Mars: Near-Infrared Spectral Reflectance of Surface Regions and Compositional Implications

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Reflectance spectra (0.65-2.50 μm) are presented for 11 Martian areas. The spectral resolution is \( \sim 1/4 \text{ nm} \) and the spatial resolution is 1000-2000 km. These are the first high-quality spectrophotometric data at these wavelengths for regions on the surface. Spectral features previously observed are confirmed and better defined, and a number of important spectral properties are characterized for the first time. The spectra show water ice absorptions in the 1.5- and 2.0-μm regions, which if due to surface frost, would imply the presence of 1 to 2 mg/cm\(^2\) H\(_2\)O. However, other studies have shown that the presence of an unprotected surface frost in late morning is unlikely. Water ice is stable at night even at the equator and might persist until late morning when the air is well undersaturated if it is intimately dispersed in weathering products, especially if clays are present. The dark region spectra indicate about 4 times less water ice than seen in bright regions. Since some bright material is present in dark regions there may be no water ice associated with the dark materials themselves. This tends to confirm that weathering products (thought to be more abundant in bright regions) are involved in the mechanism that allows temporary persistence of unstable water ice. The presence of weak 2.3-μm features in many of the spectra is consistent with the presence of hydroxylated magnesium-rich minerals such as sheet silicates (serpentine, talc, and magnesite smectites) or amphiboles (anthophyllite). The apparent absence of a 2.2-μm absorption implies that montmorillonite may not be a major component of the Martian regolith. Many of the spectra also show an apparent bound molecular water. Observed dark regions have distinctive near-infrared spectral shapes, previously not well determined, which are characteristic of thin semi-transparent alteration coatings overlying dark unaltered rock. Previously observed ferrous- and ferric-iron absorptions in the 1-μm region are better defined by these new data. Cinnabar (cinnabar) is definitely present, but olivine is not spectrally apparent.

INTRODUCTION

To define and characterize surface geologic units on Mars, one needs both morphological and compositional information. Although the recent spacecraft missions to Mars have provided a wealth of data on the type of surface features present, limited compositional and mineralogical information was returned, and most of that information was obtained only in the immediate vicinities of the two Viking landers. The reflectance spectrum of minerals, rocks, and soils often contain electronic and molecular absorptions which are diagnostic of surface mineralogy. A review of this technique for geochemical remote sensing as applied to Mars is provided by Singer et al. [1979]. The Viking orbiters provided three-color images, some of which have been processed into multispectral maps showing the extent of compositionally different surface color units [Soderblom et al., 1978; Strickland, 1979; McCord et al., 1982]. The visible spectral region is dominated by Fe\(^{2+}\) charge-transfer and crystal-field absorptions, and most other mineralogic information is masked. Reflectance spectra covering a broader spectral region, particularly at near-infrared wavelengths, are required to investigate further the mineralogy and petrology of the Martian surface.

The ideal source for this type of data would be a visible and near-infrared spectral mapper in orbit around Mars; this experiment is unfortunately not likely to be flown for a number of years. It is clear that earth-based telescopic reflectance spectroscopy will be an important source of compositional information for many years to come.

We report here on new, near-infrared reflectance spectra (0.65 to 2.50 μm) for regions on the Martian surface observed in 1978. The high photometric quality of these data combined with increased near-infrared spectral coverage compared to previous regional observations provide new information about the spectral behavior and therefore the composition and physical nature of Martian surface materials.

OBSERVATIONS AND DATA REDUCTION

The spectral reflectances (0.65 to 2.50 μm) of 11 regions on Mars, 1000-2000 km in diameter, were obtained during the 1978 apparition using the University of Hawaii 2.2-m telescope located on Mauna Kea, Hawaii. A cooled (to 77 K) CVF (circular variable filter) spectrometer with an InSb detector was used to measure alternatively Mars and the standard star Beta Geminorum. The instrument and the method are described in detail by McCord et al. [1978, 1981].

