INFRARED COLORIMETRY OF THE MOON

by

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I hereby recommend that this dissertation prepared under my direction by Dale P. Cruikshank entitled Infrared Colorimetry of the Moon be accepted as fulfilling the dissertation requirement of the degree of Doctor of Philosophy.

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ABSTRACT

For the purpose of studying the effects of the solar wind flux on the infrared reflectivity properties of rocks and minerals on the moon, a laboratory apparatus was constructed for irradiation of rock samples with a proton flux having the same energy as the ambient solar wind, but with $10^7$ to $10^8$ times the flux density. The design and development of the equipment are described. Several volcanic rocks were irradiated with this apparatus and the infrared colorimetric profiles in the wavelength range 0.8 µ to 2.2 µ were measured for the natural and irradiated samples. Irradiated rocks became redder, and absorption bands attributed to Fe$^{3+}$ were transformed into Fe$^{2+}$ bands. The relationship of the visual darkening of the rocks on irradiation and the changes in iron absorption bands are discussed relative to the lunar surface. The problem of oil contamination in the proton system is discussed and it is concluded that in the present experiment, the observed changes in rock samples result mostly from sputtering of sample materials and from reduction of the oxidation state of metal atoms by the action of the protons.

Colorimetric observations of small spots (diameter 7 km) on the moon were made in the spectral region 0.8 to 2.2 µ in an attempt to discern differences from one lunar region to another that would give information on the composition of the surface of the moon. Approximately one hundred such areas were observed, including crater floors,
rays, and mare units having definite geological classifications in the U.S. Geological Survey system of stratigraphic nomenclature. Large differences were found among lunar regions. The floors of Aristarchus and Kepler as well as the dense rays from these craters show definite colorimetric properties indicating the presence of orthopyroxene minerals such as enstatite. Other craters resembling Kepler and Aristarchus morphologically have very different color profiles which are less definitive in interpretation. Color differences seen in the visual spectrum on the floor of Mare Imbrium and Sinus Iridum do not extend into the infrared. Many regions considered covered with ejecta have color profiles like the dark mare regions nearby. These regions show a spectral band which correlates with a band in the spectrum of olivine family minerals. There are approximately six types of colorimetric curves into which most of the points measured fall. It is suggested that those features (Aristarchus and Kepler) showing the spectral properties of orthopyroxenes may have formed from impacts of enstatite or other orthopyroxene chondritic meteorites and that the rays have the same composition as the crater floors.

A major absorption band in the spectra of several lunar features, but which has no known laboratory counterpart, is found at 1.6 μ.

There is no direct correlation of color profile type with the albedo or topographic expression of the features studied, except for Aristarchus and Kepler. Infrared colorimetry can be used for rough classification of the Imun units in those maria where different units
occur. It is also shown that lunar features of a wide variety of classifications in the U. S. Geological Survey system of stratigraphic nomenclature can have strikingly similar color profiles, and vice versa.

It is concluded that a spacecraft orbiting the moon with an infrared sensing device working in this spectral region could provide information on the gross mineralogy of the lunar surface.
CHAPTER I
INTRODUCTION

Direct information on the composition of the lunar surface exists for only three positions on the moon; the landing sites of Surveyors V, VI, and VII. This general condition will prevail even after the first and several succeeding manned lunar landings in the 1970's because of the great difficulty and expense of going to the moon and moving about on its surface. For this reason, it is highly desirable to establish techniques for remote determination of mineralogic or chemical composition of different regions of the lunar surface from earth-based instruments and/or vehicles orbiting either the earth or the moon. A remote sensing technique must measure properties of lunar surface areas that will permit the determination of the composition of those areas, and must give high areal resolution on the moon so that regions small enough to have morphological and compositional integrity can be studied. Further, the technique must be rapid enough to permit the study of a large number of individual areas on the moon, or better, the entire moon. The technique must also be capable of laboratory application so that samples can be studied on earth to remove ambiguity of the interpretation of the lunar data.

This dissertation describes work with a technique of infrared reflectivity studies of small spots (diameter 7 km) on the moon observed with a large ground-based telescope and conventional astronomical instrumentation. Laboratory studies, both those referenced in
the literature and those performed as part of this research, are used for geologic interpretation of the lunar results. The results of this work stand as a first step toward remotely sensed data having a direct and significant relationship to the composition of different regions on the moon.
CHAPTER II
DEFINITIONS AND BASIC CONCEPTS

Reflection

Light is reflected from a body in ways which are characteristic of the structure and composition of the surface of that body. Diffuse or orthotropic reflection occurs when light strikes a surface that scatters equally in all directions, independent of the incidence angle. Perfect diffusely-reflecting surfaces are rare, but Romanova (1964) has noted that the surfaces of blown sand dunes are approximately diffuse reflectors. Orthotropic diffuse reflection can be contrasted with specular reflection which occurs when light falls on a polished surface having only irregularities small compared with the wavelength of the light. If we define an indicatrix of reflection as the total reflected energy (in some arbitrary units) in some direction, and then plot the envelope of these indicatrices for all directions, we have the indicatrix of diffusion. For a perfect (or orthotropic) diffuse reflector, the envelope describing the indicatrix of diffusion is a hemisphere with the reflector at the center; while specular reflectors have an indicatrix of diffusion with a pronounced spike coplanar with and at an angle, relative to the reflector, equal to the angle of incidence of the light.

Between the extremes of diffuse and specular reflection are metallic and glasslike reflections which differ according to the absorption properties of the reflecting surface. Most objects in
nature are mixed reflectors, combining certain aspects of several types of reflections in their indicatrices of diffusion. Attempts to identify geological substances from the diffusion indicatrices are described in Romanova (1964).

Albedo and Luminance

The ratio of the total flux reflected in all directions by a surface to the total incident flux, is defined as the Bond albedo of the surface, and is discussed below. Geometric albedo of the moon is computed from the following formulas:

\[
\log (\text{geometric albedo}) = 0.4 \left[ m(\text{sun}) - m(1,0) \right] - 2 \log \left( \frac{R}{R_e} \sin 8^\circ.79 \right)
\]

Here, \( \frac{R}{R_e} \) is the ratio of the moon's mean radius to the earth's mean radius and has the value 0.273, \( m(\text{sun}) \) is the magnitude of the sun, \( m(1,0) \) is the magnitude of the moon at unit distance from the sun and earth, and 8°.79 is the solar parallax. Thus, the formula becomes

\[
\log (\text{geometric albedo}) = 0.4 \left[ m(\text{sun}) - m(- m(1,0)) \right] + 9.869.
\]

The geometric albedo is related to the Bond albedo by the following:

\[
\text{Bond albedo} = (\text{geometric albedo}) \cdot (\text{phase integral}).
\]

The phase integral is determined by measuring the brightness of a planet through a full range of phase angles \( \alpha \). It is defined by

\[
(\text{phase integral}) = \int_0^{\pi} I(\alpha) \sin \alpha d\alpha.
\]

The phase angle \( \alpha \) is the angle between the light source (sun) and the observer (earth) as seen from the planet (moon).

The practical difficulties of measuring the reflected flux in all directions make it useful to define another parameter. If we measure
the flux from a surface at some angle $\varphi$ to the normal to the surface we have measured the surface luminance, $B_\varphi$. When the incident flux on the surface is $I$, $a$ is the area from which the reflection occurs, and $d\Omega$ is the solid angle through which the reflected flux is measured, then we have

$$B_\varphi = \frac{dI}{a \cos \varphi}$$

where $dI$ is the fraction of the flux reflected from area $a$. The nomenclature is illustrated in Figure 1 in which the incident flux strikes the reflecting surface at an angle $k$.

The spectral luminance is defined as the surface luminance at a particular wavelength, $\lambda$, and may be denoted $B_\lambda$.

Romanova (1964) has measured the spectral luminances of many geological substances and has compared them with barite paper which she finds to approximate an orthotropic diffuse reflector. When spectral luminance is plotted relative to the wavelength, a quantitative graph of the color of the surface is obtained. The color curves of the moon and terrestrial rocks given in this paper are related to these plots of spectral luminance and wavelength, but with certain modifications made necessary by the quality and the character of the data and the instrument with which they were obtained.

**Colorimetry**

Colorimetry is the quantitative measurement of color of an object. The color is usually determined by making measurements of the radiant flux (either emissive or reflective, depending on the object) at two or more wavelengths. When measures at only two wavelengths are
Figure 1

Definition of incidence and reflection angles.
obtained, the difference or ratio of the measures is usually termed a color index or color excess. As the number of measures over a given wavelength interval increases, each being made at a different wavelength, the resulting plot of photometric intensity versus wavelength gains higher resolution. Colorimetry is one measurable parameter which allows us to distinguish among objects having otherwise similar outward appearance. It is for this reason that the present study has been undertaken for application to the case of the moon. If the wavelength spacing between two measures of the intensity near wavelength $\lambda$ is $\Delta \lambda$, then the resolution of the colorimetric curve (or spectrum) is $\lambda/\Delta \lambda$.

The relative spectral reflectivity is the spectral luminance at one wavelength compared with that at another.

Colorimetric studies of various celestial and terrestrial objects have been made for many years. The wavelength intervals for which the eye, photographic plates, and common photo-sensitive electronic detectors are sensitive were favored until recent years when the infrared spectrum became more easily accessible. Krinov (1947) collected colorimetric curves in the spectral range 4000 Å to 9000 Å for a wide variety of geologically interesting substances, and Romanova (1964) has studied sand deposits from airplanes, using equipment sensitive in the range 4000 Å to 6500 Å. Color excesses for terrestrial plants are given in Tikhov (1960). Spectral reflectivities for various terrain features are given by Penndorf (1956), again in visual wavelengths. A valuable summary of reflective colorimetry is given by Coulson (1966).
It should be noted that all of the references given above pertain to the color of the light reflected from an object. When we consider the spectral interval of wavelengths longer than about 2.5 microns (25000 Å), bodies at about 0° Centigrade begin to emit gray body radiation. Depending on the emissivity and temperature of the body, the thermal emission becomes dominant at wavelengths longer than about 3 or 4 microns. Recent studies in the emission spectrum of rocks are discussed in Lyon (1964, 1965).
CHAPTER III
COLORIMETRY OF THE MOON

Visual Light

Measurements of the color of the moon in light of visual wavelengths (0.36 - 0.70 μ) have been made since the invention of the photographic plate. A complete bibliography would be enormous; only the more modern and extensive studies will be referenced. The two most productive techniques have been photometric spectrophotometry and the photoelectric measurement of brightness with color filters.

Teyfel (1960a, 1960b) has published a catalog of color measurements of 262 small areas on the moon. He photographed the spectrum of several lunar surface strips and made microdensitometer tracings to find the color index (brightness ratio at λ= 0.55 and 0.44 μ) and the color excess in magnitudes defined as

$$ CE = -2.5 \left( \log \frac{I_{4400}}{I_{5500}} - \log \frac{I_{4400}}{I_{5500}} \right), $$

for each feature. The general results of Teyfel's study will be noted later.

Coyne (1963) studied sixteen areas by a similar technique. He defined a color contrast for two lunar regions, a and b, as

$$ CE_{a,b} (λ) = (m_\lambda - m_{5500})_a - (m_\lambda - m_{5500})_b. $$

In this equation, m corresponds to the stellar magnitude and 0.55 μ is a standard wavelength to which the observations are referred.
Coyne evaluated the color contrast for every 100 Å interval between 4380 and 6835 Å. Significant color contrasts were found, the maximum values lying between 0.15 and 0.20 stellar magnitudes.

More recently, Evsyukov (1967) has photographically measured a special color index for a large sampling of lunar features. For most of them, the differences from the average for the entire moon were found to be small. Some large differences were attributed to lunar luminescence.

The photoelectric technique was first used by Wilsing and Scheiner (1909, 1921), and later by Gehrels, Coffeen, and Owings (1964), Wildey and Pohn (1964), Coyne (1965), van den Bergh (1962), Roberts (1966), McCord (1968) and others. Of these investigators, van den Bergh, Coyne, Gehrels, and Wildey and Pohn standardized their observations to the UBV system of stellar photometry.

The photoelectric technique affords greater intrinsic accuracy than does photography; 0.1 - 0.5 percent versus 5 percent. These accuracies pertain to differential, not absolute measurements. The photographic technique does, however, make it possible to measure many lunar regions simultaneously, as done by Teyfel' (1960a, 1960b).

Photoelectric detectors have a sensitivity range not too different from the photographic plate. Some modern detectors can be used up to 1.2 μ, as can some photographic emulsions (Eastman type 2), but for measurements in the infrared, other detectors are required. The most common detector applied to astronomy is lead sulfide. The earliest applications to astronomy are discussed in Kuiper, Wilson, and Cashman (1947), and details of the manufacture, physics, and performance of
PbS detectors are given in Smith, Jones, and Chasmar (1957). Kuiper, et al. (1962) discussed the application of PbS detectors in a scanning stellar and planetary spectrometer.

Lead sulfide detectors are important because they cover the gap between, on the one hand, photographic plates and photoelectric detectors (about 1.2 μ, or more practically, 1.0 μ) and the onset of self-emission of the moon (about 2.8 μ). In this interval also, several gases have fundamental vibration-rotation bands and many more gases have their overtone bands. Kuiper, and more recently Moroz have been most active in obtaining planetary and stellar spectral in this spectral region. However, for the detection of spectral features of solid substances, this wavelength interval is of lesser interest because most lattice-vibration spectra occur beyond 3 μ. Lyon (1964, 1965) has investigated this region in the infrared in terms of compositional analysis of rocks on the earth and planets.

The spectral luminance of rocks in the PbS region is, however, a useful tool in differentiating among rock types, as was demonstrated by Romanova (1964), Krinov (1947), Binder and Cruikshank (1964, 1966a, 1966b), and Binder, Cruikshank, and Hartmann (1965). This is especially true when the wavelength interval under consideration is extended to the 1 μ region, as is done in this study.

The first infrared colorimetry of small areas on the moon was made by Binder, Cruikshank, and Hartmann (1965) who isolated areas 5 X 9 km and made rapid tracings of the interval 1.0 - 2.2 μ using the 21-inch Lunar and Planetary Laboratory telescope and the infrared spectrometer described by Kuiper, et al. (1962). The results are
discussed in the next section. Moroz (1966) made similar measurements with the Crimean 50-inch reflector, extending the study to 3.8 \mu.

