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COMPARATIVE LUNAR-TERRESTRIAL COLORIMETRY

By R. M. Hively and J. K. Westhusing
Manned Spacecraft Center
Houston, Texas

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ABSTRACT

Within this paper are examinations and evaluations of the methods of measuring color, a brief history of lunar color observations, the limitations of lunar colorimetric studies, and the results of laboratory colorimetric study of terrestrial materials. Resulting data are correlated with colorimetric data from selected lunar regions. The postulated use of lunar-surface colorimetry to establish surface composition and rock type is evaluated systematically, although the study and laboratory work were appreciably restricted by time and equipment limitations.

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SUMMARY

The postulated use of lunar-surface colorimetry to establish surface composition and rock type is evaluated systematically in this paper, although the study and laboratory work were appreciably restricted by time and equipment limitations. The study examines and evaluates the methods of measuring color, a brief history of lunar color observations, the limitations of lunar colorimetric studies, and the results of a laboratory colorimetric study of terrestrial materials. The resulting data are correlated with colorimetric data from selected lunar regions. From these comparisons it was concluded that:

1. Spectrophotometric curves are necessary to make meaningful correlations between the colorimetric properties of lunar and terrestrial materials.

2. Several terrestrial volcanic rocks exhibit colorimetric similarities to lunar surface areas.

3. The statistical approach offers the best means of obtaining a significant correlation between rock type and color and, from this, a correlation with lunar surface color.

4. Pulverizing samples to smaller particle size causes increased brightness and increased sample redness.

INTRODUCTION

The report contained within this document is a review of colorimetry literature and the results of laboratory experimental work done at the Manned Spacecraft Center, Houston, Texas, for the National Aeronautics and Space Administration by R. M. Hively, a coauthor of the paper, during the summer of 1965. The responsibility for organizing and completing this report was assigned to Lockheed Electronics Company, Houston Aerospace Systems Division.

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*Lockheed Electronics Company.

Much of the present knowledge concerning the chemical and physical properties of the moon surface has been acquired from analyses of reflected and emitted electromagnetic radiation. Such radiation is best described by its intensity and by the orientation of its oscillating magnetic and electric fields as a function of wavelength and time. Accordingly, a detailed investigation of the lunar crust in the visual portion of the electromagnetic spectrum consists of simultaneous study of the photometric, the polarimetric, and the colorimetric properties and of the determination of the variation of these quantities with time. Presumably, these optical parameters can yield information concerning the physical constants and properties of lunar materials.

Since 1900, the method used in this simultaneous-study approach has involved the comparison of the measurements of lunar characteristics with the similar measurements obtained from terrestrial materials and the attempt to determine the significance of the comparison within an integrated experimental-theoretical framework. This technique of comparison has been especially employed in lunar colorimetry in an attempt to utilize one of the most signficant characteristics of any surface — its color. Unfortunately, at the present time no mathematical theory affords a reliable description, much less a prediction, of the color of a solid substance such as rock. This has not deterred such specialists as field geologists who use color as an important criterion in the classification of rock samples despite the fact that most terrestrial rocks display a wide diversity of color.

Fortunately, it has been found that when a large number of samples are examined, a particular type of rock often possesses a color which is characteristic of its type. Rock coloring has particular significance in the colorimetric measurements which have been made in small areas of the moon that were measured in tens of kilometers, supporting a hypothesis that an average color observed is characteristic and presumably indicative of a particular rock type.

In general, the color differences between various regions of the moon are slight, yet have significant magnitude to indicate that these various surface regions are not homogeneous. Therefore, colorimetric measurements could offer a valuable clue in determining the nature and scope of lunar surface variations. To determine if colorimetry is a useful diagnostic tool to differentiate areas of the moon, it was felt that a systematic approach to the subject should be made. In order to test the diagnostic value of colorimetry, it was necessary to examine and evaluate the reports of observations of color on the lunar surface and the reports pertaining to the colorimetric properties of terrestrial rocks. Based on conclusions resulting from these evaluations, a laboratory study was conducted:

1. To determine the efficiency and practicality of spectrophotometric measurements of rock color

2. To investigate the efficiency of the tristimulus method of color measurement and to evaluate the method relative to the spectrophotometric method

3. To compare the results of laboratory measurements with lunar colorimetric data

The intent of the study was to compare lunar features with terrestrial rocks through the consideration of both color and brightness characteristics, and, from the resulting correlations, to define the types of material prevalent on the lunar surface at specific locations. The relative success of the effort is given in succeeding sections.

SYMBOLS

A	spherical or physical albedo
a	phase angle
B	luminance of an object
B_o	luminance of a perfectly reflecting substance
C	color index
C_1	Constant in black body radiation formula, 3.703×10^{23}
C_2	Constant in black body radiation formula, 1.433×10^{7}
$C_{1,2}$	color indices used to provide a rough indication of energy distribution; the difference between magnitudes measured through two or more broadband filters (see equation (1) in the appendix)
C_s	color index of the sun
E	energy emitted per sec per cm^2
E_s	energy of the sun emitted per sec per cm^2
$E_s(\lambda)E_s(V)$	relative spectral-energy distribution function of the sun
$E(\lambda)$	the illumination or surface density of luminous flux
e	the base of the natural system of logarithms
I_a, I_b	intensity of the light observed through two respective filters
m	magnitude as evaluated by particular color indices
m_1, m_2	stellar magnitudes of the intensity measured in two spectral regions relative to an arbitrary zero

m_a, m_b	stellar magnitudes of I_a and I_b, respectively, relative to an arbitrary zero
m_ν	visual stellar magnitude
p	geometric albedo
q	phase integral
r	visual albedo
S	square measurement of entrance-pupil area in an optical system
T	temperature of emitting body
$T(\lambda)Q(\lambda)$	the product of the spectral transmission function of the filter-and-optical system and the quantum efficiency function of the receiver defining the spectral region of the magnitude m
V	value in the filter magnitude scale in which the zero point agrees with the international photovisual magnitudes of standard stars of the north-polar sequence
v	visual range index value
w	width of diffracting obstacle
X, Y, Z	trichromatic coefficients describing a color (see equations in section entitled "Reflectance (Tristimulus) Measurements")
x, y, z	tristimulus values of a color (see equations in section entitled "Reflectance (Tristimulus) Measurements")
$\Delta\lambda$	bandwidth
δC	color index range
θ	one-half the angular width of the central maximum of the diffraction pattern
λ	wavelength
λ_e	effective wavelength
μ	adopted value of -14.05 ± 0.05 for the stellar magnitude
μ_1	the constant of the stellar magnitude of 1 lux
ϕ	luminous flux entering an entrance pupil area of S

SYSTEMATIC APPROACH

Methods of Measuring Color

Two basic methods are used to qualify lunar-observational and terrestrial rock colorimetric data: (1) the spectrophotometric approach, which attempts to pinpoint the reflectivity of a region as a function of wavelength throughout the visible spectrum or in a number of discrete spectral regions, and (2) the colorimetric approach, which attempts to describe the color of lunar features or rock with a single parameter, such as the color index, or with tristimulus values which quantitatively express the physiological visual effects of a certain color.

The spectrophotometric method. - The most complete analysis of color is accomplished with a spectrophotometer. This instrument contains a dispersing element which breaks the light reflected from an object into its component wavelengths and permits the measurement (usually by photoelectric means) of the incremental distribution of the reflected energy in the spectrum relative to a standard object. Theoretically, all other colorimetric parameters may be derived from these data although this may require laborious numerical approximations. The obvious drawback in this approach is that it becomes tedious to establish the statistical parameters if a great number of samples must be observed. In the case of the moon, a high spatial-resolution spectrophotometric analysis of the entire visible surface would be a very valuable scientific tool.

Perhaps the biggest obstacle in lunar colorimetry is the fact that a sufficient number of spectrophotometric studies have not been carried out to yield reliable results. Even those investigations which have been conducted (ref. 1) often obtained data in the form of color contrasts or yielded information on reflectivity relative to a standard lunar region. Unless values of reflectivity relative to a perfectly white surface can be obtained from such data, relative data are of limited value in the determining of absolute color correlations. Perhaps the main reason for the preoccupation with comparative rather than absolute spectrophotometry of lunar details is because most measurements have been made photographically. It is an extremely complex process to relate effective exposure time, developmental procedures, and quality of seeing and guiding, as well as the response function of a photographic emulsion, to absolute intensities (ref. 2). Consequently, photographic spectrophotometry normally is done on a relative basis by interpolating plate densities between those of standard images produced by some standard illuminant. It would be highly desirable to develop a technique for obtaining photoelectric measurements of the continuous spectra of lunar regions which are more easily reduced to absolute values than are photographic measurements.

The color-index method. - Many observers, such as Teifel (ref. 3) and Sharonov (ref. 4), believe that since most lunar investigations have revealed that colors and color contrasts on the moon are rather slight and that lunar colors do not depart too much from those of sunlight, the color of the lunar surface could be aptly described by a single parameter such as a color index or a color temperature. A color index is defined as 2.5 times the log of the ratio of the intensities measured when an object is observed in two different regions of the spectrum. It is usually expressed in terms of stellar magnitudes. For instance, if the intensity of the light observed through color filter A is I_a and the intensity observed through filter B is I_b, then the color index C can be expressed as $C = 2.5 \log \left(I_a/I_b\right) = m_b - m_a$; where m_b and m_a are the stellar magnitudes of I_a and I_b relative to an arbitrary zero. (See the appendix for a discussion of color indices.)

As in most photometric observations, it is important to reduce measurements to a standard system when measuring color indices. The system most frequently used in measuring color indices is the UBV system, described in detail by Johnson and Morgan (ref. 5). The designation UBV refers to the ultraviolet, blue, and visual color filters with peak responses at about 0.37, 0.45, and 0.55 micron (μ), respectively. Astronomical observations made in the UBV system are usually made photoelectrically, thereby avoiding many of the errors which might occur in photographic photometry. In all cases, corrections are made for atmospheric extinction.

Many recent observers, such as Gehrels (ref. 6), Pohn (ref. 7), and Coyne (ref. 1), have published the results of color observations in the form of color indices giving the difference of intensities B-V in stellar magnitudes for specific regions, or in the form of differential colors giving the differences in the values of B and V for different lunar regions. The V filter magnitude scale is such that its zero point agrees with the international photovisual magnitudes of standard stars of the north-polar sequence. The zero points for magnitudes of U and B filters were chosen so that the color indices U-B and B-V are zero for stars of spectral type A0-V in the MK classification system in reference 8.

The efficacy of color indices as valid color indicators has been subject to much dispute. Sharonov (ref. 4) and Teifel (ref. 3) defended the use of color indices in opposition to Barabashov (ref. 9) who sharply criticized the use of indices and indicated that regions with identical color indices could be of different colors. It might seem strange that a ratio of intensities in only two regions of the spectrum could adequately describe color. However, the rationale for the procedure evolves from the fact that the intrinsic coloring of the moon is very subdued and that the colors of lunar regions depart in only a rather small degree from that of the sun which is a good approximation of a black body radiator.

The Planck equation for the spectral distribution of the radiation emitted from a black body is

$$E = \frac{C_1 \lambda^{-5}}{e^{\frac{C_2}{\lambda T}} - 1} \tag{1}$$

where E is the amount of energy in ergs per second per square centimeter of surface within a spectral band one millimicron in width (or energy emitted per square centimeter per second); C_1 is a constant, 3.703×10^{23}; C_2 is a constant, 1.433×10^{7}; λ is the wavelength of light in millimicrons; and T is the absolute or Kelvin temperature of the emitting body (ref. 10). By measuring the ratio of the intensities at two wavelengths of the emitted radiation, the temperature of the body can be calculated and the spectral distribution described. If the radiation being measured does not depart too far from Planck's radiation equation, a color index (ratio of intensities) or a color temperature can adequately describe the color of the feature.

In addition, some researchers claim that the spectral brightness of most terrestrial and lunar rocks increases monotonically from the ultraviolet end to the red end of the spectrum. In such a case, a color index acquires a definite physical significance because it expresses a type of mean-gradient characteristic of the region of the spectrum under consideration. Furthermore, there is a definite relationship between complete spectrophotometric data and colorimetric data when they are described in terms of color indices and temperatures.

