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17. The stable carbon isotope data are presented as δ values defined as per mil deviations relative to the Pee Dee belemnite (PDB) standard [H. Craig, *Geochim. Cosmochim. Acta* **3**, 53 (1953)].
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23. We thank C. Oman for valuable assistance, P. M. Williams and P. Kinney for contributing substantially to the design of the UV DOC oxidation line, and J. L. Hughes who assisted with the Barstow, California, groundwater study. The manuscript benefited from review comments by J. A. Leenheer, R. L. Malcolm, and I. Friedman.

23 September 1974

Microwave Emission Spectrum of the Moon: Mean Global Heat Flow and Average Depth of the Regolith

Abstract. *Earth-based observations of the lunar microwave brightness temperature spectrum at wavelengths between 5 and 500 centimeters, when reexamined in the light of physical property data derived from the Apollo program, tentatively support the high heat flows measured in situ and indicate that a regolith thickness between 10 and 30 meters may characterize a large portion of the lunar near side.*

Direct determinations of the thermal regime and physical properties of the lunar near-surface layers by in situ experiments and measurements on returned samples lend fresh significance to the earth-based observations of the lunar microwave emission spectrum made prior to the Apollo landings. Measurements of the physical properties at a number of sites permit a much less ambiguous interpretation of the remote measurements in terms of regolith physical properties, homogeneity, and thickness. Comparisons of the observed thermal emission with global models of the lunar surface layers can, in turn, be utilized to determine how representative the local property deductions are on a moonwide scale.

It is well known that the material in the lunar regolith becomes increasingly more transparent at longer electromagnetic wavelengths. Thus, observations of the brightness temperatures at different wavelengths can be correlated with the subsurface temperature profile and with regolith physical properties. Observations at wavelengths of a millimeter to a few centimeters support the in situ and sample measurement determinations of the near-surface physical properties, indicating that a large portion of the lunar near side, at least near the disk center, is characterized by similar thermal and electrical properties (*1*). At wavelengths greater than 5 cm, no significant time variation in the brightness temperature can be detected, an indication that the effective emitting layers at these longer wavelengths lie below the depths at which diurnal temperature variations are substantial. Thus, any observed change in the disk-average brightness temperature with wavelength is due to the steady-state temperature gradient characterizing heat flow from the interior as well as the subsurface physical properties and the upper crustal structure of a large region of the moon surrounding the subearth point.

The data shown in Fig. 1 represent two sets of observations. The cluster of points up to a wavelength of 70 cm is based on measurements made in the Soviet Union between 1961 and 1964 with the use of the "artificial moon" calibration technique (*2*). The four observations between 69.8 and 406.5 cm were made at the Arecibo Observatory by Salisbury and Fernald (*3*) in 1969. The Arecibo data are included only as feasible support for the possibility of a negative spectral gradient existing at meter wavelengths. Because of problems of substantial sky background and the difficulties of absolute calibration at meter wavelengths, the accuracy of the Arecibo data is highly questionable.

The primary inferences contained in this report depend only on the reliability of the Russian data. Absolute temperature levels produced by feasible physical models which incorporate direct measurements from the Apollo program are in good agreement with the Russian measurements, especially when the large scatter of other earth-based measurements is considered. However, the slope of the Russian data, that is, the spectral gradient at wavelengths between 5 and 20 cm, which is contingent on the global heat flow, cannot be considered to be definitively accurate from a statistical viewpoint because of the short range of apparent linearity (5- to 20-cm wavelengths) relative to the uncertainties in absolute temperature measurements. Thus, our conclusions with regard to the global heat flow must be considered tentative until additional, more refined measurements are made.

Two features of the Russian data stand out. The near linear increase in brightness temperature with wavelength between 5 and 20 cm (see the expanded-scale inset of Fig. 1) is consistent with a regolith that is homogeneous over a depth interval relevant to the 5- to 20-cm emissions. If the regolith homogeneity were maintained to depths on the order of 100 m, a continuation of a near linear increase in brightness temperature to meter wavelengths would be expected. The observations, however, indicate a flattening of the emission curve beyond 20 cm followed by a possible decrease in the brightness temperature at greater wavelengths.