The CVF scans the spectrum from 0.65 to 2.50 μm every 10 s with 1/4% spectral resolution. Successive scans were co-added and then written onto magnetic tape after 10 scans (100 s), which we call a run. The spectrum is divided into 120 data points (separate spectral channels). A mirrored chopper rotating at 24 Hz was used to chop between the object and sky. The sky signal was subtracted from the object signal by the digital data system. Two chopper cycles make up one data channel. The aperture consists of a cooled mirror (at 77 K) mounted 45° to the optical axis at the cassegrain focus with the aperture hole in the center. Thus the location of the aperture appears as a black spot in the field of view. A beam splitter in the viewing optics allows photographs of the aperture location and the field of view to be taken while data is being obtained. The aperture location during each observation was...
determined from the photographs using an orthographic-to
mercator-projection computer program; areas of multiple ob-
servations of a region were combined to obtain the composite
locations displayed in Figure 1.

The reflectance of each Martian area was determined using
the star Beta Geminorum as a standard flux source and per-
forming an extinction analysis, as described by McCord and
Clark [1979]. The Beta Geminorum/sun spectrum was mea-
sured on previous observing runs using the Apollo 16 lunar
landing site and returned samples as intermediate standards

RESULTS

The reflectance spectra of 11 regions on Mars are shown in
Figures 2 and 3. The spectra have been scaled to unity at a
wavelength of 1.02 μm. The error bars represent ±1 standard
deviation of the mean of several independent measurements
of the same region. Bright region results are shown in Figure
2, arranged with spectra most characteristic of bright regions
at the top grading into spectra showing some intermediate
characteristics at the bottom. Figure 3 shows spectral results
for five dark regions and for the north polar region.

The locations of the bright and dark areas observed during
the 1978 apparition as well as those previously observed by
this group [McCord and Westphal, 1971; McCord et al.,
1977] are shown in Figure 1. The larger size of the 1978
regions is due to poor observing conditions and the relatively
small angular size of Mars (12.6 arc sec) at the time of these
observations. Nevertheless, these new near-infrared data sub-
stantially increase our knowledge of the Martian surface.
The dates, times, earth air mass range, integration time, and
Martian central meridian for each observation are given in
Table 1.

A comparison of representative Martian spectral types is
given in Figure 4. Included is an average of the highest quality
bright region spectra, the spectrum for area 78-5, which has
predominantly bright region characteristics but with some
indication of intermediate to dark material, and the spectrum
for area 78-10, which is the highest quality dark region spec-
trum.

These observations were made during a period (Ls =
48°–50°) of nearly maximum transparency of the Martian at-
mosphere as measured directly by the Viking landers (after-
noon visible optical depth = 0.4 [Pollack et al., 1979]). The
effect of the remaining aerosol dust on our observations
would be to cause a slight decrease in spectral variety among
observed regions. This effect is less serious in the near-
infrared spectral region discussed here than in the visible,
where all Martian materials are strongly absorbing. Observa-
tional problems caused by the earth’s atmosphere are respon-
sible for much of the variation in data quality. Bright region
spectra 78-1B and 78-2 show rather sharp but repeatable fea-
tures near 0.75, 0.93, and from 2.2 to 2.5 μm. A careful study
of these and other data obtained on the same nights has shown
that these features are most likely instrumental in origin and
probably do not represent Martian phenomena.

ANALYSIS AND INTERPRETATION

General Spectral Characteristics

Bright region spectra are characterized from the visible to
0.75 μm by the wing of intense Fe+ charge-transfer absorp-
tions centered in the UV, Fe+ crystal field absorptions in the
blue to blue-green, and by a weaker, asymmetric Fe+ crystal
field absorption near 0.87 μm. These features have been at-
btributed by many to crystalline ferric oxides although more re-
cent work has indicated that ferric iron on Mars is present in
an amorphous or poorly-crystalline form [Evans and Adams,
1980; Singer, 1981a, b; 1982a]. From the band minimum near
0.87 μm to about 1.3 μm the spectrum slopes upwards. Be-
tween 1.4 and 1.7 μm there is a broad absorption which has
been interpreted as H2O ice from previous integral disc ob-
servations [McCord et al., 1978]. Superimposed on this are nar-
worer Mars atmospheric CO2 absorptions, at 1.34, 1.45, and
1.62 μm. From 1.8 or 2.2 μm the spectrum is dominated by a
deep, partially resolved triplet absorption also caused by Mar-
tian atmospheric CO2.