Because the human eye perceives color by distinguishing between different balances of short and long wavelengths of light (ref. 11), different spectral distributions may still give rise to identical colors as perceived by the eye. However, different color indices invariably indicate a difference in the spectral distribution of energy. Therefore, while colorimetric data, such as the color index, cannot demonstrate the identity of the relative spectral distribution of two objects, it can rapidly distinguish between two objects which have different distributions. An ideal approach has been suggested by Sharonov (ref. 4). It entailed the performing of a statistical analysis of colorimetric data to determine which rocks would correspond to the material on the lunar surface. Once this has been accomplished, the more laborious process of spectrophotometry could be used to document the spectral distributions of colorimetrically similar lunar- and terrestrial-surface minerals.

The tristimulus method. - A third potential method of measuring lunar and terrestrial colors, which has had little application thus far, is the direct determination of tristimulus values. In using this method, color is assigned by the three values x, y, and z representing the relative amounts of energy in three different regions of the spectrum reflected by an object illuminated by a standard illuminant (very similar to extraterrestrial sunlight) as defined by the International Commission on Illumination. From such data one can easily derive quantitative measures of the dominant wavelength which composes a color, the purity or saturation of a color, and the visual albedo of the measured region.

An excellent discussion of the tristimulus approach to colorimetry is given in reference 10. The advantage of this approach is that it is no more complicated in principle than ordinary trifilter photometry, but gives information in quantitative form which can be related very easily to our physiological conceptions of color and brightness. If a photometer and filters could be devised with response functions suitable for measuring tristimulus values, and if the proper corrections could be made for scattered skylight, it would be highly desirable to obtain the tristimulus values of lava fields and bedrock outcrops from aircraft observations, thereby ascertaining the color of such outcrops viewed from high altitudes. It would be interesting to compare such data with similar measurements made on lunar features.

History of Lunar Color Observations

A detailed history of research conducted in lunar colorimetry is presented in references 11 and 12. Therefore, only a few of the more recent results will be described in this section. Recent visual work on lunar colorimetry apparently demonstrates that there are real color differences on the moon (ref. 13). Unfortunately, different observers often see different colors on the same places at the same times. This seeming paradox illustrates why work must be performed by instrumental methods rather than by subjective visual operations. Perhaps the most significant observation of the integral color of the moon is its redness. The sun has a B-V index of 0.63m (see appendix for discussion of the index), whereas the moon at zero phase has a B-V value of 0.84m (ref. 6). This comparison indicates that the moon is considerably richer in wavelengths, within the range of the V filter, than the sun, accounting for its relative redness. This reddening is not merely a local effect but seems to be characteristic of the entire lunar disc. This effect is also characteristic of asteroids and has been postulated to be indicative of surface texture.

Perhaps the most famous research done on lunar colorimetry involved the spectrophotometric measurements of specific regions which were made by the physicists Wilsing and Scheiner in 1909 and 1921 (reported in ref. 4). Even though their measurements exhibited an accuracy of only 10 percent and were obtained with relatively crude equipment, the values still retain significance because no comparable measurements have been made until very recently. Even now, the paucity of spectrophotometric measurements, reduced to absolute reflectivities throughout the spectrum, obstructs the use of colorimetry for the moon. In fact, in the limited time available for this study, the only data obtainable, which could be directly compared to the spectrophotometric measurements to be described in the laboratory section of this report, were those of Wilsing and Scheiner (reported in ref. 4). The results of their investigation indicated that lunar reflectivities are increased toward the red and that the brighter areas of the moon are somewhat redder than the darker areas. In addition, their work suggests that the lunar maria might be composed of matter somewhat similar to terrestrial lavas.

In 1952, the physicist Barabashov (author of ref. 9) undertook a program of moon photography with color film and detected definite green, red, blue, rust, and violet hues on the lunar surface. While color photography is not an accurate and impartial record of color, the results obtained from his efforts suggested that if color contrasts could be detected with ordinary color film (usually having low-contrast sensitivity), differential colors on the moon could be real and perhaps quite extensive. Unfortunately, the existance of color contrasts on the moon is not completely supported by the scientific community. The physicists Radlova and Sharonov have concluded that the difference in color indices for various lunar features is less than 0.01m, or about the same order of magnitude as the errors inherent in such measurements.

The authors just mentioned in the preceding paragraph appear to deny the existence of color contrasts on the moon. Their findings, however, are in sharp contrast to the findings of the majority of other observers. Barabashov and Chekirda (reported in ref. 11) found the maximum color differences by photographing 72 regions of the moon with five color filters: (1) an infrared filter (0.840μ), (2) a red filter (0.650μ), (3) a green filter (0.502μ), (4) a blue filter (0.415μ), and (5) an ultraviolet filter (0.365μ). From this work, the calculated color contrast between lunar regions was small for most features but rose occasionally to as high as 20 to 25 percent. Teifel (ref. 3), as a result of spectrophotometric analyses, found that most color contrasts were small (1 to 8 percent) and within the limits of experimental error, but that certain regions were found to exhibit color differences of 15 to 20 percent.

Recent work on differential colors on 36 lunar areas, made by measuring B-V color indices relative to a standard region, yielded a variation of 0.08m in the indices of 36 lunar regions (ref. 1). The author of reference 1 (Coyne) made spectrophotometric observations of differential colors and found that maximum color variations in various wavelength regions occasionally ranged from 0.15m to 0.20m. It is rather interesting to note the general disagreement between observers such as Radlova and Sharonov who used color indices, and observers such as Barabashov and Teifel who used spectrophotometric data, and, likewise, the difference in Coyne's results when he used the two different methods. Barabashov (reported in ref. 12) has interpreted these discrepancies as illustrating the unsuitability of color indices for revealing color contrasts on the surface of the moon. Coyne (ref. 1) concluded that the color curves of small features on the moon showed a nonmonotonic variation with wavelength. Consequently, he believed that color indices only roughly characterized the color of the reflecting surface and that really accurate work would require spectrophotometric data so that the nuances and variations in the spectral curves of various areas could be differentiated. Even photometry with several color filters is not believed to be adequate to describe the surface color since there is no guarantee that the spectra of lunar features will yield their maximum and minimum intensities at the effective wavelengths at which the photometry is conducted.

Gehrels' recent work (ref. 6) using the UBV and UGI photometric systems (UBV and UGI are filters used in the six-color photometric system of Stebbins and Kron[1]), detected a variation of B-V color indices amounting to 0.09m (ref. 6). Gehrels also found that, in general, the moon became redder with succeeding phases (as expressed by the relation $B-V = 0.84 + 0.0017a$, where a is the phase angle). Coyne's recent work (ref. 1) reveals that he could not detect a variation in differential color with phase angle, and therefore, the reddening with phase appeared to affect all regions equally.

On the basis of the most reliable colorimetric measurements, it can be concluded that colors of subdued yet significant magnitude do exist on the moon, indicating that the various regions of the moon are not homogeneous even within the maria, and that colorimetric measurements could offer a valuable clue in the determining of the nature and scope of lunar heterogeneity. A qualitative description of color on the moon, largely based on the work done by Barabashov, could be given as follows:

1. Craters on the moon possessing ray systems are generally reddish.

2. Maria and the bottoms of craters are reddish.

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[1] Stebbins is a physicist with the Mount Wilson Observatory, and Kron is a physicist with the Lock Observatory; both have done extensive work in the establishing of photometric-measurement systems.

3. Certain mountain regions, particularly in the southern hemisphere, display reddish hues.

4. Other mountainous areas and irregularly outlined maria exhibit greenish hues.

5. Some ray systems are also reddish.

6. The continents reflect more red light than the maria, and the colors of various regions appear to vary slightly with time (which might be due to shadows).

According to the recent works of Gehrels and his associates (ref. 6) and of Coyne (ref. 14), colorimetric measurements may also be valuable in detecting lunar luminescence. Some of Coyne's comparative spectrophotometric curves exhibit rather anomalous humps which, he observes, closely correspond to some of the luminescent bands purportedly isolated by Dubois.[2] Gehrels' graph A, shown in figure 1, contains some curves from Coyne's spectrophotometric data on lunar color contrasts (ref. 14). Graph B in figure 1, taken from the same reference, shows the luminescent bands purportedly isolated by Dubois. The ordinate of graph A is measured in stellar magnitudes, where each division represents 0.10m and each curve represents the ratio of intensities throughout the spectrum of two lunar regions.

The ordinate of graph B is the ratio of the luminescent intensity to the continuum intensity in the absence of luminescence, and the unit of intensity is the intensity at 5500 Å in a nonluminescent area west of the crater formation Tycho. The curves in graph A are somewhat unusual in that most of Coyne's curves do not exhibit a marked maximum but are rather smooth. Normal curves would follow the dashed lines shown. The maximum intensity at 5100 Å exhibited by all curves in graph A is very similar to that observed on curve 1 in graph B. The maximum intensity on curve 4 at 6200 Å is also similar to the maximum intensity on curve 2 in graph B. Thus, it is very tempting to suspect that these anomalous contrast curves are produced by luminescence. Curve 1 in graph B was observed on the moon in the center of Mare Crisium. Curve 2 in graph B was detected by Dubois in the dark region between Mare Nubium and Mare Humorum.

Limitations of the Lunar Colorimetric Studies

There are many limitations and precautions to be observed in a program of comparative lunar and terrestrial colorimetry. First, there is the difficulty of defining what is meant by color and the difficulty of determining the most precise and efficient means by which to measure color. To characterize color, either the detailed description of the spectral energy distribution of the light emanating from an object or the physiological sensations of sight produced by the reflected light may be described. The spectral energy specification is the more precise, but in many cases, the measuring procedures are time consuming. The physiological mode, while less precise, may be

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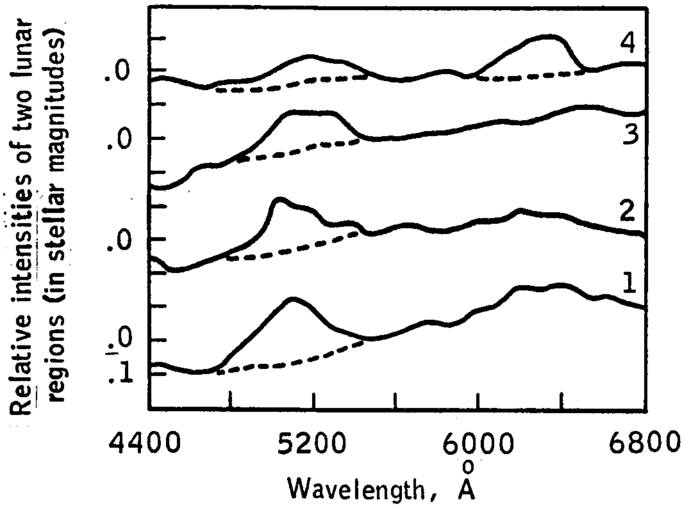
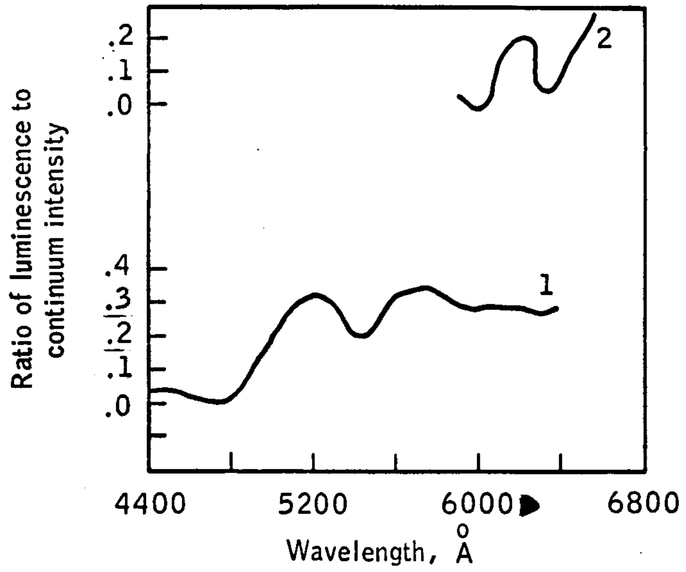
[2] J. Dubois is a French physicist, formerly associated with the department of physics of the Chalmers University of Technology, Gothenburg, Sweden; data pertaining to lunar luminescence detected by him is presented in figure 1.



