

SPECTROSCOPIC REMOTE SENSING OF LUNAR SURFACE COMPOSITION*

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(Received 23 December, 1971)

Abstract. The various regions of the electromagnetic spectrum currently being used to determine the composition of the lunar surface remotely are reviewed. The advantages and disadvantages of using each region are pointed out, and limits are set on the kind and amount of information that can be obtained. It is concluded that it would be most useful to apply all of these techniques to the problem of remotely exploring the Moon because of the complementary nature of the data obtained.

1. Introduction

As the decade of direct exploration of the Moon draws to a close with the end of the Apollo program, the importance of developing indirect exploration methods increases. Such 'remote sensing' techniques, as they are usually referred to, will not provide the same wealth of information as that obtained from Surveyor and Apollo experiments. They do offer, however, an advantage that makes the use of them highly desirable at this stage in lunar exploration. That is, they can be used to explore the entire surface of the Moon; something that could never be done by even the most ambitious Apollo program. The spectroscopic remote sensing techniques to which I refer here can be used to map surface composition, with their primary objectives the determination of compositional heterogeneity, and the identification of anomalous areas deserving of closer study.

It is the purpose of this paper to review the various wavelength regions used to determine composition remotely, to point out the advantages and disadvantages of each region, and to set some reasonable limits on the kind and amount of information that can be obtained. Primary emphasis will be placed on the mid-infrared region of the spectrum, both because it is less well-known than the others, and because it is the area in which I have done my own research.

2. Gamma- and X-Radiation

Gamma- and X-radiation are considered together here for two reasons. First, experiments in the two wavelength regions were proposed and are being flown together as being complementary. Second, both wavelength regions yield information on the chemistry of surface materials, rather than on their phase, or rock type.

* Paper presented to the NATO Advanced Study Institute on Lunar Studies, Patras, Greece, September 1971.

Observations. While it is clear that characteristic atomic and nuclear lines will be important components of gamma- and X-ray emission from the lunar surface materials, and should unambiguously indicate the presence of certain elements, very few observations have been made in this region of the spectrum. The reason for this is found in the low flux of characterizing information, which necessitates a close approach to the Moon.

The first attempt to observe lunar gamma rays was made with Ranger 3 (Arnold *et al.*, 1962), but the spacecraft did not come sufficiently close to the Moon to detect the lunar flux. However, the experiment did reveal a diffuse cosmic ray background, which is an important factor in this experiment. A similar result was obtained with Ranger 5.

The first successful detection of lunar gamma rays was reported by the Russians (Vinogradov *et al.*, 1968), who used Luna 10 to record gamma-ray spectra of different areas on the lunar surface. Because the spectra were dominated by the cosmic ray background, no spectral differences were detected among different areas. A difference in total flux was detected, however, between the maria and highlands, and Vinogradov *et al.* (1968) concluded that the maria were basaltic while the highlands were ultrabasic.

During this same time period early attempts to detect lunar X-ray emission yielded only the serendipitous discovery of galactic X-ray sources in 1962. The successful detection of lunar X-ray emission from Luna 12 was finally reported by Mandel'shtam *et al.* (1968), but no effort was made to analyze these data in terms of surface composition.

At the time of this writing both gamma- and X-ray experiments have been successfully flown on Apollo 15, but, results have not yet been published. The experimenters report, however, that the X-ray experiment has detected definite differences in Si and Al content of the surface materials between the highlands and maria (Gorenstein, private communication).

Laboratory studies. Some idea of the kind and amount of information that may have been obtained by the Apollo 15 experiments can be gotten from the laboratory and theoretical studies that have been done in support of these experiments. The brief summary given here is taken entirely from Gorenstein and Gursky (1970), to whom the reader is referred for additional information.

The two principal sources of gamma-radiation on the lunar surface are naturally occurring radioactive nuclides and cosmic-ray interactions with the surface material.

Natural gamma-radiation arises from radioactive nuclides whose half-lives are comparable to the age of the planetary system. Principal sources are K^{40} , U^{238} and Th^{238} , plus their shorter-lived decay products. Lesser contributions may come from the rare earth nuclides, La^{138} and Lu^{176} .

Cosmic-ray interactions which produce gamma-rays are exceedingly complex. However, there is only one feature of the interaction that is of direct concern for compositional remote sensing, which is the production of discrete gamma-rays from the decay of excited nuclides. Gorenstein and Gursky (1970) have concluded that, in the absence of solar proton events, the production of lines in the gamma-ray spectra

is dominated by neutron processes – i.e. capture, activation, and inelastic scattering and reactions that leave a residual excited nucleus. Based upon this conclusion and several not very restrictive assumptions, they have calculated the line spectra to be expected from different rock types (Figure 1). The gamma-ray continuum has been omitted from Figure 1. It is of considerable magnitude, and is the background which determines the sensitivity with which the experiment can detect discrete lines in the spectra.