The area of the moon admitted to his instrument was about 20 X 40 km.

Wattson and Hapke (1966), using spectral measures from 1 - 2.5 \mu of Mare Tranquillitatis from Stratoscope II at the altitude of 83,500 feet (Wattson and Danielson, 1965), made comparisons with the reflection spectra of rock powders that had been irradiated with 2-keV hydrogen ions simulating the solar wind. Their results, discussed below, are similar to those of Binder, Cruikshank, and Hartmann (1965).

As part of the program of scientific experiments aboard manned spacecraft, the crew of Gemini 7 made lunar spectra in the range 0.22 to 2.70 \mu (Condron, et al., 1966). These spectra included the entire moon with no corrections for the absorptions of the atmosphere.

More recent photometry of the entire moon at a few selected wavelengths (Forbes, private communication) has confirmed the absolute values of the Gemini curve and its shape.

Qualitative but striking results have been obtained by E. A. Whitaker using photographs of the full moon, made with ultraviolet and near infrared filters. He made a positive copy of the red plates (\lambda=0.78 \mu) and superimposed it on a negative copy of the ultraviolet plate (\lambda=0.35 \mu). With this large baseline, color contrasts show with great clarity. Whitaker's photographs were reproduced in Gehrels, et al. (1964, p. 838) and Kuiper (1965a, pp 26-28 and 1965b, p. 295). His photograph of the Mare Imbrium-Sinus Iridum-Oceanus Procellarum regions is included in this work as Figure 28.
Results of Previous Investigations

Photographic Spectrophotometry

Observers using photographic colorimetry generally agree on the basic conclusions that 1) the color of the moon is very nearly homogeneous, but that 2) some significant variations do occur. Further, that 3) the albedo varies only a factor of about 3 over the surface, whereas the albedo variations for terrestrial rocks are 50:1 (Sharonov, 1962); and that 4) there is a correlation between color and brightness for lunar features such that the brighter features are usually the redder (Teyfel' 1960a, 1962; Coyne 1963; Sharonov 1956, 1962; and many others).

Concerning conclusions 1) and 2) above, Coyne (1963) has noted that the maria are more homogeneous in blue light than in red (above 0.55 μ). This is confirmed by the color-contrast photographs by Whitaker. Coyne also found from his curves of color excess versus wavelength that some humps about 500 μ wide occur, and suggested that they are related to luminescent phenomena as reported by Dubois (1959) and many others. Roberts (1966) made a specific photometric search for anomalous brightenings on two nights in 1964 but did not detect anything unusual, with solar activity, usually thought to trigger luminescence, at a low ebb.

The result that the brighter areas on the moon are on the whole redder is shown in Figure 2 taken from Teyfel' (1960a). As stated on page 9 the color index is the ratio of the brightness of the object at 5500 μ to the brightness at 4400 μ, and \( I_{5500} \) is the
brightness at $\lambda = 5500 \text{ Å}$. We shall presently see that the large scatter in the points at values of the brightness factor greater than about 0.10 may be interpretable. It is not primarily due to errors of measurement, which are on the order of a few percent.

In Chapter V, the age-darkening and homogenization of the upper layer of the moon are discussed from the point of view of radiation damage to the exposed surfaces. In laboratory experiments as the radiation (solar wind and ultraviolet) dosage increases, rock samples become lower in albedo and their color properties become more and more uniform. The scatter in Teyfel's diagram for higher albedo may then be due to regions of fresher rock surfaces, while points with more uniform color index and lower albedo may represent the older, radiation-darkened rocks. This interpretation, however, seems contradicted by the infrared data which show radiation-darkened rocks to be reddened; whereas on the Teyfel diagram, rocks with lower albedo, and presumably with greater radiation dosage, are bluer.

Photoelectric Spectrophotometry

The early results of Wilsing and Scheiner (1909, 1921) have been reworked by Sharonov (1956) who published curves for a few lunar regions and for several rock types in the spectral range 4500 Å to 6500 Å. Even in this narrow spectral region there are very few terrestrial rocks that match, lavas from Vesuvius and Etna, basalts, gabbros, and a few other volcanic rocks coming closest. Sytinskaya (1957) expanded on this work by constructing diagrams for lunar
Figure 2

The Teyfel color-index and albedo plot.
features showing the color index relative to a white, sunlit surface plotted against albedo. The basic diagram is shown in Figure 3. The clustering of points at low albedo and small color index is apparent. The Sytinskaya diagram is not too different from that of Teyfel' (1960a) noted above, and a slight slope can be seen toward the upper right. Sytinskaya then plotted color index-albedo diagrams for many volcanic and other rocks. No rocks fell within the region defined by the lunar surfaces studied. Stony meteorites have color indices of the right order, but their albedos vary widely. The fused crusts of stony meteorites lie closest to the lunar envelope, which has led Sytinskaya (1957, 1962) to develop the meteor-slag theory for the basic color of the lunar surface rocks. Her work was done mostly before the concept of solar radiation-darkening of lunar rocks became en vogue, and she thought that the dark color on the moon could originate from the decomposition of silicates

\[ \text{Fe}_2\text{SiO}_4 \rightarrow 2\text{FeO} + \text{SiO}_2. \]

Van den Bergh (1962) determined the color index of Mare Serenitatis on the B-V system (λ = 0.45 and 0.55 μ) and compared other lunar regions with it to look for color differences. His B-V color index for Mare Serenitatis is 0.876 ± 0.022, and the relative colors \[ \Delta (B-V) \] range from -0.070 (dark spot north of Schroter) to 0.016 (uplands regions south of Tycho). Coyne (1965) also used Mare Serenitatis as a B-V standard. For the 36 areas he observed, \[ \Delta (B-V) \] ranged from -0.051 to 0.023 stellar magnitudes. He also examined any reddening with increasing lunar phase and concluded that differential colors show no phase variation. Gehrels, et al. (1964) had
Figure 3

The Sytinskaya color-brightness plot.
reported systematic reddening of the integrated color of the moon with the absolute value of the phase angle.

Wildey and Pohn (1964) used their UBV data for 30 lunar regions with their stratigraphic classifications to correlate color effects and age. Their data suggest that with increasing age, the backscattering increases, possibly because of greater cavitation. That lunar rocks darken with age is also indicated by their plot of the brightness of a unit area of the moon with respect to relative age. It is not yet possible to determine the age-darkening rate, because the lunar stratigraphic system does not yet possess absolute ages for the various units.

The Gemini 7 results (Condron, et al. 1966) define the reflectivity of the moon from 0.22 to 2.70 \( \mu \), as shown in Figure 4, in which the ordinate is geometric albedo. On the Gemini 7 graph I have plotted also the results obtained by Moroz (1966), and by Binder, Cruikshank, and Hartmann (1965) (BCH). The data for the photographic part of the spectrum were taken from previous work. From this composite graph it can be seen that the data of BCH and Moroz parallel those of Gemini 7, either at lower or higher albedos, depending on the nature of the material. Rays and crater bottoms are brighter than the average moon (Gemini 7 curve), while maria are darker. A notable deviation in the curves occurs at 1.6 \( \mu \), probably because of the telluric absorptions of CO\(_2\) at this wavelength. Neither BCH nor Moroz corrected for the 301, 221, 141, and 061 vibrational bands of CO\(_2\) at \( \lambda \lambda \) 1.536, 1.575, 1.605, and 1.645 \( \mu \), whereas the Gemini 7 measurements were made from above the atmosphere. While it is more
Figure 4

The reflectivity of the moon, 0.2 to 2.8 microns.
meaningful to discuss the Bond albedo than the geometric albedo, the Bond albedo requires a knowledge of the phase integral which is not available for $\lambda \sim 1.6 \mu$. It is not known if the phase integral is color-dependent.

Binder, Cruikshank, and Hartmann (1965) obtained color curves for 10 lunar regions in the spectral interval $1.1 - 2.2 \mu$. A relative luminance value was calculated for four points in the spectrum and was defined by

$$I_\mu = \frac{\text{Intensity at wavelength } \mu}{\text{Intensity at } 1.3 \mu} \times \frac{\text{Intensity of Sun on MgO at } \mu}{\text{Intensity of Sun on MgO at } 1.3 \mu}.$$ 

$I_\mu$ was measured at $1.1, 1.3, 1.6,$ and $2.2 \mu$, selected so as to avoid the major water vapor absorptions. The MgO screen used was probably not completely white in the infrared. It consisted of a chemically-deposited block of MgO that had been prepared many years prior to the observations. The MgO screens used in the present investigation were made just minutes before their use, by smoke-depositing a layer of MgO on a flat metal surface. The properties of MgO prepared this way have been discussed by Edwards, et al. (1961), and Sanders and Middleton (1953).

BOH found that the color of the moon is very uniform in the infrared and that intensity ratios relative to the sun vary by less than about 5 percent for most of the ten points observed.

An important part of the BOH study consisted of reflectance observations of terrestrial rocks made with the same equipment used on the telescope. Basalts and rhyolites of various types were found to vary greatly. Three samples were then irradiated by a beam of $2.0 \text{ keV H}^+$ ions, after which the color properties were again measured.
It was found that after irradiation the colors of the rocks changed toward the lunar curve. From this, BCH concluded that irradiation by the solar wind tends to make the color properties of the moon's surface uniform, just as Hapke (1964) had concluded that it shapes the lunar photometric properties.

Wattson and Hapke (1966) used observations from 1.0 - 2.5 μ of Mare Tranquillitatis from Stratoscope II for comparison with rock and powder samples that they had irradiated in the laboratory with simulated solar wind. They found that the infrared reflectivities of powders are too high to match the moon even after equivalent exposures of $10^5$ years of irradiation. It is true that irradiation had reddened the powders making them more like the moon than before irradiation. This was basically the result of Binder, Cruikshank, and Hartmann (1965) though their laboratory samples were solid rocks. Wattson and Hapke concluded that radiation-altered layer on the moon is optically thicker than that of the laboratory samples, thus accounting for the low albedo of the moon in the infrared, compared with the irradiated laboratory samples.

Summary of Previous Studies

The basic results may be summarized in four points.

1. Color differences occur on the moon.
2. On the whole, brighter areas are redder.
3. Darker areas are probably older.
4. Simulated solar wind irradiation makes rocks redder and darker, thus approaching the color-brightness characteristics of the moon.
CHAPTER IV
INSTRUMENTS AND OBSERVING TECHNIQUES

Instruments

The observations of rock samples discussed in this work were made with the PbS spectrometer (Kuiper, et al. 1962) in the LPL spectroscopy laboratory. The same spectrometer was used on the LPL 61-inch F/13.5 reflecting telescope (Catalina Observatory, Site I) for the observations of the moon. A cut-away diagram of the spectrometer is shown in Figure 5. Light from the telescope or sample table enters through the circular aperture in the attachment plate on the front of the instrument. If the spectrometer is used on the telescope, the incoming beam is converging and is focused on the slit. Ahead of the slit is a motor-driven rotating sector which interrupts the beam 60 times per second. The slit is also at the focus of the collimator mirror having a focal length of 24 inches and diameter slightly less than 3 inches. The incoming beam is thus made parallel and is then dispersed by the diffraction grating or prism. In the present work, a 30° Littrow quartz prism was used to obtain low dispersion and an intense image. The dispersed light, still parallel for each wavelength, travels to the camera mirror which is identical to the collimator mirror. Both mirrors are spherical. The camera mirror focuses the dispersed light, after reflection by a flat diagonal mirror, on the PbS detector. The detector is housed in a cooled chamber containing a slush mixture of solid CO₂ (dry ice)
Figure 5

Scanning infrared spectrometer.
and alcohol or acetone. The slush insures better contact of the detector housing with cold metal than simple solid dry ice would afford. The PbS detector used in this work has a sensitive area 0.1 by 2.0 mm. For the usual stellar or planetary observations, the detector acts as the exit slit of the spectrometer.

For reasons described below, the entrance slit of the spectrometer was replaced with a circular aperture, 0.30 mm in diameter for the present series of lunar observations. For such observations it is essential that the operator monitor the guiding of the telescope at all times so that only the object desired will send its light through the aperture and into the detecting-recording system. In the next section will be discussed the problems of guiding as they pertain to choice of observing technique, but from the instrumental viewpoint, the following details of the design and construction of the guiding facilities are given. In order to monitor the telescopic image of the moon and the portion of this image entering the spectrometer optics, the observer must be able to see the two superimposed. This was accomplished by making the diaphragm in a flat, reflective plate, which was slightly inclined and then by viewing the reflected image. The light passing the diaphragm is transmitted into the spectrometer. The arrangement consisted of a small brass plate about 1 by 2\(\frac{1}{2}\) inches in size, and 3/16 inch thick, counterbored from the back with a special tool to within a few thousandths of an inch of the front surface. The front surface of the brass plate was then ground, polished, and figured flat to optical tolerances (one-quarter wave). The optical work was done jointly with A. B. Binder. Figuring
of the surface left a high polish. Using small drills under a stereo
microscope, Dr. A. P. Wilkska of the University of Arizona Department
of Physics kindly made the apertures in the few thousandths of an inch
of material between the polished surface and the seat of the counter-
bore hole. Apertures ranging from 0.01 to 0.60 mm were made in this
way, the smaller ones requiring much skill and patience to insure
round holes without burrs. After the apertures were completed, a few
minutes of optical polishing sufficed to remove any micro-burs and
insured that the optical surface of the brass plate remained optically
flat right up to the apertures themselves. Optical work with brass is
difficult because of the metal's tendency to sleek and scratch. A
soft metal is important, however, because of the delicacy of the
drilling operations. The drilled, figured and polished aperture
plate was then given a coating of evaporated aluminum to increase the
reflectivity, change the color from that of brass to a more nearly
white color, and to protect the brass against tarnish.