Graph A - Lunar color contrasts



Graph B - Lunar luminescence

Figure 1. - Anomalous intensity maximums in spectrophotometric curves of selected lunar regions (ref. 14).

preferred since the very concept of comparative colorimetry is rooted in the physiological discrimination of light at different wavelengths. A layer of opaque or translucent foreign material deposited on a surface could totally mask out the true color of the substance beneath. In the case of the lunar surface, the accumulation of interplanetary particles, the impact of micrometeorites, and the existence of an endogenous dust layer as suggested by the physicist Gold (reported in ref. 12) could provide a layer of material which would alter and subdue natural color differences. Accordingly, the technique of the comparison of terrestrial rocks with matter on the lunar surface while assuming that the visible surface of the moon presents a fresh, uneroded lunar crust would be unjustifiable.

In addition, optical properties of many minerals and rocks vary widely and must be measured with the utmost caution when deriving hypotheses about the nature and composition of celestial bodies. For instance, various specimens of quartz may exhibit almost any shade of color. Therefore, it is possible to select a specimen of quartz which displays colorimetric properties identical to almost any other given surface. This illustrates the need for a statistical approach to make meaningful comparisons between terrestrial and lunar materials. The comparison of lunar data with arbitrarily selected terrestrial samples has produced ambiguous results and has emphasized the need for a more systematic approach. While colors of minerals and rocks do not fall within the scope of a rigorous mathematical theory, certain generalizations can be made. For the purpose of color classification, minerals can be divided into two groups: (1) leucocratic minerals, those which possess no natural coloring but take on different colors because of the presence of minute amounts of impurities, and (2) melanocratic minerals, those which possess natural coloring of dark shades which persist even when impurities are present. The extremely low albedo of the moon could be caused by either the presence of leucocratic compounds with an admixture of dark impurities or the presence of melanocratic minerals.

The following factors must be considered in performing lunar-terrestrial comparisons:

1. The composition of lunar rocks may have been altered by chemical reactions with gases released by outgassing and exhalations of various types, as reportedly observed by N. Kozirev.[3]

2. Most terrestrial rocks are altered by atmospheric processes which are nonexistent on the moon. Lunar materials are subjected to intensive bombardment by solar corpuscular radiation, ultraviolet rays, and cosmic rays, all of which have been demonstrated to have a pronounced effect on both albedo and color.

3. Photometric and thermal studies of the moon indicate that the surface very likely consists of finely pulverized or porous material, and many investigators claim that this would have the tendency to wash out and reduce color and color contrasts.

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[3] A physicist with the Crimean Astrophysical Observatory, Simeis, Crimea, R.S.F.S.R.

Another serious difficulty arises even after the consideration of the aforementioned factors. On the moon we observe only the average integrated color of a large area. Thus, a comparison should only be made with the color of a terrestrial terrain with a comparable area observed at a comparable distance. One is then faced with the problem of determining what the color of such exposed terrestrial masses would be if viewed from a great altitude. One possible method is to obtain, by photographic or photoelectric means, colorimetric measurements of exposed bedrock and lava flows as observed from aircraft or orbiting satellites, thus determining how color is affected when an exposed mass is viewed from great heights. Here, however, one is faced with the problem of taking into account the effect of the atmosphere, which will selectively scatter light of short wavelengths. Under these conditions, the spectral character of the light illuminating the terrestrial surface would also be quite different from that of the sunlight which illuminates the lunar surface.

Identical objects will exhibit identical colors only when the spectral characteristics of the illumination are alike. Until techniques are developed which will make such aerial colorimetry feasible, perhaps the most practical method would be the statistical approach carried out on individual rock specimens in the laboratory. In selecting rocks for statistical colorimetric analysis, it is very easy to be trapped into letting bias enter the mode of selection. Geographic biases in the selection of samples are apt to strongly influence the results of the experimental technique because of the difficulty in obtaining samples from remote sites. Samples derived entirely from industrial concerns and museum collections would also tend to introduce undesirable biases. Although statistical colorimetric measurements have been undertaken by Sytinskaya (ref. 15) and Sharonov (ref. 4), a rigorous statistical approach, using materials altered by the effects of simulated lunar conditions, has not been made.

An added complication is the fact that we do not only observe radiation passively reflected from the lunar surface but also luminescent radiation excited by solar ultraviolet radiation, solar corpuscular radiation, and cosmic rays. Recent researchers have definitely established the existence of several luminescent spectral bands linked with a great number of lunar regions. This luminescent component may total as much as 10 to 20 percent of the reflected light for some regions (ref. 8). It appears that the phenomenon of luminescence should be accounted for in colorimetric studies.

MANNED SPACECRAFT CENTER GEOPHYSICAL LABORATORY COLORIMETRY STUDIES

The scope of the investigation of the colorimetric properties of terrestrial rocks conducted at MSC was limited by time and equipment restraints and by the small quantity of rock samples available. The objectives of the study were the following:

1. To determine the effectiveness and practicality of spectrophotometric measurements of rock color

2. To investigate the effectiveness of the tristimulus method of color measurement and, in particular, to compare the method with the spectrophotometric method

3. To compare the results of the spectrophotometric and tristimulus measurements of rock samples with lunar colorimetric data

4. To investigate the effect of pulverization of rock samples on their brightness and color

Sample Selection

In order to be selected for the laboratory measurements, rock samples had to meet the following criteria:

1. Albedos within the albedo range determined for the moon

2. Coherent structure so that a smooth section could be derived

3. No evidence of exceptional weathering (although all samples used were slightly weathered)

4. Freedom from abundant impurities and inhomogeneities so that surfaces would have a relatively constant hue

It is realized that these standards introduced definite bias into the selection, but the study was considered as a preliminary examination of colorimetric properties and was not intended to represent the ideal approach.

Spectrophotometric Measurements

The percent of diffuse reflectance relative to a magnesium oxide (MgO) standard was measured throughout the visible spectrum for each sample using a spectrophotometer and a reflectance unit (fig. 2). The spectrophotometer operates in the following manner:

The light from the tungsten lamp is passed via mirrors through a prism which then reflects a small portion of the spectral light by mirrors onto an oscillating mirror that alternately causes the sample and the standard to be illuminated. The reflected light from both the sample and the standard is then gathered by an integrating sphere and detected by a photomultiplier. This signal is fed into an automatic recording device which traces (on graph paper) the percentage of light diffusely reflected by the sample in that wavelength band which is relative to MgO as 100 percent. An automatic wavelength-drive slowly rotates the prism, changing the wavelength of the illuminating light and permitting the recording of the percentage of reflectance throughout the visible spectrum. A slit in the optical part, operated by a servomechanism, continually adjusts in width so that a constant amount of energy is incident upon the sample and is referenced throughout the measurement.

The MgO standard was prepared by burning a magnesium ribbon under a glass slide so that it became coated with a layer of MgO. Magnesium oxide is a usable standard inasmuch as it has virtually a constant reflectance of 98 percent throughout the visible spectrum. After the spectrophotometer was adjusted and calibrated to perform

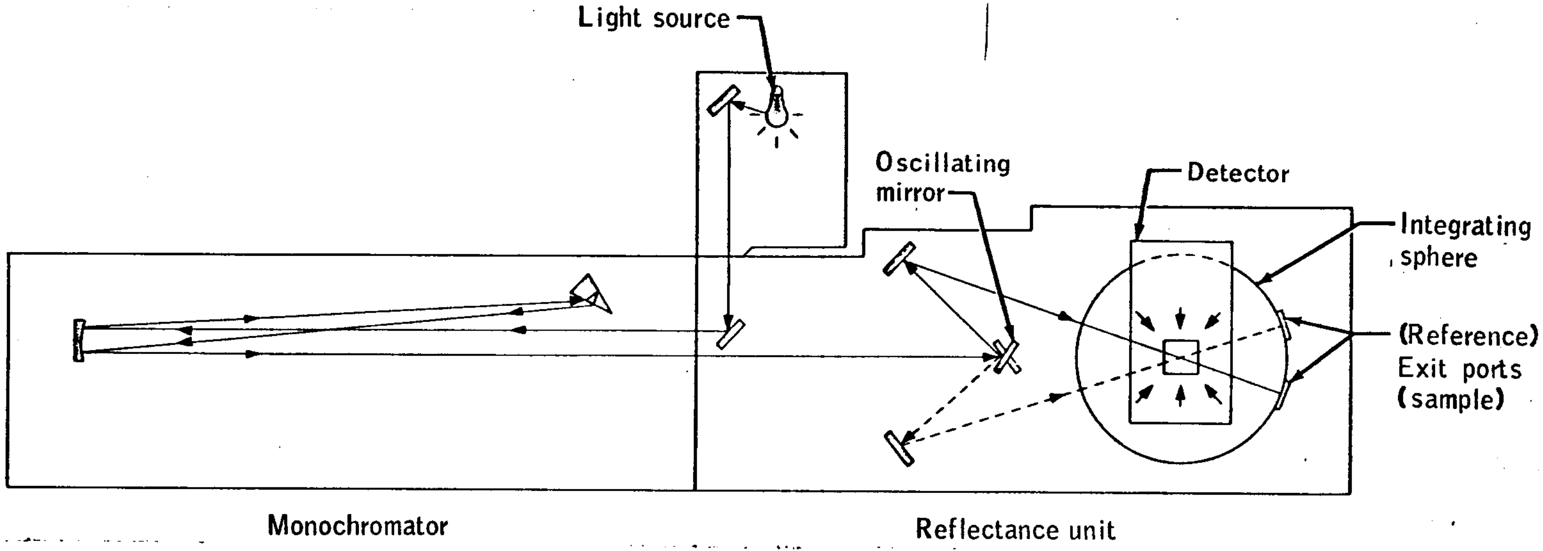


Figure 2. - Schematic of spectrophotometer and reflectance unit used for sample colorimetry measurements.

reflectance measurements, the accuracy of the adjustments was checked in the following manner: the reflectance of a white enamel plate with a known constant reflectance of 77 percent was measured and the brightness calibration was found satisfactory. The wavelength calibration was checked by placing a green tristimulus filter with peak transmission at 546 $m\mu$ in front of the white enamel plate; consequently, the peak reflectance measured occurred at precisely this wavelength.

Reflectance (Tristimulus) Measurements

Having obtained the spectral-reflectance curves of the samples, their tristimulus values were determined from measurements taken with a photovolt reflection meter (fig. 3). The reflectance meter consisted of two units: (1) the instrument proper, which contained the indicating meter and the controls, and (2) the search unit, which contained the light source and photocells. The tristimulus values of an object were determined by placing the search unit on the sample and measuring its reflectance on a galvanometer through three different tristimulus filters which were alternately inserted in the bottom of the search unit. Before each reading, the galvanometer had to be calibrated relative to a white enamel working standard provided with the meter.

The reading taken with the green tristimulus filter in the search unit also measured the visual albedo r of the object. Visual albedo is defined as B/B_0, where B is the luminance of the object, and B_0 is the luminance of a perfectly reflecting substance. Given the tristimulus values x, y, and z, the trichromatic coefficients describing a color are defined as $X = \frac{x}{x + y + z}$, $Y = \frac{y}{x + y + z}$, and $Z = \frac{z}{x + y + z}$. Once the trichromatic coefficients are known, the dominant wavelength and purity are obtained from the chromaticity tables of Hardy (ref. 10).

All samples were analyzed under the conditions of normal illumination. Both the spectrophotometer and the reflectance colorimeter were constructed to measure only the diffuse reflection and to exclude the specular component of reflection. The reflectance colorimeter detector used for measuring tristimulus values views the sample at an angular range with an average angle of about 45 degrees. The spectrophotometer measures the total diffuse reflectance of the sample, and the reference surfaces are held normal to the radiation beam so that the specular component is reflected back along the beam path allowing only the diffuse component to be reflected from the walls of the integrating sphere onto the detector.