In contrast to bright region spectra, dark region spectra
have a more distinctive peak near 0.75 μm and slope fairly
uniformly downward to 2.5 μm. This infrared spectral shape
was not previously well defined and has important implica-
tions for compositional analysis, as discussed below. The
Martian CO2 absorptions are of course the same as those dis-
scussed for bright regions. Dark region spectra show Fe+ crystal
field absorptions near 1 μm as well as the Fe+ band near
0.87 μm described for bright regions.

Dark regions observed in 1978 had approximately one half
the reflectance at 1 μm as bright regions. This value is con-
sistent with previous observations of regional reflectance dif-
ferences made by McCord and Westphal [1971] and Binder and
Jones [1972]. Typical bright and dark region spectra from 0.3
to 2.5 μm are shown scaled to approximate normal reflectance
in Figure 5. The spectra are composites of infrared data pre-
sented here and visible data from McCord and Westphal
[1971] and McCord et al. [1977]. Spectral effects of a model
Martian CO2 atmosphere have been removed [Kieffer, 1968;
McCord et al., 1978]. This CO2 correction is approximate, ne-
glecting variations in pressure and temperature (surface top-
ography).

Spectrum 78-5 is for Arabia, which, although considered a
classic bright region, shows characteristics in some ways in-
termediate between bright and dark regions. The near-infrared
absorption minimum occurs at longer wavelengths than for
other bright regions and the slope is much flatter from 1.0 to
1.3 μm, although not negative as it is for dark region spectra.
The implication here is that Arabia has a moderate amount of
exposed dark material or at least an excess ferrosilicate soil
component compared to some other bright regions. Similar
properties were noted by Huguenin et al. [1977] in 1969 obser-
vations of this area [McCord and Westphal, 1971]. If these
characteristics have, in fact, survived (perhaps intermittently)
through nearly 10 years of global dust cycling, a surface com-
pared of some dark boulders scattered on a background of
bright soil seems plausible. Such a situation, probably with
greater rock cover than Arabia, is observed at both Viking
lander sites, for which no detailed spectra have yet been ob-
tained. This scenario for Arabia is not immediately reconcil-
able with those based on the low thermal-inertia measure-
ments from Viking IRM [e.g., Zimbleman and Kieffer,
1979]; more detailed comparisons of these data sets might
allow the surface properties of this region to be constrained
very well.

The spectrum of the Martian north polar cap region is
shown in Figure 3. The spectrum appears similar to the dark
region spectrum 78-10 shortward of 1.3 μm. Longward of 1.3
μm is a relatively strong water ice absorption extending from
Fig. 1. Locations on Mars for spectrophotometric observations by McCord and others. The first two digits represent the year of observation (e.g., 69-1 was observed in 1969). The 1969 observations (0.3 to 1.1 μm) are described by McCord and Westphal [1971]; the 1973 observations (0.3 to 1.1 μm) are described by McCord et al. [1977]; the 1978 observations (0.65 to 2.50 μm) are presented in this paper. The locations of observations for which the surface was partially or wholly obscured by atmospheric dust are not shown. (Base map: U.S. Geological Survey [1976].)
Fig. 2. The reflectance spectra of bright regions obtained in this study are plotted here scaled to a value of 1.0 at 1.02 μm. The error bars represent ±1 standard deviation of the mean of several independent observations.
Fig. 3. The reflectance spectra of the dark regions and the north polar region obtained in this study are plotted here scaled to 1.0 at 1.02 \( \mu \)m. The error bars represent \( \pm 1 \) standard deviation of the mean of several independent observations.
1.4 to 1.8 \mu m. Centered at 2.0 \mu m is the strong CO$_2$ (atmospheric) absorption and the 2-\mu m ice band. Beyond 2.2 \mu m the reflectance decreases as seen in spectra of water frost. This spectrum is analyzed in detail by Clark and McCord [1982].

