SPECTROSCOPIC DETERMINATION OF SURFACE PRESSURE AND ELEVATION DIFFERENCES ON MARS

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Abstract. Observations of a carbon dioxide band at 1.2206 μ (8192.6 cm^{-1}) made at the opposition of Mars in June, 1969, are used with laboratory data to derive a value for the pressure at the surface of Mars. This band is especially suitable because it is sensitive to pressure, lying in the transition region of the curve of growth, but is relatively free of telluric contamination. The pressure derived is $5.3^{+2.2}_{-2.6}$ mb, corresponding to the Martian desert region Amazonis.

Using a five-channel spectrometer, the strengths of two carbon dioxide bands at 1.5753 and 1.6057 μ (6347.8 and 6227.9 cm^{-1}) were compared over a Martian dark area (Mare Acidalium) and a nearby bright area in Amazonis. The bands were 1.32 times stronger in the dark area than in the bright area. Interpreting this as evidence for elevation differences on the Martian surface, it is found that the dark Mare Acidalium is 2.5 km lower in elevation than the bright area with which it was compared.

1. Introduction

The observations described in this paper were made jointly with V. I. Moroz using his equipment on the 125-cm reflector of the Southern Station of the Sternberg State Astronomical Institute (Moscow, U.S.S.R.) in the Crimea, while the author was a guest of the Soviet Academy of Sciences. The laboratory measurements and the interpretations in this paper were made by the present author, and the appearance of the data here does not preclude their elaboration and further interpretation elsewhere, either by Moroz alone or jointly with other investigators. The author wishes to record his gratitude to V. I. Moroz for his generosity in making the observational material freely available.

2. Determination of the Surface Pressure

Previous spectroscopic investigations of the Martian surface pressure have been made in two steps. First, the CO_2 abundance is determined from observations of weak lines which are essentially independent of the pressure. Then, strong bands, frequently those near 1.6 and 2.0 μ, which are sensitive to pressure broadening are used for deriving the surface pressure. Reviews of earlier studies of this problem are given by Cann *et al.* (1965) and Chamberlain and Hunten (1965).

Contradictory and uncertain values for the Martian surface pressure resulting from analyses of various CO_2 bands made it seem desirable to study previously neglected bands in order to establish an independent pressure value. The study of faint bands requires more spectral resolution than can easily be achieved with scanning spectrometers in the infrared, and for this reason the bands we are considering here were not

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treated in the lengthy investigations of Owen and Kuiper (1964), Chamberlain and Hunten (1965), and others. However, using a scanning spectrometer built by Moroz, and a Cu:Ge photoconductive detector cooled with liquid nitrogen, it was possible to obtain good spectra of Mars in the 1.2 μ region with resolution 1700, or about 7 Å. The 125-cm reflector of the Southern Station of the Sternberg State Astronomical Institute (Moscow) was used in its location in the Crimea at latitude 45°N. The northern latitude of the observatory made it difficult to observe Mars because of the planet's low declination.

Figure 1 shows representative spectra of Mars and the moon (at similar airmass) taken on June 6–7 and June 5–6, 1969, respectively. While the band designated 023

