ancient Martian craters. Phobos and Deimos can be regarded as old, relative to Martian surface structures on the kilometer scale.

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Infrared Spectroscopy Experiment on the Mariner 9 Mission: Preliminary Results

Abstract. *The Mariner 9 infrared spectroscopy experiment has provided good-quality spectra of many areas of Mars, predominantly in the southern hemisphere. Large portions of the thermal emission spectra are significantly affected by dust with a silicon oxide content approximately corresponding to that of an intermediate igneous rock, thus implying that Mars has undergone substantial geochemical differentiation. Derived temperature profiles indicate a warm daytime upper atmosphere with a strong warming over the south polar cap. Atmospheric water vapor is clearly observed over the south polar area and less strongly over other regions.*

The infrared spectroscopy experiment on the Mariner 9 mission was designed to provide information on atmospheric and surface properties by recording a major portion of the thermal emission spectrum of Mars. The original intent was to determine vertical temperature profiles, the surface temperature, and the atmospheric pressure at the surface, and to acquire information related to the surface composition. The experiment also was designed to search for minor atmospheric constituents, including H_2O vapor and isotopic components of CO_2 (*1*). The biological implications of the Martian environment were to be studied. Although the Martian dust storm has complicated the task of attaining the scientific objectives originally formulated for a dust-free atmosphere, unexpected information was obtained on the dust composition and on the general circulation associated with the storm.

The Michelson infrared interferometer spectrometer (IRIS-M) records the spectral interval from 200 cm^{-1} (50 μm) to about 2000 cm^{-1} (5 μm) with a nominal spectral resolution of 2.4 cm^{-1} in the apodized mode of data

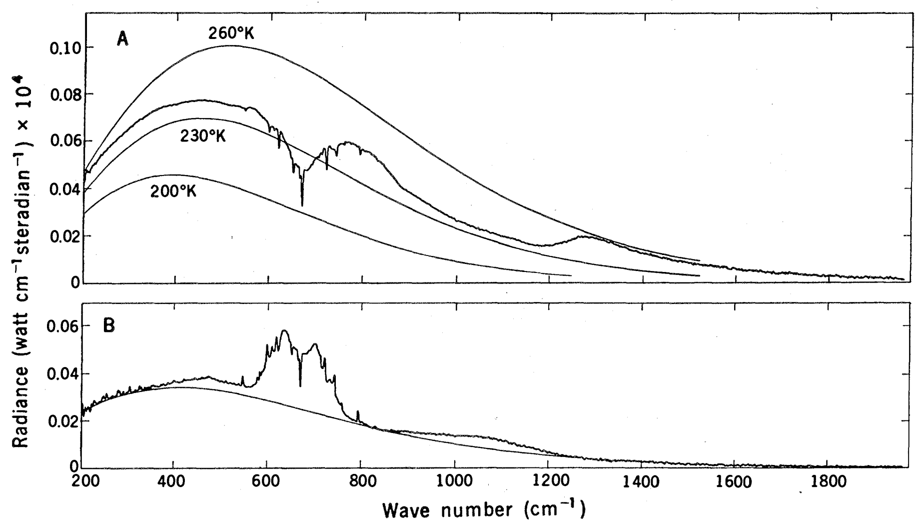

Fig. 1. (A) Example of nonpolar thermal emission spectra. The spectrum is the average of six spectra obtained from revolution 8 in the region of 18°S, 13°W at about 12:00 local time. Three blackbody curves are included for comparison. (B) Example of polar thermal emission spectra with the south polar cap in the IRIS field of view. This spectrum is the average of six individual spectra obtained from revolutions 29 and 30. The smooth curve is the composite of two blackbody spectra, as described in the text.

reduction. A noise equivalent radiance of about 5×10^{-8} watt cm^{-1} steradian^{-1} has been achieved. The field of view is almost circular with a half cone angle of 2.25 deg. Wave-number calibration is provided by a fringe control interferometer for which the 0.6929-μm line of a Ne discharge source is used as a standard. Intensity calibration is achieved by scaling Mars spectra to calibration spectra recorded periodically during alternate observation of deep space and of a 296.4°K on-board blackbody. After Fourier transformation and scaling of the raw spectra in an Earth-based digital computer, the individual calibrated spectra are displayed in absolute radiometric units as a function of wave number.

