Spectral Reflectivity of Mars

Abstract. *Analysis of data on the spectral reflectivity curves for both bright and dark areas of Mars disclosed several features not considered in previous models of the martian surface. The shape of the mean spectral geometric albedo curve between 0.3 and about 1.3 microns for Mars is defined to within a few percent. Spectral reflectivity curves based on relative reflectivity data were calculated for both a bright and a dark region between 0.4 and 1.1 microns. The curve for the dark region shows a broad, deep (~13 percent) absorption feature centered near 1 micron. The curve for the dark area crosses that of the bright area between 0.4 and 0.5 micron during some martian seasons.*

The spectral reflectivity of Mars has been used to support several different models of martian surface. This is possible because the spectral reflectivity of a material is determined by its composition, mineralogy, texture, and particle size. We here describe an attempt to uncover and interrelate almost all existing data on the spectral reflectivity of Mars with the inclusion of some measurements not previously available. When these data are synthesized, they reveal several important features in the reflectivity curve for both bright and dark martian regions. These features are not explained by some previous models.

Two general types of data on broadband reflectivity exist for Mars: most measurements include the entire martian disk; a few are confined to a few specific areas on that disk. Some of the latter are relative, giving the ratio of the reflectivities of two martian areas.

De Vaucouleurs (*1*) used most of the data available up to about 1961 to calculate the mean spectral geometric albedo. We have used these values arbitrarily as standards to which all other measurements have been adjusted. O'Leary (*2*) reported a sharp increase in the reflectivity of Mars with decreasing phase angle for very small phase angles (the opposition effect). De Vaucouleurs did not include this effect in his determination of the geometric albedo. The opposition effect is not considered here because the effect is not yet well defined, and it does not change our results significantly.

Most of the available data on the spectral geometric albedo of Mars is shown in Fig. 1. Some values (*3–5*) are presented without modification. O'Leary values (*2*), for the case of no opposition effect, were reduced by 6 percent to give the best fit to the standard values. Data by Irvine *et al.* (*6*) were reduced by 5 percent before being plotted. McNamara (*7*) and Younkin (*8*) measured the relative reflectivity of the entire martian disk at a phase angle of 37° by computing the ratio of the observations for Mars to those for solar-type stars. These measurements, after adjustment to the values of de Vaucouleurs, are in good agreement with each other and with the other data on the geometric albedo. This agreement holds without the need for a correction for the change in color of Mars with phase angle (*1*). (The term "geometric albedo" implies a phase angle near zero.)

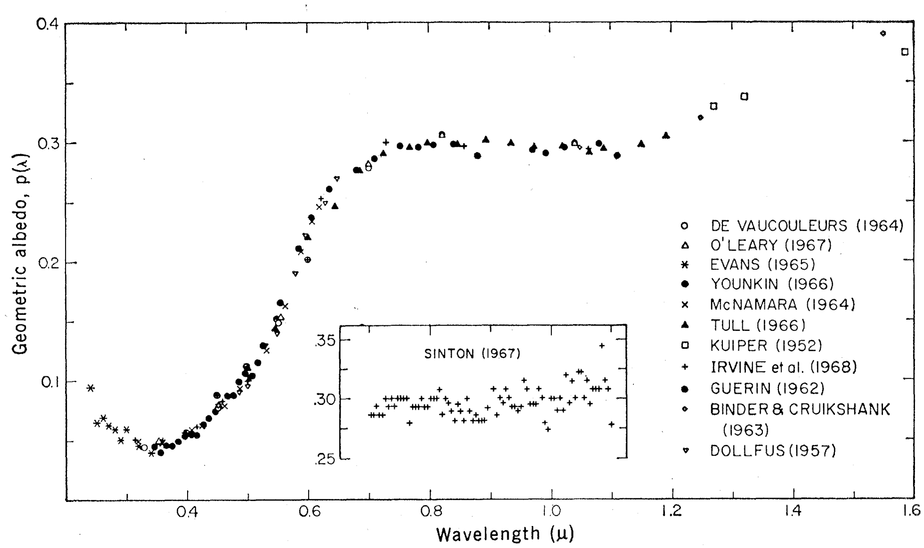

Fig. 1. Spectral geometric albedo of Mars. All measurements have been adjusted in vertical scale to match the albedo values calculated by de Vaucouleurs (*1*).

