RELATIVE ELEVATION DIFFERENCES REVEALED BY NEAR INFRARED CO_2 BANDS ON MARS

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Abstract. High dispersion spectroscopic observations of Mars, carried out with the new 107-inch and 82-inch Struve telescopes at McDonald Observatory, were used for detection of relative elevation differences on the surface of Mars. The dispersion of the spectra was 4.4 Å/mm for the 0.87 CO_2 band and 3.5 Å/mm for the CO_2 bands in the 1 μ region. Spatial resolution during the 1969 opposition was about 20° by 10° for 0.87 μ and 15° by 15° on the planet for the 1.03 μ and 1.05 μ bands. The results are shown in Tables I, II, III and Figures 2 and 3. The observed differences in elevation are on the order of 10 km, which is in good agreement with the latest radar measurements of the topographic features on the Martian surface.

1. Introduction

The growing possibility for study of the planetary system by direct means of space probes provides us with new, very accurate, and frequently surprising information about physical conditions on planets and in interplanetary space. On the other hand, these direct means require better and better initial data to insure the success of planetary orbiters, fly-bys, probes, and especially soft-landers. The physical properties of planetary atmospheres still remain rather poorly known. For example, successful realization of the projected unmanned soft landing on Mars in 1973 demands a special effort in acquisition of the data.

The 1969 opposition of Mars provided a good occasion for this. During more than a month the geocentric distance of the planet was less than 0.5 AU, its diameter greater than 19 arcsec, and declination not too low for observation at McDonald Observatory. Furthermore, the new 107-inch telescope and its excellent coudé spectrograph went into operation three months before opposition. Large blocks of observing time being available on both the 107-inch and 82-inch telescopes at McDonald Observatory for the planetary work, a large number of spectroscopic observations of Mars, chiefly in the region 8000–12 200 Å, were obtained. This material can be used not only for total-disc abundance and pressures determination of Martian CO_2 and its seasonal variations, but also, due to relatively large disc size and good seeing, for differential measures of CO_2 over different aerographic regions of the planet.

2. Recent Determination of the Relative Elevation Differences

Relative altitudes of the dark and bright areas on Mars have been subjects of great interest during the last few years. Traditionally, the prevailing opinion of most observers of Mars has been that the dark areas are lowlands and the bright areas highlands. This opinion, in lack of direct supporting evidence, was based mainly on

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analogies with terrestrial weather patterns: lowlands would be warmer and more likely to support the life forms which could be responsible for the regenerative properties of the dark areas. The observed 8° temperature difference in favor of the dark areas gave some support for this opinion. However, there is strong evidence that the differences in temperature are connected rather more closely with the local surface albedo than with altitude difference (Sagan and Pollack, 1968). Also, the regenerative properties can be explained as purely mechanical, wind-driven phenomena (Rea, 1963, 1964; Sagan *et al.*, 1967), or as meteorological effects (Wells, 1965, 1966).

To interpret early radar-reflectivity observations, Sagan *et al.* (1966a, 1966b) developed models of the Martian surface in which elevations up to 15 km existed. The dark areas were highlands or continental blocks, the bright areas were low basins filled with sand, and the canals were mountain ranges. In disagreement with these last hypotheses are the results of the direct time-delay radar measurement of Mars by Haystack Microwave Facility operated by M.I.T. Lincoln Laboratory (Counselman *et al.*, 1968; Pettengill *et al.*, 1969). These observations, made along the subterrestrial latitude of 21°N, also showed elevation differences of up to 12 km, but indicated a definite lack of correlation either with radar-reflectivity or with optical reflectivity. Similar results were obtained by this laboratory during the 1969 opposition (Rogers *et al.*, 1969) for Martian latitude between 3°N and 12°N.

The spectroscopic method provides a completely independent method for checking the different elevation hypotheses. The surface pressure is simply the summation of the partial pressures produced by the various particles in a vertical column from the surface, and a change in the number of particles in a unit area column implies a change in the total surface pressure. This method was used by Belton *et al.* (1968) and Belton and Hunten (1969) to measure the relative altitude differences between different dark and bright regions of Mars, and by Barker (1969). Their results agree roughly with Pettengill's (Pettengill *et al.*, 1969) radar observation in the conclusion that the highlands are not restricted to the dark areas and that the vertical scale of height variation is on the order of 10 km.

