Interpretation of the Martian Polar Cap Spectra

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Laboratory measurements of CO₂-H₂O frost spectral reflectance are applied to spectral observations of the Martian polar caps. There is some discrepancy between the 1.5-μ absorption feature reported for the polar cap and the spectra of either H₂O or CO₂ frost. Even if the original interpretation of absorption due to H₂O frost is accepted, the predominantly CO₂ polar cap model cannot be excluded. Similar spectra could result from the concentration of H₂O expected on a CO₂ cap during the late spring, the season the Martian cap spectra were taken. Thus the existing observations of the polar cap are inconclusive and do not demonstrate that the Martian polar caps are composed primarily of H₂O.

INTRODUCTION

Infrared spectral [Kuiper, 1952, pp. 381-382; Moroz, 1964, p. 279] and visible polarization [Dollfus, 1961, pp. 381-382] observations of the Martian polar caps have been interpreted to mean that the caps are composed of H₂O frost. Theoretical discussions [Leighton and Murray, 1966] based on recent determinations of the composition and pressure of the Martian atmosphere suggest that H₂O caps would require an extremely planetary circulation system, whereas a model of CO₂ frost caps does not require exceptional meteorology and is compatible with all information about Mars except the interpretations just mentioned.

The purpose of this work is to compare the telescope observations with laboratory spectra for simulated Martian frosts and to examine the possible role of H₂O in a predominantly CO₂ polar cap model. This study includes only CO₂ and H₂O as they are the only likely chemicals with the required physical properties that have not had prohibitively low limits placed on their abundance by spectroscopic observations.

OBSERVATIONS OF MARTIAN POLAR CAPS

The only infrared spectral observations of the Martian polar cap reported are those of Kuiper [1952] and Moroz [1964]. Both authors reduced the spectral resolution of their equipment to one-ninth the wavelength in order to have the sensitivity required to detect light reflected from the polar cap alone. The apparent sizes of the polar cap when Kuiper and Moroz made their measurements were about 2 and 1.5 square seconds of arc, respectively.

Kuiper observed natural snows and water frost formed on dry ice and found the spectra to be equivalent to the spectra of water absorption cells of different thickness. He made no mention of the marked frequency shifts between H₂O gas, liquid, and solid absorption features. He found terrestrial snow 'nearly black beyond 1.5 μ and almost fully black beyond 2.0 μ.' Measurements with CO₂ snow showed it to remain 'white' up to 2.5 μ except for the 2-μ absorption band. The reflection spectrum of the Martian polar cap was similar to terrestrial snow 'though the drop at 1.5 μ is less steep.' No data or spectra of Martian caps, H₂O or CO₂ frosts were published. The implied date of this observation is February 1948 (early northern summer). He concludes that 'the Martian polar caps are not composed of CO₂ and are almost certainly composed of H₂O frost at low temperature (much below 0°C).'

Moroz observed the polar cap spectrum in the region of 1 to 2 μ and found in the 1.5- to 1.8-μ region the cap intensity was relatively lower than that of the central portion of the disk. He published averaged spectra of the north polar cap (late spring) and the center of the
polar Cap Spectra

The reflectance are applied to spectral response between the 1.5-μm absorption either H₂O or CO₂ frost. Even if accepted, the predominantly CO₂ result from the concentration of ason, the Martian cap spectra were inconclusive and do not denote H₂O.

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observed the polar cap spectrum in of 1 to 2 μ and found in the 1.5- to 2 μ the cap intensity was relatively that of the central portion of the bluish averaged spectra of the north (late spring) and the center of the planet. Moros interpreted the polar cap spectrum as being similar to the spectra of snow and hoar frost which he had observed, concurred with Kuiper’s interpretation.

Visual polarization measurements of the polar cap have been interpreted as evidence of the presence of H₂O frost and clouds [Dollfus, 1961, p. 382]. Dollfus made no measurements of CO₂ frost or clouds. Polarization is so highly dependent on texture (see, for instance, the laboratory measurements by Dollfus [1961, pp. 361–366]) that it is not likely to yield reliable diagnostic results as to composition in any event.

The above measurements constitute the direct observational evidence for the composition of the Martian polar caps. The rate of spring regression of the polar caps constitutes indirect evidence of the polar cap composition. However, the relaxation of composition, quantity of frost, and details of the daily thermal balance and planetary circulation are complex and the observational data have been used in support of both CO₂ [Leighton and Murray, 1969] and H₂O [Miyamoto and Hattori, 1969] polar caps.