COMPARISON OF MEASUREMENTS

Direct comparisons of spectrophotometric and colorimetric methods of measurement were probably biased to a slight degree because identical areas of each sample were not measured. However, in most cases, the sample surfaces were rather homogeneous in color; consequently, this effect is probably very small. The correspondence between the two methods was tested by calculating the trichromatic coefficients of one sample from its spectrophotometric curve by the weighted-ordinate method described by Hardy (ref. 10) and then by comparing these values to the coefficients of the same

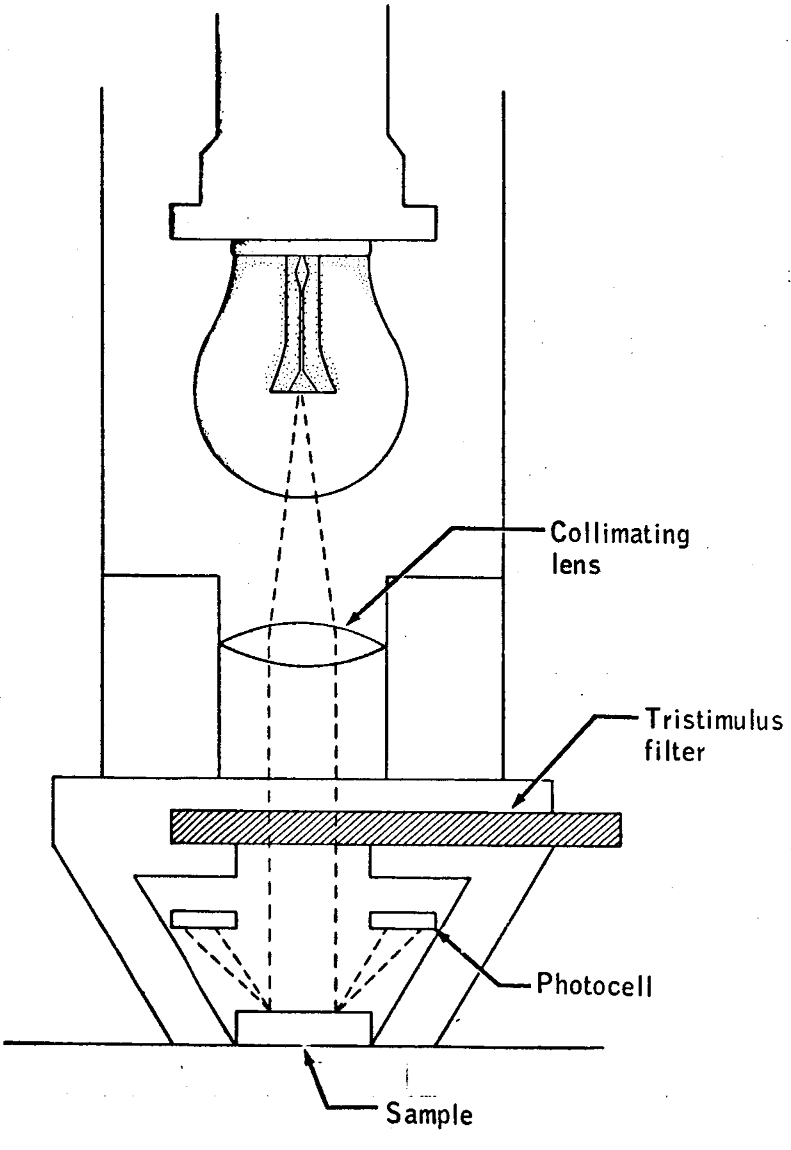


Figure 3. - Search unit of reflectance meter.

sample measured by the colorimeter. These values agreed to the second decimal place. This indicated that, within the accuracy intended for this study, the two methods measured the color of the same area and that they offered alternative modes of description of the same color.

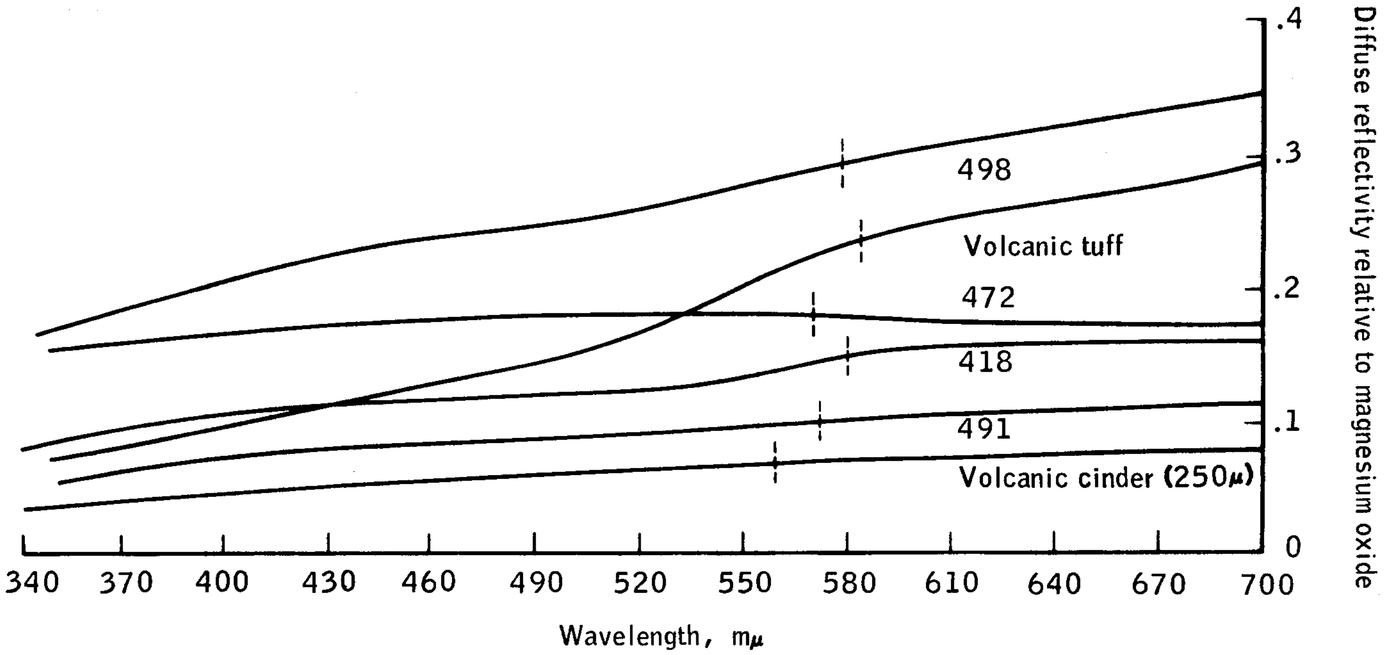
The results of these measurements appear in figures 4 to 10. At the bottom of each graph the following information is given: (1) a number which identifies the sample held by the Geochemistry Laboratory; (2) the rock type and a number in parentheses indicating its maximum particle size in microns if the sample was pulverized (the Roman numerals beside the rock types distinguish different samples of the same type); (3) the geographic location where the sample was obtained; (4) two of the trichromatic coefficients (the third may be obtained from the equation $X + Y + Z = 1$); (5) the dominant wavelength (the dashed line through each of the spectrophotometric curves indicates the dominant wavelength), and when preceded by a small "c," it denotes a purple (ref. 10); (6) the purity; and (7) the visual albedo. The method of measuring and determining visual albedo is described in the foregoing subsection entitled "Reflectance (Tristimulus) Measurements."

It must be understood that the colors described colorimetrically by tristimulus values (such as dominant wavelength) are those colors which would be observed if the samples were illuminated normally by a standard source known as "Illuminant C." This source was chosen as the standard illuminant because its spectral distribution closely approximated that of extraterrestrial sunlight, and, therefore, the colors described by this method would be very close to those that would be observed under the conditions of illumination prevailing on the moon. Accordingly, colors measured in this way could be meaningful when compared to the colors observed on the moon.

The accuracy of the spectrophotometric measurements was expected to be within 2 percent, with the chief source of error being electronic noise superimposed upon the reflectivity tracings. The trichromatic coefficients, determined with the colorimeter, were expected to possess approximately three-place accuracy, although the coefficients for those rocks with albedos under 10 percent would probably be less accurate. Some difficulties were encountered in maintaining a stable calibration of the galvanometer which was used to determine the tristimulus values. Possibly due to an unstable voltage supply, this instability caused an additional error in the tristimulus values approximating as great as 5 percent in some cases.

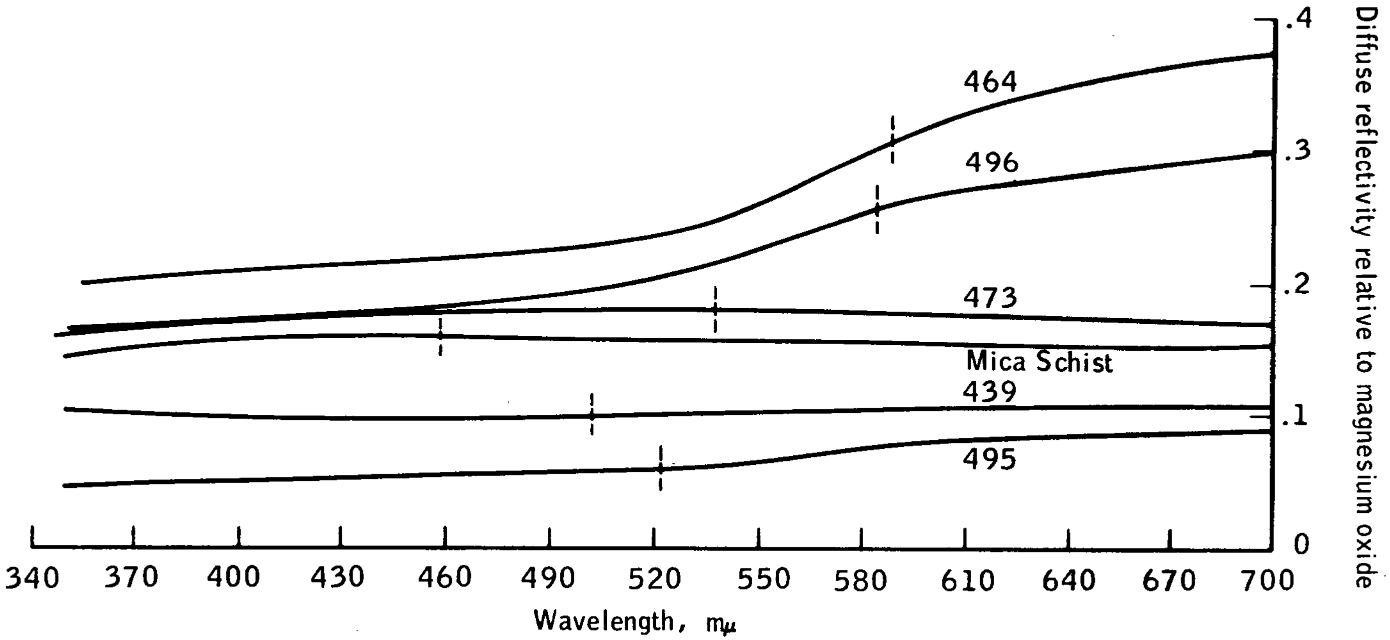
Comparison of Laboratory and Lunar Colorimetry

After the colors were measured, they were compared with the spectrophotometric data of the moon obtained by Wilsing and Scheiner as reworked by Sharonov (ref. 4). These curves appear in figures 11 and 12. In order to compare the colorimetric data (such as dominant wavelength and purity) with the lunar surface data, the trichromatic coefficients and visual albedo of the lunar regions had to be calculated from their spectrophotometric curves. The calculations were made by the weighted-ordinate method at 10-mμ intervals as described by Hardy (ref. 10). To make these calculations, the curves were extrapolated to 400 and 700 mμ, and a constant mean reflectivity was adopted in the extrapolated regions. From these data, the dominant wavelength and the purity of the lunar regions were obtained from tables (ref. 10).