On a planetary scale, the Martian spectra obtained so far exhibit a fair degree of uniformity in comparison with similar spectra obtained from the Nimbus satellites for Earth (2). The major exception in the appearance of Maritan spectra occurs in the vicinity of the south polar cap. Examples of nonpolar and polar spectra are shown in Fig. 1, A and B, respectively.

Major features common to all spectra are the two broad regions at 400 to 600 cm^{-1} and 850 to 1250 cm^{-1}, which appear in absorption in the nonpolar spectra and in emission in the polar spectra, and the molecular absorption by CO_2 in the range from 540 to 800 cm^{-1}. The differences in appearance of the spectra may be qualitatively ascribed to differences in the atmospheric temperature profile, the underlying lower boundary surface, and the amount of dust in the atmosphere. In most of the nonpolar spectra, all of the molecular bands of CO_2 appear in absorption, an indication that the atmospheric temperatures decrease with height on a gross scale. In the polar spectrum, the parts of the spectrum from 550 to 625 cm^{-1} and 700 to 800 cm^{-1} appear in emission, an indication

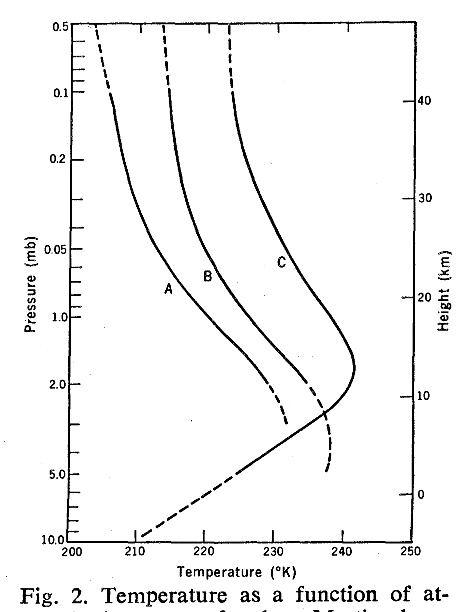

Fig. 2. Temperature as a function of atmospheric pressure for three Martian locations: curve A, 15.0°S, 64.2°W (Sinai) at 19:00 local time; curve B, 38.0°S, 282.8°W (Hellas) at 19:00 local time; curve C, 86.6°S, 342.2°W (south polar region) at 13:00 local time. Dashed parts of the curves are regarded as uncertain. An approximate height scale is included, with the triple-point pressure of water (6.1 mb) used as a reference level.

that the lower atmospheric region in which this radiation originates is at a warmer temperature than the underlying surface.

The most striking result of the experiment thus far is the strong effect of the atmospheric dust on the emission spectra. The entire spectrum, with the exception of the strongly absorbing part of the 667-cm^{-1} (15-μm) CO_2 molecular band, apparently is influenced to varying degrees by the opacity of the dust in the atmosphere. A rigorous treatment of spectra from a dust-laden atmosphere must be based on a radiative transfer model which incorporates absorption and scattering by the dust along with molecular CO_2 absorption. Until that treatment can be accomplished, more simplified methods must suffice.

