Spectral Reflectance and Emittance of Apollo 11 and 12 Lunar Material

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The thermal radiation properties of Apollo 11 and 12 fines (soils) are reviewed and presented as a function of wavelength, angle of illumination and bulk density. The spectral directional reflectance is presented for wavelengths from 0.6 to 2 μm and for angles of illumination of 10°, 20°, 30°, 45°, and 60°. The normal emittance is presented for wavelengths from 2.5 to 14.5 μm. The solar albedo and total normal emittance as a function of temperature were calculated from the spectral values. The solar albedo for Apollo 11 fines is 0.099 whereas for Apollo 12 fines is approximately 0.119 for angles of illumination of 10° and a density of 1600 kg/m³. The total emittance varies from 0.98 at a temperature of 90°K to a value of 0.93 at a temperature of 400°K.

Introduction

SCIENTISTS have used remote sensing techniques such as astronomical observations in the visible, infrared, and radar wavelengths ranges in the past to study the lunar surface and to infer its physical properties. The returned lunar samples now are allowing them to compare previous inferred physical property results with those obtained directly from the returned samples.

The thermal radiation properties which are the subject of this paper are needed for calculations of energy balances on scientific equipment, astronauts, and spacecraft on the lunar surface as well as the calculation of the lunar surface temperature and its variation with depth and time.[1–3] These properties also have been of immense value in understanding remote sensing results.

The fines samples studied consisted of a distribution of small crystalline and glassy fragments with a variety of shapes. During the Apollo 11 and 12 missions core tube samples of fines were obtained. The bulk densities of the fines were selected according to the reported bulk densities of these core tube samples. The Apollo 12 Preliminary Science Report[4] reported average in situ bulk densities of 1640 ± 40 kg/m^3 for Apollo 11 and an average in situ bulk density 1800 ± 200 kg/m^3 for Apollo 12. In this study the bulk densities used were approximately 1300, 1400, 1600, and 1800 kg/m^3.

The directional reflectances were measured for a wavelength range from 0.55 to 2.2 um and for angles of illumination of 10°, 20°, 30°, 35°, and 60°. The normal emittances were obtained for a wavelength range from 2.5 to 14.5 μm and for an angle of viewing of 10°. Studies were made on lunar fines, Apollo 11 sample 10084,68, and Apollo 12 sample 12070,125. This paper reviews the spectral radiation results 5–7 and presents new results for the total radiation properties of the lunar material.

The directional hemispherical reflectance is defined as the ratio of the hemispherically reflected energy to the energy in the incident beam for a particular angle of illumination from the normal; and the hemispherical directional reflectance is defined as the ratio of radiance in a given direction to the diffuse incident hemispherical radiant flux divided by π. The two reflectances can be shown to be identical[8] under conditions that the angles of illumination and viewing are the same. Either one is commonly called just directional reflectance. The energy absorbed by lunar fines is easily calculated by substracting the directional reflectance from unity.

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The directional spectral emittance of a sample is defined as the ratio of the radiance from the sample to the radiance from a blackbody at the same temperature

$$\varepsilon(\theta, \lambda, T) = i(\theta, \lambda, T)/i_B(\lambda, T) \tag{1}$$

where θ is the angle of viewing, T the temperature of the sample, i and i_B are the radiance of the sample and blockbody, respectively.

In this paper the sample is of sufficient density and thickness over the wavelengths studied that to a first approximation it behaves like a solid opaque sample.

Measurement Techniques

Directional Reflectance

The directional reflectance was obtained with a sample, center-mounted in a 0.20-m-diam integrating sphere reflectometer. The sphere coating was magnesium oxide. The sphere system is constructed with the sample held in a horizontal position, a necessity for powders, while by rotation of the sphere and external optics, angles of illumination or viewing up to approximately 75° are obtained.

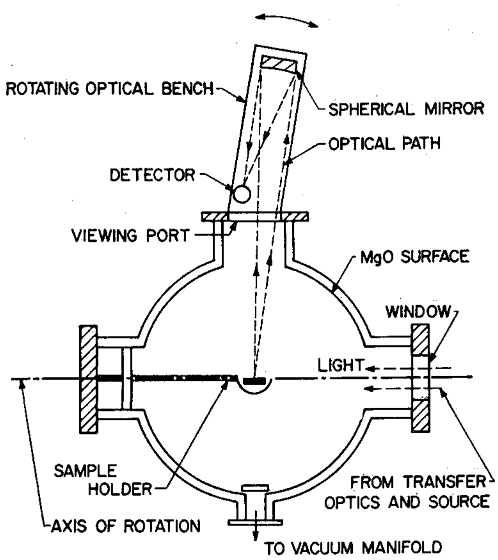

Fig. 1 Integrating sphere reflectometer.

