K is assumed for the sun in the wave-length band accepted by the

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telescope. This temperature is chosen near the 8.5-mm measurement, since there must be a leveling-off of the drop in apparent temperature with decreasing wave length in this range. Lunar temperatures are then derived by assuming a lunar emissivity of 0.95 and correcting for the differences in the diameters of the sun and the moon.

OBSERVATIONS

The total eclipse of January 18–19, 1954, was observed with this equipment. This eclipse was a rather poor one, in that its magnitude was only 1.037 and totality lasted for only 30 minutes. On the other hand, it occurred in midwinter and consequently with the moon at a high declination. Both factors substantially reduce the strong absorption caused by atmospheric water vapor. The eclipse began when the moon was at an hour angle of 5^h32^m east and ended at 0^h01^m west.

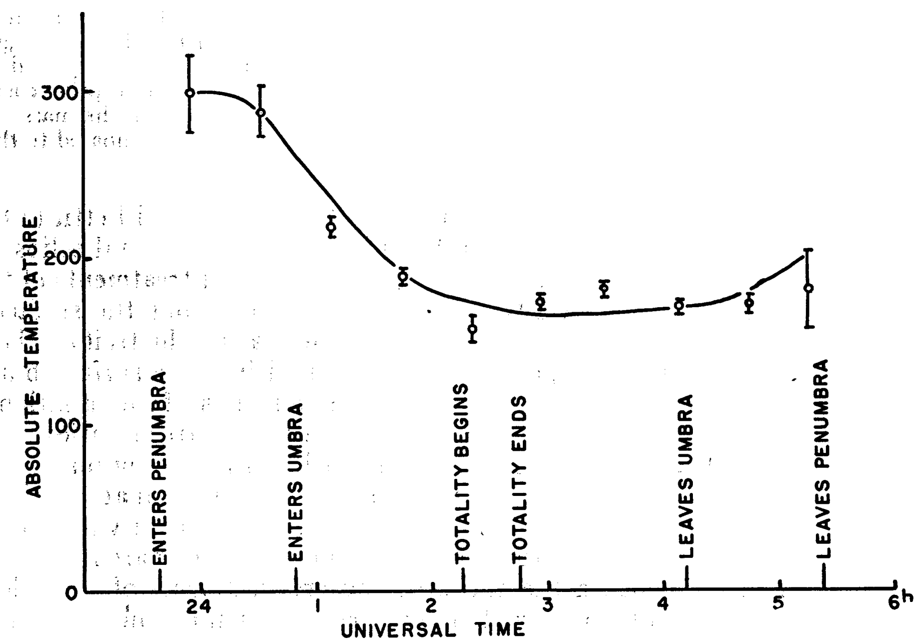

FIG. 1.—Observed lunar temperatures during eclipse of January 18–19, 1954. The brackets about each point show the probable errors determined from the ten measurements averaged in each point.

Observations were made with the telescope 2° east of the moon for 1 minute, on the moon for 1 minute; 2° west of the moon for 1 minute and on the moon again for 1 minute. This sequence was repeated throughout the eclipse. Although the signal-to-noise ratio was poor, an average of ten deflections above the sky background results in a reasonably accurate value for the deflection. The solar comparison observations were made during the previous morning and have been discussed (Sinton 1955).

The derived lunar temperatures are shown in Figure 1. The brackets about each point show the probable errors which were determined from each group of ten deflections. The diagram also shows the significant times for the eclipse. Unfortunately, no measurements were made after the ending of the eclipse, as the delayed character was not realized during the measurements.

INTERPRETATION

Piddington and Minnett (1950) and Jaeger (1953*b*) have found that a dust layer over the top of solid rock fits the microwave data better than a single dust-layer model. This more elaborate model will not be used to analyze the present measurements because of their crudeness and because it is likely that the millimeter waves arise from levels above the proposed lower layer of rock.

Figure 2 shows the assumed semi-infinite plane surface of the moon of thermal conductivity k, density ρ, specific heat c, absorption coefficient a, and refractive index n. Radiation emitted at an angle θ to the normal by the layer of thickness dx at a depth x from the surface suffers absorption by the amount $1 - e^{-ax \sec \theta}$ in reaching the surface. According to Kirchhoff's law, the emission of the layer of thickness dx per unit solid angle and square centimeter is given by $n^2 B(\lambda, T)\, a \sec \theta\, dx$, where $B(\lambda, T)$ is from Planck's formula and may be approximated in the millimeter region by $CT\lambda^{-4}$, where C is a constant. Just above the surface the total emission is

$$I = a \sec \theta \int_0^{\infty} B(\lambda, T)\, e^{-ax \sec \theta} dx\,. \tag{1}$$