The diffuse features appearing near the 470- and 1075-cm^{-1} absorption in nonpolar spectra and near the 470- and 1075-cm^{-1} emission in polar spectra are attributed to dust particles in the atmosphere. The features are characteristic of the SiO_2 bands in silicate-bearing minerals. Lyon (3), Hovis (4), Aronson *et al.* (5), Salisbury *et al.* (6), and Conel (7) have shown that the spectral position of absorption and reflection peaks depends on the silica content; acidic minerals [70 to 75 percent (by weight) SiO_2] suspended in powder form absorb most strongly at 1100 cm^{-1}, whereas ultrabasic materials (less than 45 percent SiO_2) show absorption peaks near 950 cm^{-1}. A preliminary comparison of the emission features measured over the south polar region with the absorption spectra of fine dust measured by Lyon shows generally good agreement with those of minerals and rocks whose SiO_2 content is in the intermediate range (55 to 65 percent), but poor agreement with highly acidic (greater than 65 percent) as well as basic (45 to 55 percent) and ultrabasic material. Silicates are also indicated in nonpolar areas. If this result is substantiated by continuing analysis (additional laboratory measurements of emission and absorption spectra of various dust samples, radiative transfer calculations for a scattering and absorbing atmosphere, analysis of additional spectra), its implications are of great planetological significance.

There is at this time no agreement on whether Mars is differentiated [see (8), for example]. The SiO_2 content of planetary surfaces is probably the best gross geochemical indicator of the degree of differentiation. Thus, the relatively high SiO_2 content indicated by these preliminary results, if representative of the Martian surface, would show that Mars has undergone at least as much differentiation as the moon (*9*), and perhaps as much as Earth. In this discussion it is assumed that the suspended dust has the same bulk composition as the surface rocks. This assumption is based on the probable absence of extensive chemical weathering on Mars.

The fact that the silicate features associated with the dust appear in emission in the polar spectra confirms that the absorption is produced by dust suspended in the atmosphere rather than the surface itself. The strength of the dust features in the spectra indicates a fairly substantial optical depth for the dust, especially in the regions away from the south polar cap or away from high plateaus.

It has thus far been possible to observe the Martian surface only in the region of the south polar cap, and perhaps over highlands, where the atmospheric dust is sufficiently thin. For quantitative interpretation, it is first necessary to establish the radiance originating from the planetary surface. This radiance, in general, depends on the emissivity of the surface material, the degree of homogeneity of the surface within the field of view in terms of temperature and composition, and the opacity of the dust-filled atmosphere. From a working model, a background radiance curve for the average south polar spectrum shown in Fig. 1B has been calculated and is included in Fig. 1B. In the model it is assumed that an unknown fraction of the field of view is filled with a blackbody emitter at one temperature, whereas the rest of the field of view is filled with a blackbody at a second temperature. The model is based on the fact that the apparent size of the cap is slightly smaller than the IRIS field of view and is heterogeneous in structure. By using measured radiances at 295, 840, and 1330 cm^{-1}, and by assuming that the measured radiances are unaffected by the atmosphere and by the dust in it, a fit was obtained with 65 ± 5 percent of the field containing an emitter at $140° \pm 10°K$ and the remainder of the field filled with an emitter at $235° \pm 10°K$. This result is consistent with a frozen CO_2 cap, in agreement with earlier work (*10*).

Estimates of the vertical temperature structure of the Martian atmosphere can be obtained from measurements in the 667-cm^{-1} CO_2 absorption band by inversion of the integral equation of radiative transfer. If the atmospheric transmittance is known, the temperature as a function of atmospheric pressure can be derived. Preliminary retrievals of temperature profiles have been made on the assumption that the atmosphere consisted of 100 percent CO_2, and on the basis of the neglect of possible additional opacity due to dust. A knowledge of surface pressure is also required for an accurate specification of temperature in the lower atmospheric levels. The apparently near-isothermal structure of the lower atmosphere and the effects of dust opacity have prevented determination of surface pressure from the spectral data. Therefore, use has been made of surface pressure estimates from Earth-based measurement and from Mariner 6 and 7 data in regions where such data exist.

Examples of retrieved profiles are shown in Fig. 2. The profiles over Hellas and Sinai are typical of those obtained from spectra similar to the nonpolar cases of Fig. 1A. Surface pressure was estimated for Hellas from Mariner 7 ultraviolet spectrometer measurements (*11*) and for Sinai from Earth-based radar measurements (*12*), which were normalized at coincident points to Mariner 6 ultraviolet spectrometry pressure estimates. The lower lapse rates below 2 mb may be real. However, if the dust has an optical depth in the 15-μm band at this level of approximately unity, a similar effect will result, regardless of the true thermal structure in this region. When the optical depth of the dust is less than unity, the temperature retrieval data will be essentially unaffected by the presence of the dust. As the optical properties of the dust become better understood, the lower portions of the profiles therefore may be subject to revision. The temperatures above 2 mb are generally warmer than either those predicted theoretically for a dust-free atmosphere (*13*) or those obtained from the Mariner 6 and Mariner 7 occultation experiments (*14*).