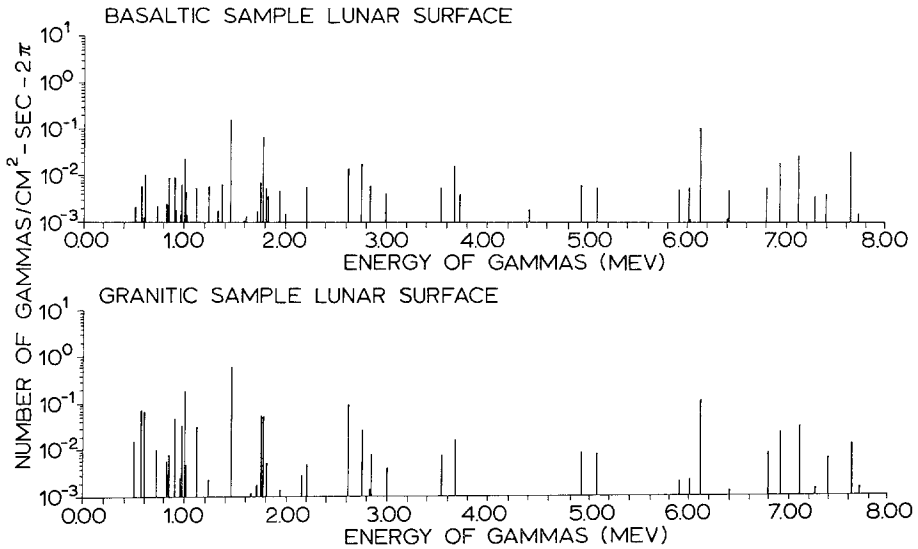


Fig. 1. Gamma-ray line spectra calculated for different rock types by Gorenstein and Gursky (1970). The gamma-ray continuum has been omitted.

Several mechanisms have been suggested that may be capable of inducing characteristic X-ray emission from the lunar surface. These are: (a) natural radioactivity in the surface material; (b) cosmic-ray bombardment; (c) ionization by locally trapped particles; (d) interaction with the solar wind; (e) fluorescence induced by cosmic X-rays, and (f) fluorescence induced by solar X-rays. Gorenstein and Gursky (1970) conclude that solar X-ray induced fluorescence is the most important mechanism for producing characteristic X-ray emission from the lunar surface.

Solar X-ray emission originates partially in the corona, but the most important contribution, particularly at short wavelengths, comes from localized active regions and flares. Consequently, the total solar X-ray flux and the wavelength distribution of its energy are highly variable on a time scale of minutes to hours. This, in turn, results in a variable flux from the same surface at different times. In addition, solar emission lines occur at wavelengths not far removed from the fluorescence emission of abundant elements in the surface material, leading to some difficulty in resolving fluorescence lines when scattered solar radiation is also present. For these reasons, it is important to know the solar X-ray flux in almost as much detail as the lunar flux itself.

Again, Gorenstein and Gursky (1970) have computed X-ray spectra to be expected from various rock types (Figure 2). These spectra show the fluorescence line emission from elements together with the scattered solar continuum, but the line components of the solar spectrum have been excluded for purposes of clarity.

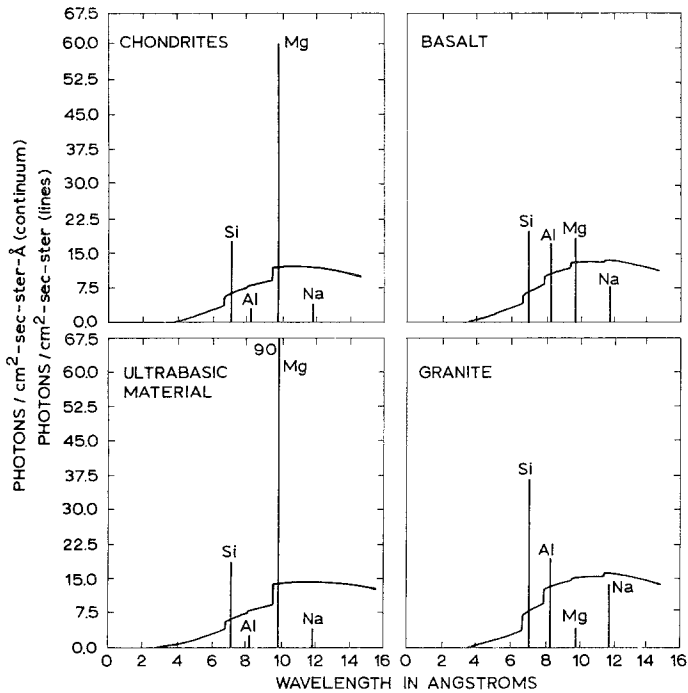


Fig. 2. X-ray line spectra, together with the solar continuum, calculated for different rock types by Gorenstein and Gursky (1970). Line components of the solar spectrum have been excluded for purposes of clarity.