If T is independent of x, this expression reduces to the black-body formula. Normally, T is a function of x, and we will assume that T is given by the polynomial

$$T = T_0 + T_1\left(\frac{x}{w}\right) + T_2\left(\frac{x}{w}\right)^2 + \ldots + T_n\left(\frac{x}{w}\right)^n, \tag{2}$$

where at present w is just a unit of length. The apparent temperature is given by

$$T_a = \frac{I}{C\lambda^{-4}} = aw \sec \phi \int_0^{\infty} T(\xi)\, e^{-aw\xi \sec \theta} d\xi\,, \tag{3}$$

where ξ has been substituted for x/w. Substituting the polynomial, we obtain

$$T_a = T_0 + \frac{T_1}{aw \sec \theta} + \frac{2!T_2}{a^2 w^2 \sec^2 \theta} + \ldots + \frac{n!T_n}{a^n w^n \sec^n \theta}\,. \tag{4}$$

In order to determine the temperature variation beneath the surface, a solution to the problem for the variation of the insolation for this eclipse must be found. Wesselink has shown how to do this by numerical integration, but the process requires arduous calculations. Instead of making them for the 1954 eclipse, I will use his calculations for the 1939 eclipse and will compare the calculated temperature variation at millimeter wave lengths for several values of $aw \sec \theta$ to the surface-temperature variation calculated for the 1939 eclipse. From the lags shown by the apparent temperature-curves for various values of $aw \sec \theta$, one will be selected as being nearest to the lag found for the 1954 eclipse. Although the lengths of totality are much different foı the two eclipses, the total durations of the eclipses are similar.

Figure 5 of Wesselink's article gives the temperature distribution beneath the surface as a function $\xi = x/w$, where w is now the heat wave length for a temperature variation with a period of lunation P, and W is given by $2(\pi Pk/\rho c)^{1/2}$. This graph shows the temperature distribution for five specific times during the eclipse and for a range of ξ from zero to 0.03. The temperature variation at larger values of ξ is small compared to the variation between zero and 0.03.

Cubic polynomials were fitted to the five curves for ξ between zero and 0.03. For larger values a linear variation of temperature was assumed which joined smoothly with the curves at $\xi = 0.03$. The integral (3) was performed in two parts, over the range 0–0.03 with the cubic polynomial and from 0.03 to infinity with the linear variation. The results for different values of $aw \sec \theta$ are shown in Figure 3, together with the surface variation of temperature. The contributions to the apparent temperature from the region beyond the range of Wesselink's graph is relatively small.

The observations with which these curves are to be compared were of the entire moon. Thus θ varies from zero at the center of the disk to a value set by Snell's law at the edge of the disk. The refractive index is unknown, but its value for the dust surface of the moon is probably smaller than the usual values for terrestrial rocks at radio wave lengths. If a value of n of 1.4 is assumed, the average sec θ over the visible disk is 1.2. The maximum range of the average of sec θ is from 2 to 1 for n ranging from 1 to infinity.

It is difficult to state specific values of the lags from the different curves of Figure 3. This is a result of the dispersion in the velocity of the thermal waves. A sudden change in the surface temperature, such as the ending of totality, is propagated into the surface more rapidly than more gradual changes, like the recovery to equilibrium at the end of the eclipse. A value of αw sec θ of 100 seems to give an over-all lag nearest to that found in the eclipse. In addition, the amplitude of the apparent temperature change seems to fit well.

We may write αw as $2\pi^{1/2}\mu(k\rho c)^{1/2}P^{1/2}/c$, where $\mu = \alpha/\rho$ is the mass-absorption coefficient of the surface material; $(k\rho c)^{1/2}$ is 0.008 cal cm^{-2} min$^{-1/2}$ (° C)$^{-1}$ from Pettit and Wesselink's work; and P, the period of rotation, is accurately known. The specific heat, c, is close to 0.2 for most common rocks, soils, and minerals. Using an average sec θ of 1.2, we find that μ is 2.9 cm^2 gm^{-1}.

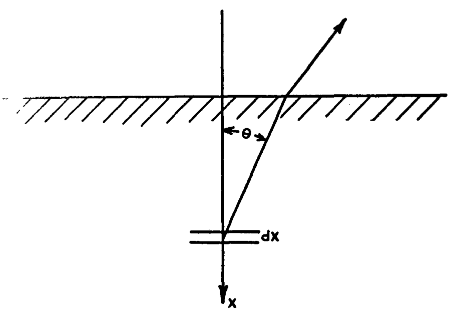

FIG. 2.—The assumed semi-infinite surface of the moon. The co-ordinate x is measured downward from the surface.