The aperture plate was placed in the slit position of the
spectrometer, inclined 5° to the optical axis. That part of the moon's
image that did not enter the aperture was reflected off axis to a small
microscope with which the observer could monitor the image with dia-
phragm superimposed. The high optical quality of the diaphragm plate
preserves the quality of the image formed on it by the telescope. One
can, for example, use this same plate for observations of small areas on
Venus, Mars, and Jupiter, because the observer can see details on the
planets from their images reflected from the plate. The study of the
mineralogical composition of small areas on Mars in 1965 (Binder and
Cruikshank, 1966a) was made with this plate on the 36-inch telescope of the Kitt Peak National Observatory.

The AC signal from the detector, which is proportional to the amount of radiation incident on the detector, is amplified, rectified, and recorded on a strip chart recorder. To observe all parts of the spectrum of the object under study, the prism or grating is rotated at one of six pre-selected rates. This scans the spectrum across the fixed detector. The recorder then traces the intensity profile, or spectrum, of the object under study.

Spectral resolution is governed by entrance aperture size, detector dimensions, grating/prism scan rate, and time constant (smoothing circuitry) in the amplifier system. Here, it was desired to scan the spectrum (0.8 - 2.4 μ) in the shortest possible time but with resolution sufficient to show the major telluric absorption bands of H2O and CO2. The details of this requirement will be discussed in the next section.

For the laboratory studies of rock samples, the spectrometer was used without the telescope. The configuration of rock samples, illumination source, and spectrometer are shown in Figure 6. Sunlight was directed through an open door from a mirror on the roof of the Space Sciences Building to the mirror at A. This illuminated the sample in the dish B. The smaller mirror C reflected light from the sample into the spectrometer D. The phase angle was 30°.

**Observing Techniques**

The constraints on the observing techniques in this work were imposed by the brightness of the moon and the sensitivity of the PbS
Figure 6

Laboratory arrangement for sample studies.
detector. The objective of the lunar work was to obtain spectral curves in the region 0.8 - 2.4 μ of the smallest possible areas on the moon, in the shortest time interval, for as many lunar areas as possible. Using the PbS spectrometer with a detector 0.1 mm in width, working near full moon when the surface brightness of the moon is greatest, circular lunar areas about 7 km diameter provided sufficient signal with the 61-inch telescope to obtain the desired tracings. The drift of the telescope and image motion caused by atmospheric turbulence required that no more than a few minutes could be spent on an individual lunar spot during a single scan. The entire spectral range was scanned in about 1.5 minutes, during which the wandering and drift were less than about 10 percent of the diaphragm diameter. This accurate guiding was possible only because the 61-inch telescope is equipped with an adjustable declination drive. The guiding accuracy governs the type of lunar area that can be observed, in that obviously only surfaces of uniform brightness over the area of the diaphragm plus drift pattern can be studied. For this very important reason, a system of recording all spectral information simultaneously is highly desirable. A multichannel instrument which, with a separate detector for each spectral increment, is able to detect all the information simultaneously, has been designed jointly with A. B. Binder. Working models of instruments using this concept, but with different purposes, have been built at other institutions.

A sample of a lunar scan is given in Figure 7 with the absorptions of telluric H2O and CO2 indicated. The transmitted spectral
Figure 7

The low-resolution spectrum of a lunar region.
intervals among the strong H$_2$O absorptions are regarded as "windows". The H$_2$O absorption bands do not overlap, so the amplitude of each window is a measure of the continuum intensity of the spectrum at that wavelength. The shape of the spectrum in Figure 7 is determined by the energy distribution of the moon and the instrument-detector sensitivity profile.

**Data Reduction**

For each spectrum, the amplitudes of the six maxima at 0.82, 0.90, 1.05, 1.25, 1.55, and 2.10 $\mu$m were measured. The sum of the amplitudes of the last four wavelengths was taken and divided into each of the six amplitudes to give relative quantities independent of the absolute brightness of the object. The 0.82 and 0.90 $\mu$m points were not included in the sum dividend because their amplitudes are very sensitive to small changes in the telluric water vapor content. For this reason, these two wavelength points in the lunar data in this work have less weight than the remaining four. In the earlier work of BCH, all wavelength points were divided by the amplitude at a single wavelength. The present approach is considered better because of all the raw amplitude data, the quantity having the greatest weight is the sum of the amplitudes.

For comparison with the rock samples, a screen of fresh smoked MgO was observed under solar illumination in the sample apparatus shown in Figure 6. The relative reflectivity at the different wavelengths was also computed for MgO, and then the differences

$$(\text{Relative reflectivity of rock})_\lambda - (\text{Relative reflectivity of MgO})_\lambda$$
were taken and plotted against wavelength. In this way, the reflectivity of MgO is represented by a straight horizontal line.

Similarly, for the lunar observations the reference standard was a spot on the floor of Plato. Its reflectivity at each wavelength point was subtracted from those corresponding points for each lunar region and the differences were plotted against wavelength.

Error Analysis

The lunar observations were made with reference to a standard spot on the floor of Plato, which was observed after every six or eight other spots. The lunar points were arranged into small groups, each addressed to a specific problem, such as flooded crater floors, and each of the points was observed in sequence, led and followed by a Plato reference. In the comparison of the points to the standard, the average of the leading and following Plato reference observations was used. Each Plato observation consisted of four separate scans, giving a total of eight determinations of the spectral reflectivity at each of the six wavelengths. Using the eight measurements for each wavelength, standard deviations from the averages were taken to find the fractional error in the relative spectral reflectivity at each wavelength. For Plato observations No. 67 and No. 76, for example, the fractional errors for the different wavelengths are: 0.8 μ, 3.8 percent; 0.9 μ, 1.3 percent; 1.1 μ, 0.9 percent; 1.3 μ, 0.9 percent, 1.6 μ, 0.5 percent; and 2.1 μ, 1.7 percent. The larger errors at 0.8 μ and 0.9 μ arise partly from the fact that these points in the spectral scans are defined by the water vapor bands nearby and these
are subject to change throughout the night. The absolute amplitude of these points is also small. The error at 2.1 μ is also related to the small absolute amplitude of the spectral tracings at this wavelength.

For the other lunar points, at least four scans were made. The errors are proportional to the square of the ratio of the number of scans, so that the factor by which the errors are increased over the Plato fractional errors for each wavelength point is \((8/4)^2 = 4\).

Figure 8 gives the reflectivity curve of the floor of Aristarchus relative to Plato with the error bars drawn for each of the six wavelength points. This an extreme case because the amplitudes of the quantities \(I(\text{Point}) - I(\text{Plato})\) are large, and the fractional errors have their greatest absolute values. In Figure 8, as in all the colorimetric curves to follow, the abscissa is the wavelength in microns, and the ordinate is the difference between the lunar point considered and Plato. The quantities on the ordinate are all multiplied by 1000 to present them as whole numbers. Samples of the actual numbers that appear in the ratio and difference calculations are presented in a subsequent section, chapter VI.

Choice of Lunar Regions

The features on the moon chosen for colorimetric study were selected from four criteria. First, the areas of greatest potential geological significance were selected, based on photographs and lunar stratigraphic maps by the Astrogeology Branch of the U. S. Geological Survey. These included the different units in the maria and highlands
Figure 8

Colorimetric curve with error bars.
and areas of particularly light or dark tone. The region near Aristarchus where volcanic activity has been suspected in very recent times was included. Second, features were chosen on the basis of topographic interest. These included large craters and their floors, known flows on the maria, structural plateaus, crater rays, etc. Third, E. A. Whitaker's photographs were used to select features of obvious color contrast. Fourth, the most stringent criterion was the visibility of the feature at full moon. It eliminated many potentially interesting objects because of the limitations of the contrast of the lunar image seen at high magnification in the spectrometer guiding device, often in inferior atmospheric conditions, all of which tends to wash out the many features which, under oblique lighting, are prominent. Related to this is the criterion of a large area of continuous albedo. As noted above, wandering of the image in the spectrometer renders the spectral data meaningless if areas of different albedo enter and exit the diaphragm during a spectral scan. The projected diameter of the diaphragm corresponds to 7 km on the moon, but it was necessary to observe regions no less than about four times this size in their smallest dimension because of problems of finding and guiding on the region.
CHAPTER V
COLORIMETRY OF SIMULATED LUNAR ROCK SAMPLES

Introduction

While the processes of alteration that affect rocks on the earth are rather well understood, this is not presently true for lunar rocks. Planetary surfaces in space, not shielded by an atmosphere or by strong magnetic fields, are subjected to bombardment by protons, electrons, alpha particles, and ultraviolet radiation from the sun. The stream of particles is called the solar wind and protons comprise more than 90 percent of the flux. The rocks on the moon are bombarded by the solar wind, and terrestrial rocks to be compared with the moon must be subjected to simulated solar wind for periods commensurate with the exposure times of lunar rocks (several hundred to a few billion years).

The Solar Wind

The data on the solar wind have been obtained from the Explorer X satellites (launched March 25, 1961) and the Mariner II Venus probe (launched August 26, 1962). Mariner II sampled the solar wind during its 109-day flight to Venus while away from the disturbing influence of the earth and its magnetic field. More recently Imp I (Explorer 18) made additional solar wind measurements inside and outside the magnetosphere. Properties of the solar wind derived from observations of the Explorer and Mariner spacecraft are summarized
in Table 1. The data for Explorer X are from Bonetti, et al. (1963), for Mariner II from Neugebauer and Snyder (1965), and for Imp I from Wolfe, Silva, and Myers (1966). The Mariner II results are taken as most representative of the ambient conditions in interplanetary space away from the earth's magnetic field.

It is difficult to evaluate the solar wind flux at the lunar surface. Individual charged particles of low energy are deflected by planets having appreciable magnetic fields (earth and Jupiter). If the moon has a magnetic field we cannot properly use the simple model of solar wind flux incident on the surface with no attenuation. The lunar magnetic moment was investigated by a Soviet spacecraft, Lunik II, launched September 12, 1959. On this basis, Dolginov, et al. (1960, 1962) showed that the lunar magnetic moment must be smaller than $1 \times 10^{-4}$ that of the earth, corresponding to a surface field strength of less than 50 to 100 gammas. Imp I detected a magnetohydrodynamic wake of the moon in 1963 extending at least 150 lunar radii from the moon, thus indicating a weak lunar field (Ness, Scearce, and Seek, 1964). The failure of the Lunik II probe to detect a field has been discussed by Mrs. Neugebauer (1960). She notes that the lunar magnetic field would be greatly distorted by the reaction to the solar wind, and at the subsolar point the field may lie very near the surface. Gold (1962, quoted by Ness, et al., 1964) suggested that the finite electrical conductivity of the moon can capture the interplanetary magnetic field as it is compressed by the magnetized solar plasma stream. This would then give rise to the magnetohydrodynamic wake observed by Imp I (Ness, 1965). In a
### Table 1

Measurements of Protons in the Solar Wind

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Velocity km/sec</th>
<th>Energy eV</th>
<th>Particle Number Density cm⁻³</th>
<th>Flux cm⁻² sec⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Explorer X</td>
<td>300</td>
<td>420</td>
<td>-</td>
<td>2-5 x 10⁸</td>
</tr>
<tr>
<td>Mariner II</td>
<td>320-770</td>
<td>535-3090</td>
<td>4.6**</td>
<td>2.2 x 10⁸</td>
</tr>
<tr>
<td></td>
<td>505* 1330*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Imp I</td>
<td>378*** 747***</td>
<td>3</td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

* Average for entire mission.

** Evaluated at distance of 1 astronomical unit from sun.

*** Time-weighted average of three months in 1964.
preliminary analysis of data from Explorer 35, which was injected into a selenocentric orbit on July 22, 1967, Ness, et al. (1967) find that the magnetic moment of the moon is less than $1 \times 10^{-5}$ that of the earth; no lunar magnetic shock bow was detected.

Arnowitz and Milford (1965) have modified the results of Spreiter and Jones (1963) to relate the shielding effects of a lunar magnetosphere to the ratio of the lunar magnetic moment to that of the earth. For Ness' value of less than $10^{-5}$, particles of velocity 300 km/sec and greater can reach the lunar surface. This velocity is typical of the ambient solar wind, as seen in Table 1. It will be assumed here that the solar wind particles impinge on the lunar surface. There will be occasion to refer to an equivalent "exposure age" on the moon that would normally be proportional to half the ambient flux (the factor $1/2$ corrects for the diurnal rotation of the moon with respect to the sun). If the lunar magnetic field partially shields the surface and if aerodynamic effects or local electrostatic charges divert part of the flux, then the experimentally simulated exposure ages could be longer by factors of 10 to $10^4$.

**Early Laboratory Studies**

The particle type, energy (velocity), and flux of the solar wind can be simulated in the laboratory, but to compensate for the very long exposure times that lunar rocks receive, it is necessary to increase the flux by several orders of magnitude. Hapke (1962) used a proton gun in a vacuum chamber to bombard rock samples with a flux approximately $10^5$ times denser than the ambient solar wind. Some material
was eroded away by sputtering of individual atoms and clumps of atoms and molecules, and certain minerals developed metallic whiskers on a microscopic scale. Rocks and minerals containing Cu, Fe, or other metals of low oxidation potential turned a dark brown or black under bombardement; Hapke (1964, 1965) regarded this as the formation of reduced metal at the surface of individual grains in the minerals. Salisbury and Glaser (1964) irradiated rocks and confirmed the general darkening effects. Similar experiments to determine sputtering rates under bombardment were made by Wehner, KenKnight, and Rosenberg (1963a, 1963b), who were less concerned with color effects than with the alteration of surface microstructure.

These authors have stressed that the darkening effect of an ion beam is difficult to study because of the possible contamination of the beam with cracked hydrocarbons from the vacuum pump oils. Extensive filter systems were used to keep pump oil away from the beam, and most experimenters satisfied themselves that their systems were clean. Nash (1967) has questioned the previous experiments on the basis of new experiments with proton fluxes that did not significantly heat the samples. He found that while darkening is dependent on the total irradiation dose, it is also dependent on the power density for a given dose, i.e. the dose rate. Nash showed that contamination by sputtered electrode atoms and pump oil may be the most significant darkening agent with high current densities. This point will be considered later.
Experiments at the Lunar and Planetary Laboratory

So that studies of the infrared reflectivity of irradiated rock samples could be carried beyond the initial work of Binder, Cruikshank, and Hartmann (1965) and Wattson and Hapke (1966), several irradiated samples were required. An ion beam device was designed and constructed under the direction of Prof. S. A. Hoenig. The preparation of a suitable apparatus was undertaken in two stages; design and construction of a multistage proton accelerator, and a glow-discharge ion source.