In principle, gamma-ray observations of the decay of natural radioactive nuclides allow detection of the presence of K, Th and U, plus H, C, O, Si, Al and Fe from cosmic-ray induced effects. X-ray measurements are sensitive to Mg, Al, Si, K, Ca and Fe. The geologist is, however, often more interested in rock type (phase) than he is in surface chemistry. In general, rock types differ in their abundance of certain elements. Gorenstein and Gursky (1970) have pointed out, for example, that aluminum is a major constituent in acidic, intermediate and basic rocks, but is much less abundant in ultrabasic rocks and chondrites. Calcium is much more abundant in basic rocks than in acidic and ultrabasic types. The amount of radioactive elements and silicon increases progressively from ultrabasic to acidic, while the reverse trend occurs for magnesium and iron. In particular, they point out that the magnesium/potassium ratio is about 370, 12 and 0.3 for the average ultrabasic, basic and acidic rock respectively, and, hence, is a very sensitive index for classifying rocks. As has been pointed out elsewhere (Salisbury *et al.*, 1970), however, it is deceptive to work with *average*

composition. When the compositional variability of *individual rocks* making up a given rock type is considered, significant scatter in elemental abundance is found to be the rule, except for an extreme rock type such as granite. This fact is best illustrated, perhaps, by the Russian conclusion that the highlands must be more basic than the maria, which is not supported by any evidence other than their natural radioactivity level. Consequently, the conversion of chemical information into phase information is not a simple matter.

Limitations of the techniques. Both the gamma- and X-ray remote sensing techniques have certain disadvantages or limitations. (1) Both have continuum background problems which limit the sensitivity of measurement. (2) As part of this problem, both have low fluxes of characterizing radiation from the surface, which results in very low spatial resolution on the lunar surface (nominal spot size for the X-ray experiment is 112×960 km). (3) Again, as part of this problem both require a close approach to the target surface, and consequently are not as 'remote' as the other remote sensing experiments discussed here. (4) Both experiments have special problems, whether from background radiation or from assumptions that must be made in order to deconvolve the data, that make it difficult to determine *absolute* elemental abundances. (5) Finally, as discussed above, both yield chemical information, which can be converted to rock type only with some uncertainty.

On the other hand, both experiments have decided advantages. (1) They are sensitive to certain elements, such as the radioactive nuclides, which are important for a geological understanding of planetary evolution. (2) Within the limits of their spatial resolution, they can detect inhomogeneities in composition on the lunar surface, which is more important than determining absolute abundances.

3. Visible and Near-Infrared Radiation

Visible and near-infrared regions of the spectrum are considered together in this third section because they provide the same kind of information. That is, information on electronic transition phenomena which may take place within minerals in the surface layer.

Observations. Because the Earth's atmosphere is relatively transparent in the visible and near-infrared, and the illuminated moon is a powerful source in these regions, visible and near-infrared spectra of the Moon have been available for some time. Some of the best observational work has been done by McCord and Johnson (1970), who found that many lunar areas, such as Mare Serenitatis, displayed an absorption band near 0.9μ (see Figure 3). They use the spectrum of a standard reference for comparison with spectra of other lunar areas. Figure 4 shows that the spectra of most of these areas display the band near 0.95μ , but may differ in the strength of this band, in the overall slope of their respective spectral curves, and in the presence or absence of a possible upturn of the curve beyond 2.3μ . Thus, spectra of the lunar surface displays absorption bands in this region, and these bands differ in the spectra from different areas on the surface.