A profile obtained over the south polar cap is included in Fig. 2. The most outstanding feature is the pronounced temperature inversion, which

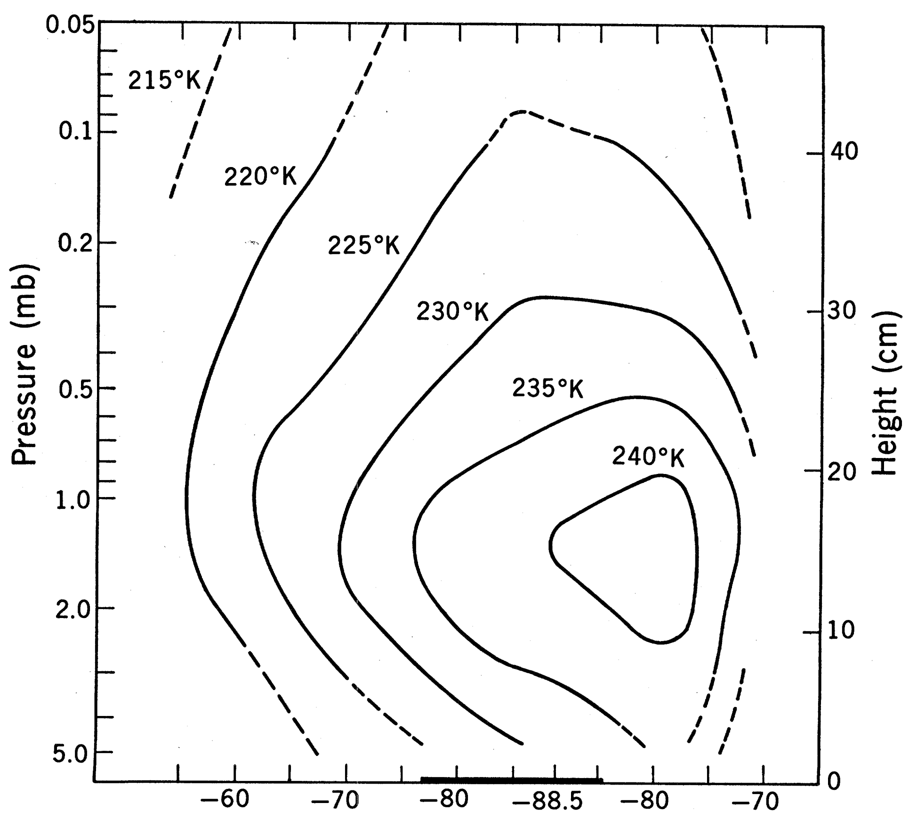

Fig. 3. Isotherms for a cross section obtained from a single pass in the south polar region. The abscissa indicates the latitude of the center of the instrument's field of view as it approached the pole and then moved away from it. Atmospheric pressure is given along the ordinate with an approximate height scale similar to that of Fig. 2. Dashed parts of the contours are uncertain. The heavy line at the bottom represents the extent of parts of the polar cap observed by the instrument.