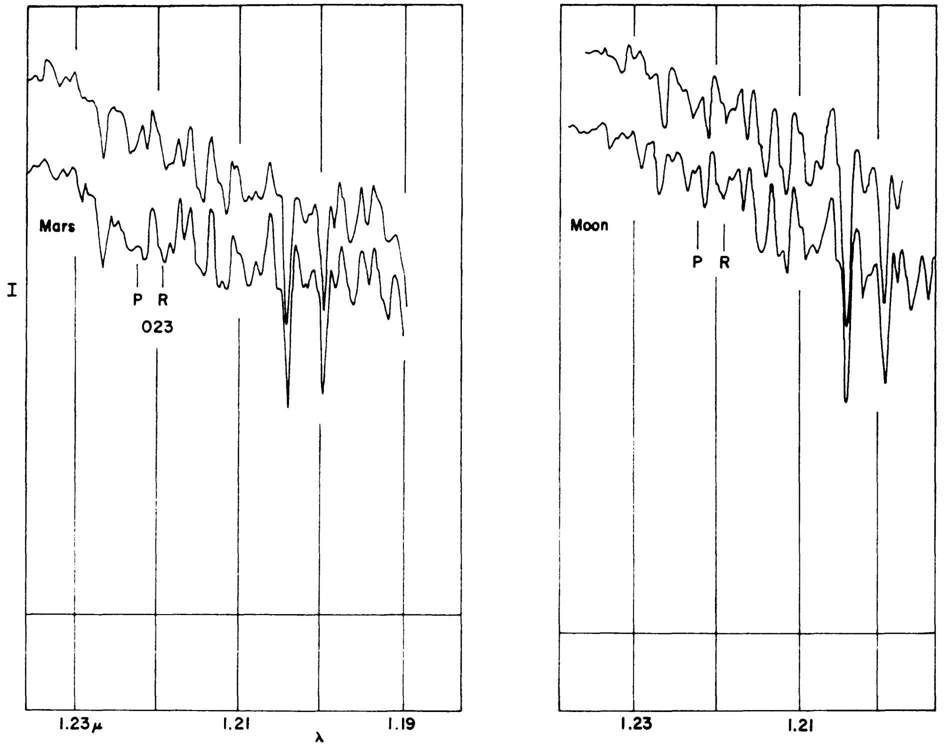

Fig. 1. Spectra of Mars and the moon in the region of the bands of CO_2 at 1.2206 and 1.2055 μ. Made with scanning spectrometer having resolution 7 Å.

(old style) shows distinctly in the Martian spectrum, the companion band (103) at 1.2055 μ (8294.0 cm^{-1}) is too strongly blended with telluric water vapor lines to be disentangled for measurement. The 023 band was measured by Moroz on the original tracings, and he found 2.6 Å $\pm$ 0.5 Å for the equivalent width. It is upon this value that the following analysis is based. The spectra were taken with the slit accepting an equatorial strip across the planet.

In this analysis, the empirical approach used by Owen and Kuiper (1964) was adopted. Laboratory spectra of pure CO_2 were made at the Lunar and Planetary

Laboratory using a scanning spectrometer adjusted to give the same spectral resolution as that with which the Mars spectra were obtained. The gas was admitted to the 40 m multiple-pass White cell and for a given pressure, spectra were taken at three or four different total path lengths up to 2.47 km (64 traversals through the cell). Because the bands at 1.2206 and 1.2055 μ are weak, they did not show well on the spectra with