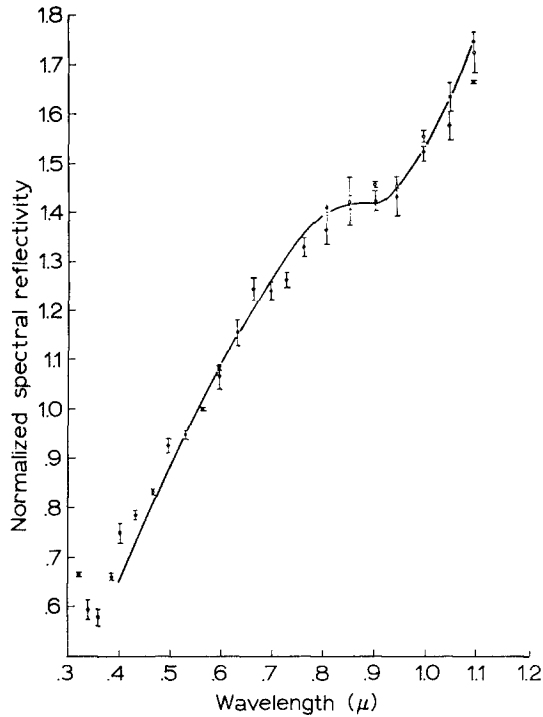


Fig. 3. Reflection spectrum of a region in Mare Serenitatis. From McCord and Johnson (1970).

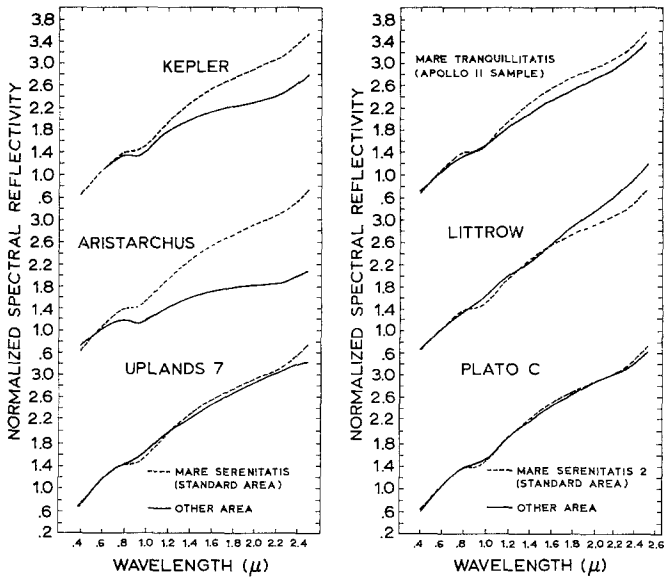


Fig. 4. Spectra of different areas on the Moon showing the limits of variability in their reflection spectra as compared to a region in Mare Serenitatis (dashed curve in each case). From McCord and Johnson (1970).

Laboratory studies. Early laboratory studies, such as those of Adams and Filice (1967), showed that the spectra of some common rockforming minerals displayed strong absorption bands between 0.8 and 2.0 μ . The bands were most commonly due to the iron ion, and consequently were usually displayed by basic rocks (see Figure 5). Adams and Filice demonstrated that by using these bands, the red/blue ratio in the visible, and the maximum visible reflectance of a particulate rock, it was possible to make the distinction among basic-ultrabasic rock, crystalline acidic rock, and rock

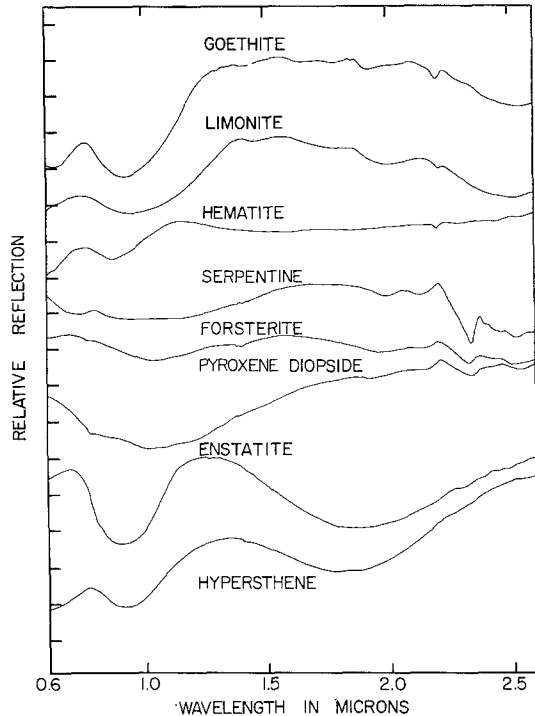


Fig. 5. Spectra of particulate samples of different iron-bearing minerals. Note that the iron band is so strong that it is still displayed by minerals (forsterite, diopside) containing less than one percent iron by weight. From Salisbury and Hunt (1971).

glass. Using this approach, Adams (1968) studied lunar spectra which, although poorly defined at that time, appeared to display a weak band near 1 μ . He concluded that the lunar surface layer was basaltic, containing some orthopyroxene in addition to olivine or clinopyroxene, or both. Hapke (1968) also concluded that the surface material was basaltic, based upon both spectral and polarimetric behavior of the surface.

