Martian Surface Materials: Effect of Particle Size on Spectral Behavior

Abstract. *The presence of abundant limonite on Mars has long been the subject of controversy. Some advocates of abundant limonite also suggest that the albedo differences between Martian light and dark areas are caused by different sizes of particles in those areas. We show that the relative albedo is reversed from the blue to the red for samples of limonite with particles of different sizes. Observations of Mars reveal no blue-red albedo reversal between the light and dark areas. Consequently, the hypothesis of particle size control of albedo is incompatible with the presence of abundant limonite on Mars.*

The light areas on Mars have traditionally been described as deserts, with limonite [mainly $FeO{\cdot}OH{\cdot}nH_2O$ with impurities (*1*)] as the major soil constituent. Such a soil is consistent with polarimetric, spectrometric, color, and albedo measurements (*2*). In a previous paper, Van Tassel and Salisbury (*3*) broke with this tradition and concluded that the evidence for such abundant limonite is ambiguous and that abundant limonite is geologically unlikely.

Rea (*4*) and Sagan (*5*) took issue with these conclusions, reasoning that abundant limonite could, in fact, be present on the Martian surface. These two authors have also suggested that variations in the size of particles in the surface materials could be responsible for the albedo differences between the light and dark areas on Mars (*6*). It is the purpose of this report to point out that these two hypotheses are mutally exclusive.

The visible spectral response of solid materials as a function of particle size allows them to be classified as transparent, opaque, or trans-opaque. We define trans-opaque materials as those that are transparent in one part of the visible spectrum and opaque in another part. Consequently, trans-opaque materials are always colored. Each of these classes is referred to below and an example of the spectral behavior of each is presented in Fig. 1.

Silicate minerals as a class exhibit transparent behavior in the visible region of the spectrum. Characteristically, a decrease in particle size will result in an increase in the spectral albedo (bidirectional reflection) throughout the visible region.

Other minerals, such as metal sulfides, exhibit opaque behavior in this spectral range; with them, a decrease in particle size results in a decrease in albedo. A few minerals, such as limonite, goethite, and hematite, exhibit what we call trans-opaque behavior. For these minerals, a decrease in particle size causes the albedo to increase in one portion of the visible (trans), while it decreases in another (opaque). Consequently, the spectral curve for one particle size will cross that for a different size, leading to a reversal in relative albedo between the two particle sizes within the visible range. This behavior, illustrated in Fig. 1C, is typical of the many different samples of ferric oxide that we have investigated.

The spectra in Fig. 1 were recorded from samples that were ground in an alumina ball mill and sieved through brass screens in an atmosphere of dry nitrogen, which permitted better separation of particle sizes than could be obtained in (humid) air. As suggested to us by D. G. Rea, a more complete separation can be obtained by washing coarse particles in acetone to remove the clinging fine particles. When this additional operation was performed on our samples it resulted in increased reflectivity differences; for example, for the sample of limonite, the reflectivity of the coarsest particles was further reduced in the red and increased in the blue, because of the removal of additional fines.

Figure 2 shows curves of observed spectral reflectivity compiled by Loomis (*7*) for the light and dark areas on Mars. Although some disagreement persists concerning the exact height and slope of these curves, there is general agreement that they do not intersect within the visible range (*8*). If the albedo variations on Mars were caused by differences in particle size *and* the surface material were composed of pulverized limonite (*6*), then there should be a relative albedo reversal between 0.5 and 0.6 μ.

Because such a relative reversal does not take place, as shown by the telescopic observations, the accuracy of which are well within that required to detect such a reversal, we point out here that the hypothesis of particle size control of albedo is not compatible with a soil composed in large part of limonite.

The presence of some trans-opaque material on the Martian surface is indicated by the slope of its spectral curve (*9*). (Such trans-opaque material does not have to be limonite, although some form of ferric oxide is a most likely candidate.) Rocks have a tendency to have their color and albedo strongly affected by that of their opaque and trans-opaque accessory minerals, and this makes it possible for less than a few percent of trans-opaque material to provide the slope of the Martian spectral curve (*10*). Providing that there is

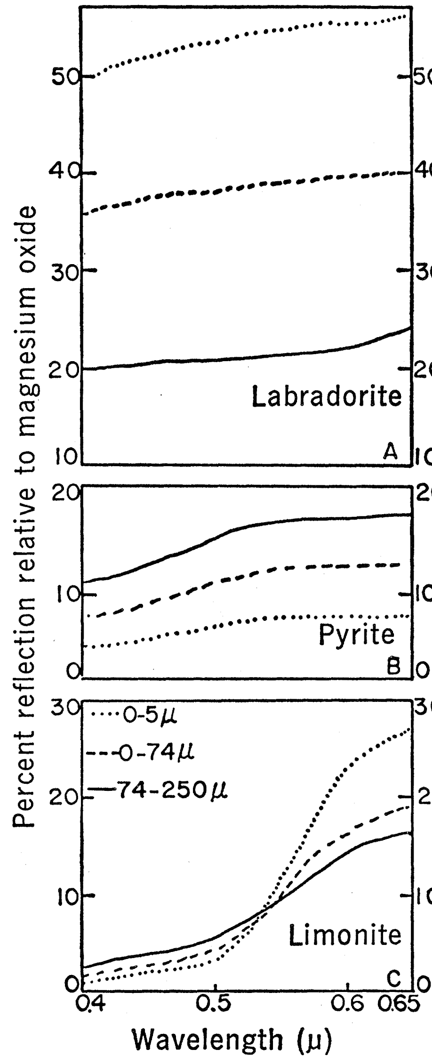

Fig. 1. Reflection spectra samples of labradorite (St. John Lake, Quebec), pyrite (Rico, Col.), and limonite (Tuscaloosa Co., Ala.), each having three different sizes of particles. The spectra were recorded, relative to a freshly prepared magnesium oxide surface, with a Cary spectrophotometer, model 14, fitted with a double-beam bidirectional reflection attachment (*12*). Samples were obtained and ground by the University of Denver.