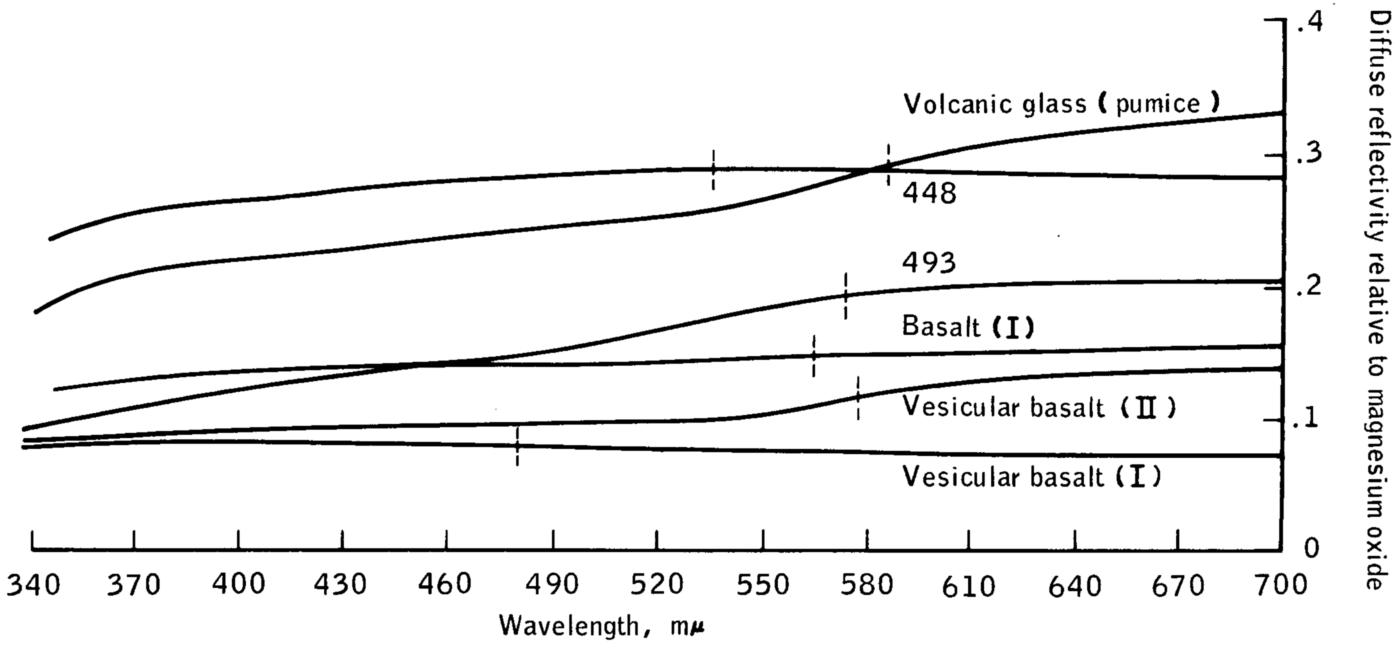
Number	Rock type	Location	Trichromatic coefficients		Dominant wavelength, mμ	Purity, percent	Visual albedo, percent
			x	y			
498	Volcanic ash	Ft. Rock, Oregon	0.335	0.335	581	12	32.1
	Volcanic tuff	Unknown	.356	.346	584	20	27.3
472	Diorite	South America	.311	.318	570	1	19.9
418	Amygdaloidal basalt	Keweenau Co., Michigan	.333	.333	582	11	15.2
491	Volcanic tuff	Mono, California	.320	.330	572	6	7.7
	Volcanic cinder (250μ)	Flagstaff, Arizona	.319	.362	560	15	6.8

Figure 4. - Spectral dependence of diffuse reflectance from six igneous rocks.



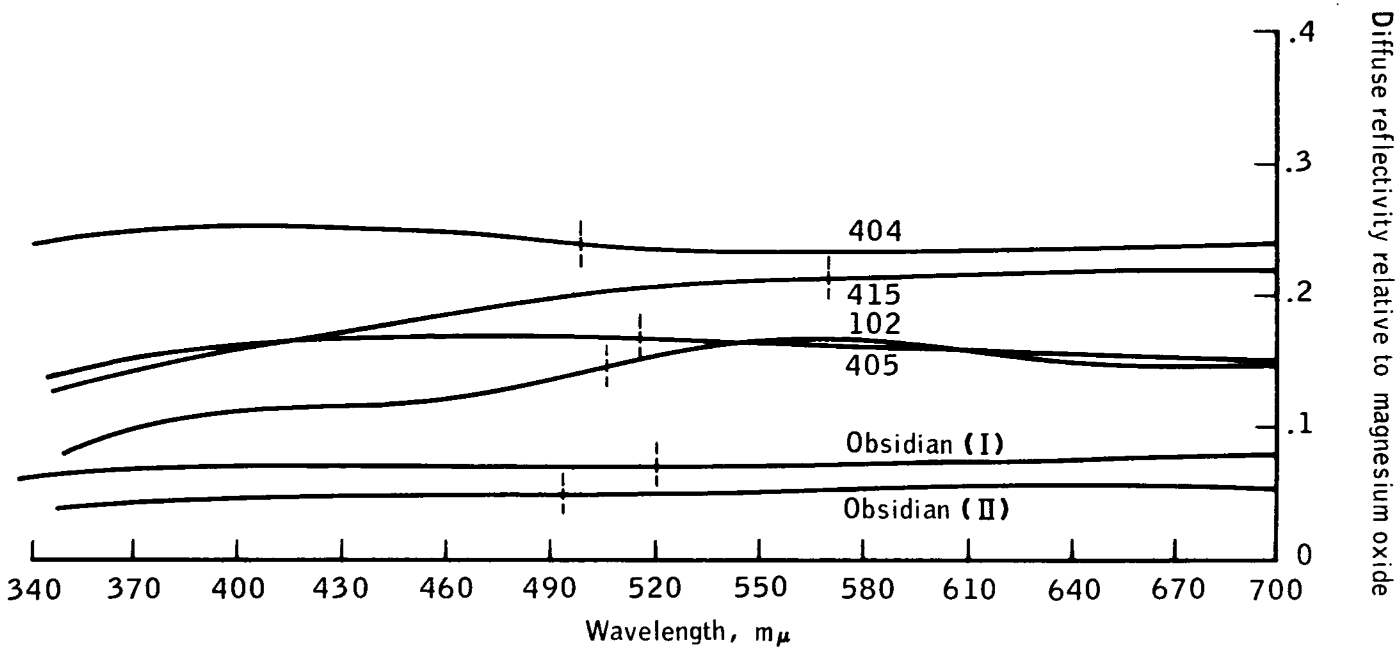
Number	Rock type	Location	Trichromatic coefficients		Dominant wavelength, mμ	Purity, percent	Visual albedo, percent
			x	y			
464	Rhyolite tuff	Ennis, Montana	0.344	0.334	587	14	28.2
496	Volcanic ash	Los Alamos, N. Mex.	.350	.340	584	17	27.0
473	Augite syenite	Larvick, Norway	.300	.358	537	9	14.5
	Mica schist	Unknown	.310	.316	460	0	16.0
439	Gabbro	Ontario	.300	.328	506	3	12.0
495	Vesicular basalt	Mt. Vesuvius, Italy	.300	.340	522	5	9.7

Figure 5. - Spectral dependence of diffuse reflectance from igneous and metamorphic rocks.



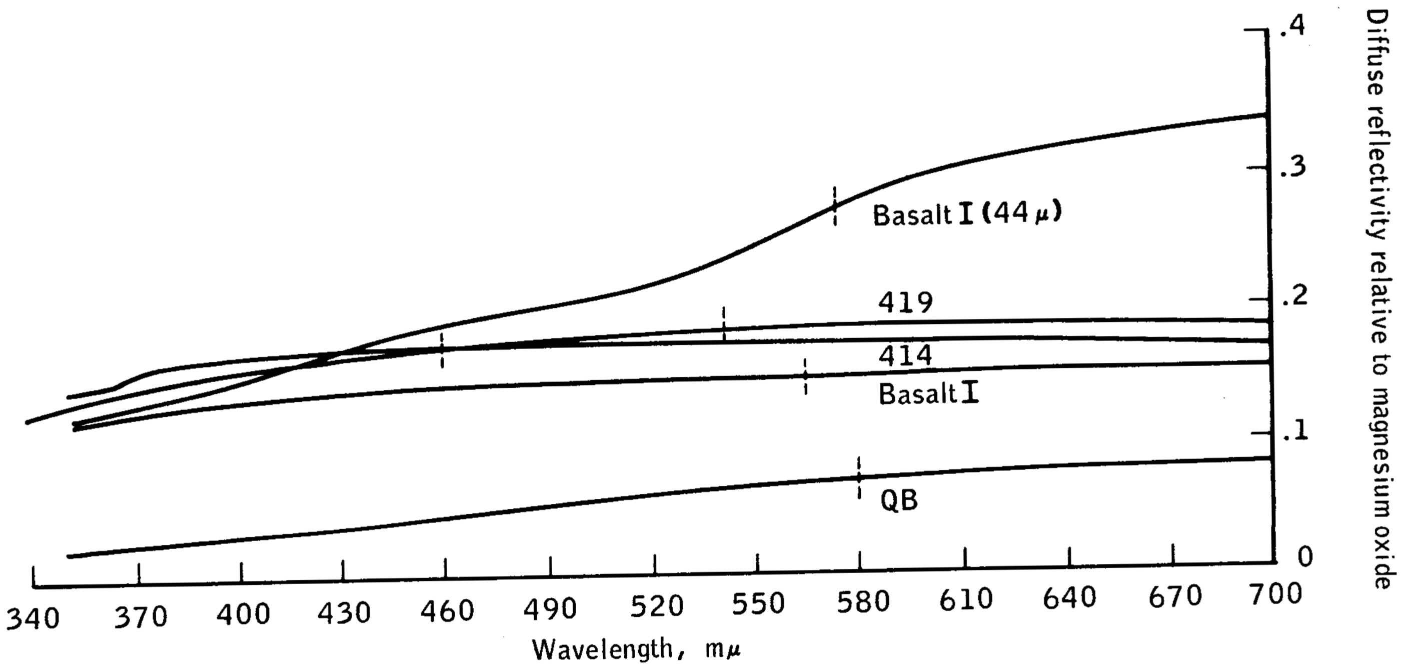
Number	Rock type	Location	Trichromatic coefficients		Dominant wavelength, mμ	Purity, percent	Visual albedo, percent
			x	y			
	Volcanic glass	Mono Crater, California	0.334	0.330	584	10	28.0
448	Monzonite	Colorado	.304	.344	536	6	28.1
493	Hornblende andesite	West Texas	.348	.364	574	23	15.9
	Basalt I	West Texas	.314	.328	565	4	16.6
	Vesicular basalt II	Unknown	.328	.334	578	9	11.0
	Vesicular basalt I	Unknown	.286	.299	c481	10	9.0

Figure 6. - Spectral dependence of diffuse reflectance from volcanic glass, monzonite and four volcanic rocks.



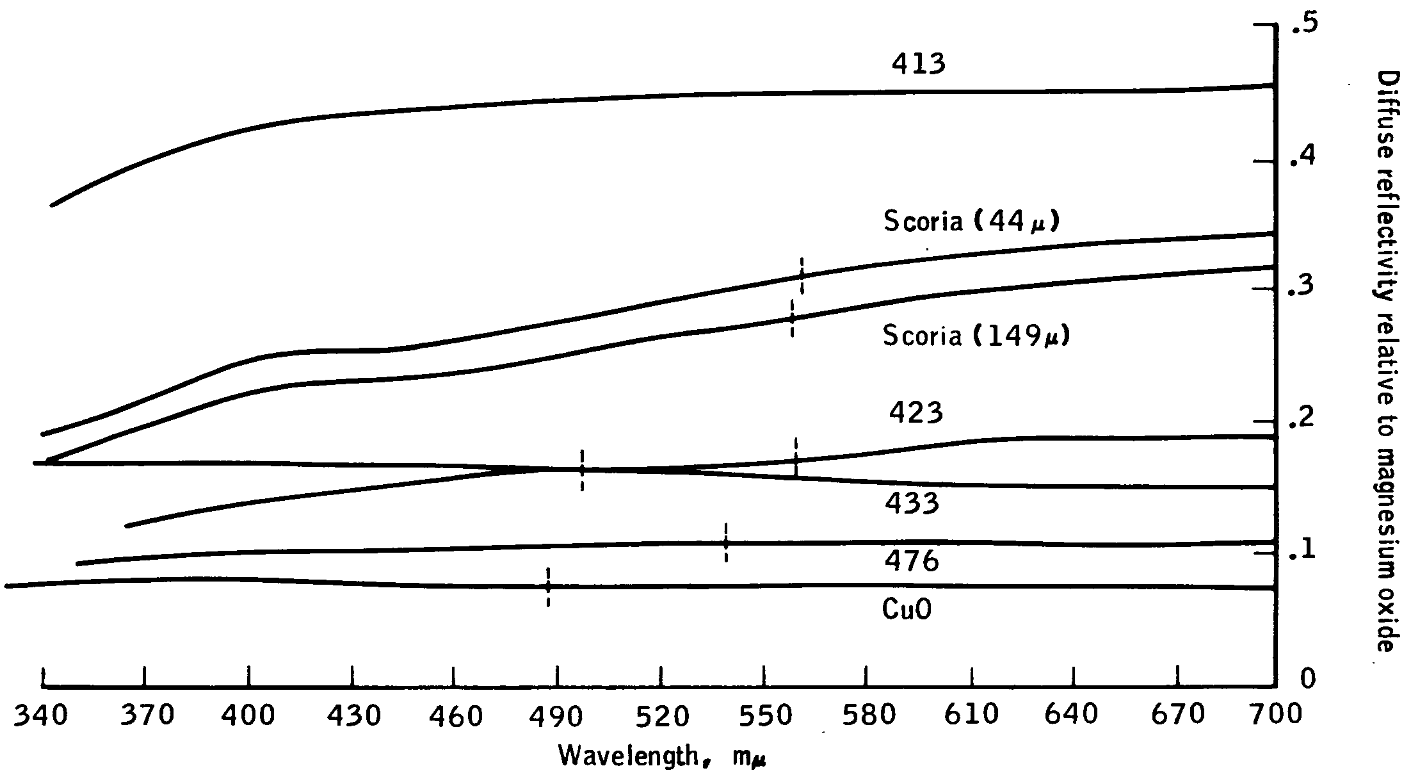
Number	Rock type	Location	Trichromatic coefficients		Dominant wavelength, mμ	Purity, percent	Visual albedo, percent
			x	y			
404	Andesite	San Juan Co., Colorado	0.303	0.323	503	2	25.0
415	Olivine basalt	Boulder Co., Colorado	.324	.336	573	9	18.1
405	Gabbro	Quebec	.307	.323	518	1	16.0
102	Olivine	Unknown	.331	.289	c508	15	11.0
	Obsidian I	Unknown	.301	.338	522	4	9.9
	Obsidian II	Unknown	.320	.314	c496	3	4.9

Figure 7. - Spectral dependence of diffuse reflectance from igneous rocks.