Recent studies of returned lunar samples have confirmed these conclusions (eg. Adams and McCord, 1970; O'Leary and Briggs, 1970). This success has led Adams and McCord (1970) to state that electronic transition bands can be used for identi-

fication of minerals that exhibit bands. The implication is that it is possible to do remote sensing of surface mineralogy. It must be remembered, however, that most common rock-forming minerals do not display well-resolved electronic transition bands, that mixtures of minerals displaying bands may yield a composite spectrum that is ambiguous in terms of mineralogy, that some bands become difficult or impossible to detect as the particle size becomes small or when opaque minerals are plentiful, and that some bands are not diagnostic of a single mineral (for example the band at 1.0μ). Consequently, the original claim of Adams and Filice (1967) for the utility of this wavelength region appears to be most realistic at this point in time – i.e. the distinction among general rock types can be made if the particle size can be estimated. Laboratory work now in progress may further extend the usefulness of the technique (Adams, private communication).

Limitations of the technique. Electronic transition spectra in the visible and near-infrared have certain advantages and disadvantages for remote sensing of composition. The difficulties inherent in the technique are: (1) It does not yield direct information on bulk composition or rock type. This must be inferred from the presence (or absence) of electronic transition bands displayed by one or two minerals making up the rock. (2) This inference may be complicated by the ambiguities discussed in the previous section, caused by the presence of more than one band-displaying mineral, by the loss of spectral contrast due to particle size or opaque mineral effects, or by the presence of a non-diagnostic band.

On the other hand: (1) This region of the spectrum yielded early results which correctly characterized the general rock type prevalent on the surface. (2) Absorption bands change from place to place on the surface, giving good evidence for some heterogeneity, which can be mapped in this way. (3) Observations can be made from the surface of the Earth. (4) This technique offers the highest spatial resolution of any of the remote sensing techniques studied here. (5) This technique is the only one which may identify the presence of specific minerals in the soil.

4. Mid-Infrared Radiation

The mid-infrared region of the spectrum differs from those regions already considered because mid-infrared spectral features are directly related to bulk mineralogical composition, or rock type. This is because features which occur in mid-infrared spectra are caused by vibrations within the basic repeating units of the material. The number and location of the bands depends directly on molecular structure and, hence, on bulk composition. Infrared spectroscopy has been used for a very long time in inorganic chemistry to identify unknown compounds, and extension of this technique to remote sensing of the composition of inorganic surface materials would appear to be a natural step.

Observations. Dr Graham Hunt and I first attempted to detect differences in the infrared emission spectra of different areas on the lunar surface in 1964 (Hunt and Salisbury, 1964). We did detect differences in the $16\text{--}24 \mu$ region between the emission

from different areas, and concluded that infrared spectroscopy would be useful as a remote sensing tool. Subsequently, Murcay (1965) made an observation which showed that the Moon did not radiate as a black body, but deviated quite markedly from black body behavior. These results were very much in conflict with the common belief at that time, which is still strong today, that the Moon is a black body source in the infrared, without spectral features of any significance. Very careful work by Goetz (1968) did not resolve the conflict, because he found two areas that definitely differed in emissivity from their surroundings, but many more that did not.

It seemed to us that the main source of confusion was probably the atmosphere, which is an unknown wavelength-dependent attenuator, which, unfortunately, is also time-variable. Consequently, we developed a balloon-borne telescope system with which we engaged in a cooperative effort with a group led by Dr David Murcay at the University of Denver to make a better measurement of lunar infrared emissivity. Observations with a 24-in. aperture balloon-borne telescope at a float altitude of 31.5 km were undisturbed by the principal infrared attenuator in the atmosphere, water vapor. Figure 6 shows typical spectra obtained in this way by Murcay *et al.* (1970). They display a peak near 8μ , with a fall-off in emissivity of approximately 10 to 15% to longer and shorter wavelengths respectively. The strong band at 9.6 microns is due to residual absorption by ozone in the atmosphere.