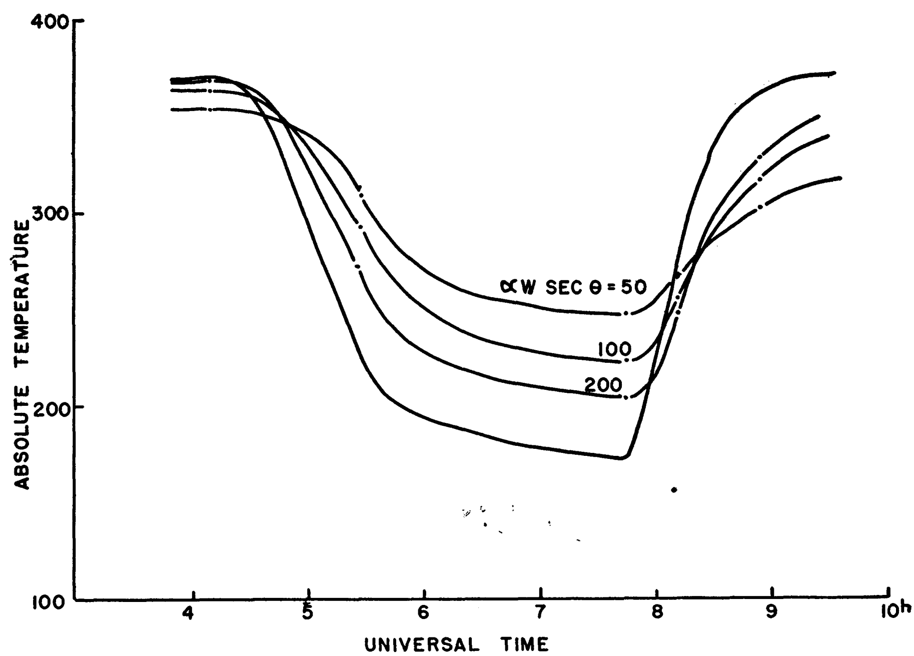

FIG. 3.—The theoretical variation of surface temperature for the eclipse of October 28, 1939 (Wesselink 1948) is shown by the solid line. The theoretical variation of the apparent temperature for several values of αw sec θ is shown for the same eclipse. The dots designate the points which were computed.

MEASUREMENTS OF MATERIALS

A number of common rocks and minerals that have been suggested as likely materials covering the lunar surface were measured to determine their mass-absorption coefficients. An early series of measurements was made with the 24-inch searchlight-telescope and the sun as a source. It was rather impractical to place the samples at or near the focus of this instrument, and hence large sheets of the materials were needed for placing in front of the aperture, which was reduced to 12 inches. In order to prepare large sheets, the samples were powdered and mixed with high-melting-point paraffin and cast into 12-inch-diameter disks with approximately 0.3 gm of material per square centimeter. As controls in the experiment, sheets were also made with powdered quartz, which has negligible absorption, and rock salt, whose absorption is known. The purpose of the paraffin is to match more closely the refractive index of the material and provide a plane surface, as well as to serve as a binder. A paraffin disk having the same quantity of paraffin as the others was used as a standard for the other measurements. It was found

TABLE 1

MASS-ABSORPTION COEFFICIENTS OF MATERIALS

Material	Early Measurements		Later Measurements	
	Per Cent Trans-mission	$cm^2\ gm^{-1}$	Per Cent Trans-mission	$cm^2\ gm^{-1}$
Paraffin	64	. .	78	. .. ..
Quartz	39	0 0	76	0 12
Rock salt	32	0 67	72	0 28
Pumice	33	0 52	62	0 78
Basalt .	18	2 7	50	1 54
Obsidian	21	2 6	66	0 69
Plainville meteorite	2	10 3	10	7 0

that there was appreciable scattering by the samples, and consequently transmissions much less than the true amount were measured. However, the scattering effect was partly eliminated by using the quartz measurements instead of the paraffin measurements as the standard. The mass-absorption coefficients so obtained are shown in the third column of Table 1.

Later, while solar observations were being made with the 61-inch reflecting telescope of Harvard College Observatory, these same samples were remeasured. They were placed at the Newtonian focus and a silver-plated horn used to condense the energy which passed through the sample onto the Golay cell. This system is much more free from errors caused by scattering. The mass-absorption coefficients obtained with the paraffin as a standard are shown in the fifth column of Table 1. The measured coefficients of quartz and rock salt compare favorably to previous determinations when allowance is made for errors in the transmissions of 1 per cent or so. The mass-absorption coefficient of rock salt at 1.5 mm has been determined to be 0.42 $cm^2\ gm^{-1}$ (McCubbin and Sinton 1950).

CONCLUSIONS AND FUTURE OBSERVATIONS

It must be kept in mind that the absorption coefficient found pertains to an average over the entire surface of the moon. Furthermore, the lunar surface is probably heterogeneous, since it does not appear uniform. Thus we cannot say from the measurements that the lunar surface consists of basalt, though this seems to have the coefficient nearest to the average of the moon. However, if the one stony meteorite that was measured is typical of meteoritic dust, then a covering entirely of such dust is excluded. One would expect it to be uniform over the surface, and the coefficient of the lunar surface does not agree with that for the meteorite. Obviously, more measurements are needed of likely materials.

Another eclipse should be observed in order to confirm these results and to obtain apparent temperatures throughout the eclipse and until the initial value is recovered. Also one should strive to observe a limited part of the surface so that averages do not enter. The author is planning to observe the November 18, 1956, eclipse with the Harvard 61-inch reflector. Unfortunately, this is the last eclipse which will occur in cold weather for some years. Only in winter will there be much chance for sufficiently small atmospheric absorption for observation.

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