The integrating sphere was operated in the reciprocal mode, that is, the sample was illuminated by diffuse light from the sphere walls. The ratio of radiance when the center mounted sample was viewed to the radiance when the wall was viewed is the directional reflectance $\rho(\theta)$. As discussed earlier this measurement is equivalent to illuminating the sample at an angle of incidence Ψ equal to the angle of viewing θ and measuring the hemispherically reflected energy.

The viewing optics were arranged so that the sample or sphere wall could be viewed by rotating the optical bench, Fig. 1. The spectral results were obtained with a Perkin-Elmer 112 U spectrometer having a tungsten-iodine source and a lead-sulfide detector mounted on the rotating optical bench.

The sampler holder consisted of a Teflon cup 25 mm in diameter and approximately 6 mm in depth. Samples were measured out to the proper weight corresponding to the desired density and then carefully poured into the sample holder. To achieve a level surface the fines were packed by use of a vibrating tool held on the holder edge. Initial smoothing and packing of the surface is achieved with a stainless steel spatula.

Directional Emittance

The directional spectral emittance is obtained from Eq. (2) and a computer controlled spectroradiometric system shown in Fig. 2. The sample is surrounded by a water cooled blackened environment and a heated blackbody is used as a reference source for our method. The energy emitted by the heated sample or

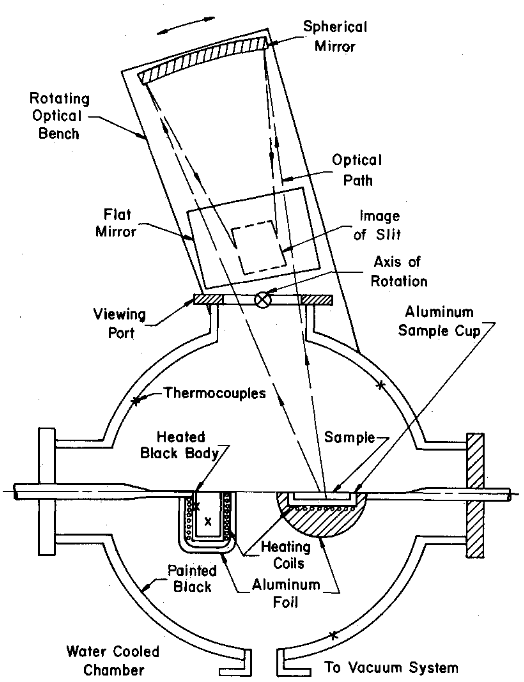

Fig. 2 Directional emittance system.

reference blackbody is collected by transfer optics and focused on the entrance slit of a spectrometer. The spectral emittance of the sample is calculated from the measured temperatures and detector outputs for the sample, reference blackbody and the blackened surrounds, respectively. A detailed analysis is presented by Birkebak.[9] The result of this analysis for the directional emittance is

$$\varepsilon(\theta, T, \lambda) = \frac{\Delta(S) - \Delta(R)}{\Delta(B) - \Delta(R)} \frac{\exp[C_2/\lambda T_R] - \exp[C_2/\lambda T_B]}{\exp[C_2/\lambda T_R] - \exp[C_2/\lambda T_S]} \cdot \left\{\frac{\exp[C_2/\lambda T_S] - 1}{\exp[C_2/\lambda T_B] - 1}\right\} \qquad (2)$$

where $\Delta(S)$, $\Delta(B)$, and $\Delta(R)$ are the detector output when the sample, heated blackbody and reference blackbody (surrounds) are viewed by the transfer optics, respectively; λ the wavelength and T_S, T_B, T_R the absolute temperatures of the sample, heated blackbody and reference blackbody, respectively.

The sample holder was made of an outer ceramic cup into which a Nichrome heating wire was placed as shown in Fig. 2. The sample cup which held the lunar fines was a polished aluminum piece, 25.4 mm in diameter by 2.4 mm thick which was located as shown in Fig. 2. One thermocouple was installed at the base of the aluminum cup and a second bare thermocouple was stretched across the holder at a height of 1.98 mm. These thermocouples measurements were used to calculate the surface temperature of the sample needed in Eq. (2).