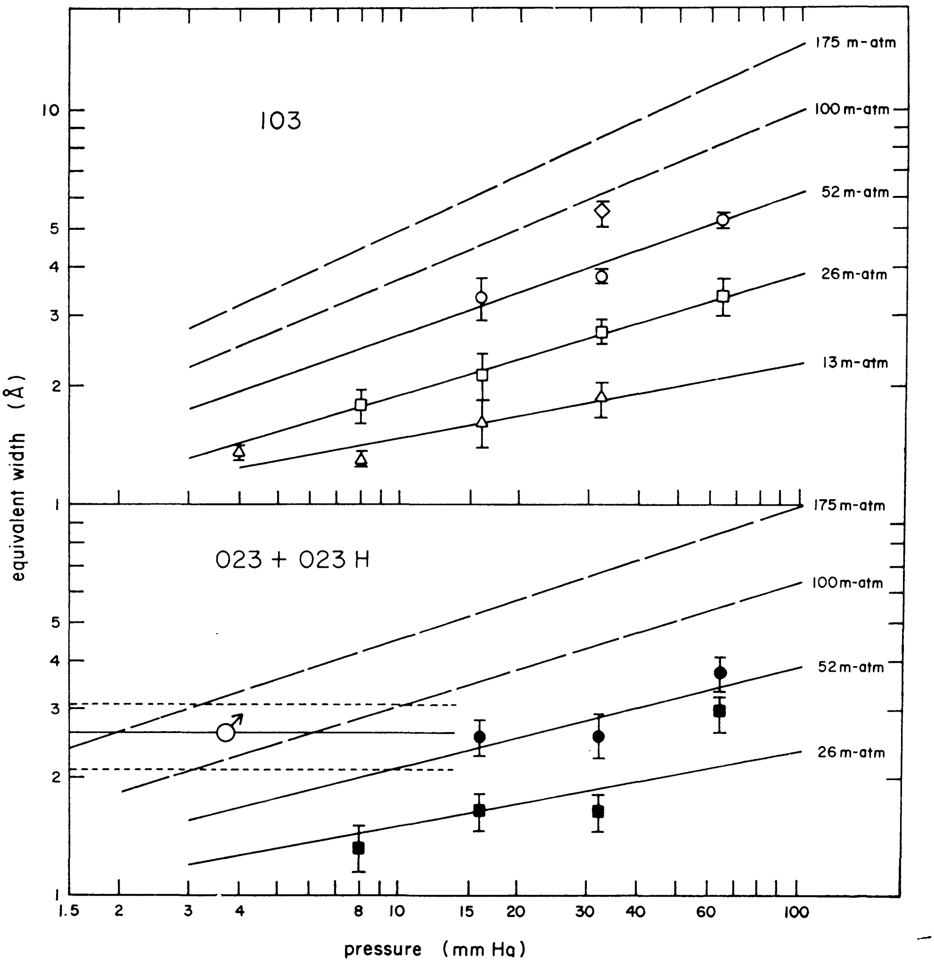

Fig. 2. Curves of growth of the CO_2 bands at 1.2055 (103) and 1.2206 (023) microns from laboratory observations. The curves of growth for the 023 band include a small contribution from the hot band 023H. This contribution does not exceed about 10%.

only 4-mm Hg pressure in the cell, but at 8 mm pressure and higher they were easily seen and measured.

The laboratory data are plotted in Figure 2 for both bands observed in the laboratory. While only the 1.2206 μ band is considered in this report, the data for the 1.2055 μ band are also included for possible future use. The data at first show that these two bands are in fact pressure sensitive – the same quantity of gas (in meter-atmospheres) gives smaller equivalent widths at lower pressures. The slope of the lines, shows, however, that the bands are neither on the 'straight-line' or 'square-root' portions of the curve of growth, but instead in the transition region.

As Owen and Kuiper (1964) pointed out, the amount of gas required in the laboratory simulation of the Martian atmosphere is given by

$$w \frac{T_{\text{lab}}}{273} \eta$$

where w is the CO_2 abundance (in meter-atmospheres) in the Martian atmosphere as determined by other spectroscopic investigations, and η is the effective airmass in the Martian atmosphere. Using the table of Owen and Kuiper (1964, p. 132) we find $\eta = 2.21$. If we adopt 75 m-atm as the Martian CO_2 abundance (Kaplan and Gray-Young, 1969), then the amount of gas required in the laboratory becomes 179 m-atm. In the range of pressures appropriate for the Martian surface (say 4 mm Hg), 179 m-atm CO_2 requires a path length of some 34 km. This was not possible in the LPL White cell, so observations were made at three different quantities of gas (four, in the case of the 103 band) and several different pressures. Then, as Owen and Kuiper found necessary, the curves were extrapolated to larger quantities of gas, as shown by the dashed lines in Figure 2. The 023 band was also observed at 13 m-atm but the data are not included in Figure 2 because of their inferior quality. They do not bear directly on the extrapolation to large quantities of gas.

Because of the gentle slope of the 175 m-atm line in Figure 2, it can be seen that the greatest source of error is the uncertainty in measurement of the equivalent width of the CO_2 band in the Mars spectrum. The error in extrapolation of the laboratory data to 175 m-atm is less significant. The horizontal line representing the equivalent width of the band in the Mars spectrum intersects the 175 m-atm line at a pressure value of 2 mm Hg (2.66 mb). Because the mean pressure along the absorbing path in the atmosphere of Mars is one-half the surface pressure (Curtis-Godson approximation), we double this value to give the *Martian surface pressure of* $5.3^{+2.2}_{-2.6}$ mb.

3. Elevation Differences

In 1965, when it became known from analysis of Mariner IV occultation data that the scale height in the lower Martian atmosphere was 9 km ± 1 km (Kliore *et al.*, 1965), speculation about elevation differences on Mars took on a new dimension. It was evident that differences in elevation of the order of a few kilometers should be detectable by the difference in atmospheric CO_2 absorption that would occur above regions of relatively different altitude.

No reliable spectroscopic results were reported from the 1967 apparition of Mars, but radar ranging data with high spatial resolution on the planet were obtained (Pettengill *et al.*, 1969) and interpreted (Binder, 1969) to show that the dark areas are uniformly lower in elevation that the bright areas. Further analysis of the radar shows that the correlation of topography with dark and bright areas is not direct. The first spectroscopic results were obtained at the 1969 apparition of Mars and reported in a preliminary form by Hunten and Belton (1969). They verified the lack of direct correlation between elevation and surface albedo, and reported a total range of altitude of more than 20 km.