In this paper we will present some preliminary results obtained at McDonald Observatory in order to check the relative elevation differences by means of the spectroscopic method.

3. Spectroscopic Method of the Detection of Relative Altitude

The preliminary result of the spectroscopic method is the equivalent width of lines, which gives the abundance of CO_2 over the area accepted by the entrance slit of the spectrograph.

The equivalent width of a line which has been corrected for saturation is given by

$$W = \sigma(S_1 \eta \omega)^b \tag{1}$$

where b is the slope of the curve of growth, σ the saturation factor, η the total airmass, and S_1 the line strength given by

$$S_1 = \frac{|m| S_b}{Q_{rot}} \left[\exp - m(m-1)\frac{hcB}{KT}\right], \tag{2}$$

ω is the number $N(h)$, of absorbing molecules in a given rotational state in a unit vertical column through the atmosphere at a constant gravitational potential.

Observed equivalent width is

$$W_0 = W/\sigma = [S_1 \eta N(h)]^b. \tag{3}$$

The differential of this equation gives us an expression for the difference in the observed equivalent widths:

$$\frac{\Delta W}{W} = b\left[\frac{\Delta\eta}{\eta} + \frac{\Delta N}{N} + \frac{\Delta S_1}{S_1}\right] \tag{4}$$

where ΔW and $\Delta\eta$ can be obtained from the observational data.

By assuming the atmosphere is exponentially distributed with a scale height H, $\Delta N/N$ is obtained from a combination of the perfect gas law ($P = NKT$), the change in pressure with height ($P = \rho gh$), and the definition of scale height ($H = kT/\mu m_H g$):

$$\frac{\Delta N}{N} = -\left[\frac{\Delta T}{T} + \frac{\Delta h}{H}\right]. \tag{5}$$

By taking the differential of Equation (2) with respect to temperature we obtain

$$\frac{\Delta S_1}{S_1} = \frac{hcB}{KT} m(m-1)\frac{\Delta T}{T}. \tag{6}$$

Substituting the last two equations into (4):

$$\frac{\Delta W}{W} = b\left[\frac{\Delta\eta}{\eta} - (1 - \frac{hcB}{KT} m(m-1))\frac{\Delta T}{T} - \frac{\Delta h}{H}\right]. \tag{7}$$

This expression gives the fractional change in the observed equivalent width between two regions in terms of the fractional changes in airmass, temperature, and height. Solving for Δh, we obtain an expression for the elevation difference between two areas:

$$\Delta h = H\left\{\frac{\Delta\eta}{\eta} - \left[1 - \frac{hcB}{KT} m(m-1)\right]\frac{\Delta T}{T} - \frac{1}{b}\frac{\Delta W}{W}\right\}. \tag{8}$$

This equation was applied to our data.

4. McDonald Spectroscopic Observations

The long term systematic spectroscopic observations of Mars at McDonald Observatory during the 1969 opposition provide a good coverage of the planet in the 0.87, 1.03, and 1.05 μ regions with reasonably good resolution in both latitude and longitude.

This actual coverage is schematically shown in Figure 1. Each line represents one spectrum, and its length, proportional to the time of exposure, gives an idea of the resolution in longitude. Effective resolution is of course affected by seeing conditions and guiding errors. These plates were obtained in the period between April 25 and October 25, 1969.