The earliest experiments were made with an eight-stage linear accelerator and ion source shown in Figure 9. The source was made from a discharge-type vacuum gauge into which hydrogen was admitted. Protons produced were removed with an extractor plate at -2 to -5 kv, and then accelerated down a series of stages until the desired energy (about 2 kv) was reached. A final plate was provided for focusing the beam, by application of positive or negative potential with a separate power supply. The beam was observed visually on a florescent screen. A copper Faraday cup was placed in a moveable insulated boat to measure the current density in the beam. Several passes of the cup through the beam showed that the peak current density was only $2 \times 10^{-4}$ ma/cm$^2$, which was somewhat less than that necessary for the rock irradiation experiments. A current density of 1 ma/cm$^2$ is necessary to give rock samples a long lunar equivalent exposure age in a few hours. This current density is approximately $6 \times 10^7$ greater than the ambient solar wind.
Figure 9

General view of proton accelerator apparatus.
An improved ion source was constructed according to the design in Figure 10. A hot filament is exposed to the incoming stream of hydrogen. Electrons emitted by the thoriated tungsten filament are attracted toward the walls of the chamber held at positive potential. The paths of the electrons to the chamber walls are curved into spirals by the action of a magnetic field perpendicular to the path, provided by a strong electromagnet, and the result is to increase the probability of a collision of the electrons with hydrogen atoms. Each such collision creates an additional proton-electron pair; the protons so produced are attracted toward the extractor and then accelerated through the linear array. The design for this source was adapted from Finkelstein (1940).

Measurements of the beam current and geometry at the target were made with the Faraday cup. Integration of the beam current data for various positions of the cup gave a total current density of $2.5 \times 10^{-3}$ ma/cm$^2$, which was regarded inadequate for the rock experiments.

To expedite the experimentation and production of irradiated samples, a simple glow-discharge ion source was made to give high current density. The source is shown in Figure 11. An aluminum disk was held above the sample and connected to a feed-through insulator in the top of the vacuum chamber. The metal parts were shielded from the rest of the system with glass to prevent glow discharge to the chamber walls. Samples were placed about 1 - 2 inches below the disk. Under, and completely covered by the samples, was a negative aluminum foil electrode. A copper wire, shielded with glass, led from this
Figure 10

Hot-filament ion source.
Figure 11

Glow-discharge ion source.
electrode, out of the vacuum system, to the negative side of the power supply to provide a floating ground.

The entire unit inside the vacuum chamber was enclosed by a stainless steel cylinder wrapped with 1/4-inch copper tubing silver brazed to the outside (Hoenig, 1966). During the irradiation process liquid nitrogen (-196°C) was circulated through the tubing by a gravity-feed dewar outside the vacuum chamber to provide a cold trap for molecules of pump oil that might otherwise enter the beam. After about thirty hours of operation it was noted that a thin deposit had formed on the outer surfaces of the steel cylinder; this was assumed to be pump oil and sputtered material from the samples.

The vacuum chamber was pumped to $10^{-7}$ torr for several hours before each irradiation experiment began. Hydrogen was admitted with a needle valve and the diffusion pump was throttled to achieve a steady state with the backing pressure about 75-100 microns and the pressure inside the chamber about 190 microns. The glow discharge was uniform around the sample area when the potential difference was 1.5 - 1.8 kv. The current in the discharge was continuously monitored; total currents around 20 ma were found to be best for reasons noted below.

A satisfactory balance between sample heating, gas pressure, and potential difference was obtained with a current of 20 ma, voltage about 1.5 kv, and hydrogen pressure 180 microns. When higher currents were used, the discharge was erratic because the heating of the sample caused outgassing. The outgassing occurred in spurts, sometimes several per second, and the pressure inside the chamber would make sudden changes.
These pressure increases caused the discharge to draw more current, heating the sample more and therefore releasing more and more gas. This snowballing effect was noted several times, and once when the equipment was unattended, the entire system became so hot that the aluminum anode melted and stuck to a sample. For most samples a current of 20 ma was the practical maximum. Nash (private communication) has estimated a sample temperature of 100°C based on his laboratory experiments with different materials exposed to different flux densities.

It is assumed that all of the current in the discharge flowed through the sample lying between the electrodes. This may be an overestimate because of the high dielectric constants of rocks, but for the accuracy of the work here, the assumptions seems adequate. Furthermore, the ion cloud formed in this system is composed of not only protons and electrons, but aluminum ions sputtered from the anode, helium nuclei (impurities in the incoming hydrogen stream), and ions and clumps of ions sputtered from the surface of the sample and redeposited nearby. The solar wind is also impure, but the fraction of heavy atoms is very small. In future experiments it would be useful to evaluate the populations of ion types in the discharge with a mass spectrometer.

Nash (1967) has shown that heating by high-density ion beams combined with the effect of the protons themselves can cause color effects on rocks that the protons alone would not produce. To separate possible heating effects, several samples studied here were heated in a vacuum oven, without irradiation, at 600 - 800°C for periods corresponding to the irradiation times in the discharge chamber. No
effects were noted except for a slight bleaching of sample No. 3 (semi-welded tuff). This experiment does not answer Nash's point entirely, but does eliminate heat as the sole cause of the color changes observed in the present collection of samples.

The Samples

The samples irradiated in this experiment were volcanic and pyroclastic rocks in both solid and granulated form. Smooth, fresh surfaces were chosen when possible, and the solid samples were cut or broken to form a relatively uniform plate of 1-2 cm thickness. Pulverized samples were ground and sifted with screen to eliminate the very fine fraction which could damage the vacuum system if allowed to disperse from acquired electrostatic charges. Most grains used were in the size range 0.5 - 1.5 mm. The grains were contained in a 2-inch diameter Pyrex dish in a layer 1.5 cm deep on a pad of aluminum foil. A wire extended from the top of the dish at the edge and was shielded with a glass tube. The surface of the pulverized material was smoothed flat and the sample placed in the vacuum system. After irradiation the glass tube and electrode were cut away and discarded. The surface of the material remained undisturbed until the colorimetric observations could be made. In all cases, a second sample of identical composition, surface structure, and texture was retained unirradiated so that comparisons of the samples both before and after could be made.

Each of the samples for which the color was measured is described below. Certain of the samples observed are not included in
this discussion but the sample numbering system follows that in the observing record book.

Sample No. 2: Dacite pumice from the Crater Lake region, Oregon. This is a Quaternary nueé ardente deposit which blankets much of the area around Crater Lake. It is light tan in color and has a filament texture with void spaces ranging up to several millimeters across. It is of low density, soft, and powders easily.

Sample No. 3: Semiwelded tuff from the Bend quarry, Oregon, Section 6, Tl3S, R12E. This is a standard sample for lunar research as established by Green (1965), who has given a detailed chemical analysis and petrographic description. The tuff is light brown mottled with lapilli of various colors. Fragmental lapilli breccia consisting of pumice, dacite, vitrophyre, and welded tuff fragments are included in a volcanic dust and glass matrix. The overall SiO₂ content is 71.2 percent and total water content is 2.45 percent.

Sample No. 6: Frothy black basalt from Hawaii. This is a low-density rock that occurs in thin (2 - 3 cm) plates, one surface of which is uniformly coarse in texture on a millimeter scale. This rock has the approximate photometric properties of the fairy-castle structure commonly considered to occur on the moon. The rough surface was irradiated.

Sample No. 7: Frothy black basalt from Pinacate region, Sonora, Mexico. This is a very glassy, highly vesicular rock of low density. A natural surface with very little weathering was used. The vesicles range in size from less than 1 mm to about 2 cm.
Sample No. 8: Black basalt from the Bonito lava flow at Sunset Crater, northern Arizona. The sample was pulverized and sifted as noted above. The flow is massive aa lava with few vesicles, and dates from around 1065 A.D. This date and a description of the basalt can be found in Smiley (1958).

Sample No. 2: Black basaltic ash from Sunset Crater region, northern Arizona. Powder fraction and fragments larger than 2 mm were removed. The sample was taken from a deposit adjacent to the Bonito lava flow, but may have originated in a vent different from Sunset Crater.

Sample No. 10: Red basalt from Black Mesa, south of Tucson, Arizona. This rock was pulverized. It is a slightly weathered basalt with a red-brown color. The original rock was moderately vesicular.

Sample No. 12: Obsidian from the Newberry Caldera, "Big Obsidian Flow", Oregon, Section 36, T21S, R12E. This is a standard sample for lunar research established by Green (1965). The solid rock has the outward appearance of pitchstone, but the analysis given by Green shows that it is obsidian with 72.8 percent SiO₂ and 0.30 percent H₂O. The texture is glassy, macroscopically holohyaline. The structure is massive with an oriented splintery fracture system. No individual minerals are apparent. Microlites, crystallites, and glass shards comprise 65 percent of the rock. The material was pulverized and the resulting grains had a flakey structure.

Colorimetry of the Irradiated Samples

Table 2 summarizes the irradiation exposure data with a brief description of the visual appearance of the altered surfaces.
<table>
<thead>
<tr>
<th>No.</th>
<th>Rock Type</th>
<th>State</th>
<th>Irrad. Time (hours)</th>
<th>Charge Deposit (coulombs)</th>
<th>Corresponding Time on Moon (years)</th>
<th>Visual Effects of Irradiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Dacite pumice</td>
<td>Solid</td>
<td>5.0</td>
<td>28.3</td>
<td>$5.7 \times 10^4$</td>
<td>Black smudge on surface. No visible alteration of surface structure.</td>
</tr>
<tr>
<td>3</td>
<td>Semi-welded Tuff</td>
<td>Solid</td>
<td>7.9</td>
<td>48.4</td>
<td>$9.63 \times 10^4$</td>
<td>Entire sample turned light gray. Dark smudge in area of glow disc.</td>
</tr>
<tr>
<td>6</td>
<td>Black Basalt</td>
<td>Solid</td>
<td>9.5</td>
<td>20.5</td>
<td>$4.17 \times 10^4$</td>
<td>Irradiated area darkened.</td>
</tr>
<tr>
<td>7</td>
<td>Black Basalt</td>
<td>Solid</td>
<td>10.6</td>
<td>22.8</td>
<td>$4.54 \times 10^4$</td>
<td>Irradiated area darkened. Ring of yellowish deposit around irradiated zone.</td>
</tr>
<tr>
<td>8</td>
<td>Black Basalt</td>
<td>Pulv.</td>
<td>10.5</td>
<td>41.6</td>
<td>$8.29 \times 10^4$</td>
<td>No apparent color change.</td>
</tr>
<tr>
<td>9</td>
<td>Sunset Crater Ash</td>
<td>Pulv.</td>
<td>9.3</td>
<td>36.9</td>
<td>$7.35 \times 10^4$</td>
<td>Slight blackening of exposed surface.</td>
</tr>
<tr>
<td>10</td>
<td>Red Basalt</td>
<td>Pulv.</td>
<td>10.3</td>
<td>41.0</td>
<td>$8.16 \times 10^4$</td>
<td>Darkened fragments to average depth of 2 mm in dish.</td>
</tr>
<tr>
<td>12</td>
<td>Obsidian</td>
<td>Pulv.</td>
<td>6.5</td>
<td>25.6</td>
<td>$5.10 \times 10^4$</td>
<td>No apparent change.</td>
</tr>
</tbody>
</table>
Colorimetric observations were made for comparison with the lunar data presented in Chapter VII. The data were reduced as described in Chapter IV and the relative reflectivity of the standard MgO screen subtracted for each wavelength point. The samples with the unirradiated comparisons were all observed on the same day with sunlight illumination. Figure 6 (p. 27) shows the sample table, mirrors, and the spectrometer during the sample measurements.

The colorimetric curves for the natural (U) and irradiated (I) samples are plotted in Figure 12. There was a pronounced infrared color change for all but one sample; pulverized obsidian (No. 12). Most samples became visibly darker with irregular, smooth, black-brown smudges on the exposed surfaces. In no case did the surfaces of the samples suffer structural damage as seen through a 50X microscope. Figure 12 shows a general increase of relative reflectivity with wavelength upon irradiation such that all samples were "red" relative to the MgO surface. This is in agreement with the results of Binder, Cruikshank, and Hartmann (1965) and Wattson and Hapke (1966).

The fact that obsidian showed no change argues against Nash's (1967) interpretation of color effects as simple pump oil and sputtered metal contamination. Nash (1967, p. 3095) noticed that quartz darkened less than basalt for a given radiation dose, as did Hapke (1965). These results are very likely related to the low sputtering yield of quartz and glass. This in turn implies that much of the color change observed in the laboratory on samples of higher sputtering yield is caused by the removal and redeposition of sample material. It is also significant in the interpretation of the
Figure 12

Rock colorimetric profiles.
present experiments that if a deposit of hydrocarbons from the pump
oil is responsible for the color effects on most samples, a similar
deposit should have occurred on the obsidian, changing its color.
We can infer that since no color change was observed on the obsidian,
which received an irradiation dose similar to all other samples, the
color changes detected on other samples resulted from an effect
independent of contamination.

In the vacuum chamber, the glass dishes containing the
pulverized samples were placed in an aluminum oxide boat under the
anode. Solid samples were placed directly in the aluminum oxide boat.
The boat acquired an irregular dark color on parts of its inner surface
during the experiments. Nash (1967) has discussed this effect seen
in his own experiments and in those of Hapke and Wehner. In this
work, a pronounced shadowing effect occurred with the deposition of
the dark material on the aluminum oxide making it clear that the
deposition came from the sample and not directly from the discharge.
The glass rim of the Pyrex dish cast a shadow on the aluminum oxide,
outside of which was dark material. Small amounts of a similar
deposit were noted on the inner surface of the enclosing steel cylinder
after several samples had been irradiated.