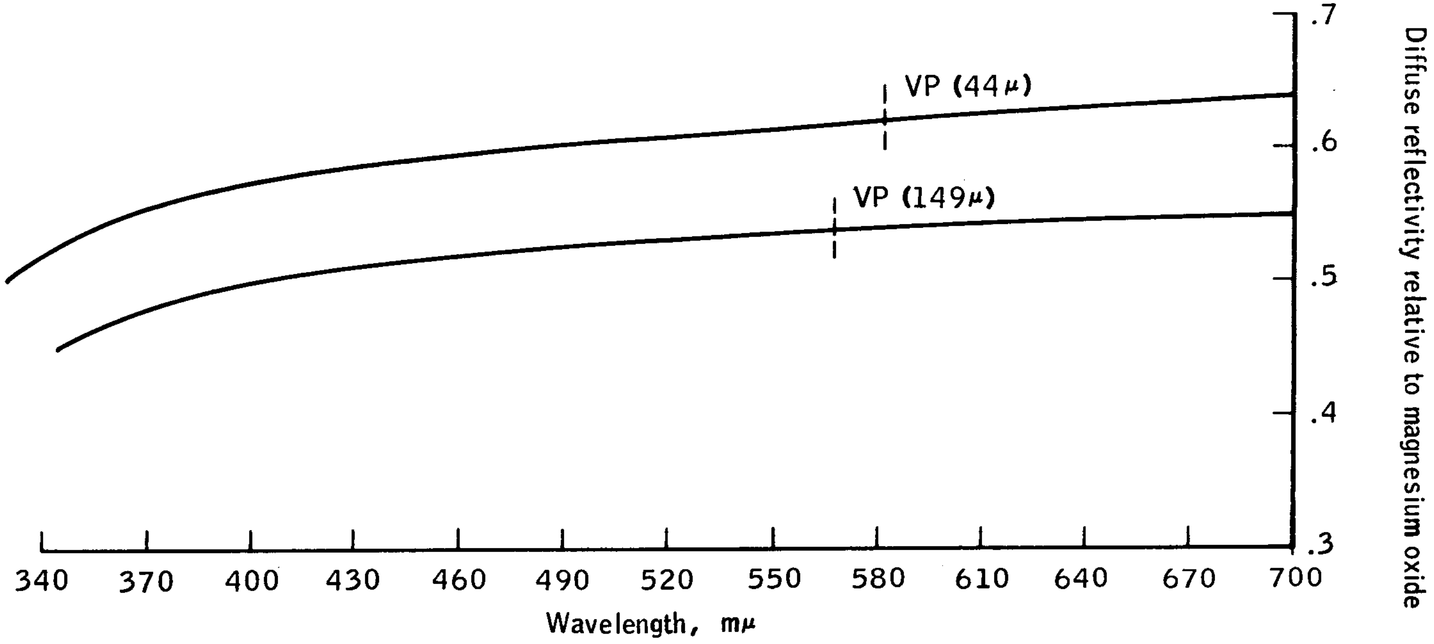
Number	Rock type	Location	Trichromatic coefficients		Dominant wavelength, mμ	Purity, percent	Visual albedo, percent
			x	y			
	Basalt I	West Texas	0.314	0.328	565	4	16.6
	Basalt I (44μ)	West Texas	.332	.342	575	13	25.8
419	Hornblende basalt	Chaffee Co., Colorado	.307	.343	542	9	17.1
414	Basalt	Lintz, Prussia	.310	.316	460	0	15.5
	Quartzite basalt	Unknown	.331	.334	579	10	8.4

Figure 8. - Spectral dependence of diffuse reflectance from five basalt samples.



Number	Rock type	Location	Trichromatic coefficients		Dominant wavelength, mμ	Purity, percent	Visual albedo, percent
			x	y			
413	Hornblende andesite	Mt. Shasta, California	0.314	0.318	588	2	40.0
	Scoria (44μ)	New Mexico	.328	.381	563	22	27.0
	Scoria (149μ)	New Mexico	.326	.395	560	25	23.3
423	Basalt		.316	.338	561	8	17.0
433	Olivine gabbro	Wichita Mts., Oklahoma	.314	.314	c500	2	14.0
476	Biotite diorite	Unknown	.308	.334	540	4	11.6
	Copper oxide (CuO)	Fisher Scientific Co.	.301	.315	489	3	6.8

Figure 9. - Spectral dependence of diffuse reflectance from copper oxide, scorias, and other igneous rocks.



Rock type	Location	Trichromatic coefficients		Dominant wavelength, mμ	Purity, percent	Visual albedo, percent
		x	y			
Volcanic pumice (44μ)	Mono Crater, California	0.317	0.321	582	3	55.7
Volcanic pumice (149μ)	Mono Crater, California	.314	.323	570	3	50.6

Figure 10. - Spectral dependence of diffuse reflectance from pumice samples.

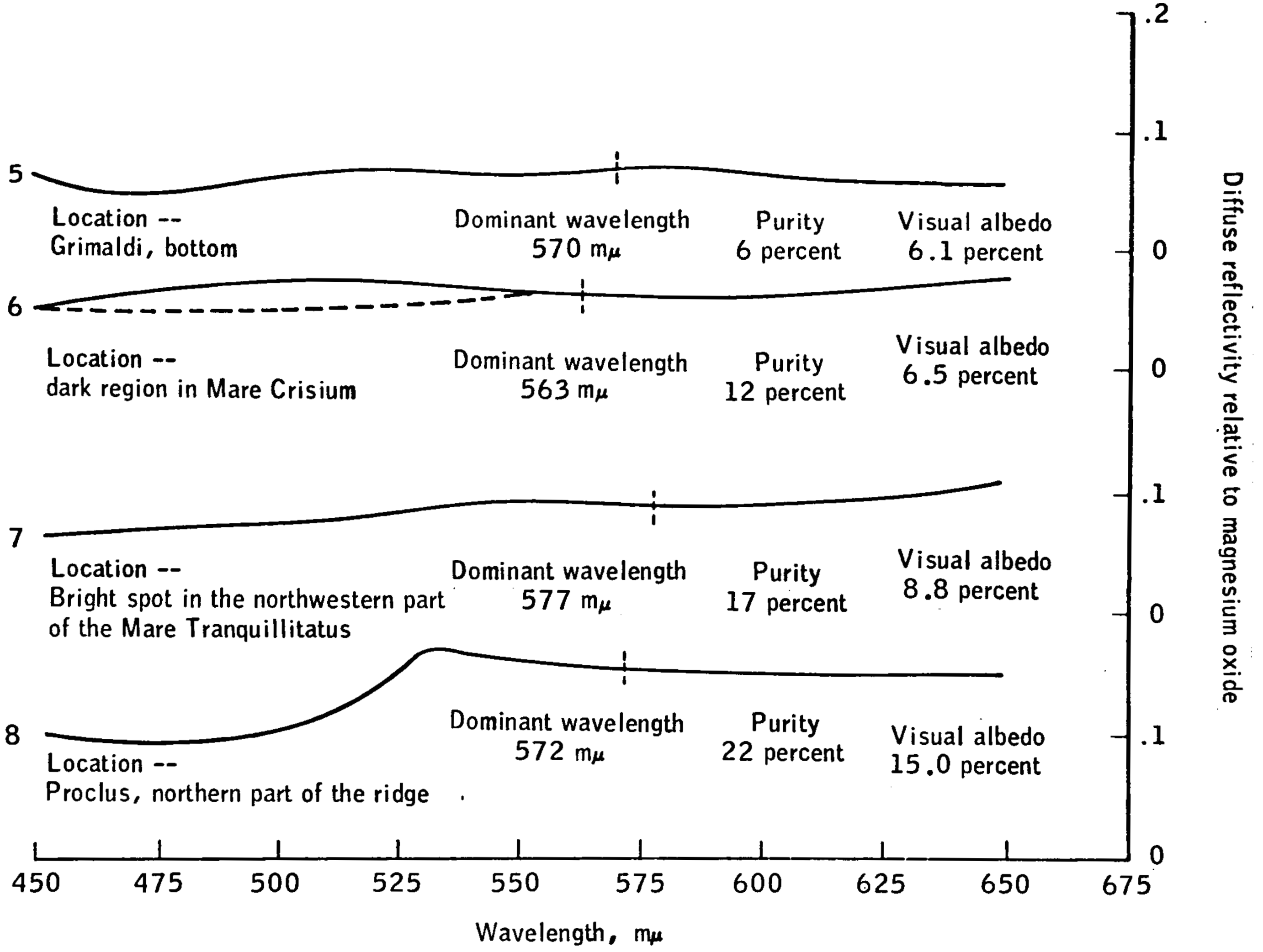


Figure 11. - Spectral dependence of the relative reflectance of Mare Imbrium, Proclus, Mare Serenitatis, and Copernicus (after Sharonov, 1963).