Results

The directional reflectance for three lunar samples at about a bulk density of 1300 kg/m^3 is shown in Fig. 3. In general the Apollo 11 fines always had a lower reflectance than the Apollo 12 fines. The difference in the reflectances is associated with the chemical composition of the samples and the amount of glass fragments in each.[10]

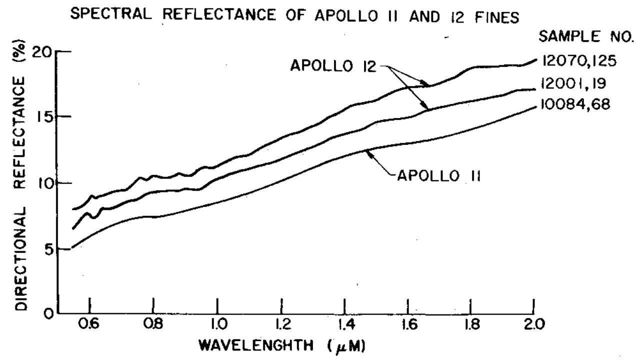

Fig. 3 Spectral reflectance of Apollo 11 and 12 fines.

Sample 10084,68

The results for this Apollo 11 sample for a density of approximately 1300 kg/m^3 have been previously reported by Birkebak et al.[5] A typical reflectance curve is shown in Fig. 4. The reflectances, generally, were reproducible to within $\pm 1\%$. In general, the reflectance increases with density for all wavelengths with an increase of up to 40% from the smallest to the largest density. As the surface becomes more compacted, that is a greater number of particles per unit volume, the void faction decreases, and hence fewer number of cavities to trap and absorb radiation are present. Therefore, the reflectance increases for the sample.

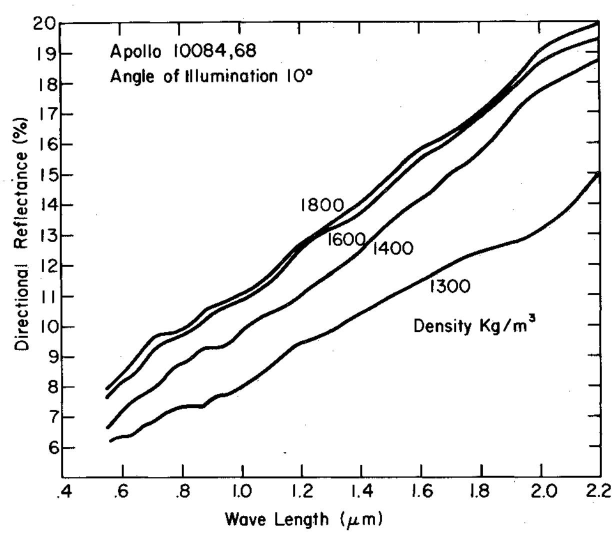

Fig. 4 Spectral directional reflectance as a function of density—Apollo 11 fines.

The reflectance increases more rapidly for the smaller density changes. From these data it can be seen that the results are approaching the limit where the porosity of the sample does not affect the reflectance values, that is, the material behaves as if it were a solid material.

The effect of angle of illumination on reflectance for sample 10084,68 with a density of 1600 kg/m^3 is shown in Fig. 5. Table 1

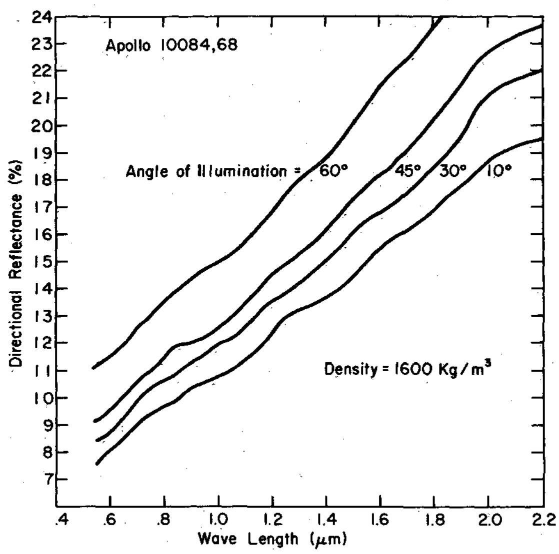

Fig. 5 Spectral directional reflectance as a function of angle of illumination—Apollo 11 fines.

Table 1 Solar albedo for lunar fines

Angle of illumination, deg.	Apollo 11 10084 density, kg/m^3				Apollo 12 12070 density, kg/m^3		
	1300	1400	1600	1800	1300	1600	1800
10	0.076	0.087	0.099	0.101	0.101	0.119	0.120
20	0.082	0.095	...	0.102	0.106	0.114	0.126
30	0.084	0.102	0.107	0.108	0.109	0.115	0.131
45	0.095	0.113	0.113	0.116	0.122	0.136	0.138
60	0.108	0.132	0.133	0.132			

presents the calculated solar reflectance (albedo) for various densities as a function of angle of illumination. The general characteristics of the data are those of a dielectric material. These results were fitted to the following equation and when $\theta = 90°$, the reflectance is 1:

$$\rho(\theta) = A + B\theta + C\theta^2 + D\theta^3 + E\theta^4 \tag{3}$$

where the coefficients are given in Table 2.