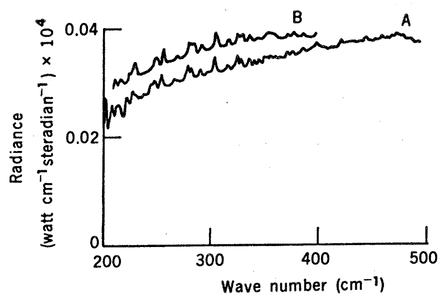

Fig. 4. The 200- to 500-cm^{-1} portion of the spectrum of the south polar cap of Fig. 1B shown on an expanded scale (curve A). The numerous spectral lines appearing in emission are due to rotational H_2O vapor lines in the lower Martian atmosphere. A synthetic H_2O vapor spectrum (curve B) is included for comparison; the spectrum has been shifted upward by 0.005 radiance unit.

is responsible for the fact that the CO_2 bands are seen partly in emission as in the polar spectrum shown in Fig. 1B. Surface pressure estimates are not yet available in this region, but the basic behavior of the profile was essentially unaffected as the surface pressure varied from 5 to 20 mb. Only the profile obtained with a surface pressure of 10 mb is shown. Figure 3 shows isotherms for a vertical cross section along a single scan pass down onto the cap and back off the cap again. The lower part of the diagram is uncertain because of the neglect of dust in the analysis and lack of knowledge of the surface pressure. The cross section shows a highly localized region of warm air at approximately 1 to 2 mb in the vicinity of the cap. The substantial solar illumination during the south polar summer, the reflection of solar energy by the cap, and atmospheric dynamical effects are all possible mechanisms that could produce this effect.

The polar spectra also show rotational lines of H_2O vapor in the region between 200 and 350 cm^{-1}. This portion of the IRIS spectrum from Fig. 1B has been expanded in Fig. 4. Consistent with atmospheric temperatures warmer than surface temperatures, the H_2O vapor lines appear in emission. Also shown in Fig. 4 is a synthetic slant path spectrum composed by the use of the two-surface temperature model described above. The excellent spectral correspondence verifies the existence of atmospheric H_2O vapor in the south polar region. Spectral features of H_2O vapor appear more weakly over other regions of the planet. Possible reasons for the fact that H_2O vapor is not more prominent there may be sought in the near-isothermal nature of the temperature profiles, the shielding effect of the dust, or possibly a lower H_2O vapor concentration away from the south pole.

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Infrared Radiometry Experiment on Mariner 9

Abstract. *The brightness temperatures at 10 and 20 micrometers measured by the Mariner 9 infrared radiometer differ substantially from those predicted by the radiometer results of Mariners 6 and 7. The results indicate a significant latitude-dependent contribution of the atmospheric dust to the observed thermal emission.*

A two-channel infrared radiometer similar to that carried on Mariners 6 and 7 was included on Mariner 9 in order to extend and improve the surface coverage and spatial resolution obtained on the earlier flights (*1*). The radiometer measures the 10- and 20-μm radiation over an area coaxial with, and equal to about two-thirds of, that covered by the high-resolution television camera. At periapsis, the linear scale resolved by the radiometer approaches 20 km. The temperature resolution is on the order of 0.5°K. The radiometer has operated in orbit as expected. We now present preliminary results provided by the radiometer, particularly those related to the dust storm prevalent on Mars during these observations. This discussion is qualitative because geometry data and local times have not been available for most of the orbits.

In 1969, radiometric measurements of the largely dust-free planet could be explained in terms of simple thermal models with no appreciable influence by the Martian atmosphere. In 1971, in contrast, the general features of the observed thermal variations do not follow such simple models. The most striking difference is exhibited by the amplitude of the diurnal variations. On the basis of a typical 1969 model (thermal inertia = 0.006 cal cm^{-2} sec$^{-1/2}$ °K^{-1}, albedo = 0.3), the surface temperatures at a latitude of about −30° were expected to range from 185°K near the morning terminator to a peak of 290°K near the local noon. In fact, the observed brightness temperatures at this latitude have ranged only from 195°K just before sunrise to a maximum of 225°K. The maximum temperatures measured (around 250°K) occur at latitudes close to −65°. This observed thermal behavior cannot be explained by a simple conductive model without invoking unreasonable values of the thermal inertia. On the other hand, qualitative agreement with the observations can be obtained using simple models that incorporate an atmospheric dust layer with modest visual absorption and reflectivity, with infrared emissivity and absorption coefficients of about 0.5, and with a heat capacity corresponding to that of the