This spectrum suggests an increasing effective opacity of the lunar material at depths from which 30-cm and longer wavelengths are emitted. The greater opacity may result from buried rubble layers or alternating lava and ejecta layers which effectively scatter the longer-wavelength emissions originating in the rubble layers. The existence of such layers is supported by the seismic profiling results (*4*). To examine the feasibility of such a process, we have modeled the upper 100 m of the lunar crust in terms of a compact, powdered regolith overlying alternating layers of rock and soil material. The models are not meant to represent the actual crustal structure. They are utilized only to demonstrate the effect of scattering processes upon the lunar emission spectrum. The method of emission from a multilayer medium, including multiple reflections, will be published elsewhere (*5*). The physical properties and layer thicknesses which were common to all models are listed in Table 1. The real permittivity, ε; the thermal gradient expressed as the ratio of the heat flow, q, to the thermal conductivity, k; and the electrical absorption length, ℓ_λ ($1/e$ penetration depth), shown as fixed values, are based on results from in situ experiments and sample measurements (*6*–*8*). The thicknesses of the rock and soil subregolith layers (1.9 m of rock over 4.5 m of soil over 1.9 m of rock, and so on) were chosen to produce a spectral gradient of ~ -10°K m^{-1} at meter wavelengths, commensurate with the Arecibo data. The particular physical property values chosen for the subregolith layers are not critical in that a different set of properties can produce the same negative spectral gradient at meter wavelengths if the boundary spacing in the rubble layers is allowed to vary. The subregolith physical properties and layer spacings have negligible effect on the 5- to 20-cm spectral gradient and emission peak. The parameters constrained by the emission spectrum are the regolith temperature gradient, the electrical absorption length, and the thickness.

For the models shown in Fig. 1 we utilized a regolith temperature gradient of 1.3°K m^{-1}, based on a mean heat flow of 3.0×10^{-2} watt m^{-2} and a mean thermal conductivity of 2.3×10^{-2} watt m^{-1} °K^{-1} determined for the Apollo 15 and Apollo 17 heat flow sites (*8*). The electrical absorption length, $\ell_\lambda = 50\lambda$, is based on the measurements of Gold *et al.* (*6*) on Apollo 15 and Apollo 16 soil samples at a density of 2.0 g cm^{-3} and a wavelength of 68 cm. The assumption of regolith homogeneity is based on evidence that packing differentials are confined mainly to the upper few centimeters, the properties of which have a negligible effect on emissions at $\lambda > 5$ cm. Core-tube samples, conductivity measurements, and drill-resistance analysis all indicate that, immediately below the surface, the density rapidly increases but that at greater depth the density varies only slightly with depth in an irregular way. A gradual and continual increase in density and associated properties such as thermal conductivity and the electrical absorption coefficient is not supported by the related measurements and observations.

Absolute temperature values are based on the measurements at the Apollo 15 heat flow site (*9*) with an adjustment for the lunar latitude being applied for the determination of the integral emission from the entire disk. The models of Fig. 1 are distinguished by regolith thicknesses of 10, 20, and 30 m.

It is apparent that model II, with a regolith thickness of 20 m, produces an emission peak at a wavelength of ~ 45 cm, in best agreement with the observations, even though resolution of the models is difficult as a result of the scatter in the observations at wavelengths between 30 and 70 cm. Estimates of the lunar regolith thickness based on observations of steep-walled craters, seismic evidence, and radar measurements have ranged between one and hundreds of meters. However, no models with regolith thickness outside the range of 10 to 30 m produce

Table 1. Physical parameters of the multilayered models of the upper 100 m of the lunar surface.