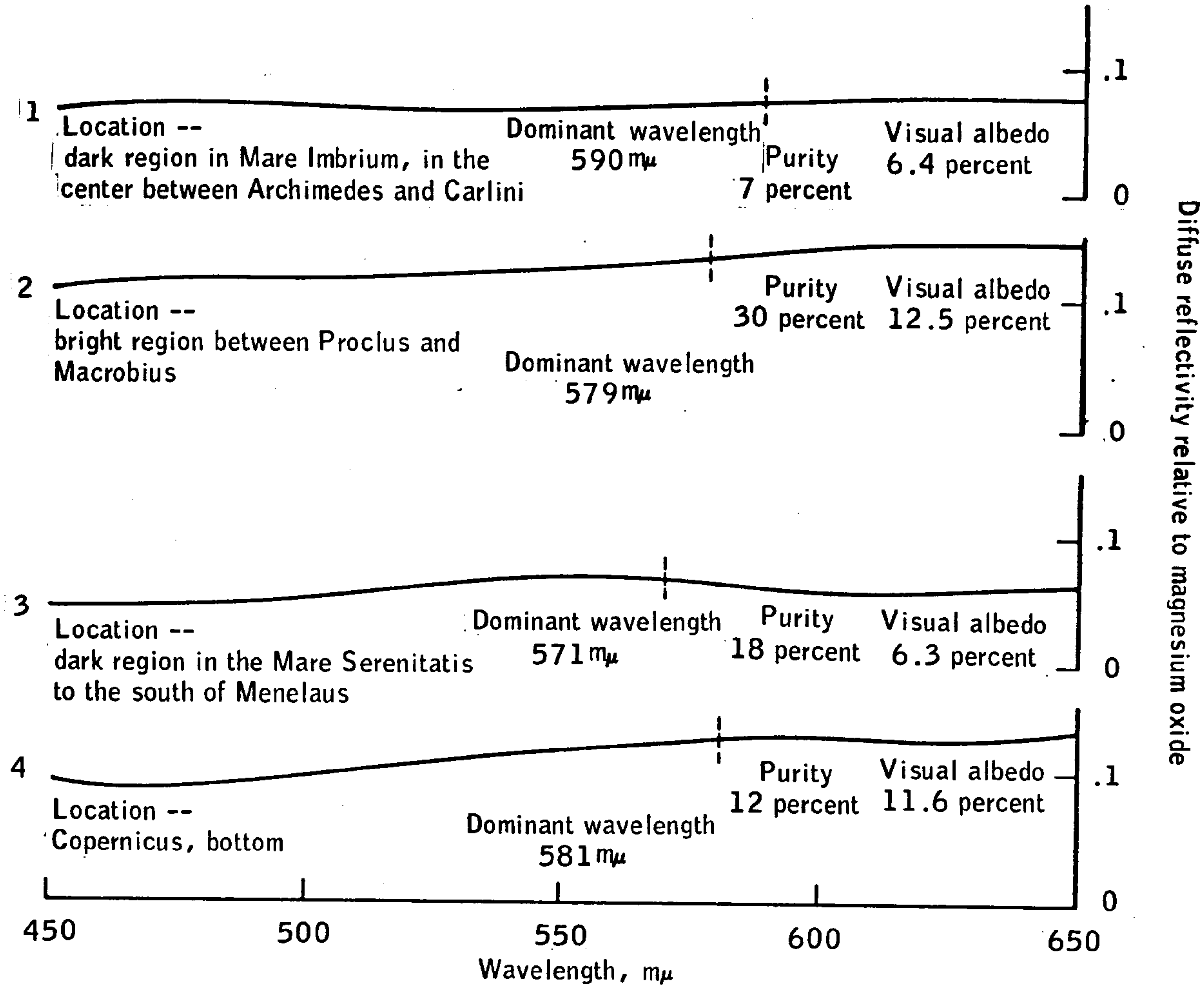


Figure 12. - Spectral dependence of the relative reflectivity of Grimaldi, Mare Crisium, Mare Tranquillitatis, and Proclus (after Sharonov, 1963).

From a superficial comparison of the lunar curves and terrestrial curves, it is obvious that very few of the rocks studied showed simultaneously a close similarity in brightness and color to the moon. The dominant wavelength of all lunar regions is over 570 mμ, demonstrating quantitatively the general redness of the moon surface. The rocks which exhibited some similarity to the lunar data, (that is, having dominant wavelengths between 560 mμ and 590 mμ) were as follows: 413, 415, 418, (44μ) (250μ); 423 (44μ) (250μ); 464, 472, 491, 493, 496, 498, obsidian II (44μ) (250μ); volcanic cinder (250μ); volcanic glass, basalt I, basalt I (44μ); scoria (149μ) (44μ); quartz basalt; and vesicular basalt II. Thus, almost one-half of the investigated samples displayed a rough similarity to the lunar surface on the basis of this criterion. However, when the low-albedo criterion was added, the list was considerably reduced. The rocks which had an albedo of 12 to 20 percent and a dominant wavelength of 560 to 590 mμ were 415, 418, 472, 493, and basalt I. The rocks possessing an albedo below 12 percent and a dominant wavelength of 560 to 590 mμ were 491, 418, (250μ); 491 (44μ); volcanic cinder (250μ); quartz basalt, and vesicular basalt II. Previously it has been demonstrated that solar-wind bombardment results in a lower albedo for practically all rocks (ref. 16). If it were assumed that the rocks tested would have their albedos reduced in a lunar environment, then the two groups of rocks separated by albedo differences would roughly correspond to the lunar continents and maria, respectively. However, if the stricter colorimetric condition that had been observed for the moon were employed (that is, if the group of rocks corresponding to the continents should be redder than the group corresponding to the maria), then this correlation would not apply because the two groups would show no distinct colorimetric difference. The value of colorimetric data is apparent in the determination of which of the terrestrial rocks do and do not closely duplicate lunar properties.

The comparison between specific lunar regions and the samples which were found to be similar is shown in table I. The spectrophotometric curves for the pulverized samples, with the exception of the volcanic cinder sample, are not available because a technique for placing particulate samples in a vertical position was not developed until most of these measurements were completed. Comparison of the reflectivity curves for the samples with the curves of the lunar regions to which they apparently displayed a marked colorimetric similarity revealed that only in the case of Lunar Region 2 and vesicular basalt II did the closely matching pairs show a significant similarity in their spectrophotometric curves. Here the advantage of the fine discrimination available in spectrophotometric comparison was again apparent. All the other listed matches exhibited rather dissimilar reflectivity curves. In comparing the lunar curves with the terrestrial curves, it should be noticed that the scales of the abscissa are somewhat different and that the detail of the lunar curves is not quite so pronounced as the detail of the terrestrial curves.

Conclusions from the Comparison Study

The following conclusions were drawn from this comparative study:

1. Terrestrial volcanic rocks can be found which exhibit color and brightness roughly similar to certain sections on the lunar surface. Basalts, dark volcanic tuff, and dark volcanic cinders show similar properties.

TABLE I. - COLORIMETRIC COMPARISON OF LUNAR REGIONS AND TERRESTRIAL ROCKS

Name	Dominant wavelength, mμ	Purity, percent	Visual albedo, percent
Lunar Region 1	590	7	6.4
418 (250μ)[a] (basalt)	589	16	8.6
Lunar Region 2	579	30	12.5
Vesicular basalt II	578	9	11.0
Lunar Region 3	571	18	6.3
491 (44μ)[a]	572	6	7.7
Lunar Region 4	581	12	11.6
491 (volcanic tuff)	582	15	10.1
Lunar Region 5	570	6	6.1
491	572	6	7.7
Lunar Region 6	563	12	6.5
Volcanic cinder (250μ)[a]	560	15	6.8
Lunar Region 7	577	17	8.8
Quartz basalt	579	10	8.4
Lunar Region 8	572	22	15.0
493 (andesite)	574	23	15.9

[a] Size of particles in microns.

2. Fine color discrimination of spectrophotometric curves is necessary if meaningful correlations are to be made between lunar and terrestrial materials.

3. Rather than only attempting to match arbitrarily selected individual samples (the method used in this investigation), it appears that a statistical approach should be required in order to obtain a significant correlation between rock types and color. Such an approach should consider the rock-property changes determined under simulated lunar conditions in preference to the arbitrary matching of selected samples.

In comparing the lunar and the terrestrial reflectivity curves, it will be noticed that most of the terrestrial rocks display a reflectivity which increases monotonically with wavelength, whereas most of the lunar curves exhibit anomalous intensities in the middle portion of the spectrum. This is especially apparent for Lunar Regions 3, 5, 6, 7, and 8. Sharonov (ref. 4) has pointed out that the accuracy of these curves discloses that much of the detail exhibited may not be real. However, many of these anomalous maximum intensities appear to extend over wavelength bands approximately 100 mμ wide and do not appear to be of a random nature; consequently, it is tempting to regard them as real. The maximum intensity at 520 mμ on the curve of Lunar Region 6, shown in figure 12, is strikingly similar to the luminescence detected by Dubois, shown in figure 1. In addition, Sytinskaya's catalog of lunar albedo (ref. 15) shows the visual albedo of Lunar Region 6 to be as follows: 1935, 4.0 percent; 1938, 6.5 percent; and 1939, 7.5 percent.

According to Abetti (ref. 17), a minimum in the solar cycle occurred in 1933 and again in 1944. Lunar luminescence appears to increase successively with recurring solar minima according to the physicist Danjon's findings (reported in ref. 18). Therefore, if Lunar Region 5 luminesced in the visible wavelengths, the albedo trend would be satisfactorily explained. Furthermore, the luminescent band discovered by Dubois at 520 mμ, shown in figure 1, was observed in Mare Crisium where Lunar Region 6 is located. Also, Wilsing and Scheiner made their observations from 1908 to 1910 during an exceptionally weak solar cycle (ref. 17). Since the intensity of lunar luminescence is connected with the strength of solar activity, the albedo calculated from the Wilsing and Scheiner measurements (6.5 percent) could be expected, in regard to Lunar Region 6 luminescings, to be somewhat lower than the albedo given in Sytinskaya's catalog for 1939 (7.5 percent). Therefore, it is tempting to suggest that the hump on the curve characterizing Lunar Region 6 is a luminescent phenomenon and to postulate that the apparently anomalous humps exhibited by the other curves might also be due to lunar luminescence. These results indicate that accurate lunar spectrophotometry is useful for monitoring lunar luminescence.

EFFECT OF SAMPLE PULVERIZATION

The last phase of the laboratory study was to investigate the effect of pulverization on the color of rock samples. This investigation was made by grinding a rock sample, sifting it through a series of sieves to obtain samples of different particle size, and measuring its brightness and color with the colorimeter. At the end of the experimental study, a technique was developed for preparing samples so that they could be successfully placed in a vertical position for spectrophotometric analysis. Unfortunately, this could only be accomplished by pressing a powdered-rock sample into a metal ring, using a hydraulic press with a ram force of about 15 000 pounds. As the result, the samples were highly compressed and did not simulate lunar porosities. Colorimetric measurements for solid and particulate samples are given in table II.

The results of this study were summarized as follows:

1. In almost every case, the particulate samples were brighter than the solid rock.

2. In all cases, the brightness increased with decreasing grain size.

3. In all cases, the particulate samples were redder than the solid samples, and this reddishness increased with decreasing grain size.

The fact that the brightness of the samples increased with decreasing grain size can be explained by internal reflection. When light is incident on a particle, it may be reflected, absorbed, and converted into some other form of energy, or it may be transmitted. When light is transmitted, it undergoes another reflection when it encounters the exit surface of the particle and again when it encounters the entrance surface of the second particle, and so on. Consequently, more light is often scattered back toward the observer than in the case of a solid substance because of the innumerable internal reflections which occur in a pulverized substance. As the particle size decreases, the number of particles capable of contributing to internal reflection per unit area will increase. Accordingly, the light scattered toward the observer and the brightness of the sample will increase with decreasing particle size.

The reddening of the particulate samples, indicated by a comparison of the spectrophotometric curves of the last three samples which appear in figures 9 and 10, is more difficult to explain. From an examination of the elementary diffraction formula ($\sin \theta = \lambda / w$, where θ is one-half the angular width of the central maximum of the diffraction pattern, λ is the wavelength, and w is the width of the diffracting obstacle), it can be seen that light of longer wavelengths is more readily diffracted with decreasing maximum grain size. More particles with dimensions comparable to that of the wavelength of light will be present; consequently, diffraction effects should become more prominent. Since red light is more easily diffracted than light of shorter wavelengths, red light could have the greater probability of emerging from internal reflections just beneath the surface because of its superior ability to bend around particles of small size. If the trend of increasing redness with decreasing grain size has the validity expected, the general redness of the moon could be evidence supporting the hypothesis of a prevailing pulverized lunar surface layer containing a significant percentage of particles comparable in size to the wavelength of light.

Observations by Strong in 1958 (reported in ref. 19) are purported to show that the reflectivity of a roughened surface depends on the ratio of the wavelength of the incident light to the scale of roughness characterizing the surface. These observations would add to the support of the diffraction hypothesis. The fact that the purity of the color in several cases seemed to increase with decreasing grain size, as shown in table II, seems to contradict the opinion of many observers that progressive pulverization will tend to wash out color; however, far too few samples were examined to form a definite opinion. It would be desirable to have more extensive investigations of this type performed encompassing a greater number of smaller grain sizes. If redness

TABLE II. - COLORIMETRIC RELATIONSHIPS OF PULVERIZED SAMPLES[a]

Name	Dominant wavelength, mμ	Purity, percent	Visual albedo, percent
418 (basalt)	582	4	15.2
418 (250μ)[b]	589	16	8.6
418 (44μ)	598	18	15.2
491 (volcanic tuff)	c500	1	7.0
491 (250μ)	554	11	5.6
491 (44μ)	582	15	10.1
423 (basalt)	561	8	17.0
423 (250μ)	576	15	27.2
423 (44μ)	579	16	30.0
Obsidian II	c496	3	4.9
Obsidian II (250μ)	572	8	25.7
Obsidian II (44μ)	574	8	38.6
Vesicular basalt I	c481	10	9.0
Vesicular basalt (250μ)	507	2	12.5
Vesicular basalt I (44μ)	511	4	16.5
Pulverized samples prepared with hydraulic press			
Basalt I	565	4	16.6
Basalt I (44μ)	575	13	25.8
Scoria (149μ)	560	25	23.3
Scoria (44μ)	563	22	27.0
Volcanic pumice (149μ)	570	3	50.6
Volcanic pumice (44μ)	582	3	55.7

[a] Pulverized samples were prepared by sprinkling the sample on a glass plate.