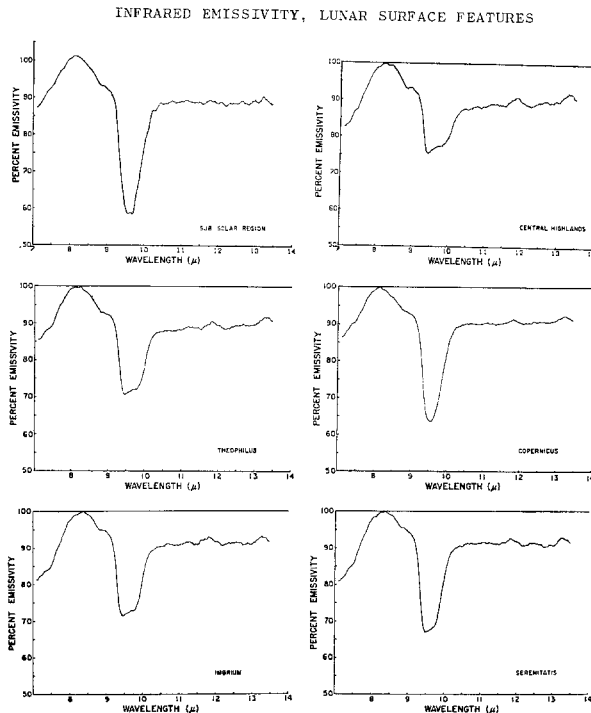


Fig. 6. The spectral emissivity of six different regions on the Moon obtained with a balloon-borne telescope. The strong band near 9.6 microns is due to absorption by residual ozone in the atmosphere. From Murcay *et al.* (1970).

This result was surprising even to those who believed that spectral information was present in lunar infrared emission, because of the very large departure from black body behavior.

Laboratory studies. There was, to be sure, what appeared to be good laboratory evidence to show that the Moon should radiate approximately as a black body. Lyon (1963) and Van Tassel and Simon (1964) had shown that when mineral powders are heated in a furnace, the depth of the molecular vibration band (reststrahlen band) decreases as particle size decreases (see Figure 7). It became common knowledge that characterizing spectral information was lost as a mineral or rock was ground to a fine powder.

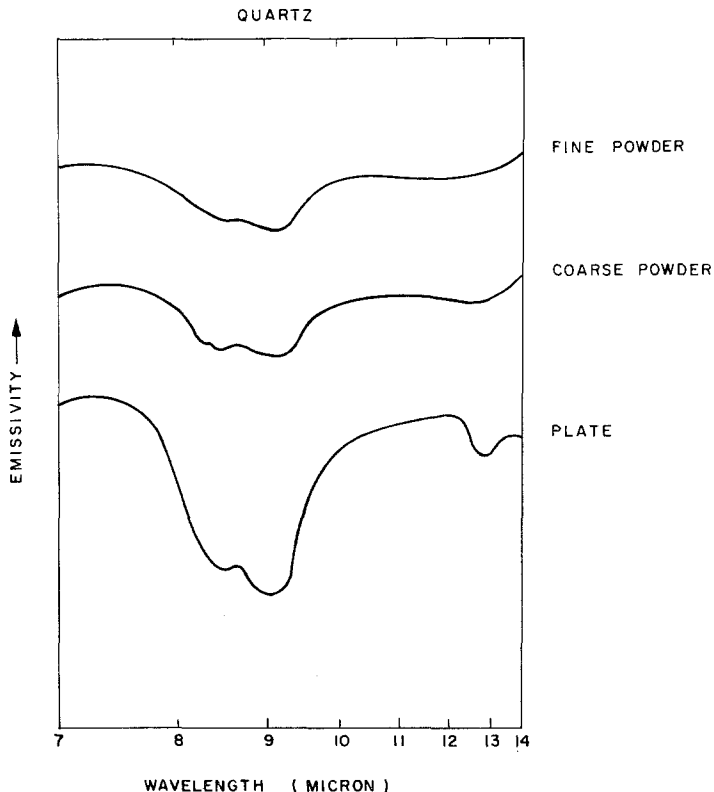


Fig. 7. Emission spectra of a quartz plate, coarse powder and fine powder illustrating the decrease in spectral contrast of the reststrahlen band as particle size is decreased. Adapted from Van Tassel and Simon (1964).

However, later laboratory work by Conel (1969) showed that this was not entirely true. He showed that as the average particle size of a powdered mineral becomes less than about 10μ a peak appears in its emission just shortward of the contrast-depleted reststrahlen band. As illustrated in Figure 8, this peak in emission is related to a peak in transmission of the powder, which is called the Christiansen frequency. This peak in transmission results because the refractive index approaches that of the surrounding

medium (in this case 1) due to anomalous dispersion, while the absorption coefficient is still low. Thus, radiation can pass relatively freely through the sample without scattering or absorption. In a fine powder sample, where scattering is important for the emitted radiation, a peak develops. Essentially, the long wavelength fall-off is due to absorption, and the short wavelength fall-off is due to scattering.