LABORATORY MEASUREMENTS

The spectral reflectances of pure CO₂, pure H₂O, mixed CO₂-H₂O, and H₂O on CO₂ were measured from 0.8 to 3.2 μ [Kieffer, 1970]. The results of the laboratory spectral measurements relevant to Mars are summarized below:

1. Spectral contrast is strongly affected by grain size (dominant textural scale).
2. CO₂ frosts have high reflectance outside the 2.0- and 2.7-μ bands for grain sizes up to at least 3 mm.
3. H₂O frosts have appreciable absorption near 1.5 and 2.0 μ and longward of 2.3 μ for grain size larger than 10 μ. For grain size larger than 100 μ, reflectance is high only at wavelengths less than 1.4 μ.
4. Small relative concentrations of H₂O have a major effect on the spectra of mixed frosts. This effect increases with grain size. Identification of CO₂ when the weight fraction of H₂O is greater than 10% is difficult except at 2.7 to 2.8 μ.
5. Surface additions of small amounts of H₂O on CO₂ frosts will result in H₂O reflection spectra. The alteration is noticeable at 0.4 mg cm⁻² and complete at less than 7 mg cm⁻² for fine frosts.
6. The intensity of oblique backscatter (sun-Mars-earth geometry) between absorption bands for the fine frosts approximately follows the cosine of the incident angle. Spectral contrast of fine frosts does not change appreciably with inclinations (measured to 65°) for small phase angles. The scattering from strong bands in coarse frosts behaves more like diffuse isotropic reflectance except for anomalous widening of the extremely strong 3-μ H₂O band.
7. High visible reflectance can be obtained with as little as 0.5 mg cm⁻² of fine H₂O frost.
8. Thin, very fine H₂O frosts have a general decrease in reflectance from 0.8 to 3 μ.

APPLICATION TO MARS

Though there is no evidence that Martian frosts have anomalous scattering properties, the possibility that they have ‘unusual’ grain shape, size distribution, or packing resulting in an anisotropic phase function or possibly some spectral effect must be remembered. The measured spectral contrast for backscatter from fine laboratory frosts did not vary significantly for inclination up to 65°. This is greater than the inclination of the edge of the Martian cap at the time of both Moros’ and Kuiper’s observations. Thus it appears that the spectral contrasts of laboratory frosts measured at normal backscatter are directly applicable to the geometry of Martian observations.

The atmospheric H₂O mixing ratio on Mars is observed to be about 10⁻⁵ [Kaplan et al., 1964; Spinrad et al., 1966; Schorn et al., 1967]. As this is similar to the mixing ratio for terrestrial polar conditions (saturated air at −40°C), the behavior and form of H₂O frosts on Mars might be much the same as on earth. However, the condensation of CO₂ on Mars has no terrestrial analogy as it would involve freezing of a nearly pure gas with the latent heat released being lost by radiation. This process does not occur naturally on earth, and possibly cannot be produced in the laboratory [Kieffer, 1968, p. 21]. Though a dense layer can form by this process, the visual albedo of the Martian caps (0.5) implies that they have a scattering, and therefore probably permeable, surface layer. This albedo is lower than the albedo for any laboratory sample. It could,
however, be caused by large (minimum size unknown) textural scale, anisotropic scattering, incomplete frost coverage, or contamination by Martian dust or dirt.

INTERPRETATION OF EXISTING MARTIAN POLAR CAP SPECTRA

Moroz [1964] reported that the spectrum of the polar cap in the 1.5- to 1.8-μ interval was less intense than the spectrum of the central region of Mars. An estimate of the spectral reflectance of the polar cap can be obtained from his data [Moroz, 1964, Figure 6] by dividing the cap spectrum by the spectrum of the center of the planet. McCord and Adams [1969] show the reflectance of Mars as approximately 0.5 in the 0.8- to 1.1-μ region and then increasing smoothly to about 0.4 at 1.6 μ, though they present only two data points beyond 1.33 μ. Recent observations with 0.05-μ resolution (T. B. McCord, personal communication, 1969) do not indicate appreciable detailed structure on this general trend for either light or dark areas on Mars. Thus the major features in the cap to center ratio should be attributed to the polar cap. The resulting spectrum is compared with representative laboratory results in Figure 1. Moroz's cap spectrum represents the average of three selected tracings so that detailed analysis may not be warranted. The peak at 1.3 μ in the cap to center ratio does not correspond to any H₂O or CO₂ feature and the minimum is clearly at shorter wavelength than for H₂O frosts. These discrepancies may reflect changes in the transparency of the terrestrial 1.4-μ water vapor band. These difficulties aside, the strength of the absorption feature observed for the cap is comparable that for H₂O frosts with textural scale from 20 to 100 μ. An absorption of this strength due to CO₂ would require a textural scale larger than 10 cm. Apart from these uncertainties, if one accepts the original interpretation that the absorption in the cap spectrum is due to H₂O frost, then the common inference that this interpretation excludes the CO₂ cap model must be examined.