Sample 10, pulverized red basalt, changed color to a depth of
2 - 3 mm in the loosely packed material. This may have also occurred
with other samples but was most easily noticed with the red basalt
because of the visual color contrast. This penetration has not been
reported by other investigators, perhaps because their powdered
samples were very fine. The implications of this result are noted below.
Application to the Moon

Surveyor III with its soil mechanics surface sampler (SMSS) made it possible to compare the texture, albedo, color, and strength of the upper millimeter of the lunar surface with the subsurface material to a depth of several centimeters. Shoemaker, et al. (1967) made observations with Surveyor III and the SMSS in April, 1967. The SMSS excavations showed that the immediate subsurface appears darker in tone (lower albedo) than the uppermost surface. This can be understood if particles just below the surface have a dark coating, postulated by Shoemaker, et al. (1967, p. 49) and called lunar varnish. Exposed rocks appear lighter in tone than the subsurface and lack the varnish coating. Particles in the upper millimeter of the surface are mixed by bombardment with tiny meteorites in roughly one hundred to one thousand years, and Shoemaker, et al. (1967) regard the varnish as a coating that must be deposited continuously and preferentially on particles in the shallow subsurface in a relatively short time.

Surveyor V also provided information on the immediate subsurface. On landing, the spacecraft bounced after initial impact, leaving an impression of the landing pads in the soft lunar surface. Figure 13 is a photograph of the impression, or footprint, of one of the pads, also showing the pad in its final position. The dark halo of disturbed material around the lighter depression is a notable feature of this picture.

The observations of Sample 10 are relevant to the interpretation of the shallow subsurface because the particles in the
Figure 13
Footprint of Surveyor V with dark halo.
dish were affected at depth. A second process must, however be invoked to remove the color from the outermost layers of granules on the moon. Shoemaker, et al. (1967, p. 49) call the lighter surfaces "scrubbed".

Filice (1967) has studied the problem of the Surveyor footprints in terms of particle size of the lunar surface materials. He found that differences in the mean particle size can explain the observed albedo differences. Dark material thrown up by the footpad impact is coarser than the brighter material, and this correlates with the laboratory demonstrations of the decrease of albedo with increase in particle size. Filice concluded that at the locations of the Surveyor spacecraft where excavations with footpads or SMSS devices were made, the lunar surface layer is very fine grained and less than about 5 cm thick.

Halajean (1968, private communication) has shown that the albedos of the Surveyor footprints and ejecta might also be explained in terms of degree of compaction of a lunar surface material uniform in particle size, composition, and albedo. If the ejected particles are more loosely packed than before the disturbance, their microshadows give the appearance of lower albedo than the background, unless the observations are made at zero phase angle. Zero phase angle observations were not made of the Surveyor footprints. In principle, the problem can also be solved from photometric studies of pictures of the footprints at several phase angles different from zero because the loosely packed materials would give a different photometric phase function curve from the background of more consolidated particles.
Until such an analysis can be made from Surveyor photographs the question of albedo differences will remain open. If the albedos are the same, this implies a uniform mixing of the upper few centimeters in time intervals commensurate with the radiation-darkening time, which, as Hapke has shown, is about $10^5$ years. This is within the overturn time estimate of $10^2$ to $10^3$ years by Shoemaker, et al. (1967).

The colorimetric profiles in Figure 12 can be interpreted with the new data of Adams (1968, private communication) who obtained spectral reflectance curves in the spectral region considered here for many rock and mineral powders. Absorption bands, mostly due to electronic transitions in iron in its various valence and coordination states, were found as shown in Figures 14 and 15, reproduced here with Dr. Adams' kind permission. Bands of silicate absorptions also occur in the diopside-biotite series. The carbonates, dolomite and siderite, show structures characteristic of hydroxyl and carbonates in addition to the band of Fe$^{2+}$. The centers of major absorption bands in Adams' spectra are listed in Table 3. Several of the bands found by Adams can be recognized in the color profiles in Figure 12. The low spectral resolution of these traces makes the precise wavelengths of the centroids of the bands somewhat uncertain, however. A major band in the samples studied in the present work is centered near 1.1 μ, appearing in samples Nos. 2, 8, 9, and 12. According to Adams' analysis this is attributed to Fe$^{2+}$ in six-fold coordination. This ion occurs in the olivine family spectra in Figure 14. The band at 0.9 μ seen in samples Nos. 6 and 10 is due either to Fe$^{3+}$ or
Figure 11
Adams' spectra of minerals.
Figure 15

Adams' spectra of minerals and meteorites.
### Table 3

Spectral Absorption Bands in Iron-Bearing Minerals

<table>
<thead>
<tr>
<th>Mineral and Formula</th>
<th>Band Centers ((\mu))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Silicates</strong></td>
<td></td>
</tr>
<tr>
<td>Forsterite, (\text{Mg}_2\text{SiO}_4) (with minor (\text{Fe}^{2+}) for (\text{Mg}))</td>
<td>1.02</td>
</tr>
<tr>
<td>Fayalite, (\text{Fe}_2\text{SiO}_4)</td>
<td>1.05</td>
</tr>
<tr>
<td>Enstatite, (\text{MgSiO}_3) (with minor (\text{Fe}^{2+}) for (\text{Mg}))</td>
<td>0.90</td>
</tr>
<tr>
<td>Bronzite, ((\text{Mg}, \text{Fe}^{2+})\text{SiO}_3)</td>
<td>0.90</td>
</tr>
<tr>
<td>Hypersthene, ((\text{Mg}, \text{Fe}^{2+})\text{SiO}_3)</td>
<td>0.90</td>
</tr>
<tr>
<td>Diopside, ((\text{CaMgSi}_2\text{O}<em>6)</em>{\text{Fe}^{2+}}) (with minor (\text{Fe}^{2+}) for (\text{Mg}))</td>
<td>1.03</td>
</tr>
<tr>
<td>Pigeonite, ((\text{Mg, Fe}^{2+}, \text{Ca}) (\text{Mg, Fe}^{2+})\text{Si}_2\text{O}_6)</td>
<td>1.0</td>
</tr>
<tr>
<td>Augite, ((\text{Ca, Mg, Fe}^{2+}, \text{Fe}^{3+}, \text{Ti}, \text{Al})_2 (\text{Si, Al})_2\text{O}_6)</td>
<td>0.3</td>
</tr>
<tr>
<td>Hedenbergite, (\text{CaFe}^{2+}\text{Si}_2\text{O}_6)</td>
<td>0.7</td>
</tr>
<tr>
<td>Hornblende, complex iron-bearing silicate</td>
<td>0.6</td>
</tr>
<tr>
<td>Biotite, complex iron-bearing silicate</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>Oxides</strong></td>
<td></td>
</tr>
<tr>
<td>Hematite, (\text{Fe}_2\text{O}_3)</td>
<td>0.85</td>
</tr>
<tr>
<td>Goethite, (\text{FeO(OH)})</td>
<td>0.89</td>
</tr>
<tr>
<td><strong>Carbonates</strong></td>
<td></td>
</tr>
<tr>
<td>Dolomite, (\text{CaMg(CO}<em>3\text{)}</em>{\text{2}})</td>
<td>1.0</td>
</tr>
<tr>
<td>Siderite, (\text{FeCO}_3)</td>
<td>1.15</td>
</tr>
</tbody>
</table>
to Fe\(^{2+}\) in six-fold coordination. The only other major band seen in the present samples is that centered near 1.6 \(\mu\) in the unirradiated sample No. 6. Adams saw no such band in his studies, but the clinopyroxenes have a strong band nearly in this position due to Fe\(^{2+}\) in four-fold coordination. The resolution of the color profiles in this study does not preclude this as the identification of the band in sample No. 6.

It is important to observe the effects of irradiation on the character of the bands seen in the unirradiated samples. The most prominent band at 1.1 \(\mu\) in samples Nos. 2, 8, 10, and 12 was, in all cases except for sample No. 12, intensified during the irradiation process. Judging from the relative depths below the zero reference of the band in the natural and irradiated samples, the enhancement was from 50 to 100 percent. In a highly reducing environment of proton bombardment, reduction of the valence state from 3\(^+\) to 2\(^+\) can proceed efficiently at the surfaces of minerals in the rocks. That this effect of reduction occurs seems evident in sample No. 10, red basalt. The red color is due largely to Fe\(^{3+}\) in the form Fe\(_2\)O\(_3\), and the band characteristic of Fe\(^{3+}\) shows well at 0.9 \(\mu\). The irradiation removed the 0.9 \(\mu\) band and produced an Fe\(^{2+}\) band at 1.1 \(\mu\). The 0.9 \(\mu\) band in unirradiated sample No. 6 was deepened and greatly broadened by the irradiation, while the depression at \(\lambda > 1.3 \mu\) was removed completely. The latter effect could result from the reduction of four-fold Fe\(^{2+}\) to Fe\(^+\) or Fe.

These physical changes in the bands in the rock samples further support the statements made earlier that contamination in the vacuum
system is not the major cause of the observed darkening of the samples in this study. If the sample heating by the flux were the main cause of the reduction of Fe ions, the vacuum oven treatment should have produced the effects of band enhancement noted above. Heat alone did not produce such effects, from which it is concluded that the reducing properties of the protons caused the observed changes.

Conclusions

With our imperfect understanding of irradiation on the lunar surface and the uncertainty of laboratory simulation experiments, only tentative explanations of likely processes or combinations of processes are possible. The following seem worthy of consideration.

1. Solar protons and ultraviolet radiation reduce metallic oxides to free metals on granule surfaces but the darker products are sputtered off the uppermost surfaces and preferentially deposited in tiny crevices between granules and on their undersides, as suggested by Hapke (1966), making the undersides of surface grains darker than the tops.

2. Darkening of loosely packed granules occurs to a depth of a few millimeters by reduction of metallic oxides to free metals having lower albedo, while another process—perhaps bombardment with higher energy particles—removes accumulated metals from the upper surfaces of granules, giving rise to their apparent scrubbed condition.

3. Carbon atoms in the solar wind adhere preferentially in crevices between and on the undersides of granules, as suggested
in part by Nash (1967). Those striking the uppermost surfaces fail to stick.

1. The apparent darkening of subsurface material thrown up by Surveyor footpad impacts and SMSS devices is a result of particle size or packing instead of an effect of solar wind darkening or scrubbing. Darkening of the lunar surface layer occurs as a result of solar wind activity, as shown in the laboratory, but the rate of darkening and the rate of overturn of the darkened materials are quite uncertain.

While there is evidence from the present study for the reduction of iron oxides alluded to in the first explanation above, the possible variation of albedo with depth is answered most simply in the last paragraph above.
CHAPTER VI
CALIBRATION OF THE PLATO OBSERVATIONS TO THE SUN

In order to present the color profiles of lunar formations relative to their source of illumination, the sun, intermediate observational steps are required. Ideally, one would like to observe the sun with the same spectrometer-telescope combination used for the lunar work, but this is unfeasable because of the extreme disparity in the brightness of the sun and moon. Accurate photometric magnitudes of the bright stars have been published by Johnson, et al. (1966) for eight colors in the spectral range 0.33 - 3.4 p (UBVRIKLM photometry). Johnson (1965) also gives the magnitude and colors of the sun for the same wavelengths, thus permitting comparison of the infrared colors of stars to the sun. The procedure best suited to the instrumentation used in this present work was to compare all lunar points to a single spot on the moon, the floor of Plato, to calibrate Plato relative to a star that could be measured with the same detector-diaphragm combination, and then to use Johnson's 1965 and 1966 data for calibration of the star to the sun.

On January 19, 1968, the standard comparison spot on the floor of Plato was observed alternately with α Ursa Majoris (K0 III) for calibration as noted above and to investigate the possibility of short-term changes in the brightness and color of this lunar region. The observations of Plato and α UMa are summarized in Tables 4 and 5. The standard deviations (σ) for the star observations are greater than 64.
## Table 4

Observations for Standardization of Plato Colorimetry

<table>
<thead>
<tr>
<th>Obsn. No.</th>
<th>Object</th>
<th>Time Interval Universal Times</th>
<th>Median Hour Angle</th>
<th>Airmass</th>
<th>Number of Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Plato</td>
<td>0720 - 0740</td>
<td>3h 10m E</td>
<td>1.529</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Plato</td>
<td>0752 - 0808</td>
<td>2 37 E</td>
<td>1.360</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>Plato</td>
<td>0915 - 0944</td>
<td>1 15 E</td>
<td>1.140</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>Plato</td>
<td>1025 - 1048</td>
<td>0 00</td>
<td>1.087</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>Plato</td>
<td>1210 - 1230</td>
<td>1 35 W</td>
<td>1.183</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>α UMa</td>
<td>0656 - 0716</td>
<td>3 28 E</td>
<td>1.815</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>α UMa</td>
<td>0806 - 0840</td>
<td>2 10 E</td>
<td>1.345</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<td>α UMa</td>
<td>0946 - 1004</td>
<td>0 42 E</td>
<td>1.160</td>
<td>10</td>
</tr>
<tr>
<td>9</td>
<td>α UMa</td>
<td>1054 - 1120</td>
<td>0 15 W</td>
<td>1.143</td>
<td>12</td>
</tr>
<tr>
<td>10</td>
<td>α UMa</td>
<td>1115 - 1203</td>
<td>1 23 W</td>
<td>1.218</td>
<td>7</td>
</tr>
</tbody>
</table>
### Table 5