**Dark Region Composition**

The earliest positive determination that dark regions on Mars consist largely of mafic igneous rocks was provided by Adams and McCord [1969], who successfully modeled a dark region spectrum from 0.3 to 1.1 \mu m using basaltic grains with authigenically induced surface oxidation. Huguenin [1976] interpreted previously obtained spectrophotometry of 0.3 to 1.1 \mu m [McCord and Westphal, 1971; McCord et al., 1977] to indicate a surface alteration layer a few micrometers thick on basaltic rocks.

The near-infrared dark region spectra presented here provide new information about dark region spectral shape. The negative slope from about 1.1 to 2.5 \mu m had not been previously determined and is atypical of unweathered or homogeneously oxidized rocks and minerals. Singer [1982b] has shown that this distinctive shape is, in fact, consistent with a brighter, oxidized layer overlying a dark unoxidized iron-bearing substrate, such as basaltic or ultramafic rock, in agreement with the earlier work described above. Analogy to naturally occurring surface coatings on terrestrial basaltic units indicates that the coatings on Martian rocks (or rock fragments) are thicker than previously suggested, being up to tens of micrometers thick. The coating material is not necessarily genetically related to the underlying rock [Singer, 1982a, b; Evans et al., 1981].

Absorptions near 1 \mu m, observed in nearly all previous dark region spectra, are defined significantly better in the new data, particularly for region 78-10. Adams [1968] was the first to suggest that these might be caused by Fe$^{3+}$ in ferromagnesian minerals such as pyroxenes and olivines. Huguenin et al. [1977, 1978] have provided detailed interpretations of the dark region spectra obtained in 1969 [McCord and Westphal, 1971] and 1973 [McCord et al., 1977]. Spectrum 78-10 shows a compound structure near 1 \mu m, with a band centered near 0.88 \mu m and one near 0.99 \mu m. Detailed analysis by Singer [1981a] has shown that the 0.88-\mu m band is most likely caused by Fe$^{3+}$ crystal field transitions in the oxidized coating. The possibility that there is some contribution from Fe$^{2+}$ crystal field absorptions in orthopyroxene or low-calcium pigeonite in the underlying rocks can be neither proven nor disproven with existing data. The 0.99-\mu m band is firmly interpreted as an Fe$^{2+}$ crystal field absorption, indicating an augite clinopyroxene as a major component of these dark region rocks. Olivine, interpreted by Huguenin et al. [1977, 1978] to be abundant in most previously observed dark regions, is not indicated in the data presented here as a major constituent in dark regions observed in 1978 [Singer, 1982c].

**Spectral Evidence for Water**

The spectra in Figures 2 and 3 all show a drop in reflectance from 1.3 to 1.4 \mu m. McCord et al. [1978] interpreted integral disc spectra with features similar to those seen here to be due to water ice plus a highly desiccated mineral hydrate. To investigate this possibility further, the Martian spectra were modeled using an ice spectrum and spectra typical of oxidized basalt. Figure 6 shows the spectra used in simulation. The simulated spectrum for the bright area is typical of alteration products of mafic igneous rocks. The simulated spectrum for the dark area is typical of spectra of a thin (a few to over ten micrometers thick) layer of alteration product overlying unweathered basalt [cf. Adams and McCord, 1969; Singer, 1982b].

The ice spectrum in Figure 6 is typical of a medium-grained frost with grain sizes around 200 \mu m [see Clark, 1981a] and is scaled to a value of 0.18 at 1.02 \mu m since this scaling gave the best fit in the simulation below. The reflectance of an optically thick, medium-grained frost is above 0.9 at 1.02 \mu m. If the simulated bright spectrum and the ice spectrum are added, then rescaled to 1.0 at 1.02 \mu m, the result can be compared to the Mars average bright area spectrum as seen in Figure 7a (top). The resultant simulation shows a reasonable match to the Mars spectrum. Dividing the bright area spectrum by the simulated spectrum gives the residual spectrum shown in Figure 7a (bottom). This residual spectrum agrees very well with the martian atmospheric CO$_2$ transmittance spectrum (described previously).
A similar analysis for the dark area spectrum 78-10 is shown in Figure 7b (top). The fit is not as good as that obtained for the bright area, although some of the apparent drop beyond 1.4 $\mu$m may still be explained by water ice. If the water ice absorption features were only about half as deep as those in Figure 7b, the fit would be better. Also, since the dark areas have a reflectance about half that of bright areas, the amount of water contributing to the dark area 78-10 spectrum is less. Thus the amount of water ice present is at least 4 times less in the dark areas.