In order to compare Martian atmospheric CO_2 absorption over the bright and dark areas of the planet, a 5-channel, simultaneously recording spectrometer was used with a multi-element PbS detector on the 125-cm reflector in the Crimea. The dispersion of the spectrometer and the spacing interval of the PbS detector elements were such that the two strong bands of CO_2 at 1.5753 and 1.6057 μ (6347.8 and 6227.9 cm^{-1}) fell on elements 2 and 4 of the five-element detector array. Elements, 1, 3, and 5 covered the regions outside and between the two strong bands, thus providing a measure of the intensity of the continuum. The normal entrance slit of the spectrometer was replaced by a plastic plate in which several tiny holes had been drilled and the front surface of which had been aluminized for high reflectivity. This made it possible for the observer to continuously monitor the image of Mars with the spectrometer guide microscope during the integrations. A diaphragm of diameter 3 sec of arc

Fig. 3. Photograph of Mars showing the regions observed for comparison of CO_2 band strengths and the derivation of elevation difference. Photograph by John Fountain, June 18, 1969, 01 05 UT, Cerro Tololo 60-inch reflector, Kodak High Speed Infrared film with filter transmitted 6600–8700 Å. Composite of four images. Central meridian longitude 61.24°.

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gave suitable signal levels and provided the highest practical resolution on the disk of Mars. Figure 3 shows the appearance of Mars during the measurements with the appropriate size of the diaphragm superimposed. The innermost circle is the actual projected diameter of the entrance diaphragm, and the outer circle represents the degree of smearing by seeing. The guiding of the telescope was exceedingly accurate.

The observed points on Mars were centered over a dark area (approximate coordinates 35°W longitude, +45°N latitude) and a light region (100°W longitude, +10°N latitude). Many integrations were made over the dark area (Mare Acidalium) and over the bright region which was equidistant from the limb of the planet (Amazonis desert), each with a sky background integration for comparison. An attempt at absolute calibration of the measurements was made by observing a bright star, but only the relative measurements are of interest here. From observations of the same bright and dark regions over two nights (June 8–9 and 9–10, 1969), there was clear indication that the intensity of the two CO_2 bands was greater over the dark Mare Acidalium than over the comparison desert region. Averaging the data of both nights, we find that the absorption in the dark area is stronger by a factor 1.32 than in the bright region.

In the simplest interpretation of these data, we can find the elevation difference knowing only this ratio of band intensities and the atmosphere scale height. If N_0 is the number of molecules in the atmosphere at some datum h_0, then the number of molecules at height h_1 is $N_0 \exp(-h_1/H)$ and at height h_2 is $N_0 \exp(-h_2/H)$. Then, the ratio of the absorption band strength at the two levels h_1 and h_2 is given by $\exp[-(h_1-h_2)/H]$. H is the scale height, taken here as 9 km. The difference in elevation, $h_2-h_1=H \ln 1.32=2.5$ km.

The uncertainties in this last quantity depend on the probable errors in the scale height (about 10%) and in the observed ratio of band strengths (10–12%). Thus, the observed elevation difference with its probable error is 2.5 ± 1.2 km.

Two further sources of error exist, both considered minor. First, the low altitude of Mars during the observation results in atmospheric dispersion of the image seen in the telescope. This means that the infrared image is displaced slightly from the visual light image, and while the observer positions the visual image correctly with respect to the entrance diaphragm, the infrared image (detected by the spectrometer) lies in another position. During the observations reported here, the effect of image displacement was tested by moving the image around with respect to the diaphragm and noting the signal level received by the detector. For the Mare Acidalium point, the signal level was the lowest that could be seen for any region of the planet, and from this it is concluded that atmospheric dispersion was a minor effect, displacing the infrared image of the dark region less than one diaphragm diameter from the visual image.

The second source of error is in the assumption of an isothermal lower atmosphere on Mars. This assumption considerably simplifies the analysis of the present observations and any reasonable departure from isothermal conditions will not significantly affect the results given here, especially since the observed elevation difference is relatively small.

