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Lithological and Mineralogical Investigation of the Surface of Mars

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Results are presented of a continued investigation of the infrared colorimetry of the Martian bright and dark areas. Laboratory comparisons indicate that the infrared color profile of the Martian deserts matches that of a naturally occurring limonite stain which forms and is preserved on igneous rocks in a terrestrial desert environment. The colorimetry of the Martian dark regions is compared to that of fresh basalt samples and volcanic ash and is found to be greatly discordant.

INTRODUCTION

The problem of the composition of the surface layer of Mars has been investigated using several basic astronomical techniques. That some form of limonite ($Fe_2O_3 \cdot nH_2O$) occurs in the bright desert regions has been indicated by polarization measurements (Dollfus, 1955, 1961), photometry in the visual spectrum (Sharonov, 1961), and infrared colorimetry (Draper *et al.*, 1964; Moroz, 1964; Van Tassel and Salisbury, 1964; Binder and Cruikshank, 1964 [Paper I], 1966 [Paper II]; Sagan *et al.*, 1965; and Hovis, 1965). There has been considerable confusion, however, about the exact physical form in which limonite occurs on Mars. Limonite can take several physical forms depending upon the environment of formation. Investigations of the dark areas on Mars from a lithological standpoint have given less conclusive results than those concerned with the bright regions.

This paper reports the results of an infrared colorimetric study of the Martian bright and dark areas with laboratory comparisons in the spectral region 0.8 to 2.4 microns. Areas approximately one-fourth the diameter of the planet were isolated for observation. In this way, two areas composed of mare material were observed, one covering Syrtis Major, and one in the region Mare Cimmerium-Mare Tyrrhenum. Two desert regions were also observed, Elysium, and Zephyria. The methods by which these observations were made and reduced are described fully in Paper II.

Comparison studies of terrestrial rocks and minerals were made with the same equipment and reduced in the same manner as the observations at the telescope, and are described in detail in Papers I and II.

MINERALOGY OF THE MARTIAN DESERTS

The rock samples used for comparison were selected on the basis of the results of Paper I, in which all fresh rock surfaces were rejected when compared to the Martian deserts. In this earlier study, only igneous rocks with a weather-produced surface stain of limonite were found to compare with the deserts. In Paper II, the spectra of three such samples collected from the Southern Arizona (Sonoran) desert

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were found to match closely the spectral curve of the Martian deserts. The deviations in the spectra of the individual samples were small. Each sample has a heavy surface stain of yellow-orange limonite, which extends approximately 2 mm into firm rock and much farther into friable rock, as determined from cut samples. This form of limonite is produced on igneous rocks by the oxidation and hydration of iron in iron-bearing minerals such as biotite, augite, olivene, and hornblende. Geologically, limonite is a general term that includes the minerals goethite ($HFeO_2$), lepidocrocite [$FeO(OH)$], and iron oxide of undetermined crystallization and hydration.

In papers dealing with the composition of the Martian surface there has been some confusion in the use of the term limonite. There seems to be a tendency among investigators to limit the term limonite to the yellow, friable, earthy variety and/or the brownish massive form, the latter becoming a yellow powder when pulverized. The weather-produced limonite stain referred to in this paper is an amorphous mixture of iron oxides that matches the visual color of a mixture of 70% geothite and 30% hematite. These comparisons were made with synthetic samples of goethite and hematite in the above ratio prepared by Dr. A. Draper and Dr. J. Adamcik. Although the development of limonite from the above iron-bearing minerals is not completely understood, one reaction sequence in which limonite can form from weathering of an iron sulfide mineral has been described by Keller (1957).

As chemical and physical weathering proceeds on crystalline rocks, making their surfaces more friable, the limonite stain forms in cracks and crevices. In a desert environment, where rocks decompose by exfoliation, this results in the fragments as well as the newly exposed surface being coated with the limonite stain. In areas of alluvial fill where the limonite stain is highly developed on igneous rock fragments, the soil and sedimentary rocks and fragments are often also heavily stained. This limonite in the soil and on the nonigneous rocks is derived from the igneous rocks. In the Sonoran desert of southern Arizona where average annual rainfall is 15–20 inches, a surface stain of limonite can form on igneous rocks in a few years.

Atmospheric pressure (found by Kaplan *et al.*, 1964; Owen and Kuiper, 1964) and water vapor content (found by Kaplan *et al.*, 1964; Dollfus, 1963) on Mars indicate that limonite is probably not now forming there. Therefore, the presence of limonite on Mars suggests that in the earlier history of the planet, the atmosphere was more conducive to chemical alteration of the surface. The chemically formed limonite has been preserved because of the lack of intense mechanical weathering on Mars since the development of this mineral stain and deposit.