Measurements by Binder and Cruikshank for a phase angle of 30° (*9*) have been adjusted to the geometric albedo measurements. No color effect with phase angle is expected at near-infrared wavelengths (*9*), and thus no correction was applied. Sinton's (*10*) data are presented separately (Fig. 1) without adjustment because of the large scatter and also because Sinton used a reference star that is slightly bluer than the sun; this probably caused the increase in his values at longer wavelengths.

Measurements by Guerin (*11*) and Dollfus (*12*) are based on only a small area on the martian disk, and thus they are not geometric albedo measurements. However, without any adjustment they are in good agreement with the albedo data (Fig. 1.) Moroz's measurements (*13*) for the wavelength region beyond 1.3 μ do not overlap those in Fig. 1, except for points in the far-red region; these data are not included. Furthermore, Moroz's measurements show a small decrease in martian reflectivity with wavelength beyond 1.3 μ, contrary to the trend indicated in Fig. 1.

The agreement among the sets of data is remarkable, considering the variety of sources. It appears that the shape of the mean spectral geometric albedo curve for Mars is known to within a few percent. However, the absolute scale for the curve is dependent entirely upon de Vaucouleurs' calculations and probably is less well determined. The fact that the only other determinations of the geometric albedos (*2, 6*) had to be reduced by about the same amount (~5 percent) to fit the values of de Vaucouleurs suggests that these values (*1*) might be low. The curve (Fig. 1) generally confirms previous thinking about the martian spectral albedo. General features of the curve include a minimum just short of 0.4 μ, a sharp increase in reflectivity between 0.4 and 0.7 μ, and a very shallow minimum near 1.0 μ. Mars is quite red in color.

Photoelectric measurements of the relative reflectivity of selected pairs of areas on the martian surface have been presented (*8*). More recently, new techniques have made possible even more accurate measurements (*15*). Data from these sources (*8, 15*) are derived from measurements of specific area-pairs at specific times. Most measurements were made for the area-pair consisting of Arabia and Syrtis Major, although McCord (*15*) gives values for two other area-pairs. Measurements for the Arabia–Syrtis Major area-pair at specific times are shown in Fig. 2. All relative spectral curves are shown with the vertical scale adjusted to give the best fit to Younkin's curve (*8*). The fitting factor *f* (a constant) that must be applied to individual curves in order to reconvert them to relative reflectivity curves, as originally measured, is also given in the figure.

Data on the relative color of the area-pairs (*15*) (Fig. 2) are not as plentiful as the integral data, but the agreement among the three sets shown is within a few percent. It appears that the relative color of the dark area (Syrtis Major) and the bright area (Arabia) is very nearly constant throughout the martian season, and that only the overall brightness contrast changes, as described by *f*. The systematic darkening with season of some martian dark regions (the darkening wave) seems to affect the reflectivity of these two areas at all wavelengths by the same fraction. The bright area seems to become darker than the dark area near 0.4 μ at times, as shown by the application of factor *f* to the values in Fig. 2. This implies a crossing of the reflectivity curves near 0.45 μ for the two martian areas. The general shape of the relative reflectivity curve is smooth except for points near 0.8 and 0.9 μ, which are low; this may indicate a shallow differential absorption feature. There are no irregularities near 0.4 μ, such as there would be if martian blue clouds had affected either of the relative measurements. The bright region is definitely redder than the dark region but no green coloration is evident (*15*).