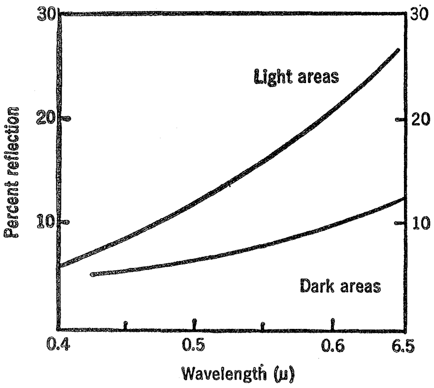

Fig. 2. Spectra of Martian light and dark areas, compiled by Loomis (*7*).

a very low percentage of trans-opaque material present in the soil, the spectral curves for different sizes of particles may not cross.

Thus, although we have shown here that the two hypotheses are mutually exclusive, there is insufficient evidence available to allow a choice between the particle size–albedo hypothesis and the hypothesis that the Martian soil consists in large part of limonite. Whatever the cause of the albedo differences on Mars, we believe that the most likely soil, from the standpoint of geology, is one composed of silicates lightly stained or coated with ferric oxides, as advocated by Van Tassel and Salisbury (*3*). This belief is consistent with the conclusions of Adams (*11*), based upon the suspected Martian band near 1 μ.

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Vision: The Additivity Law Made To Work for Heterochromatic Photometry with Bipartite Fields

Abstract. *Additivity failures are common in heterochromatic photometry when the usual criterion of equal brightness is used. Using instead the criterion of a minimally distinct border between two precisely juxtaposed fields, we found that the additivity law holds.*

The photometric quantity called luminance (L) is derived from the physical quantity called radiance (N) by taking into account the spectral sensitivity of the eye (V_λ) (*1*). If the radiance of a surface is known as a function of wavelength, luminance may be calculated by evaluation of the definite integral

$$L = K\int_{380\text{ nm}}^{750\text{ nm}} N_\lambda V_\lambda d\lambda \qquad (1)$$

Equation 1 states that superposed lights, of differing spectral compositions, should have luminances that add linearly (Abney's law); such additivity is true by definition and international agreement. The assumption that fields of equal luminance are also equally bright holds only when additivity is demonstrated and brightness judgments are used as a criterion. Despite Abney's claim, such additivity is generally not found; in particular, the superposition of lights that are complementary, or nearly so, results in clear cancellation of brightness as well as of chromaticness (*2*).

We now show that one can make a direct side-by-side comparison of photometric fields in a manner that causes the additivity principle to be obeyed. This experiment is performed by juxtaposing two fields with high precision and then asking the observer to set the radiance of one field relative to the other until the border between them is minimally distinct. Our search of the literature has found no evidence of such an experiment; nearly all writers refer to an equal-brightness criterion, making no reference to the quality of the border between the fields (*3*).

We measured the residual contrast between two heterochromatic fields when the contrast between them was at a minimum (*4*). We found that, when two such fields are precisely juxtaposed, a minimally distinct border generally does not occur between them when the fields are equally bright. When one field is white, the chromatic half must be brighter than the white half for the border to be minimally distinct. If the brightnesses of the fields are equated (by reducing the radiance of the chromatic field, for example), the border between the fields becomes clearly more distinct than it was before.

This finding led to development of a model of visual brain activity. The key idea is the supposition that there are chromatic and achromatic neural elements in the visual brain that can be in either an active or inactive state (*5*). When active, a given chromatic element provides one unit of chromatic signal and one unit of brightness (*6*). Chromatic signals are related to sensations of red, green, yellow, or blue; other bright colors (*7*) are blends of some of these within a receptive field. The more the units of activity within a receptive field and period of temporal integration, the more intense is the sensation. A given element can give rise to only one kind of chromatic sensation (*8*). Moreover there are achromatic brain elements which, when active, give rise to sensations of whiteness and brightness.

An example of how the model is applied is shown in Fig. 1 for a blue (B) versus a yellow (Y) field. The blue field is assumed to activate 10 B units for every 10 W (white) units; this is shown on the left of the inset circle. The yellow field (right), being less saturated, is assumed to activate 1 Y unit for every 10 W units.

Contrast (C) (Fig. 1) is determined by the sum of the absolute differences between the numbers of active elements of each type on the two sides, divided by the total number of elements active on both sides. In the example, ΔB is 10, ΔY is 1, and ΔW is zero—a total of 11. In the denominator, the total number of active units is 31: 20 on the left plus 11 on the right. Curve C is calculated in this way and is plotted as a function of the ratio of white units active on the left to the number of white units on the right. We assume that minimum contrast yields a minimally distinct border. It is exactly true that the minimum contrast always occurs when the numbers of active white elements are equal on the two sides, regardless of the assumed ratio of chromatic to achromatic elements. Thus