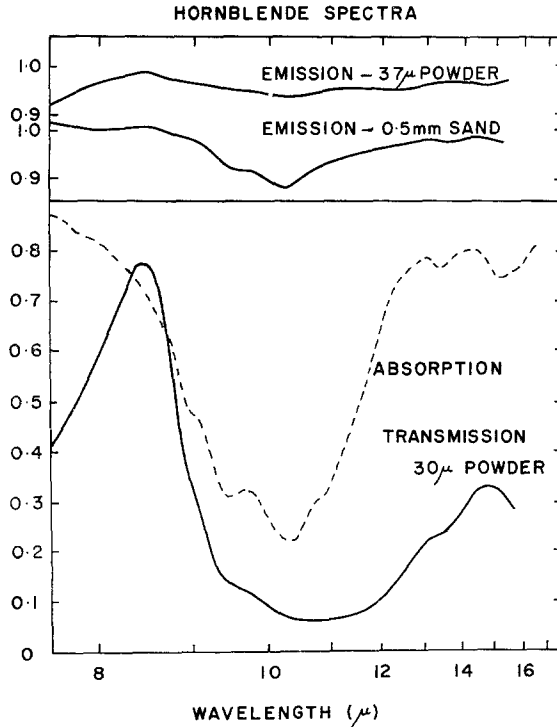


Fig. 8. Comparison of the absorption and transmission properties of powdered hornblende with the emissivity of coarse and fine particulate samples. This diagram shows that a fine particulate sample displays an emissivity peak which is associated with a peak in transmission at the so-called Christiansen frequency. Adapted from Conel (1969).

Although Conel found a peak in emission, it was only a 2 or 3% effect, and bore no resemblance to the 10 to 15% effect that was detected in lunar emission with the balloon-borne telescope system. Logan and Hunt (1970) found, however, that this was a result of his experimental conditions. As illustrated in Figure 9, a reduction in pressure and the application of a cold (simulated space) background to a sample heated by illumination introduced a marked change in its spectral behavior. It displayed a very strong peak associated with its transmission maximum due to the steep thermal gradient induced near the surface by these thermal conditions. Figure 10 shows that the position of this peak, like the position of the molecular vibration bands, is related to composition. The more basic the rock, the longer will be the wavelength at which the peak falls.

We have lately been examining all of the variables that can affect the position of the emissivity peak, such as particle size distribution, temperature distribution on the surface of the sample, phase angle, pressure and packing factor. We find that the peak position can be shifted significantly by changing environmental conditions, so

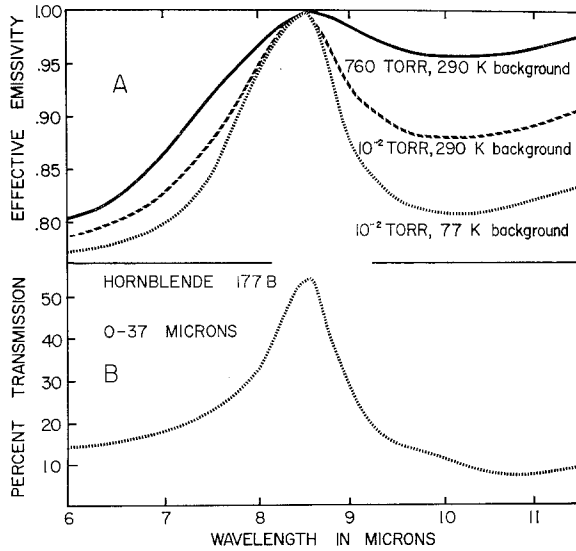


Fig. 9. Effect of reduced pressure and cold background on the spectral contrast of the emissivity peak displayed by the mineral hornblende. (B). Transmission peak measured for a thin powder film of the same mineral. From Logan and Hunt (1970).

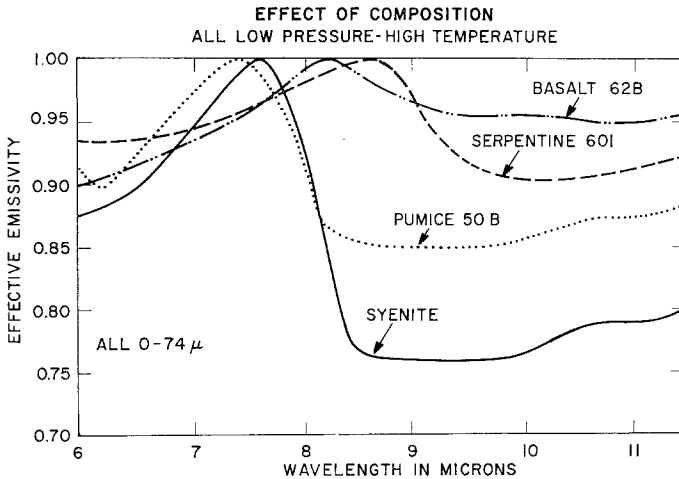


Fig. 10. Emission spectra of different rocks obtained at low pressure, but without a simulated cold space background. Basic rocks show less spectral contrast than do acidic, intermediate and ultrabasic rocks. All samples would show increased contrast if exposed to a cold background. From Logan and Hunt (1970).