**Plato Colorimetry Standardization with Errors**

<table>
<thead>
<tr>
<th>Obsn. No.</th>
<th>Measurements of Intensities and Standard Deviations ( \times 1000 )</th>
<th>( \lambda )</th>
<th>0.80 ( \mu )</th>
<th>0.92</th>
<th>1.05</th>
<th>1.25</th>
<th>1.55</th>
<th>2.10 ( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>( \sigma )</td>
<td>103.3</td>
<td>169.8</td>
<td>282.2</td>
<td>321.5</td>
<td>289.5</td>
<td>109.2</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>( \sigma )</td>
<td>99.2</td>
<td>174.5</td>
<td>281.1</td>
<td>317.1</td>
<td>290.1</td>
<td>111.2</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>( \sigma )</td>
<td>100.1</td>
<td>177.5</td>
<td>282.1</td>
<td>316.1</td>
<td>292.1</td>
<td>111.1</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>( \sigma )</td>
<td>100.1</td>
<td>180.2</td>
<td>282.1</td>
<td>316.1</td>
<td>291.1</td>
<td>112.1</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>( \sigma )</td>
<td>100.2</td>
<td>181.4</td>
<td>280.2</td>
<td>315.2</td>
<td>293.2</td>
<td>112.3</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>( \sigma )</td>
<td>112.5</td>
<td>194.6</td>
<td>307.2</td>
<td>319.5</td>
<td>279.3</td>
<td>95.4</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>( \sigma )</td>
<td>108.6</td>
<td>192.9</td>
<td>302.4</td>
<td>319.6</td>
<td>275.4</td>
<td>103.6</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>( \sigma )</td>
<td>106.5</td>
<td>197.3</td>
<td>308.4</td>
<td>319.5</td>
<td>272.4</td>
<td>102.5</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>( \sigma )</td>
<td>103.7</td>
<td>192.8</td>
<td>299.9</td>
<td>317.7</td>
<td>280.6</td>
<td>104.3</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>( \sigma )</td>
<td>104.4</td>
<td>192.6</td>
<td>304.6</td>
<td>314.3</td>
<td>276.6</td>
<td>106.4</td>
</tr>
</tbody>
</table>

Averages of \( \alpha \)-UMa data with propagated errors

| \( \lambda \) | 0.80 \( \mu \) \( \pm 2.5 \) | 0.92 \( \pm 3.0 \) | 1.05 \( \pm 2.5 \) | 1.25 \( \pm 2.2 \) | 1.55 \( \pm 2.1 \) | 2.10 \( \mu \) \( \pm 2.0 \) |

Averages of Plato data with propagated errors

| \( \lambda \) | 0.80 \( \mu \) \( \pm 0.9 \) | 0.92 \( \pm 2.3 \) | 1.05 \( \pm 0.7 \) | 1.25 \( \pm 1.2 \) | 1.55 \( \pm 1.1 \) | 2.10 \( \mu \) \( \pm 0.9 \) |
those for Plato because of the star's smaller image in the spectrometer diaphragm; as the star wandered around in the aperture different parts of the detector were alternately exposed in a random manner. Parts of the detector vary in sensitivity up to 20 percent, and when the star's spectral image is incident on a detector "hot spot", the output of the recorder responds accordingly. This does not occur in the lunar observations where a more or less continuous surface is being examined. Small wanderings of this image have much less effect on the spectrometer output, hence in the Plato values the sigmas are smaller. The data of Table 5 were graphed to discern any regular time variations in the color of Plato, assuming the star constant. No variations in the Plato data were noted during the five-hour period covered by this series of observations; the detectibility limit was about 3 percent.

Averages of all Plato and all star observations for the night are entered in Table 5. Probable errors in each color observation were calculated from

\[
p.e. \sqrt{\sum \left(\sigma_i \right)^2}
\]

and then similarly propagated to the average. The ratios \(\frac{\text{Plato}}{\alpha \text{UMa}}\) were then taken. These numbers, when multiplied by \(\left(\frac{\alpha \text{UMa}}{\text{Sun}}\right)\), give the desired ratio \(\frac{\text{Plato}}{\text{Sun}}\).

The data of Johnson, et al. (1966) and Johnson (1965) were used to obtain the ratio \(\left(\frac{\alpha \text{UMa}}{\text{Sun}}\right)\) in the following way. The ratio of the brightness of two different colors is given by
\[
\log \left( \frac{\text{brightness in filter } x}{\text{brightness in filter } y} \right) = 0.4 (Y-X),
\]

where \( Y \) and \( X \) are expressed in stellar magnitudes. This quantity was calculated for all of Johnson's wavelength points between 0.55 \( \mu \) and 3.4 \( \mu \) (filters V through L) and plotted, justifying the curve so that the ratio at 0.55 \( \mu \) was 1.00. The graph of both the sun and the star were necessary because the wavelengths used in this work are slightly different from those of Johnson's filters, necessitating graphical interpolation. From the graph so constructed, the ratios \((\alpha \text{ UMa/Sun})\) were calculated and multiplied by \((\text{Pluto}/\alpha \text{ UMa})\) to give \((\text{Pluto/Sun})\) as required. The resulting graph of the color of Pluto relative to the sun is given in Figure 16, showing that the crater floor is redder than the sun. The curve has been adjusted so that at 0.8 \( \mu \), the ratio is 1.00. The shallow inflection in the curve centered at about 1.1 \( \mu \) is real and will be discussed in another context later.

It must be emphasized that the graph of the color of Pluto is valid only for the phase angle of the moon at which it was made. The color change of the moon with phase angle has been described from photoelectric photometry in the visual spectrum by Gehrels, et al. (1964). If the phase integral of the moon were known for different wavelengths in the infrared, the data of Figure 16 could be compared directly to the observations of Plato used as standards on other nights represented by the lunar color curves in subsequent illustrations. Phase integral data for the infrared do not now exist, though their importance to studies of this type and to the general problem of the photometry of the lunar surface is basic. There will be occasion to
Figure 16

Color curve of Plato relative to sun.
remind the reader that the lunar point data presented in Chapter VII are relative only to the color of Plato at that epoch and are not absolute. Plato represents a conspicuous, uniform, and characteristic are of the lunar surface and is among the most suitable observable spots on the moon for standardization purposes.
CHAPTER VII
LUNAR COLOR PROFILES AND INTERPRETATION

Introduction

In this chapter the lunar data are presented in curves drawn relative to the standard spot on the floor of Plato. Figure 17 shows Plato photographed by Orbiter IV with the standard area drawn in. The Orbiter photograph corresponds to a vertical projection and the circular diaphragm used at the telescope appears as an ellipse. The setting accuracy of the diaphragm on the standard spot is about half the diaphragm diameter, shown in Figure 17 by the dashed ellipse.

In the lunar point graphs to follow, the quantity on the ordinate is

\[ L(\text{Point}) - L(\text{Plato}) = (\text{relative spectral luminance of lunar point})_\lambda - (\text{relative spectral luminance of the floor of Plato})_\lambda \]

and the abscissa is wavelength in microns. All quantities on the ordinate have been multiplied by 1000, as in Figure 12 (p. 52).

The discussion of minerals detected from the colorimetric curves is based mostly on the work of Adams (1968, in press). Details of his assignments of these bands and the effect of irradiation by the solar wind on them were given in Chapter V. It must be reiterated that the very low spectral resolution of the lunar data given here preclude the precise wavelength determination of the centroids of absorption features, leaving uncertainties in the identification of some bands.

71
Figure 17

The standard spot in Plato
Discussion of Color Profiles

1. Alphonsus and Ptolemaeus

Figure 18 shows the color profiles, relative to Plato, of regions in and around Alphonsus. Points 70 and 73 cover two major centers of dark halo craters near the main crater walls. Points 71 and 72 were chosen to cover typical, uniform samples of the floor of the crater for comparison with 70 and 73. Point 75 is a monotonous area in eastern Mare Nubium and point 74 is near the center of the floor of Ptolemaeus. The Alphonsus and Mare Nubium points are shown in Figure 19 which is composed of two Ranger 9 frames taken March 25, 1965. The similarity in profiles 71 and 72 is striking, suggesting that these two regions are petrologically quite similar. Likewise, the agreement of profiles 70 and 73 adds confidence that the instrument guiding over the dark halo craters was good. The fact that points 70 and 73 diverge at $\lambda < 1.0 \mu m$ with point 70 trending more toward the profile of the floor suggests that the entrance diaphragm included a bit more of the Alphonsus floor in addition to the dark halo material when point 70 was observed. Curve 73 would then be regarded as the more nearly correct profile for a dark halo crater uncontaminated with Alphonsus floor material. The depression at $1.6 \mu m$ in the color curves for the halo craters suggests a specific absorption band; Adams (1968, in press) does not report bands at $1.6 \mu m$ independent of shorter wavelength bands. The profile for the Alphonsus floor shows a depression longward of $1.1 \mu m$ but with no upturn, suggesting either a very broad band or a cluster of bands that are unresolved in the lunar color curves in Figure 15.
Figure 18

Colorimetric curves, Alphonsus region.
Figure 19

Index photograph of Alphonsus spots.
The spectra of the orthopyroxenes show two deep bands at 0.90 µ and 1.85 µ, but the former is certainly not present in the best halo curve. The floor of Alphonsus shows, however, the pronounced downward trend short of 1.1 µ that is suggestive of the presence of bands there. In particular, Adams' table (Table 3 here) shows that the orthopyroxene bands might be augmented by silicate bands at 0.6-0.7 µ (hedenbergite, hornblende, or biotite). These silicates also have bands at 2.3 µ which could account for the lack of upturn at the 2.1 µ point. It is therefore possible to interpret the spectrum of the floor as that of a mixture of silicate rocks and basic rocks containing orthopyroxenes which produce an effective broadening of the silicate bands when observed at low spectral resolution. It is clear in Figure 14 that one cannot distinguish on the basis of the lunar data given here, among bronzite, enstatite, and hypersthene in the orthopyroxene spectra.

That the dark halo craters in Alphonsus are the sources of effusive material having a pronounced smoothing effect on local topography is shown in Figure 20 (frame E-78, Ranger 9). The smoothing as related to crater counts is discussed by Hartmann (1967), and the probable endogenous origin of the dark halo pits is reviewed by Kuiper, Strom, and Le Poole (1966, p. 122). The ash interpretation of the halo craters would be well supported by the colorimetric curves given here if an explanation of the deep band at 1.6 µ could be found within the framework of known mineral assemblages occurring in volcanic ashes.

The Mare Nubium spot (No. 75) shows a broad depression from about 1.0 µ to 1.8 µ with uncertain structure. Adams' data (Figure 14)
Figure 20

Dark halo craters in Alphonsus.
show a broad absorption between 0.8 \( \mu \) and 1.5 \( \mu \) in the olivine group, possibly accounting for the shape of the Nubium curve. A mineralogic interpretation of the Ptolemaeus curve is even less direct. This will be considered further in a discussion of Ptolemaeus and the Fra Mauro formation.

2. Comparison of the Ipm Units in Mare Humorum

Spectral tracings were made of several areas in Mare Humorum classified Ipm 1 through Ipm 4 by Titley (1967). These data are plotted relative to Plato in Figure 21, and the locations of the observed points are given in Figure 22. The classification of individual points is given in Table 6.

Table 6

<table>
<thead>
<tr>
<th>Point No.</th>
<th>Ipm Unit</th>
<th>Point No.</th>
<th>Ipm Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>2</td>
<td>21</td>
<td>3</td>
</tr>
<tr>
<td>17</td>
<td>1</td>
<td>25</td>
<td>4</td>
</tr>
<tr>
<td>18</td>
<td>3</td>
<td>26</td>
<td>3</td>
</tr>
<tr>
<td>19</td>
<td>2</td>
<td>41</td>
<td>2</td>
</tr>
<tr>
<td>20</td>
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<td>42</td>
<td>3</td>
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</tr>
<tr>
<td>22</td>
<td>4</td>
<td>47</td>
<td>1</td>
</tr>
</tbody>
</table>

The curves for the Ipm units in Figure 21 are averages of the respective points 16 through 26 in Table 6, except for the Ipm 1 curve which is for a single point, No. 17. Points 41 through 47 will be discussed.
Figure 21

Colorimetric curves of Mare Humorum units.
Figure 22

Index photograph of Mare Humorum.
in section 1 below. The color curves of the Ipm units do not depart greatly from the Plato reference. In particular the Ipm 2 and Ipm 3 curves are nearly identical except for the departure at 0.8 \( \mu \). In their preliminary geologic map of the Plato Quadrangle, McGonigle and Schleicher (1966) classified the floor of Plato as Ipm without reference to different subdivisions. On the basis of observations reported here, one would classify the Plato floor as Ipm 2-3 if the Humorum exposures were type examples.

To show the structural and topographic details of Mare Humorum in greater detail, views at medium resolution from Orbiter IV (1967) are given in Figures 23 and 24. The Orbiter photographs do not show the strong effect of spherical projection evident in earth-based photographs, such as Figure 22.

Using visual criteria, Titley (1967) classified the Mare Humorum units (Procellarum Group) in order of decreasing albedo, Ipm 1 through Ipm 4. Those of lowest albedo are considered youngest. Wildey and Pohn (1964) found from UBV photometry of several rock units on the moon that older exposures are bluer in the wavelength region 0.35 - 0.65 \( \mu \). The regular progression of the relative spectral luminance with Ipm type at the 1.3 \( \mu \) point is a noteworthy feature of Figure 21. At 2.1 \( \mu \) the progression is nearly regular, but reversed. Thus at 1.3 \( \mu \), blueness increases with relative age but at 2.1 \( \mu \) the redness increases. Further, because the profiles nearly all intersect at 1.6 \( \mu \), an image of Mare Humorum at this wavelength (possible with image-scanning devices) would show little distinction among the Ipm units, apart from albedo variations.
Figure 23

Orbiter photograph of eastern Mare Humorum.
Figure 2h

Orbiter photograph of western Mare Humorum.
The mineralogical interpretation of the Ipm units in Mare Humorum is not direct or convincing. The Ipm 1 curve shows depressions where Adams lists silicate bands (Table 3), while the structure in the Ipm 2 and Ipm 3 curves is minimal. Ipm 1 shows pronounced bands at 0.8 μ and 1.1 μ, resembling curves of the olivine family in Figure 11. If Ipm 1 is truly younger than Ipm 1, and the former contains olivine while Ipm 1 is more silica-rich, this is the reverse order of composition that would be expected from a single differentiating magma yielding its products at different stages in its evolution. The mineralogical evidence in this study for such a sequence is weak, however, and does not merit further detailed discussion here.

3. Aristarchus and Environs

The geologic structure and photometric/colorimetric properties of the region around Aristarchus have been of great interest for many years. The structure of the region has not been discussed in detail but mention is made by Kuiper (1959, pp 296, 299) and Hartmann (1963, p. 11). A review of the optical studies of this area, often called the Aristarchus uplift, is given by Fielder (1961, chapters 4 and 5). Specific attention was directed to the region by Wood (1912) whose photographs through color filters showed the very low ultraviolet reflectivity of the uplift. This has been confirmed in detail by Whitaker (private communication). R. W. Wood has noted that sulfur has a similar low violet reflectivity, and suggested that the Aristarchus uplift is covered with such material. Observations of transient color phenomena in and around Aristarchus by Greenacre and
Barr in 1963 (Greenacre 1965, and Anonymous 1964) make this region an important object for study as a possible source of active volcanism on the moon.