[b] Maximum particle size in microns for sample regularly tested or prior to pressing.

could be definitely correlated with grain size, colorimetric measurements of the moon would have significance in obtaining data on the particle sizes of lunar surface materials.

DISCUSSION AND RECOMMENDATIONS

From the preceding review of lunar colorimetry and from the results of the laboratory work, certain conclusions and recommendations can be drawn. The greatest need at the present time is for accurate spectrophotometric data on areas of the lunar surface. Undoubtedly, the spectrophotometer provides the most precise mode of color specification and has the added advantage of offering a possible method of monitoring lunar luminescence. Both Barabashov and Coyne (refs. 9, 1, and 14) have concluded that the spectral curves of lunar regions depart far enough from a monotonic variation with wavelength to render a spectrophotometric documentation of their reflectivity curves necessary and desirable. Unfortunately, recently applied photographic spectrophotometry does not appear to possess the desired accuracy. A photoelectric technique is needed to perform spectrophotometric measurements of the lunar surface. A photoelectric spectrograph built by John Grainger and James Ring (reported in ref. 18) to detect lunar luminescence by the line-depth method seems to be the type of instrument needed for such measurements. A thorough investigation of absolute and differential colors across the visible face of the moon by photoelectric spectrophotometry should be a project of high priority.

Along with a rigorous investigation of lunar color, it would be most desirable to administer an equally rigorous investigation into the colorimetric properties of terrestrial rocks. This would be advisable not only to deduce the possible surface composition, the texture, and the evolution of the moon, but also to determine what terrestrial materials could be used to build a lunar simulation which would be realistic both colorimetrically and photometrically. The copper oxide (CuO) which is presently used by technicians at the Manned Spacecraft Center to duplicate the photometric function of the lunar surface is entirely unsuitable colorimetrically; this is disclosed in an analysis of the data for CuO given in figure 9.

If it were presumed that our first lunar astronauts would undergo training in the observation of objects in a simulated lunar environment, it would be desirable to build simulations which would be colorimetrically realistic for the training of our astronauts in the range and the significance of the colors which might be observed eventually on the lunar surface either visually or with auxiliary aids such as color filters. Perhaps the best approach would be to perform a rough, statistical classification of rocks on the basis of one colorimetric parameter such as the color index, then these rocks could be further classified on the basis of brightness. Those rocks and pulverized specimens which displayed a marked similarity to matter on the moon could then be classified according to the nature of their reflectivity curves determined with a spectrophotometer.

Although the statistical analyses, which have been carried out on terrestrial rocks to date, have yielded significant information, they are all inadequate because the rocks tested were not subjected to a simulated lunar environment before their colorimetric properties were measured. Many recent experiments have shown that practically all terrestrial rocks are affected to a marked degree by the bombardment of corpuscular radiation similar to that which is constantly showering on the lunar surface from the solar wind. The properties of the lunar crust which are most difficult to duplicate with terrestrial materials are the pronounced backscatter, the negative polarization, the low albedo, and the marked reddening of the surface. It has been shown that the effect of ion irradiation on fine powders is to make them much more similar to the lunar surface in all the aforementioned areas. On the basis of irradiation experiments, Rosenberg and Wehner (ref. 20) concluded that irradiated powdered basalt gives reflection and albedo characteristics very similar to those of the moon and that many of the unusual properties of the lunar surface can be explained by the action of solar-wind bombardment. Thus, detailed colorimetric measurements on irradiated rock samples should be made when a comparison with the lunar surface is desired.

It has been pointed out that luminescence contributes a sizeable amount of the light (10 to 20 percent) in some regions of the spectrum in the lunar areas which exhibit this phenomenon. Thus, for accurate colorimetric comparisons and measurements, this effect should be considered. There is a great need to investigate the luminescent spectra of terrestrial materials under simulated lunar conditions. Such an investigation would not only allow the determination of how much luminescence contributes to or alters the colors of lunar areas as observed from earth, but it would also provide information on a promising optical method for the identification of lunar surface materials — the identification of specific minerals or rocks by their luminescent spectra. These investigations should be carried out on minerals rather than on rocks since minerals exhibit better-defined spectra. Once the luminescent properties of the common rock-forming minerals have been thoroughly documented, the luminescent spectra of rocks can be calculated (ref. 21).

The utilization of the investigations of luminescence is illustrated by the recent research of Kopal (ref. 18) who investigated the luminescent spectrum of achondritic enstatites to verify if proton bombardment of these minerals could result in significant luminescence comparable to that which has been detected on the moon. He found that a broad luminescent band at 670 mμ was excited when meteoritic material was irradiated with protons. In an extension of these studies, Kopal proceeded to photograph the lunar surface with three interference filters, including one in the red region which transmitted light in the vicinity of the luminescent band. A striking enhancement of luminescence was found in a series of photographs of a region near the crater Kepler when the red filter was used, although the enhancement only lasted for a short time.

The problem of determining how the colors of lava-flow rock and particulate volcanic rocks (such as cinders) change when viewed from high altitudes should be investigated to establish data on the nature of the systematic error which results in the comparison of the color of individual rock samples with the observed color of large areas of the moon. Terrestrial observations made from aircraft or orbiting satellites conducted visually or photoelectrically with color filters might yield significant data on this point. Undoubtedly, the effects of atmospheric scattering should be considered in the making of such observations.

Ideally, one could develop a photometer and color filters with response functions capable of directly determining the tristimulus values of such outcrops, but the necessity of having to make corrections for atmospheric scattering, as a function of time and altitude, would probably make such absolute determinations of color prohibitively complex. However, aerial observations could produce valuable qualitative information on the color of extended areas viewed from high altitude.

Since it seems likely that lunar color may be directly related to rock types and to regions exhibiting similar geological characteristics, the possibilities of mapping the moon on the basis of color and color differences should be thoroughly explored. One of the more promising of such methods is a proposal for a television colorimeter as outlined by Rennilson (ref. 22). He proposes a television camera with three color filters with response functions corresponding to the three tristimulus functions used in colorimetric measurements. The video signals from this camera could be computer-processed so that information could be presented directly in the form of trichromatic coefficients. Working with processing techniques made available by high-speed computers, these coefficients could be linked together on a positive transparency to display areas of equal color in a lunar landscape and thus be used directly for geological interpretation. Such a device on the lunar surface or in an orbiting lunar satellite could provide a very efficient and informative method of mapping the moon.

CONCLUDING REMARKS

One of the greatest weaknesses involved in comparative lunar and terrestrial colorimetry is the absence of a rigorous theoretical framework to explain and predict colors and to determine the significance of color differences. This deficiency resulting from insufficiencies reduces colorimetric studies to a rather crude form of empiricism. Classical electromagnetic theory has been applied in detail only to smooth specularly reflecting surfaces and probably is not as yet applicable to the lunar surface.

One of the most vexing problems in selenology is the transition from simple and generally inapplicable cases to those where roughened surfaces are encountered. Theories should be developed so that the colorimetric properties of scattered light can be related to the dielectric characteristics and texture of the surface. The fact that this type of precision is not available in lunar colorimetry is a major obstacle to the interpretation of colorimetric data. This shortcoming, combined with the fact that color differences on the moon are extremely small relative to terrestrial standards, has caused some authorities to believe that colorimetric information is of less value than information on surface texture derived from photometric and polarimetric studies. Until the significance of lunar colors is brought into the scope of physical theory, this fact will probably continue to be true. In addition to colorimetric observations and comparisons, a detailed theoretical study of lunar surface composition, lunar evolution, probable mechanisms of erosion on the moon, and other factors possibly responsible for the observed color distribution on the moon, should be made to help unravel the significance of lunar color.

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APPENDIX

COLOR INDICES AND STELLAR MAGNITUDES

The luminosity and reflectivity of the moon in visible light (that is, near $\lambda = 0.55\mu$) is fundamental to optical observations. The stellar magnitude of the disk at full phase determines the maximum general reflectivity or geometric albedo p of the moon and, consequently, also determines its surface brightness (luminance) in either conventional photometric units or in absolute energy units. The spherical or physical albedo $A = pq$ is a measure of the fraction of the incident flux reflected in all directions in space and is determined by the phase integral q which results from the variation of relative luminosity with the phase angle (that is, the geometric relationships between the sun, moon, and observer). The variations of p and q as a function of wavelength are required for gaining any knowledge about the nature of the lunar surface. When detailed spectrophotometric data are not available throughout the visual spectrum, color indices are used to provide a rough indication of energy distribution. These are commonly given as the difference between magnitudes measured through two or more broadband filters and are therefore defined as

$$C_{1,2} = m_1 - m_2 = -2.5 \log \frac{\int_0^\infty E(\lambda)T_1(\lambda)Q_1(\lambda)\,d\lambda}{\int_0^\infty E(\lambda)T_2(\lambda)Q_2(\lambda)\,d\lambda} \tag{2}$$

where $T(\lambda)Q(\lambda)$ is the product of the spectral transmission function of the filter-and-optical system and the quantum efficiency function of the receiver defining the spectral region of the magnitude m, and $E(\lambda)$ is the illumination or surface density of luminous flux. In the standard UBV photometric system, the magnitudes refer to broad bands in the ultraviolet, blue, and visual (yellow) ranges defined by a specified filter plus photocathode combinations (ref. 23). The center of gravity of the area under the curve $E(\lambda)T(\lambda)Q(\lambda)$ defines the effective wavelength of a given source-filter-receiver combination.

The practical usefulness of this system is illustrated by an example such as that presented by a gray or neutral scatterer which would have the same color indices as the source of illumination. Selective reflectivity is indicated by the positive or negative color excess of the body with respect to the color index of the sun over the same spectral range. The moon has a positive color excess or is "redder" than the sun. When the relative spectral-energy distribution function of the moon is desired, it can be given to a first approximation by

$$\log \left[\frac{E(\lambda)}{E(V)}\right] = \log \left[\frac{E_s(\lambda)}{E_s(V)}\right] - 0.4\,\delta C(\lambda) \tag{3}$$

where $E_s(\lambda)/E_s(V)$ is the relative spectral-energy distribution function of the sun, normalized to $\lambda_V = 0.555\mu$, and $\delta C(\lambda) = C(\lambda) - C_s(\lambda)$ is the color excess of the moon. When a reference other than the sun is used, it is necessary to correct for the change of effective wavelength of the filter-receiver combination depending on the source function. The effective wavelength λ_e, for example, for the B standard photometric system varies from approximately 0.44μ for white stars ($B-V \approx 0$) to 0.46μ for red stars ($B-V \approx +1.5$); the range is smaller in the U and V systems with their smaller bandwidths. For narrow bandwidths $\Delta\lambda < 0.01\mu$ which are used in monochromatic-magnitude systems and in spectrophotometry, the error is small enough to be neglected. In the case of spectrophotometry, a precise accounting must be made for effects of even slight differences between the spectra of the sun reflected by the moon and those of the comparison stars because such differences can cause apparent fluctuations in the derived spectral-energy curve of the moon.

The color index is the ratio of intensities measured when an object is observed in two different regions of the spectrum and is usually expressed in stellar magnitudes (see equation (2) where m_1 and m_2 are the stellar magnitudes of the intensity measured in the two spectral regions relative to an arbitrary zero).

The traditional system of visual stellar magnitudes m_ν measures the illumination E which determines the luminous flux ϕ entering a given optical system having an entrance pupil area of S (that is, $\phi = ES$). By definition,

$$m_\nu = \mu_1 - 2.5 \log E \qquad (4)$$

The constant μ_1, "the stellar magnitude" of 1 lux $\left(\text{that is, the unit of illumination equaling } 1\ \text{lm}/\text{m}^2\right)$, is not precisely known and is most logically defined by the illumination at the limit of the atmosphere. The adopted value $\mu = -14.05 \pm 0.05$ is subject to a large margin of error. This uncertainty is inconsequential because only magnitude differences are normally measured, and absolute determinations require only a knowledge of the known, photometric constants for the sun. The zero point of the V photometric system of Johnson is defined by the mean magnitude of 10 primary standard stars (ref. 23).

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