Infrared Emission Spectra: Enhancement of Diagnostic Features by the Lunar Environment

Abstract. Information diagnostic of general rock type is available as a welldefined emission maximum (related to the Christiansen frequency), rather than as contrast-depleted minima, in the infrared spectra of particulate solids. The amount of spectral information varies directly with the sharpness of the thermal gradient at the sample surface. Lunar thermal conditions optimize this gradient, making the moon an excellent target for remote sensing.

The usual conclusion reached from feasibility studies (1) is that mid-infrared spectroscopy is of limited usefulness for remote compositional sensing of the moon. The basis of this conclusion is that the amount of spectral information in the emission minima, which result from fundamental stretching vibrations in silicates, decreases as a material becomes more finely divided until, for size ranges corresponding to those on the lunar surface, it is essentially lost.

Recently, Conel (2) pointed out the importance of scattering in silicates of small particle size (less than 100 μ) and showed that an emissivity maximum appears on the short-wavelength side of the commonly measured vibrational features. This maximum is associated with the minimum in scattering cross section that occurs at the so-called Christiansen frequency, which is located

where the refractive index of the sample is equal to that of the surrounding medium (1 for air or vacuum). Such maxima were not observed in previous studies (3) of emission spectra under simulated lunar conditions because of the limited wavelength range covered. Our studies of the emission spectra of particulate silicates under simulated lunar conditions show that the contrast of the maxima is greatly enhanced by these conditions.

To simulate the lunar thermal environment, we evacuated the sample to a pressure of less than 10^{-4} torr and surrounded its surface with a radiation shield which could be cooled to 77°K to simulate radiation from the lunar surface to cold space. The optically thick (5 mm) samples could be heated either from above by visible energy from a quartz iodine lamp, thus simu-

lating radiation from the sun in the lunar condition, or from below with a hot plate for comparison with spectra obtained by more conventional heating. Using a Cu/Ge detector cooled to liquid helium temperature, and a 118°C blackbody against which the emitted energy was referenced at 100 hz, we recorded emission spectra between 6 and 11 μ (signal-to-noise ratio > 100:1) with a circular variable-filter spectrometer. The heating energy was adjusted in all cases so that the energy detected from the sample at the wavelength of peak emissivity was equal to that from the reference blackbody. The data are presented in the form of effective emissivity spectra. These were obtained by dividing the emission spectrum of each sample by the reference blackbody profile.

The effective emissivity spectra shown in Fig. 1 for samples of the same material (gabbro) of different particle size demonstrate the increasing importance of scattering effects as the particle size becomes smaller. In the two samples of large particle size (250 to 1200 μ and 74 to 250 μ) the features consist of minima which become less well defined for the smaller particle size, in agreement with the commonly quoted maxim that spectral contrast is lost in





Fig. 1 (above left). Effective emissivity spectra of gabbro samples of different particle size. All spectra were recorded under low-pressure, high-temperature conditions. Fig. 2 (above right). (A) Effective emissivity spectra of a sample of hornblende (particle size, 0 to 37μ) recorded under different experimental conditions. (B) Transmission spectrum of a thin film of hornblende (0 to 37μ) supported on a potassium bromide disk of the same sample recorded on an infrared spectrophotometer

(Perkin-Elmer model 521). Fig. 3 (below left). Effective emissivity spectra of samples of different materials of the same particle size (0 to 74 μ) recorded under the same experimental conditions. All spectra were recorded under low-pressure, high-temperature conditions.

the reststrahlen frequency region with decreasing particle size. Not only is detail lost in the minimum, but also there is an increase in the departure of the minimum from unity. This result is in agreement with that of Goetz (3). For the two samples of small particle size (0 to 74 μ and 0 to 5 μ), where scattering is important, a welldefined maximum appears and its spectral contrast increases with decreasing particle size.

Figure 2A shows the effective emissivity spectra of a hornblende sample recorded under three different experimental conditions which alter the energy distribution within the sample. The spectral contrast of the emissivity maximum is increased as the pressure is decreased or as the temperature of the radiation shield is lowered.