The water ice spectrum fit to the bright area in Figure 7a indicates that an optically thick patch of medium-grained frost covers approximately 5% of the area measured if the ice and bright material are in large-scale patches. If the frost were evenly distributed on the surface, approximately 1 to 2 mg/cm$^2$ would be present based on laboratory studies by Clark [1981d]. If the water ice is mixed with other minerals in the surface, the amount of water in the top few millimeters would be about 5 to 10 wt % [see Clark, 1981b]. This amount of ice is difficult to explain based on current models [e.g., Clark, 1978; Farmer and Doms, 1979]. However, the only way we can explain the spectral shape is by requiring that water ice be present.

At most seasons and latitudes on Mars, the atmosphere is holding all the water it can on a daily basis; the relative humidity is 100% at night. However, in the afternoon the relative humidity can be very low, typically 5 to 10% for north equatorial regions in the spring [Davies, 1979]. Thus, although surface ice will be unstable during the day, it can condense each night. It is unlikely that water ice clouds in the Martian atmosphere could explain the observations since we see different ice band depths over bright and dark regions and cirrus clouds are typically very fine grained; we do not see the 1.5- and 2.0-$\mu$m ice features when observing through cirrus clouds from Mauna Kea (note that this does not mean we obtain useful data through cirrus—the transmission drops erratically and data is useless when cirrus is present). It is also unlikely that a ground fog was present, since the bright area
Fig. 5. Composite reflectance spectra from 0.33 to 2.50 μm are shown for typical bright and dark region spectra scaled approximately to normal reflectance. A model atmospheric CO₂ spectrum has been removed so that these spectra are more representative of surface material. The visible data are from McCord and Westphal [1971] and McCord et al. [1977].

Fig. 6. The reflectance spectrum representing the continuum for bright (top) and dark (middle) regions are shown. These spectra were chosen as described in the text. The top spectrum is approximately that of a heavily altered basaltic material and the middle spectrum that of a thin layer of altered material on a basalt. The bottom spectrum is that of H₂O frost [Clark, 1981b] scaled to 0.18 at 1.02 μm. The reflectance of an optically thick frost layer at 1.0 μm is greater than 0.9 for medium and fine grained frost. These spectra are used in producing those shown in Figure 7.
spectra were obtained between 1040 and 1240 Martian local time and the 78-10 dark area was obtained about 1100 local time [see Kieffer et al., 1977]. Clouds high in the atmosphere or a ground fog would dissipate rapidly due to the low humidity and small grain size. Plasar and Goody [1976] showed that ground ice would rapidly sublime in the early morning. Thus it is not obvious why ice was observed in mid to late morning. What is needed to explain the observations of ice is some form of hysteresis effect so that ice, stable at night, is also apparent when the measurements were made (~10–12 hours local time). Perhaps ice trapped in weathering products is involved.