Figure 25 shows the location of several points observed in and around Aristarchus. Points 59, 60, and 61 lie on the plateau and point 63 includes similarly dark material just north of Prinz. These four points yield the color profiles in Figure 26, among which the differences are small. The low depression at 0.9 μ for point 63 may represent a composition difference of the mare and plateau materials, but for the present purpose we use the average of these four points as representative of the underlying material of which the plateau itself is composed. A second wide-spread material is the moderately ray-covered mare surface represented by points 62, 64, and 65. This has higher albedo than the undisturbed mare surface and is assumed to have a light overcoating of ejecta from Aristarchus and other ray-craters.

The average profile of the dark mare-plateau material and the average profile of the moderately ray-covered mare material are plotted in Figure 27. Both deviate from Plato by about the same amount, but in different senses such that the dark mare-plateau is darker than Plato around 1.3 μ and brighter longward of 1.5 μ, while the reverse is true for the ray-covered surfaces. References is made to Figure 21 which shows the mare units in Mare Humorum. The ray-covered surface strongly resembles Humorum Ip 1, the oldest and brightest of that region. The albedos of the two materials are different, however.
Figure 25

Index photograph of Aristarchus region.
Figure 26

Colorimetric curves of mare material, Aristarchus region.
Figure 27
Colorimetric curves of Aristarchus region.
In Figure 27 is also plotted point No. 66, located between Herodotus and Aristarchus, and heavily covered by ray material from the latter. The deviation of the color profile of this area from those described above is significant, magnifying the effect of moderate ray cover on points 62, 64, and 65. The darkening longward of 1.5 μ and the brightening short of this wavelength are further greatly exaggerated in the profile of a point on the floor of Aristarchus. These measurements in the infrared confirm the anomalous nature of Aristarchus and its surrounding. We will return to a mineralogic interpretation of the colorimetric profiles.

Figure 28 shows the color contrasts in northern Mare Imbrium and part of Oceanus Procellarum including the Aristarchus region. Dark regions on this photograph are redder. The floor of Plato, large areas in Mare Imbrium, and the central regions of Aristarchus are blue. The blue color of Aristarchus is further borne out by the photographic photometry of Rackham (1967) who worked in the visual part of the spectrum. Deviations of Aristarchus from Plato are pronounced in the infrared, however, as shown in Figure 27.

A principal source of the red glow activity in 1963 (Greenacre 1965) was the "cobra head" at the southern extremity of Schroeter's Valley on the Aristarchus plateau. Point 58 lies on the cobra head, a gentle swelling with diameter about 25 - 30 km. The surface is pockmarked with irregular depressions, miniature rilles, and other disorganized topography on the 0.5 - 1 km scale. This is well shown in Figure 29 from Orbiter IV. The side of the swelling toward Aristarchus is lighter because of deposition of material, either from the event that
Figure 28
Whitaker's color-contrast photograph of Mare Imbrium.
Figure 29

Orbiter photograph of Aristarchus region.
created the Aristarchus rays, or by escape of sublimate-bearing gas from below the crust. The color profile of point 58 is included in Figure 27; the difference from Plato is in the same sense as the profile of the light ray material (points 62, 64, and 65) but more pronounced.

There is considerable topographic resemblance of the cobra head region to Liamana volcano formed in 1960 at Kapoho, Hawaii, except that the scale is somewhat different. A photograph of Liamana and surroundings is given in Figure 30. Steam permeating upward through the cinders deposited large expanses of sublimated CaSO$_4$·2H$_2$O on the surface of the cone, giving a general patchy whitish appearance. The sublimate has been discussed by Kuiper (1965c). Rain has washed away much of the sublimate so that the modern appearance is somewhat different from that in Figure 31, which was taken in February, 1960, during the eruption.

That the cobra head is the source area for flowing materials, probably of a volcanic nature, is evidenced in part by the presence of a narrow, meandering rille on the floor of Schroeter's Valley. There is considerable structural evidence for the tectonic origin of the Valley itself (Cruikshank, in preparation).

A mineralogical interpretation of the Aristarchus region can be made on the basis of Adams' work (see Figure 14 and Table 3). The curve for points 59, 60, 61, and 63 (dark mare on or near the uplift) shows a single depression centered around 1.3 μ. This matches very well with the broad absorption observed in Figure 14 for the olivine family. This band shows prominently in samples of basalt studied in
Figure 30

Figure 31
Chapter IV, and it is concluded that the dark areas in this region of the moon are covered with basalts bearing minerals of the olivine family.

The ray-covered points (62, 61, and 65) have a profile which, taken alone, shows little definite structure. As noted above, however, it suggests a trend toward the color profiles of more densely covered areas (No. 66) and the floor of Aristarchus. The floor of Aristarchus and the rim point nearby (No. 66) show two prominent absorption features, one centered near 0.9 μ and the second longward of 1.5 μ. These very closely resemble the orthopyroxene curves in Figure 14. The low spectral resolution of the lunar data precludes a precise identification of the wavelength of the centers of the absorption bands, but the general shape is unmistakable. Whether or not the surface material on the floor of Aristarchus and that within a crater diameter of the rim is the same material of the impacting body that formed the crater is not known. Crater ejecta may be more representative of the basement material in which the impact occurred. From the curves in Figure 27, it is concluded that much of the material in the immediate ejecta blanket around Aristarchus has the same composition as the crater floor material. These materials appear to contain orthopyroxene minerals. Orthopyroxenes occur in terrestrial basalts (Mason 1962, Figure 15), but they also comprise the major minerals of chondrites, the most common class of meteorites. It is concluded from the colorimetric evidence here that Aristarchus is the product of the impact of an orthopyroxene chondrite and that the rays and crater floor bear traces of the original impacting body.
Comparison of Ipm Units in Mare Humorum and Mare Serenitatis

Observations were made of the four Ipm units in Mare Humorum and the four in Mare Serenitatis to examine the possibility of a direct correlation between these two maria in terms of rock composition. The Mare Humorum units were classified by Titley (1967) and those in Mare Serenitatis by Carr (1966) whose maps were used for selection of the observed points. The Mare Humorum points (h1, h2, h6, and h7) and the Mare Serenitatis points (s0, s3, s5, and s8) are plotted in Figures 32 and 33. The Humorum point locations were given in Figure 22 and their classifications in Table 6. The data were taken so as to minimize the possibility of errors caused by slight changes in the spectrometer and atmospheric conditions. The tracings of the spectra were made in a two and one-half hour period on October 16, 1967, and were bracketed by Plato standard point observations.

From Figures 32 and 33 it is apparent that the differences among the Humorum and Serenitatis Ipm units are great. Those for Mare Humorum are not substantially different in shape from those in Figure 21. The differences in amplitude or "contrast" of features in the Humorum curves in Figures 21, 32, and 33 are probably due to differential phase-color effects.

In Mare Serenitatis, the Ipm 1 and Ipm 2 units both show a depression centered near 0.9 μ, in contrast with the similar units in Mare Humorum. For units Ipm 3 and Ipm 4, the situation is somewhat reversed in that the Humorum curves show the depression. The depression near 1.6 μ is representative of Humorum units Ipm 1 and Ipm 3, and Mare Serenitatis units Ipm 1 and Ipm 4. If the Ipm 4 curve for Mare
Figure 32

Ipm 1 and Ipm 2 units in Mare Serenitatis and Mare Humorum.
Figure 33

Ip m 3 and Ip m 4 units in Mare Serenitatis and Mare Humorum.
Serenitatis is representative of the presence of olivine family minerals and the Ipm l absorptions indicate more silicous rocks, a logical sequence of development exists. In this view, the Ipm 4 is the youngest unit and more silica rich than Ipm l. The evidence for this sequence is suggestive but not compelling. It was noted in the discussion of the Mare Humorum mineralogy that the reverse sequence from Ipm l to Ipm 4 appears there.

5. Mare Imbrium and Sinus Iridum

Several regions in northern Mare Imbrium and Sinus Iridum were observed because of the sharp color boundaries discovered by Whitaker and shown in Figure 28. Many of the blue regions on Mare Imbrium correspond to flows lying on top of the redder background (R. G. Strom, discussed by Kuiper, 1965a). Figure 34 shows the points observed in the Imbrium-Iridum region; the colorimetric tracings are plotted in Figure 35, along with the average color profile of the Aristarchus plateau points (dark material). The mare points are all less reflective than Plato (a pronounced blue feature in Figure 28) between about 1.0 μ and 1.5 μ, while all are more reflective (redder) than Plato for λ > 1.3 μ. The lunar region showing the most pronounced intensity minimum, which may be an absorption band, is No. 100 in Sinus Iridum. The highland blue point, No. 101 (Heraclides Prom.) shows a profile greatly different from the mare points in that a pronounced absorption occurs at 1.3 μ. In this respect, this spot resembles the dark material of the Aristarchus plateau, but for the disparity at 1.6 μ.
Figure 34

Index photograph, Mare Imbrium and Sinus Iridum.
Figure 35

Colorimetric curves, Mare Imbrium and Sinus Iridum.
Of particular interest is the comparison of the red mare point (no. 98) with the adjacent blue point No. 97. The profiles are identical within the errors of the individual points. In other words, the color contrast between Whitaker's red and blue regions is greatly diminished in the infrared, such that they are essentially indistinguishable. The similarity is even greater when point No. 98 and blue point No. 96 in Sinus Iridum are compared. This confirms the earlier conclusion of Binder, Cruikshank, and Hartmann (1965).

6. Kepler and Environs

Figure 36 gives the color curves for the floor of Kepler, a region in the intense Kepler ray system, and a spot in Oceanus Procellarum which is relatively undisturbed by ray material. The location of these spots is shown in Figure 37. The striking similarity in the curve of Kepler and that of Aristarchus (Figure 27) is at once apparent. The mineralogic interpretation suggested for Aristarchus and its ray also holds for Kepler. The Kepler ray point (No. 92) shows the band at 0.9 μ but not the pronounced feature at 1.6 μ. This is different from the case of Aristarchus where the ray point reflects the same structure as the floor point. From 1.3 μ to 2.1 μ, the curve for the Kepler ray is nearly coincident with that of the surrounding Oceanus Procellarum mare material. The band in the ray curve at 0.9 μ is not entirely inconsistent with the broad band of the olivine group, but one would assume, by analogy with the Aristarchus system, that the dense Kepler ray would have the same general composition as the high albedo material covering the crater floor. Point No. 91 in Oceanus Procellarum is not completely devoid of ray materials.
Figure 36

Colorimetric curves, Kepler and environs.
and this may account for the departure from the Plato reference
color profile. No well-defined structure is seen in the Oceanus
Procellarum curve.

7. Rumker

Rumker is a positive relief feature in Oceanus Procellarum,
north-west of the Aristarchus region. Its invisibility at high sun
indicates that its albedo is very similar to the surrounding mare.
Orbiter photographs do not give a clear indication of its nature
or origin. Color tracings were made of a spot centrally located
on the mass and of a spot in nearby Oceanus Procellarum, as shown
in Figure 38. The color profiles are given in Figure 39, to which
is added the average curve for the mare-type points on the Aristarchus
plateau, one of the darkest parts of Oceanus Procellarum. The devi-
ations from the Plato standard are small for both Rumker and the
mare point. There is a suggestion of the band at 0.9 \( \mu \) in the Rumker
curve, but its amplitude is very small. The mare point shows a
suggestion of similar weight of the band centered near 1.6 \( \mu \) as seen
in certain of the Ipm units in Mare Humorum and Mare Serenitatis.
There is insufficient evidence here to conclude any more than that
Rumker resembles in composition the surrounding mare material. The
differences among these two areas and the dark Aristarchus uplift
are small but perhaps significant in that the latter region shows
a fairly strong depression centered near 1.3 \( \mu \). Small variations of
this magnitude are commonly found in different regions of the same
mare as is evident in the curves for Mare Serenitatis and Mare
Humorum presented above.
Figure 38

Index photograph, Rumker and Oceanus Procellarum.
Colorimetric curves of Rumker and environs.
8. Fra Mauro and Ptolemaeus--The Fra Mauro Formation

Eggleton and Marshall (1962) concluded that Ptolemaeus is covered to an undetermined thickness with the same materials found in Fra Mauro and called the Fra Mauro Formation. The relative color profiles of these two areas were studied; color curves for Ptolemaeus (51) and Fra Mauro (52), Kepler, and the floor of Archimedes (50) are given in Figure 40. The color profiles of Archimedes, Fra Mauro, and Ptolemaeus are representative of a distinct class of curves which differ from those of Kepler, Aristarchus, and their ray systems, in the absence of the absorption band at 0.9 \( \mu \) which is prominent in the curves of the latter objects. They are all greatly different from Plato, showing an absorption band longward of about 1.4 \( \mu \). While the Fra Mauro class of curves shares this characteristic which was previously tentatively ascribed to the broad orthopyroxene band, the second band of the orthopyroxenes at 0.9 \( \mu \) is missing. It is clear that the curve for the floor of Ptolemaeus resembles that for Fra Mauro, lending support for the conclusions of Eggleton and Marshall (1962), but Archimedes, classified IpM by Hackman (1966) appears to have the same properties.

Masursky (1965) has reclassified the Ptolemaeus floor as Icy (Cayley Formation) having nearly the same albedo as the Fra Mauro Formation but presumably originating as ash-flow or ash-fall tuffs. Eggleton (1965) suggested that the Fra Mauro Formation is an ejecta blanket derived mostly from the region of Mare Imbrium, forming a heterogeneous layer of variable thickness. Hackman (1966) considered the Archimedes floor covered with volcanic materials, lava and ash.
Figure 40

Colorimetric curves of crater floors.
Figure 4.1

Index photograph, Ptolemaeus and Fra Mauro.
deposits of the Ipum units (Procellarum Group, Archimedian Series). The Fra Mauro Formation is in the Apenninian Series. The data presented here emphasize the compositional similarity of these two regions. It is important to note that two other objects whose color profiles closely match those of Ptolemaeus, Fra Mauro and Archimedes; are highland points, Lyell D (87) and a spot south of Macrobius D (88). These will be presented below.