In these samples thermal conductivity at high (atmospheric) pressure is dominated by heat conduction through whatever gas separates the particles, but this form of heat transfer is precluded in our low-pressure experiments, where evacuation lowers the conductivity by an order of magnitude (4). In this latter case the dominant mechanism becomes radiative transfer. Then radiation to a cold background is so efficient in cooling the surface layers that a sharp thermal gradient can be established very near the surface, despite the fact that the sample is heated through this surface by visible radiation from the lamp (sun). This will be true whenever the average optical depth is greater over the wavelength range of radiative heating (visible to near-infrared) than it is for radiative cooling at longer wavelengths.

The magnitude of the temperature gradient is determined by (i) the heating profile; (ii) the radiative cooling efficiency, which is related to the probability of photon escape through the surface as a function of depth at all wavelengths; and (iii) the difference in temperature between the bulk sample and the background to which the sample radiates. The greater this temperature difference, the sharper is the gradient established in any sample for a given pressure.

For a well-defined maximum to appear in an emission spectrum, the thermal gradient must occur on the same depth scale as the optical depths of the photons in the envelope of the maximum. In such a case, variations in optical depth with wavelength (demonstrated by the transmission spectrum) will map the extent to which energy

can escape from the deeper, hotter regions of the sample. The correlation between the transmission and emissivity spectra shown in Fig. 2 is consistent with this explanation, as is the change in spectral contrast of the three emissivity spectra. As can be seen, the spectral contrast is greatest for those experimental conditions which produce the sharpest thermal gradient at the surface of the sample.

This explanation is highly oversimplified but a more rigorous treatment involving radiative transfer mechanisms and consideration of exactly how the photon concentration profiles are generated leads to the same general conclusion. The important point here is that, the more closely the lunar thermal conditions are simulated, the greater is the spectral contrast of the emissivity maximum.

Figure 3 shows the emissivity spectra recorded under the same experimental conditions of several materials having the same grain size but different composition. It is apparent that the position of the emissivity maximum is as diagnostic of composition as the reststrahlen features in reflection spectra. Moreover, the departure of the emissivity minimum from unity is widely variable, with the general trend being that the more acidic materials with higher albedos display greater departures than

the more basic samples with lower albedos. Artificial alteration of the albedo of the gabbro sample by the addition of up to 50 percent ilmenite gives rise to a loss of contrast, but the characteristic emissivity maximum is not shifted.

From these preliminary results we conclude that both the thermal environment and the surface texture make the moon, and probably Mercury, unusually suitable targets for compositional remote sensing by mid-infrared spectroscopic techniques. A fuller report of the work discussed here will be presented elsewhere (5). It appears that the technique can be used to define general rock type.

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Orthopyroxene-Plagioclase Fragments in the Lunar Soil from Apollo 12

Abstract. Rock fragments consisting of orthopyroxene-calcic plagioclase assemblages appear to be more common in Apollo 12 soil samples than in the breccias or soil from Apollo 11 and are mineralogically and chemically different from any of the crystalline rocks returned by either Apollo 11 or Apollo 12. Compositionally, these fragments are orthopyroxenites and feldspathic orthopyroxenites. They are probably not fragments of meteorites; other considerations point to a near-surface lunar origin.

Several lithic fragments consisiting of orthopyroxene, (Mg,Fe)SiO₃, and calcic plagioclase have been identified in a small amount (30 mg) of the Apollo 12 lunar soil, sample No. 12070,61. No equivalent rock type has been found in any of the Apollo 11 crystalline rocks nor apparently in any of the Apollo 12 rocks, as judged from preliminary reports of the Lunar Sample Preliminary Examination Team (1).

Clinopyroxene, (Ca,Mg,Fe)SiO₃, is a major constituent in the Apollo 11 soil and in all of the Apollo 11 rocks. It appears that orthopyroxene, with only

minor Ca, occurs in trace amounts in the soil and breccia samples, since it was reported by relatively few investigators. Albee et al. (2) found a fragment in the soil, which they designated Luny Rock 1, to consist of orthopyroxene, isotropic plagioclase, "K-feldspar," ilmenite, troilite, apatite, whitlockite, and a rare-earth calcium phosphate mineral. Douglas et al. (3) reported plagioclase-orthopyroxene fragments in several breccias; Keil et al. (4) found the assemblage maskelynite, clinopyroxene, and orthopyroxene in a breccia; and Arrhenius et al. (5) reported that