The residual spectrum in Figure 7a shows apparent absorption around 2.3 and 1.9 μm in the wing of the 2.0-μm Martian atmospheric CO₂ band. These absorptions are indicative of bound water, the 1.9-μm absorption due to the ν₁ + ν₂ and ν₁ + ν₅ overtones and that at 2.3 μm due to a combination overtone of an Mg-OH bending mode and the OH stretch in the 3.0 μm region [e.g., Hunt and Salisbury, 1970; Hunt et al., 1971]. Clark [1981a] has shown that bound water absorption features do not shift in wavelength appreciably (<100 Å) in the temperature range 290 to 150 K. Clark [1981a, b] also showed that the bound water absorptions are distinguishable from pure water frost or ice. The amount of water bound (physically adsorbed H₂O) to montmorillonite decreases as the temperature is decreased below 273 K if the relative humidity is greater than about 22% [see Anderson et al., 1967, Figure 2]. As the temperature decreases, bound water is forced out of clay structures and forms microcrystals of ice in the clay structure and/or pore structure. This would tend to occur during the Martian night. As the temperature rises the next day, the ice will sublime if the H₂O vapor pressure in the atmosphere is too low and the ice has free access to the atmosphere. However, if the ice crystals are within the clay mineral grains, the clay minerals may retain the ice, although some H₂O will be converted to the adsorbed phase. Thus the increase in vapor pressure above the surface might be minimal, hence undetected.

In addition to simple physical hysteresis, it should be noted that Anderson et al. [1978] showed that the adsorption–desorption characteristics of montmorillonite exhibit a marked equilibrium hysteresis effect. In a plot of adsorbed water content versus relative humidity, the desorption curve always lies on or above the adsorption curve. Thus it appears that this mechanism is plausible for retaining ice in the optical layer of the regolith on a diurnal basis during this season. Further observations of the Martian surface as a function of time of day and of season, combined with more detailed laboratory and theoretical study, are required to confirm this hypothesis.

The dark area simulation shows that there is about 4 times less water ice apparent than in the bright area simulation. The
dark area observed was over 1000 km in diameter, and some bright area material is almost certainly present in patches. Singer and McCord [1979] investigated the affects of streaks and splatters of spectrally isolated bright material on the spectral reflectance of dark regions. Their results show that the drop in reflectance from 1.3 to 1.4 μm, and the other signatures of water ice are decreased when the contribution of bright material to the spectrum is removed. Although a unique solution cannot be obtained, the water ice signature appears to be absent in spectra of 'pure' dark materials. It should also be noted that the dark areas observed lie predominantly south of the equator where the water content of the atmosphere is much less [e.g., Farmer and Doms, 1979] and the above water-in-soil mechanism has more difficulty in operating owing to lower weathering product content and lower humidity. The results from the Mariner Mars 6 and 7 infrared spectra showed that condensed phase water is present throughout the observed surface of Mars, with the brighter areas near and north of the equator, and the regions south of 50°S being the most hydrated [Pimentel et al., 1974], agreeing with our results. Pimentel et al. interpreted the spectra based on comparisons with thin surface frosts. To first order, one can say that more ice would be needed in an ice-mineral mixture than a surface frost for a similar spectral signature, indicating that the amounts of ice determined by Pimentel et al. are extreme lower limits. However, more laboratory studies need to be performed on ice-mineral mixtures to see if Mariner results are consistent with the results presented here.

**The 2.3 μm Absorption**

Nearly every spectrum in Figures 2 and 3 shows the presence of a weak 2.3-μm absorption feature. Because of the subtlety of these features a detailed examination was conducted of observations of Saturn's rings, the Galilean satellites, and the moon taken with the same instrument and two different calibration procedures [Clark and McCord, 1980b, c; McCord et al., 1981]. No similar bands were found in other data, even those taken the same nights; therefore it seems quite possible that these absorptions are characteristic of Martian surface materials. The presence and center wavelengths of these features can be determined from these data, but the band depths, or even the relative depths, are much less certain. Positive confirmation of these absorption features requires data with lower noise in this spectral region.

A single absorption at this location (≈2.3 μm) would be indicative of an Mg-OH bond; often a weaker band of similar origin appears near 2.4 μm [Hunt and Salisbury, 1970]. An absorption near 2.4 μm is possibly also present in some of these spectra, but the depth is approaching the noise limit of the data. Absorptions near 2.2 μm, characteristic of Al-OH bonds, may also be weakly present but are much less well defined than the bands near 2.3 μm. One reason for this might be masking of any 2.2-μm features by the wing of the strong atmospheric CO₂ absorption. Weak absorptions just longward of 2.3 and 2.4 μm, and perhaps a very weak absorption just longward of 2.2 μm, are apparent in a spectrum of the in-


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