Table 2 Coefficients for directional reflectance equation $\rho(\theta) = A + B\theta + C\theta^2 + D\theta^3 + E\theta^4$

	Apollo 11 10084 density, kg/m^3				Apollo 12 12070 density kg/m^3		
	1300	1400	1600	1800	1300	1600	1800
$A \times 10$	0.7835	0.8896	1.005	1.0349	1.0098	1.192	1.20
$B \times 10^2$	−0.3452	−0.3304	−0.2674	−0.3472	−0.06783	−0.002479	−0.1041
$C \times 10^3$	0.3444	0.3405	0.2895	0.3316	0.09985	−0.002695	0.1411
$D \times 10^5$	−0.9604	−0.9379	−0.8452	−0.9191	−0.3515	−0.07244	−0.4614
$E \times 10^7$	0.8298	0.8059	0.7554	0.7960	0.4136	0.2184	0.4869

The total emittance of this sample is approximately 0.96 ± 0.02 and is shown in Fig. 6. It was measured directly[11] using a total emittance radiometer.

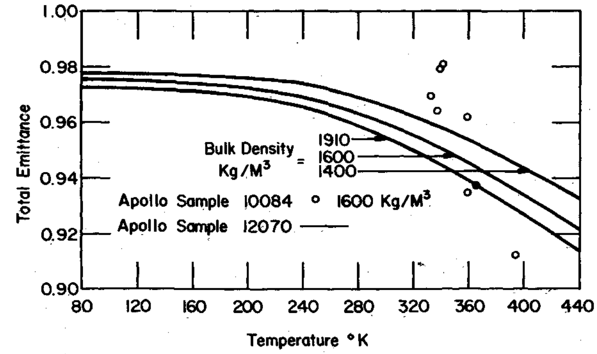

Fig. 6 Total emittance of Apollo 11 and 12 fines.

Sample 12070,125

Results for this sample were obtained for the "as received" density estimated to be 1350 kg/m^3 and for densities of 1600 and 1800 kg/m^3. Figure 7 presents the results obtained for these densities for an angle of illumination of 10°. The "as received" sample was run under vacuum conditions, 5×10^{-6} torr. Additional results for other angles of illumination are found in Birkebak et al.[6]

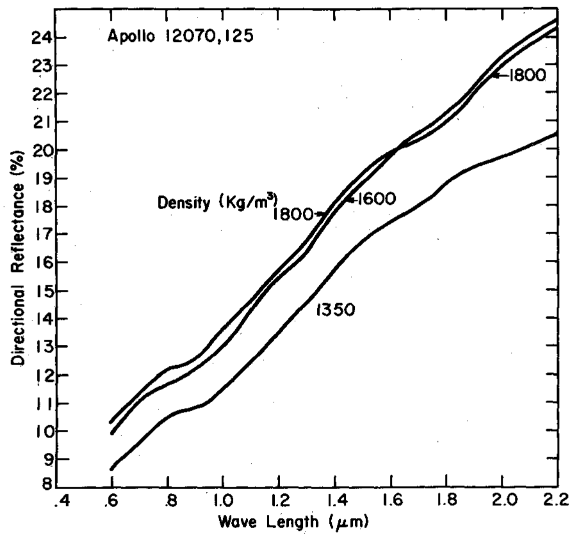

Fig. 7 Spectral directional reflectance as a function of density—Apollo 12 fines.

Again the effects of density change are the same as for sample 10084; for the middle and highest densities the increase in reflectance is small as compared to the lowest and middle densities. One must be cautious when interpreting density effects. The initial packing of the fines achieves the desired uniform density of the whole volume. However, after exposure to small vibrations in the sample handling system, the smaller particulate material will settle and the density can change and may not be uniform any longer. All measurements were made in a very short time period for a given density and therefore it is felt that this problem is minimal. The reflectance for the "as received" condition is shown in Fig. 3. The directional reflectance as a function of angle of illumination is similar to that found for sample 10084,68. The calculated solar albedo as a function of angle of illumination is presented in Table 1 and the coefficients for Eq. (3) in Table 2.

The spectral emittance results[7] for bulk densities of approximately 1400, 1600, 1710, and 1910 kg/m^3 for this sample are presented in Fig. 8. The angle of viewing, θ, used in this experiment was 10°. Each curve in Fig. 8 represents an average of 3 or more runs that we made at the specified density.