Layer	ε	q/k(°K m^{-1})	ℓ_λ	Thickness (m)
Regolith	3.0	Variable	Variable	Variable
Soil layers	3.0	Variable	Variable	4.5
Rock layers	6.5	0.027	10λ	1.9

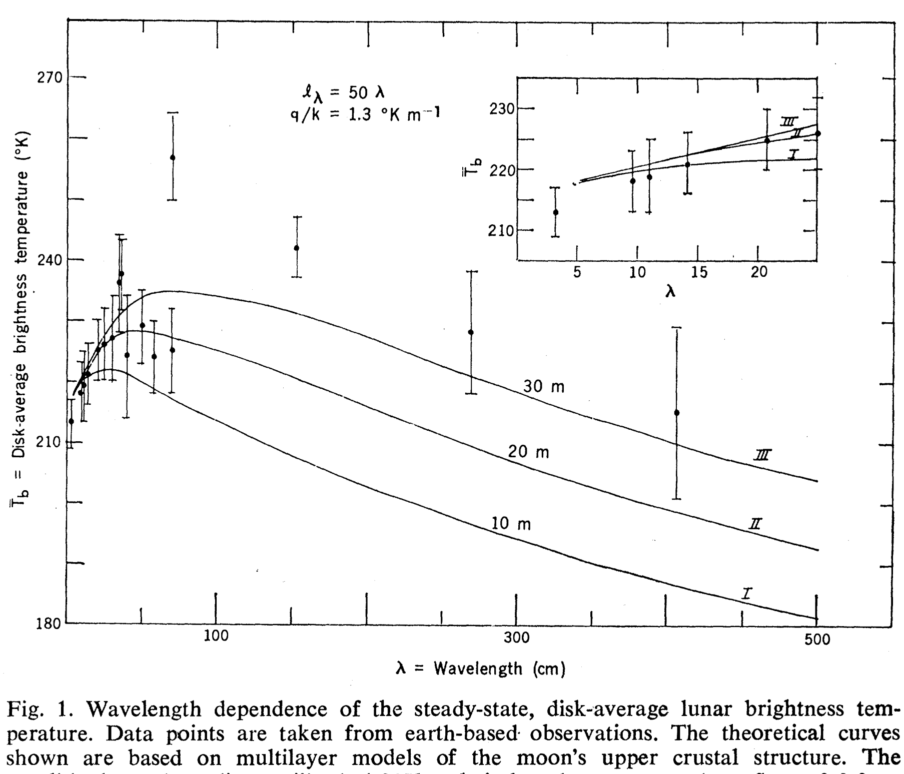

Fig. 1. Wavelength dependence of the steady-state, disk-average lunar brightness temperature. Data points are taken from earth-based observations. The theoretical curves shown are based on multilayer models of the moon's upper crustal structure. The regolith thermal gradient utilized, 1.3°K m^{-1}, is based on a mean heat flow of 3.0×10^{-2} watt m^{-2} and a mean thermal conductivity of 2.3×10^{-2} watt m^{-1} °K^{-1} measured at depths below 1 m at the heat flow sites. The electrical absorption length, $\ell_\lambda = 50\lambda$, lies near the middle of the range of the measurement values of Gold *et al.* (*6*) at a wavelength of 68 cm. The three models are distinguished by regolith thicknesses of 10, 20, and 30 m.

reasonable agreement with the available microwave observations.

It can be seen on the expanded-scale inset of Fig. 1 that none of the models reproduces the high spectral gradient of the observations in the 5- to 20-cm band. If the observed 5- to 20-cm spectral gradient is accurate, this indicates that a large portion of the lunar regolith is characterized by either larger temperature gradients or longer absorption lengths. The observed spectral gradient between 5 and 20 cm can be matched if either 50 percent higher heat flow, 35 percent lower conductivities, or 50 percent longer electrical absorption lengths are utilized. The possibility of somewhat lower moonwide conductivities and longer absorption lengths seems the most plausible. Both effects could be produced if the regolith material, perhaps in the highland areas, is somewhat less compact than that found at the Apollo 15 and Apollo 17 heat flow sites.

The possibility of significant wavelength-dependent calibration errors in the Russian microwave emission data cannot be discounted. Errors in the observed 5- to 20-cm spectral gradient would lead to comparable errors in estimates of the mean thermal gradient of the lunar near side. A new set of remote measurements in the 5- to 100-cm band, with improved resolution and calibration techniques, is obviously needed. A set of measurements utilizing consistent calibration techniques would be most useful in minimizing wavelength-dependent calibration errors. The possibility of measurements at a few discrete wavelengths between 5 and 20 cm from a lunar orbiter should also be considered. The high accuracy and resolution of such a measurement would permit accurate assessments of the global variation of heat flow, regolith physical properties, and thickness to be made.