In summary, the results of this work indicate a compositional similarity in the floors of Archimedes, Fra Mauro, and Ptolemaeus, and in the highland points near Lyell D and south of Macrobius D. The range in albedo of these points is large, as are the topographic expressions and presumed origins, as discussed by the various interpreters of the geology of the moon.

9. Eastern Mare Serenitatis, Mare Crisium, and Highlands

The index photographs for the points considered here are Figures 42 and 43. The color curves are given in Figure 44. The curves for points 87 and 88 strongly resemble those for Fra Mauro, Ptolemaeus, and Archimedes as shown in Figure 40, except that Nos. 87 and 88 turn upward at 2.1 μ. Point 87 includes the floor and part of the rim of Lyell D, classified pIC by Wilhelms (1965). Objects of this classification are craters like Copernicus and Eratosthenes but are eroded and may be covered with ejecta from Mare Crisium. Point 88 is a region south of Macrobius D, classified Iso by Pohn (1965). Iso is the Somni Formation, having medium albedo with flat smooth surfaces. Pohn considers this old mare-like material or ejecta from
Figure 42

Index photograph, eastern Mare Serenitatis.
Figure 43

Index photograph, western Mare Crisium and environs.
Colorimetric curves, Mare Crisium and environs.
mare basins, extending the range of interpretations of the material(s) giving rather uniform color profiles in the infrared.

The points for Mare Serenitatis (86) and Mare Crisium (89) are very much alike, but somewhat different from Plato, having lower reflectivity longward of 1.4 μ and greater reflectivity at shorter wavelengths. These points are thus bluer than Plato. Reference to Figures 32 and 33 shows that the Serenitatis point (86) most resembles that for Ipm 1 or Ipm 4 in the Serenitatis sequence observed for comparison with Mare Humorum. Point No. 85 is south of Littrow B in Mare Serenitatis but very close to the highland shore of the mare. The color profile indicates a close resemblance to Mare Serenitatis Ipm 3 because of the strong upturn at 2.1 μ, but there are differences at wavelengths short of 1.1 μ. Because the Serenitatis Ipm curves in Figures 32 and 33 are for single points they should not be considered as standard curves for these units in contrast with the Humorum Ipm unit curves.

10. Crater Floors (Aristarchus, Kepler, Copernicus, and Tycho)

Photographs from Lunar Orbiter show that the floors of many prominent lunar craters have evidence of volcanic activity manifested in structures morphologically resembling cinder cones, lava flow fronts and flow channels. Four such craters were included in the present study; Aristarchus and Kepler were discussed above, but are plotted again here in Figure 45 with Copernicus and Tycho. The positions of the observed spots in Tycho and Copernicus are shown in Figures 46 and 47. The similarity in color profiles between Aristarchus and Kepler was noted before. Of the four craters considered
Figure 45

Colorimetric curves, major crater floors.
Figure 16

Index photograph, Tycho.
Figure 47

Index photograph, Copernicus.
here, only these two have the depression at 0.9 \( \mu \). The Tycho curve more strongly resembles those for Ptolemaeus, Archimedes, and the other continuous type materials having the characteristic rounded appearance of the region 0.8 - 1.5 \( \mu \). The Copernicus point is different from all the others, having a strong depression at 1.6 \( \mu \). In this respect, Copernicus strongly resembles the points in and around Mare Vaporum discussed in the next section.

The interpretation of the series of crater curves is not straightforward. Hartmann (private communication) has shown that Tycho, Copernicus, and Aristarchus represent stages in the evolution of the floors of craters of this type, such that Tycho is youngest, Aristarchus is intermediate, and Copernicus is oldest. Photographs of the three craters from the Lunar Orbiter series are given in Figures 48, 29, and 49 to indicate the considerable differences in detailed topography in the crater floors. Hartmann's relative and absolute age estimates are based on crater densities on the floors compared with the average maria of the entire moon, and on the degree of softening or flooding of the crater floor relief. Hartmann considers the floor of Tycho to be relatively undisturbed volcanic topography having 10 percent of the average mare crater density. Aristarchus has 30 percent crater density and shows evidence of a light blanketing (and possible limited flooding) of the rough topography with ejecta. The floor of Copernicus, the oldest, has 50 percent of the mare crater density and shows evidence of extensive flooding and blanketing.
Orbiter IV photograph of Tycho, medium resolution.
Figure 49

Orbiter IV photograph of Copernicus, medium resolution.
The color profiles of these three features show that the floor of Copernicus most strongly resembles several areas in Mare Vaporum discussed below, some of which are classified as dark mare material and some as ejecta blanket formations. This then supports Hartmann's contention in a general way. The opposite member of Hartmann's sequence, Tycho, however, most resembles the Mare Humorum Ipm 1 unit. It is not unreasonable to assume, however, that a fresh volcanic terrain like that considered for the floor of Tycho would be composed of the same materials that would comprise a flooded floor like that of Copernicus, thus giving a colorimetric profile like Ipm mare flood units elsewhere. If the floor of Copernicus is covered in part with ejecta, one would conclude that the ejecta derives from Ipm materials; this is not inconsistent with the interpretations of various mappers who have studied the character and extent of the several formations.

The profile of Aristarchus is different from the other two craters in Hartmann's sequence, though he regards it intermediate in age and morphological development. The color profile of Aristarchus and other features sharing its properties have been discussed earlier. There is no evidence from the data presented here to show that Aristarchus is related to the Tycho-Copernicus sequence of floor evolution.

11. Julius Caesar and Environs of Mare Vaporum

Several objects were observed in the region of Mare Vaporum and Triesnecker, as shown in Figure 50. The structure of this area has been discussed by Fielder (1961) and the stratigraphic map of
Figure 50

Index photograph, Mare Vaporum region.
part of the region has been published by Morris and Wilhelms (1965). The color curves are given in Figure 51. It is apparent that there is little variation in the shape of the color curves for all these areas, suggesting a homogeneous petrography. The stratigraphic classification would indicate otherwise, however. Points 78 and 80 are mapped as Ipm, but their color curves do not resemble the Ipm units in Mare Imbrium/Sinus Iridum or in Mare Humorum. The closest match is for Ipm 4 in Mare Serenitatis. We have seen, however, that Ipm units can have a wide variety of color curves. Points 82 and 83 are mapped Icy (the Cayley Formation) which presumably originates as volcanic flows, possibly ash-flow or ash-fall tuff. Point 81 in the light region of Julius Caesar is mapped Ifs-Ifh (the Fra Mauro Formation). Comparison of the curve for point 81 with that of Fra Mauro (No. 52) in Figure 40 shows that the shape is the same but that the absolute magnitudes of the variations from Plato are different. The small anomalously dark spot No. 77 is classified CEmd and its color profile is very much like the others in Figure 51.

In summary, all the points observed in this area have remarkably similar color profiles irrespective of their classifications. If the stratigraphic classifications are correct, it is not possible to distinguish among units CEmd, Icy, Ipm, and Ifs-Ifh by the technique of infrared colorimetry used here. We have seen, however, that features of very diverse topographic and albedo characteristics have similar color profiles in other areas of the moon. This suggests that a high degree of petrographic homogenization exists or that the classification scheme is less sensitive to composition than to
Figure 51

Colorimetric curves, Mare Vaporum region.
texture and albedo. It must be recalled that the rock irradiation experiments reported in Chapter V in no case produced absorption at 1.6 u, though this does not preclude formation of such a band in the lunar environment, given the appropriate minerals.

The Cayley and Fra Mauro formations may, according to the interpretations of the mappers, originate as ejecta, ash-flow or ash-fall tuff. These ejecta coverings may derive from materials similar in composition to the Ipm and CEmd units nearby, thus giving the very similar color profiles shown in Figure 51.
CHAPTER VIII
SUMMARY AND CONCLUSIONS

It has been demonstrated that in the infrared considerable color differences occur on the moon. Most of the lunar features studied have color profiles which fall into one of six major classes. Some curves have structures strongly indicative of absorption bands which have been shown (Adams, 1963) to depend on Fe atoms in different valence states and in different degrees of crystal coordination. On the basis of Adams' laboratory spectra of the iron-bearing mafic minerals common to volcanic rocks, a limited interpretation of mineralogic composition of several lunar regions has been put forward. Many curves do not show bands which can be identified from the existing laboratory spectra, and certain other curves show bands that do not correlate well with the features of Fe.

There is no direct correlation of color profile type with the albedo or topographic expression of the features studied. It has been shown that the method of infrared colorimetry can be used for rough classification of the IpM units in those maria where different units occur. It has also been shown that lunar features of a wide variety of classifications in the system of stratigraphic nomenclature can have strikingly similar color profiles.

In the rock irradiation study it was noted that a sample of red basalt lost an Fe$^{3+}$ band and gained an Fe$^{2+}$ band upon irradiation with protons. It should be noted that several lunar features show a
band at about 0.9 μ, but at the spectral resolution of the data presented here, it cannot be ascertained if this is the Fe\(^{3+}\) band at 0.85-0.89 μ or the 0.90 μ band of Fe\(^{2+}\). There is no clear case of an Fe\(^{3+}\) band in the lunar data, suggesting that Fe atoms in minerals on the moon's surface occur most frequently in the less oxidized condition, consistent with the reducing nature of the solar wind incident on the moon.

The six basic categories of colorimetric curves are given in schematic form in Figure 52 with the name of a typical member of each category in the legend. Several lunar regions show color curves intermediate in shape and this will result in part from the standard errors in the individual wavelength points. McCord (1968) in his photoelectric differential colorimetric of about one hundred lunar points found five basic colorimetric curves. His curves cover a spectral region where absorption bands in mineral spectra are rare, but his spectral resolution is somewhat greater than achieved here.

In order to look for band-like depressions in the lunar spectrum from other observations, I have examined the lunar spectra taken by Kuiper and others from the NASA jet aircraft flying at 11,000 feet (Kuiper, 1968, and private communication). These records were made above 99.9 percent of the telluric water vapor and about 20 percent of the telluric carbon dioxide. A 12-inch telescope was used to produce an out-of-focus image of the moon on the entrance diaphragm of a Fourier transform interferometer operating in the same spectral region considered in the present work. No bands were found
Figure 52

Six categories of colorimetric curves.
in the spectrum. Nor have bands generally been seen in spectra of
the diffuse image of the moon from larger ground-based telescopes
(cf. Kuiper, 1962). Moroz (1966) reported a band-like depression
at 1 μ (shown in Figure 22) and this has also been seen by Tull
(1966) and Wattson and Danielson (1965). There is a suggestion
of this depression in Figure 22 giving the colorimetric curve of
Plato. In Figure 22 the band seems more nearly centered at 1.1 μ.
The many other band-like depressions that appear in the spectra of
various lunar regions discussed in this work seem to become visible
only when very small spots on the moon, each having a certain degree
of "mineralogical integrity", are observed. Observations of large
areas tend to homogenize the mineralogical properties of the regions
so that only a broad, diffuse band appears. It is common for bands
to appear in the neighborhood of 1.0 μ to 1.1 μ because the character-
istic electronic bands of Fe in the ferric or ferrous valence state
and in four- or six-fold coordination occur there. The broad band
reported by Moroz (1966) and others then may be a blend of several
narrower bands. This emphasizes the need for spectral reflectivity
curves of higher precision and of smaller lunar spots for the more
detailed and accurate geological study of the moon by remote sensing
methods.

Of the six characteristic curve types into which most lunar
regions studied fall, only two have fairly direct correlation with
the minerals observed by Adams and presented here in Figures 14 and 15--
curve types A and E in Figure 52.
Curve type A is typified by the several points on the Aristarchus plateau, the point south of Littrow B (No. 85), a spot on Mare Nubium (No. 75), and the several "red" and "blue" regions on the floors of Sinus Iridum and Mare Imbrium. These are all dark areas of mare-type material. The band they share in common is most closely matched by the band of the olivine family of which fayalite seems to be the most appropriate because of its large band width. Olivines are the most common ferromagnesian minerals in the subaluminian rocks and form from hot and relative anhydrous magmas (Huang, 1962, p. 75). Olivine basalts are also consistent with the chemical analysis of the landing site of Surveyor V (Turkevich, Franzgrote, and Patterson, 1967).

Curve type E is typified by the floors of Aristarchus and Kepler, the dense ray of Aristarchus, and in part by the ray of Kepler. No other lunar points studied had the characteristic bands at 0.9 μ and 1.6 - 2.0 μ. As pointed out earlier, these bands correspond closely to those in the orthopyroxene series enstatite; bronzite, and hypersthene. This is again consistent with subaluminian rocks. In view of the topographic expression of those regions showing this pair of bands--impact craters with extensive ray systems--it seems more significant, however, that the orthopyroxenes comprise the most abundant iron-bearing minerals in the most abundant class of meteorites, the ordinary chondrites. Wood's (1963) tables show that orthopyroxene-bearing meteorites comprise 80.2 percent of all observed falls. Further, of this fraction, enstatite chondrites amount to 7.2 percent, bronzite
chondrites 40.3 percent, and hypersthene chondrites 52.5 percent. These meteorites also frequently contain olivine. It is concluded here that Kepler and Aristarchus are the topographic expressions of the impacts of orthopyroxene-bearing meteorites whose mineralogical characters were not totally destroyed by the mechanics of the impact, and whose remnants are now found in the crater floors and radial ray systems. The form of the color curves for Copernicus and Tycho do not shed light on the origin of these craters beyond the remarks made in the earlier discussion of these features.

The colorimetric curves in the remaining categories and those of intermediate form do not have obvious interpretations beyond those discussed in the previous chapter. One major area of study remaining is that of the spectral reflectivity of possible lunar sublimate chemical compounds of the sort mentioned in the discussion of the cobra head near Aristarchus, and Laimana volcano in Hawaii. Such a program is now in progress at the Lunar and Planetary Laboratory.

It is further concluded that the method of infrared spectroscopy is a useful tool for the study of the mineralogy of the lunar surface provided that suitable laboratory comparisons are obtained.
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