The occurrence of limonite stain on rock outcrops, fragments, and all sizes of detrital material on Earth holds important implications in constructing a general picture of the desert regions of Mars. The large-scale structures evident in the television photographs of Mars from Mariner IV (Leighton *et al.*, 1965) indicate that solid rock outcrops may occur and that detritus probably does not cover the entire surface. As noted above, the weathering and exfoliation fragments were probably coated with limonite stain when they were formed or shortly afterwards. Most cratering debris is probably very old (Binder, 1966; Hartmann, 1966) and has been coated since its formation. The smallest fragments of clay or silt size can consist of limonite dust or of tiny silica or clay minerals coated with limonite. It is probably this smallest size range of particles that gives the polarization results of Dollfus (1955, 1961). Dr. T. Gehrels (private communication, 1965) has pointed out that the Dollfus polarization results might be realized even if only a few percent of the surface of the deserts is covered by the powdery, earthy limonite and the remainder of the surface consists of much larger fragments, for the latter would not contribute significantly to the polarization. The presence of extremely fine material on Mars is further corroborated by Koval' and Morozhenko (1962), who estimated that the average particle radius in the dust clouds of 1956 was about 1.4 microns.

Using observations of Mars in the region 8–14 microns, Sinton and Strong (1960) concluded that less than 20% of the surface of the planet is composed of silicates. In the samples that we observed and those noted in the field, the limonite stain efficiently covers all minerals in the rocks, even free quartz, to a thickness easily sufficient to mask the spectral properties of the minerals beneath. Normally, the stain on the surface was about 0.2 mm in thickness, but as noted before, it can permeate the rocks to a greater depth.

In discussing very small particles of rock and dust on Mars, Salisbury and Van Tassel (1965) have pointed out that tiny angular silica and other grains up to about 10 microns in size, which are blown about in the Earth's atmosphere, are often coated with limonite. In view of this and our aforementioned observation that even free silica (quartz) in weathered rocks can retain at least a thin coating of limonite, the occurrence of stained sand-size and much smaller particles can be understood. The limonite stain has a hardness of 6 and is not easily worn off by attrition, as was suggested by Rea (1965).

Loomis (1963) has raised the possibility that the Martian bright areas may be covered by a desert-varnish type of encrustation. Although the exact mineralogic composition of desert varnish is unknown, analyses by Engle and Sharp (1958) indicate that Fe_2O_3, Al_2O_3, and MnO are the most abundant oxides having coloring properties. A discussion of desert varnish relative to the surface of Mars is pertinent because the varnish is composed in part of an iron oxide, forms a hard surface stain, and occurs in desert environments. Although the limonite stain discussed in this paper is probably related to desert varnish, the latter is much darker in tone and its visual color is greatly different from that of Mars. The exposures of desert varnish studied by Engle and Sharp occur in regions of rather less rainfall (1.5–4 inches annually) than do exposures of the limonite stains that we have observed.

THE DARK AREAS

It is very difficult to obtain physical measurements of pure mare material of Mars because of the way in which the maria are made up. At a resolution of about 40 km, Focas (1961) has noted that the Martian maria are composed of patches of dark material superimposed on the lighter desert background. Our colorimetric observations of these dark areas in the infrared show that while there is a large difference in albedo between bright and dark regions, the color differences are small. We interpret this as indicating that the maria consist of an aggregate of small patches of dark material on the general lighter desert background. The polarization data of Dollfus (1961) for the dark areas and bright regions give a curve for the dark areas that deviates only slightly from his basic desert area curve, and indicate that the degree of deviation is dependent on the Martian seasons.

In a series of papers, McLaughlin (1954 and many others) expressed the view that the dark areas on Mars are deposits of volcanic ash expelled by a large number of active volcanoes and emplaced by prevailing winds on the planet. McLaughlin's hypothesis has been criticized, mostly on theoretical grounds, by several authors, but it seemed desirable to test this on the basis of physical observations. Rock samples observed in this connection included fresh basalts from Hawaii, Mexico, and Arizona, and basaltic volcanic ash from Sunset Crater, Arizona. Comparisons of the colors of the various black basalts and ash given in Paper II indicate that the maria are not composed of fresh lava or ash fields. This result adds credence to the statement of Sagan *et al.* (1965) that the study of the dark areas of Mars is most properly undertaken in a biological context.

CONCLUSIONS

The Martian bright areas may be composed of rock outcrops, detritus with particles ranging in size from large fragments to sand-size grains, and some limonite dust. The outcrops and detrital fragments are, for the most part, covered with a hard surface stain of the type of limonite that is formed and preserved in a desert environment. This surface stain yields the colorimetric results reported here and in Paper II, and the limonite dust gives the polarimetric results of Dollfus (1955, 1961). The limonite stain described in this paper is a naturally occurring substance that readily forms in a suitable environment during normal chemical weathering of igneous rocks.

The Martian maria do not appear to consist of basaltic lava flows or fresh deposits of volcanic ash.

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NOTE ADDED IN PROOF

Younkin [1965, 1966 (preprint)] has criticized the identification as a principal constituent of the Martian bright regions based on the absence of the intensity minimum in the Martian spectra at 8750 Å that is shown in spectra of certain forms of limonite. We have traced this region of the spectra of our samples of the naturally occurring, weather-produced limonite stains and found that there was no intensity dip in this form of limonite. This helps confirm our identification of this particular variety of limonite as a constituent of the Martian deserts.

The results of Paper I have frequently been misquoted (Salisbury, 1966, and elsewhere). The findings of Paper I were that the infrared spectra of weather-produced coatings of limonite on igneous rocks match the infrared spectrum of Mars. The misunderstanding may be related to the editorial postscript to Paper I.

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