The sample surface temperature used in Eq. (2) was calculated from the measured sample temperature gradient, the temperature measured near the surface and from the known sample thickness

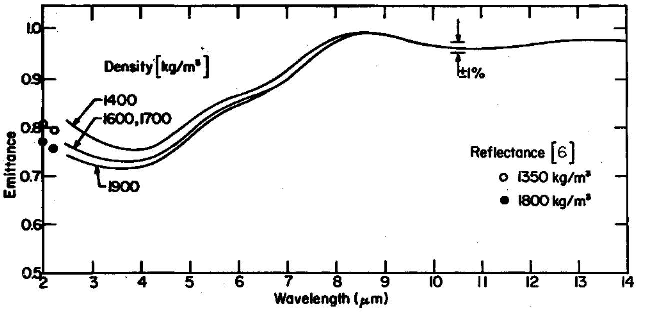

Fig. 8 Spectral emittance as a function of density—Apollo 12 fines.

and thermocouple locations. If one uses the calculated surface temperature rather than the temperature measured at 0.46 mm below the surface in Eq. (2), the difference in emittances obtained from the two temperatures ranges from essentially zero at 2.5 μm to 1% higher at 14 μm. The surface temperature for all measurements was approximately 380°K, a temperature very near the maximum temperature experienced by the sample on the moon.[1] The estimated error in these results is $\pm 1\%$.

Clearly evident in Fig. 8 is the effect of bulk density. Because the results for densities of 1600 and 1710 kg/m^3 were so close together a single curve has been drawn through them. The emittance decreases with increasing density for the shorter wavelengths with a change of approximately 7% at 3μm between the smallest and largest densities and as the wavelengths become larger the difference becomes negligible. The greatest uncertainties in these measurements are for wavelengths from 2 to 2.5 μm and in this region the maximum effect of density on reflectance was shown to occur. As the surface becomes more compacted, that is a greater number of particles per unit volume, the void fraction decreases, therefore, the size of the cavities in the surface which absorb and emit energy are reduced and the emittance decreases. From these results and the reflectance measurements, it appears that the limit has been reached where the porosity of the sample does not affect the spectral emittance values, that is, the material behaves as if it were a solid material. Comparison of the emittance values and one minus the reflectance[6] for various densities at wavelengths near 2 μm are good for the higher densities, that is, there is a reasonable match between the two results, but poor agreement for the density of 1400 kg/m^3, but this is not an unexcepted result for the lower densities since the lower densities (<1500 kg/m^3) are difficult to maintain because the fines have a tendency to settle due to vibration of the sample handling system.

There are several features of the spectral emittance that need commenting on. A maximum emittance of 0.99 occurs between wavelengths of 8.25 and 8.5 μm. In powders such as lunar fines, the maximum emittance occurs at the so called Christiansen frequency[12]; the region in the spectrum where minimum internal scattering takes places and the real index of refraction is close to that of the surrounding medium, a region of maximum transmission and emittance. An apparent absorption band is centered near 5.75 μm and is due to the composition of the fines. The minimum emittance which is also a function of composition occurs at approximately 3.6 μm.

The total emittances of the Apollo 12 sample were calculated from the three density results of the measured spectral emittances. The estimated variation for these results is ± 0.01 units. The agreement between the Apollo 11 and 12 samples is acceptable. However, one might expect that the two results would not be the same because of the different composition of the two samples. Indeed the visible thermal radiation properties of these two samples are different. The equation describing the total normal emittance for a density of 1600 kg/m^3 and for the temperature range found on the moon is

$$\varepsilon = 0.9844 - 0.1989 \times 10^{-3}T + 0.1652 \times 10^{-5}T^2 - 0.5892 \times 10^{-8}T^3 + 0.5523 \times 10^{-11}T^4 \quad (4)$$

where T is in °K.

Conclusions

The results for the lunar fines confirm, in general, the measurements made by remote sensing. The Apollo 11 reflectances are lower than the Apollo 12 by as much as 30% and this is due mainly to the composition and amount of glass fragments in the fines.

The lunar surface is not black as some investigators have assumed in their theoretical calculations of the lunar surface temperatures. Our results indicate that the emittance varies by approximately 6% over the expected temperature range for the lunar surface. This variation in total emittance with temperature effects the surface temperature variation by only 2 to 3°K out of 390°K for the maximum lunar temperature.[1] The variation of solar albedo with angle of illumination, on the other hand, affects drastically the lunar surface temperatures just after sunrise and before sunset.[3] Compared to constant solar albedo case,[1] the temperatures are lower by as much as 60°K.

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