It is instructive to compare the results of the present measurements with those reported by other investigators. The radar ranging data of Pettengill *et al.* (1969) indicate that the relative elevation difference at the longitudes of the regions observed here is 9 ± 2 km. The radar data refer to a rather narrow strip centered at latitude +21°N, and extrapolation to the latitudes of the spots observed spectroscopically is uncertain. In an independent analysis of an early version of Pettengill's data, Binder (1969) made an extrapolation in latitude, and found that the elevation difference near the two regions observed here was 7–8 km. The important thing is that analyses of both Pettengill *et al.* and Binder agree with the present study in the *sense* of the difference in elevation of these two regions, i.e. the dark Mare Acidalium is lower than nearby desert Amazonis.

Spectrographic detection of elevation differences near the regions discussed in the present paper were reported by Belton and Hunter (1969). On a solid relief map made from their observations of approximately 200 points on Mars, Mare Acidalium is seen as a low area compared with the region in the Amazonis desert at 100° longitude. The elevation difference estimated from the map is 5 km. The map was made from preliminary reductions of the observations and is subject to refinement.

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Gratitude is expressed to V. I. Moroz for his generosity in sharing the observational data obtained in June, 1969. Miss L. V. Gromova assisted in making some of the Mars observations, and A. B. Thomson assisted in obtaining the laboratory data for CO_2. The Mars observations were made while the author was a National Academy of Sciences exchangee in the Soviet Union. The laboratory studies and interpretation were completed upon return to the Lunar and Planetary Laboratory, and were supported by NASA grant NsG 161-61.

Note Added in Proof. Two detailed studies of the observational data reported here with additions have been submitted for publication in the *Astronomicheskii Zhurnal* (U.S.S.R.). In the first, 'An Attempt to Determine Differences in Height on Mars from the Intensity of the CO_2 Bands at 1.6 Microns', by V. I. Moroz, N. A. Parfentev, D. P. Cruikshank, and L. V. Gromova, it is shown that dark regions on the planet can be higher, lower, or the same in elevation as the bright regions. The maria Acidalium and Cimmerium were compared with bright regions Amazonis, Isidis, and Cebrenia. The maximum elevation difference found was in the comparison of Mare Cimmerium with Cebrenia, the mare being 7.2 km higher in elevation.

In the second paper, 'A Spectroscopic Determination of the Pressure in the Atmosphere of Mars from the CO_2 Band at 1.22 Microns', by V. I. Moroz and D. P. Cruikshank, new laboratory spectra of carbon dioxide bands at 1.22, 1.6, and 2.1 microns were used to determine a composite curve of growth. This technique reduces the error of extrapolating the laboratory curve of growth to longer path lengths (corresponding to the Martian absorption) than are physically possible in the laboratory. The result of that analysis gives the Martian surface pressure for a pure CO_2 atmosphere not substantially different from the result of the more simple analysis in the present paper.

References

Belton, M. J. S. and Hunten, D. M.: 1969, 'Spectrographic Detection of Topographic Features on Mars', *Science* **166**, 225–227.

Binder, A. B.: 1969, 'Topography and Surface Features of Mars', *Icarus* **11**, 24–35.

Cann, M. W. P., Davies, W. O., Greenspan, J. A., and Owen, T. C.: 1965, 'A Review of Recent Determinations of the Composition and Surface Pressure of the Atmosphere of Mars', NASA Contractor Report CR-298, 176 pp.

Chamberlain, J. W. and Hunten, D. M.: 1965, 'Pressure and CO_2 Content of the Martian Atmosphere: A Critical Discussion', *Rev. Geophys.* **3**, 299–317.

Gray-Young, Louise D.: 1969, 'Interpretation of High-Resolution Spectra of Mars, I. *Icarus* **11**, 386–389.

Kliore, A., Cain, D. L., Levy, G. S., Eshleman, V. R., Fjeldbo, G., and Drake, F. D.: 1965, 'Occultation Experiment: Results of the First Direct Measurement of Mars' Atmosphere and Ionosphere', *Science* **149**, 1243–1248.

Kaplan, L. D. and Gray Young, L. D.: 1970, this volume, p. 189.

Owen, T. C. and Kuiper, G. P.: 1964, 'A Determination of the Composition and Surface Pressure of the Martian Atmosphere', *Commun. Lunar Planetary Lab.* **2**, 113–132.

Pettengill, G. H., Counselman, C. C., Rainville, L. P., and Shapiro, I. I.: 1969, 'Radar Measurements of Martian Topography', *Astron. J.* **74**, 461–482.