The relative data reveal only differences between a dark and a bright area on Mars. In order to learn the spectral reflectivity curve for either area, it is necessary to know it for the other. The spectral geometric albedo curve for a sphere covered with material of the kind found in bright areas is given to a good approximation by the integral curve (Fig. 1). Bright areas comprise about 70 percent of the apparent surface area of Mars, with the dark areas more plentiful on one half of the planet. As the planet spins, an observer on the earth sees the effect of the dark area on the change of the integral intensity with the longitude of the martian central meridian. Four sets of data (Fig. 1) have this effect of martian longitude removed. Four additional sets of data (Fig. 1) were obtained when that side of Mars was visible which contains almost entirely bright regions. Only three sets of data were obtained when the darker side of Mars was visible. For one set in the infrared region the fraction of dark area included in unknown. The good agreement among the sets of

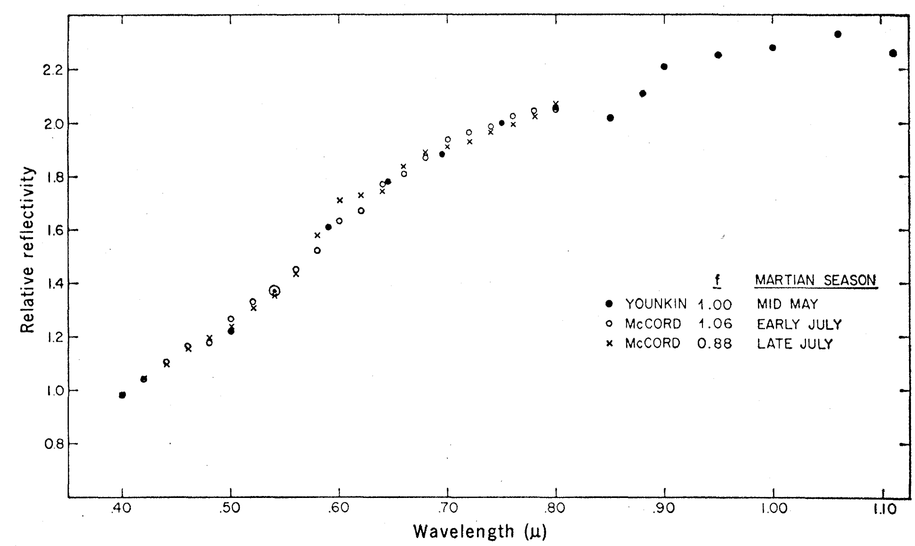

Fig. 2. Ratio of the spectral reflectivity of a bright area (Arabia) to that of a dark area (Syrtis Major) with vertical scales adjusted to match Younkin's values (*8*). The fitting factor *f* is that constant by which the particular group of measurements must be multiplied to reproduce the relative reflectivity as measured; for example, the measurements of McCord (*15*) have been adjusted by the factor f^{-1} to fit those of Younkin.