There is as yet no quantitative treatment of the role of H₂O in a carbon dioxide cap. By treating the total condensation budget of the polar cap, however, a simple limiting model can be derived. The observed H₂O mixing ratio, 10⁻⁴, is the minimum likely weight fraction of H₂O in the material condensed in the polar regions. The model of a pure CO₂ cap [Leighton and Murray, 1966] predicts about 80 g cm⁻² of average annual CO₂ deposition, though the computed rates may be in error [Kieffer, 1968, pp. 67-72]. This implies that at least about 10 mg cm⁻² of H₂O is deposited on the cap in the winter. During CO₂ sublimation in the spring at the saturation temperature of 145°K, however, the H₂O mixing ratio is 10⁻⁴ at most, so that only 1% of the condensed H₂O can have sublimed where any CO₂ remains. Any atmospheric circulation would increase the efficiency of the polar cold trap, yielding a larger spring residual of condensed H₂O than derived by this simple approach. It is likely that during the spring a surface concentration of H₂O frost would grow locally in proportion to the fraction of CO₂ sublimed.

This total budget model omits the details of many relevant possibilities (cloud formation and snowfall, formation of a cap fringe of pure H₂O frost, daily enrichment of H₂O on equatorial facing slopes, and the increase of grain size through the spring). It exhibits, however, the basic principles of the CO₂ polar cap cold trap and time lag of H₂O sublimation that constitute a plausible case for a surface accumulation of H₂O frost in the spring.

The laboratory results indicate that a 5-mg cm⁻² H₂O surficial layer is sufficient to disguise a CO₂ frost. As the amount of H₂O that would be trapped in a conservative CO₂ cap model is
Material condensed in the polar regions of a pure CO₂ cap [Leighton, 1966] predicts about 80 g cm⁻² of CO₂ deposition, though the amount may be in error [Kieffer, 1968, pp. 505-510] implies that at least about 10 mg cm⁻² is deposited on the cap in the spring. Sublimation temperature of 145 K, however, implies that at most, 3% of the condensed H₂O can have any CO₂ remains. Any atmosphere would increase the efficiency of the cold trap, yielding a larger spring sublimed H₂O than derived by this method. It is likely that during the freeze concentration of H₂O frost increases in proportion to the fraction added.

Budget model omits the details of interstellar possibilities (cloud formation formation of a cap fringe of pure CO₂ enrichment of H₂O on equator, and the increase of grain the spring). It exhibits, however, no predictions of the CO₂ polar cap cold front lag of H₂O sublimation that laudable case for a surface accumulation frost in the spring.

Theory results indicate that a 5-mg fractional layer is sufficient to account for the amount of H₂O that would be conservative CO₂ cap model is assumption is summarized here. Leighton assume the effective emissivity of the Martian atmosphere to be low. Reflectance is observed for the near infrared only near frequency CO₂ gas absorption, except for some comparatively weak transitions that are the gas phase. The longest-wavelength transition, though not yet observed, would be at 7.8 μm. No other calculated wavelength with the solid are known wavelengths less than the 88- and 92-μm bands. Thus, from 8 to 80 μm the 94.2% of the thermal radiation at 150 K, the spectral emissivity is expected to correlate with the Martian atmosphere and the visual spectra of CO₂ frost, though grain size, could be quite low. The spectral emissivity of CO₂ at wavelengths near the existing observations. Thus the conclusion that the Martian caps are composed primarily of H₂O is not warranted. Measurements of the winter or early spring frost would be more definitive, though more difficult because of the unfavorable geometry.

ACKNOWLEDGMENTS

This work was supported by National Aeronautics and Space Administration grants NGR 05-002-116.

REFERENCES


(Received August 22, 1969; revised October 21, 1969.)