For the immediate future, additional electrical property measurements on the available lunar samples at wavelengths between 5 and 50 cm would be valuable for refining the interpretation of the available brightness temperature data.

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The Postspinel Phases in the Mg_2SiO_4-Fe_2SiO_4 System

Abstract. *Samples of olivine (Fo_0Fa_{100}, $Fo_{60}Fa_{40}$, $Fo_{80}Fa_{20}$, and $Fo_{100}Fa_0$) and of spinel ($Fo_{50}Fa_{50}$, Fo_0Fa_{100}, where Fo is forsterite and Fa is fayalite) were subjected to pressures up to 250 kilobars in a diamond anvil press and were heated in situ up to ~ 1700°C by an infrared beam from a continuous-wave YAG (yttrium-aluminum-garnet) laser. The brightness temperature was determined from the intensity of incandescence of the sample by means of an optical pyrometer. X-ray diffraction patterns of the samples, obtained after quenching and unloading, show conclusively that these compositions disproportionate to (Mg,Fe)O and SiO_2 (stishovite) under these conditions.*

Jeffreys (*1*) has reported velocity-depth curves for seismic waves in the earth's interior which show that the velocities of both P and S waves undergo marked increases at depths of from 200 to 900 km in the mantle. Birch (*2*) suggested that this rapid increase in velocities could be attributed to phase transitions in ferromagnesian silicates from their low-pressure modifications in the upper mantle to high-pressure modifications in the lower mantle, probably close-packed oxides.

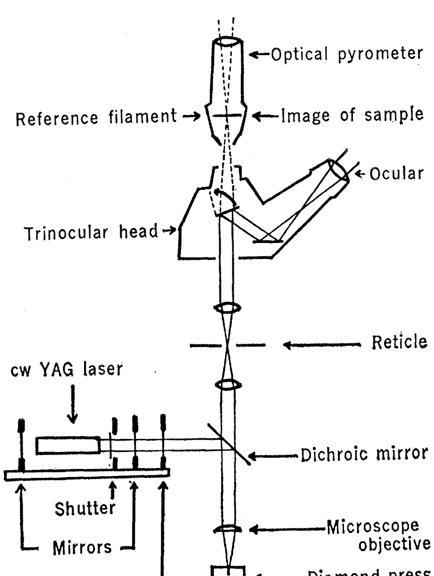

Fig. 1. An optical system for heating a sample under pressure in a diamond anvil press by means of a focused laser beam of a continuous-wave YAG laser. The brightness temperature is measured by an optical pyrometer when a sustained temperature is produced by the YAG laser.

Ringwood (*3*), Sclar and Carrison (*4*), Ringwood and Major (*5*), Akimoto and Fujisawa (*6*), and Kawai *et al.* (*7*) have shown experimentally that olivines [$(Mg,Fe)_2SiO_4$] transform to the spinel structure (γ-phase) in the pressure range from 50 to 150 kbar at 1000°C. In the composition range between $(Mg_{0.8}Fe_{0.2})_2SiO_4$ and Mg_2SiO_4, experimental results show that olivines pass through an intermediate phase, the β-phase, before transforming to the γ-phase (*8*). Shock wave experiments (*9*) have been interpreted by a number of investigators (*10*) as indicating that olivines undergo further transformations to denser phases having densities generally consistent with a mixture of close-packed oxides. Ringwood (*11*) has found that a number of olivine and spinel analogs undergo phase transformations to a variety of structures including the following: strontium plumbate, the K_2NiF_4 structure, rock salt plus ilmenite structures, rock salt plus perovskite structures, rock salt plus corundum structures, and rock salt plus rutile structures as first suggested by Birch (*2*).

Bassett and Takahashi (*12*) observed the disproportionation of Fe_2SiO_4 (spinel) to FeO plus SiO_2 (stishovite) by heating a sample that was under a pressure of approximately 250 kbar in a diamond anvil cell with a light beam from a pulsed ruby laser. Mao and Bell