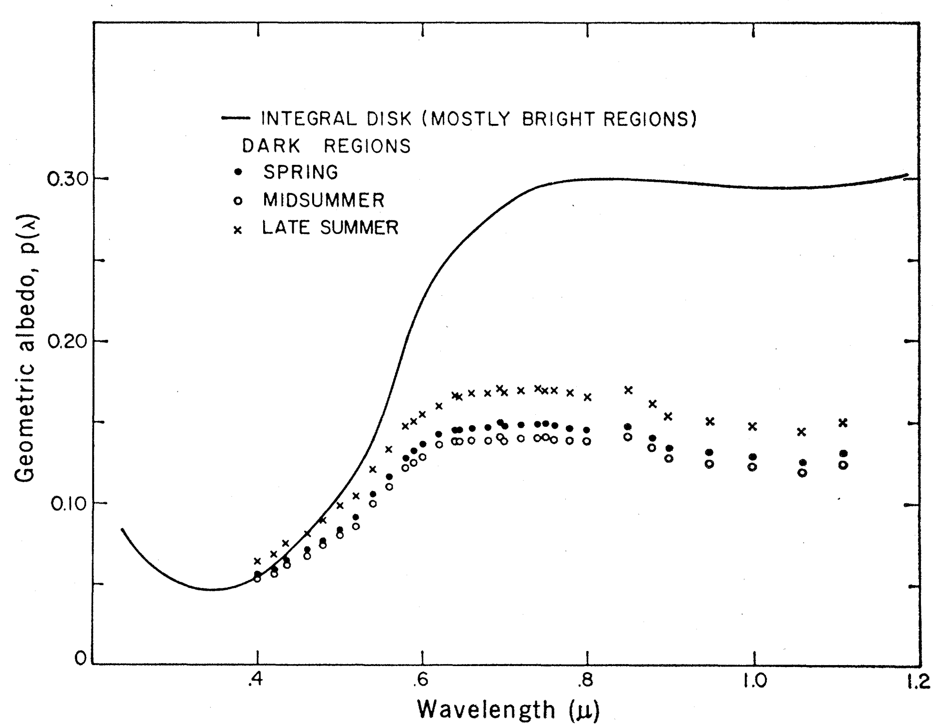

Fig. 3. Ratios shown in Fig. 2, after application of the appropriate fitting factor *f*, were used with the averaged values of the geometric albedo (Fig. 1) (shown here as the solid line) to calculate the geometric albedo for a sphere covered with material like that of Syrtis Major for different martian seasons.

data indicates that the effect of the dark areas has been removed from the curves for the integral spectral albedo given here.

Figure 1 shows the spectral geometric albedo of a sphere covered with martian bright areas. The relative measurements (Fig. 2) refer to areas near the center of the planet disk. If we assume that the limb-darkening is nearly the same for both dark and bright areas, the relative measurements, which ordinarily apply only for two flat disks, will also apply for two spheres. By using the curves (Figs. 1 and 2) and by assuming that most bright regions have similar reflectivities, one can determine the spectral geometric albedo curve for a sphere covered with material such as that found at Syrtis Major. The results are shown (Fig. 3) for the three martian seasons for which relative measurements are available. We have assumed that the reflectivity of the bright regions does not change significantly with martian season.

The spectral albedo for the dark area differs in several important respects from that of the bright area. Although both areas are red, the dark area is much less red. Both curves show the sharp change in reflectivity in the visible region; for the dark area this change terminates at a shorter wavelength, which accounts for the hump in the relative spectral curve (Fig. 2) near 0.6 μ. In addition, the reflectivity for the dark regions has a relatively strong (13 percent) absorption feature centered at about 1 μ, but the curve for the bright region shows only the suggestion of a minimum in this general spectral region.

The apparent discontinuity in the curve for the dark area near 0.85 μ is a result of the two low points in the relative curve (Fig. 2). Because of the apparent absence of a low feature in the curve for the bright area, a high feature appears in the curve for the dark area. However, a closer study of the data points (Fig. 1) reaveals that Tull's one datum point (*4*) provides the only argument against the presence of a narrow, weak minimum in the curve. If this point is neglected, the unnatural appearance of the albedo curve for the dark area (Fig. 3) and the low values for the albedo curve of the bright area (Fig. 1) would seem to indicate that the low points between 0.85 and 0.9 μ (Fig. 2) are due to a shallow ($\sim$ 3 percent), narrow absorption feature appearing in the reflectivity curve for the bright areas. Younkin (*8*) has argued against the presence of such a feature.

The crossover of the spectral curves for the dark and bright areas may be seen in Fig. 3. In the absence of the darkening wave when the relative contrast of the two regions is a minimum, it seems that the dark region is brighter than the bright region near 0.4 μ.

The spectral reflectivity of various regions of the martian surface must be explained by any model; however, some models do not appear to fit these data. Rea (*16*), Pollack and Sagan (*17, 18*), and Sagan and Pollack (*19*) have proposed that dark and bright regions on Mars are deposits of large and small particles, respectively. The seasonal changes in the brightness of dark areas are attributed to aeolian transport of desert sand and dust onto and from dark areas. However, this mechanism would cause not only a brightness change at the dark areas but also a color change. Such a color change has not been found. Thus, some mechanism that provides for darkening without causing a color change is required to explain the seasonal darkening of Syrtis Major and probably other dark areas.