that a rock identification diagram prepared for the Moon cannot be blindly applied to, for example, Mars. A lunar rock identification diagram is presented in Figure 11, showing the range in peak wavelength to be expected for different rock types in a lunar environment. This is a preliminary diagram, which does not include the full range of rock types currently under study, nor a second parameter, spectral contrast, which is useful in separating individual rock types (Logan *et al.*, in preparation). Because of our improved experimental techniques, Figure 11 differs from a similar table presented previously (Salisbury, 1970).

Because our laboratory studies have utilized terrestrial rocks, one must inquire whether or not lunar material will behave in the same way. Figure 12 shows the spectrum of Apollo 14 soil, which does indeed exhibit a well-defined peak at the expected (sub-silicic basalt) location. Thus, we can conclude that mid-infrared spectroscopy can be used as a valid remote sensing tool for the determination of rock type on the Moon. It may also be used on Mercury, Mars and the asteroids.

In this regard, it is interesting to examine briefly the conclusions that may already be drawn from lunar spectra published by Murcray *et al.* (1970). Comparison of Figures 6 and 11 indicates that the debris layer surrounding the craters Theophilus and Copernicus are basaltic in composition (emissivity peak near 8.1μ). The circular maria, Imbrium and Serenitatis, display peaks at considerably longer wavelengths (near 8.35μ), indicating that they are more basic than the material excavated by the presumed impact events which formed Copernicus and Theophilus. In fact, they lie to longer wavelengths than the peaks of any of the terrestrial basalts and gabbros that we have so far examined in the laboratory, but fall just short of the ultrabasic range. The Central Highlands yield a peak slightly below the preliminary limit of our terrestrial basic range. This peak (at 8.24μ) is identical with that displayed by the Apollo 14 soil, which is reasonable if both the Imbrian basin impact and the Central Highlands cratering events excavated a primeval lunar crust. A peak at this long a wavelength, however, indicates that the regolith in the highlands is not anorthositic (if by 'anorthositic' we mean that it is composed almost entirely of calcic plagioclase). On the contrary, abundant pyroxene and/or olivine must be present, as in the Apollo 14 soil. Consequently, we conclude from these observations that the lunar crust is gabbroic, rather than anorthositic, to the extent that the regolith in the lunar highlands is representative of crustal composition. The debris layers surrounding Copernicus and Theophilus, on the other hand, display peaks that fall just within the anorthositic range.

Limitations of the technique. Use of mid-infrared spectroscopic remote sensing has several drawbacks: (1) Information is provided on phase (rock type), but not on chemistry, and a given rock type may encompass quite a range in chemistry. (2) Observations must be made above at least most of the Earth's atmosphere in order to provide good data.

On the other hand, (1) one need not mount an orbital experiment to obtain the data, so that its cost may be fairly low, especially if an existing vehicle such as the Ames airplane were used as an observing platform. (2) Its spatial resolution can be

relatively high (on the order of 10 km from the distance of the Earth), which is a much more geologically interesting spot size than can be obtained with the gamma- and X-ray techniques, though not as small a spot size as can be obtained in the visible and near-infrared. (3) The technique has already proved successful in delineating compositional differences on the lunar surface.

5. Conclusions

A large range of the electromagnetic spectrum can be used to remotely determine something about the composition of the lunar surface layer. The gamma- and X-ray regions provide information on elemental abundance; the visible and near-infrared regions may yield information on electronic transition bands in one or more minerals, from which in turn may be inferred general rock type; and the mid-infrared region provides molecular vibration information that characterizes the rock type present on the surface. Use of each region of the spectrum has its advantages and disadvantages. It appears that it would be most useful to apply all of these techniques to the problem of remotely exploring the Moon.

Acknowledgements

Key laboratory studies which explained the large departure of lunar infrared emission from black body behavior were performed by my colleagues, Dr Logan and Dr Hunt. Without their work, the midinfrared region of the spectrum would rate only a puzzled footnote in this review. Helpful suggestions have been made for improving this paper by Dr Hunt, Dr John Adams and Dr Paul Gorenstein.

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