The reflectivity for small particles of limonite is higher in the red and lower in the blue region than for larger particles of limonite (*20*). If the light and dark areas of Mars are composed primarily of particles of limonite of different sizes, there should be a crossing of the reflectivity curves. Salisbury and Hunt (*20*) argue that the lack of such a crossover, according to the data available to them, means that a difference in particle size could not account for the existence of bright and dark areas on Mars. There is, however, evidence that limonite is not the only possible mineral on the martian surface (*2, 21*). The fact that crossing curves exist is not proof that particle size is responsible, for a crossover can be accounted for in other ways, such as by different degrees of oxidation (*22*).

Several workers have attempted to find a laboratory material matching the spectral reflectivity of Mars. Sharonov (*23*), who did not use the entire curve of spectral reflectivity, Sagan *et al.* (*24*), Pollack and Sagan (*18*), and others have argued that the curve of spectral reflectivity indicates that the martian surface is covered with limonite or goethite. On the other hand, Van Tassel and Salisbury (*25*) and Binder and Cruikshank (*9*) suggested that material of the martian surface could be mainly silicates, and Adams (*21*) was able to match the integral curve for Mars by assuming that the martian surface consists of oxidized basalt. The positions of the two minimas and the sharp increase in reflectivity toward the red region, appearing in the curves for both the bright and dark martian areas, provide valuable information on the surface composition. The much greater strength of the absorption at 1.0 μ for the dark areas, as compared to that of the bright areas, suggests an important difference in the two surface materials. It appears thus far that the model which postulates that the surface of Mars is covered with oxidized basalt shows the best agreement with data on spectral reflectivity (*22*).

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References

1. G. de Vaucouleurs, *Icarus* **3**, 187 (1964).
2. B. T. O'Leary, thesis, University of California at Berkeley (1967).
3. D. C. Evans, *Science* **149**, 969 (1965).
4. R. G. Tull, *Icarus* **5**, 505 (1967).
5. G. P. Kuiper, *Atmospheres of the Earth and Planets* (Univ. of Chicago Press, Chicago, ed. 2, 1952).
6. W. M. Irvine, T. Simon, D. Menzel, J. Charon, G. Lecomte, P. Grivoval, A. Young, *Astron. J.* **73**, 4, 251 (1968).
7. D. H. McNamara, *Rep. SID 64-78 No. 52156* (North American Aviation, Inc., Space and Information Systems Division, Downey, California, 23 January 1964).
8. R. Younkin, *Astrophys. J.* **144**, 809 (1966).
9. A. Binder and D. Cruikshank, *Commun. Lunar Planet. Lab.* **2**, 193 (1963).
10. W. M. Sinton, *Icarus* **6**, 222 (1967).
11. P. Guerin, *Planet. Space Sci.* **9**, 81 (1962).
12. A. Dollfus, *Compt. Rend.* **244**, 162 (1957).
13. V. I. Moroz, *Soviet Astron. AJ Engl. Transl.* **8**, 273 (1964).
14. T. B. McCord, *Appl. Opt.* **7**, 475 (1968).
15. ———, *Astrophys. J.*, in press.
16. D. G. Rea, *Nature* **201**, 1014 (1964).
17. J. B. Pollack and C. Sagan, *Smithsonian Astrophys. Observ. Spec. Rep. No. 258* (1967).
18. ———, *Icarus* **6**, 434 (1967).
19. C. Sagan and J. B. Pollack, *Smithsonian Astrophys. Observ. Spec. Rep. No. 255* (1965).
20. J. W. Salisbury and G. R. Hunt, *Science* **161**, 365 (1968).
21. J. B. Adams, *ibid.* **159**, 1453 (1968).
22. T. B. McCord and J. B. Adams, in preparation.
23. V. V. Sharonov, *Soviet Astron. AJ Engl. Transl.* **5**, 199 (1961).
24. C. Sagan, J. Phaneuf, M. Ihnat, *Icaurus* **4**, 43 (1965).
25. R. A. Van Tassel, and J. W. Salisbury, *ibid.* **3**, 264 (1964).
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