The Martian 8700 Å CO_2 band could be recorded in a reasonably short exposure

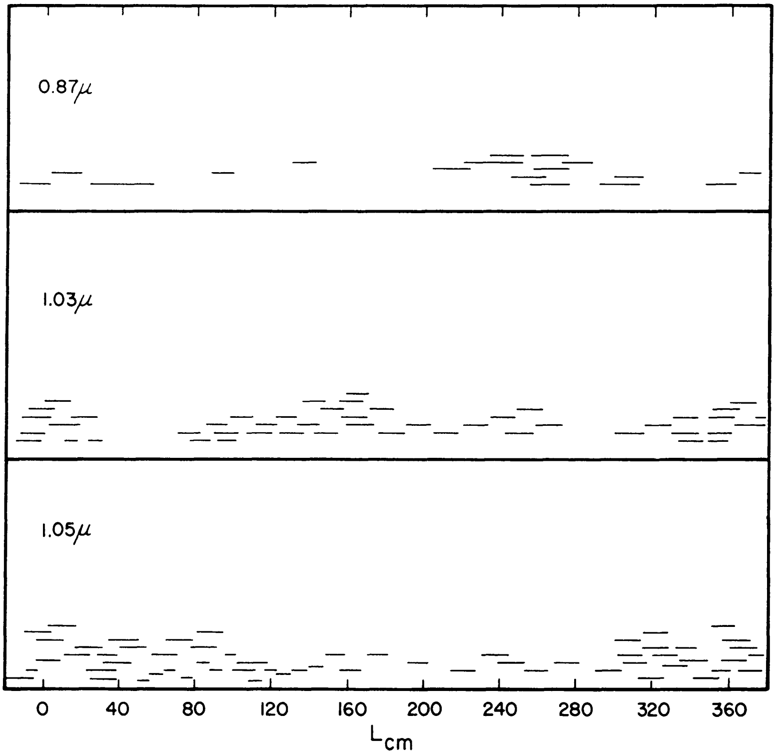

Fig. 1. Actual coverage of Martian longitude by McDonald Observatory plates in the regions of 0.87, 1.03, and 1.05 μ CO_2 bands. Each line represents one spectrum and its length the resolution in longitude.

(resolution in longitude) only with the 107-inch telescope. The six-foot camera and grating '*B*' (1200 grooves/mm, blazed at 6000 Å in first order) were used. The plate scale is about 9 arcsec/mm and the dispersion 4.4 Å/mm. Exposure time was sixty to ninety minutes and resulting resolution in longitude about 15°–20°.

Observations in the 1 μ region were carried out on the 82-inch Struve telescope. A Carnegie RCA infrared image tube with S1 photocathode was placed in offset focus of the '*A*' coudé camera. Grating I (600 grooves/mm, blazed at 2.5 μ in the second order), giving a dispersion of about 3.5 Å/mm, was used. The scale on the plate is about 8 arcsec/mm. Exposure time was thirty to, in a few cases, ninety minutes.

On both telescopes the planet was aligned visually with the direction pole to pole on the slit of the spectrograph and guided as carefully as possible with the slit over the central meridian. Tracings of a small part of the width of such spectra give us information about the CO_2 behavior on different latitudes on Mars. Many of the plates are so good that it is possible to have a good tracing of one-fifth of the image of the planetary disc.

Eight spectrograms of Barker's (1969) observations of Mars in the 8700 Å and one of 1.03 μ regions during the 1967 opposition also had sufficient areographic resolution for detection of topographic features. They were taken in an interval of about five months on hypersensitized IV–N emulsion (1.03 μ band with image tube) with the '*A*' camera of the 82-inch telescope's coudé spectrograph. The required exposure time was two to more than five hours, which gives a resolution in longitude of about 30° to 70° in extreme cases. Central microphotometric scans of one-third of the spectrum, combined with seeing and guiding errors, provided a resolution in latitude of about 30° on the planet, centered roughly on Martian latitude 20°N. By analysis of the curve of growth, the abundance and pressure over the corresponding areographic areas were determined and interpreted in terms of relative elevation differences on the planet. Because of the long period of observations, a correction for seasonal variation (see Barker's paper presented at this symposium) of the Martian abundance of CO_2 was applied. A small correction to the calculated central meridian for the middle of the exposure, due to the effect of guiding on the red image of the planet (RG8 filter blocking overlapping spectral orders), the increased atmospheric extinction during the later part of the exposure, and the effect of phase defect on guiding, was also applied. The final results are given in Table I. Figure 2 shows a

TABLE I

Relative elevation differences from 1967 observations

Coudé Number	L_s (°)	L'_{cm} (°)	Longitude resolution (°)	$\Delta h(L_s)$ ($H=9$ km) (km)
5023b	108	90	35	$+0.2\pm1.1$
5167b	134	212	75	$+0.7\pm2.0$
5187b	138	130	55	$+1.6\pm1.5$
5187c	138	130	55	$+2.3\pm1.2$
5212b	150	300	75	$+0.8\pm1.9$
5243b	167	347	45	0.0 ± 1.1
5246b	167	305	55	$+1.4\pm1.4$
5258b	170	294	40	-3.0 ± 1.7
5262b	171	246	25	-1.3 ± 1.5

comparison of these results with Pettengill's *et al.* (1969) radar profile smoothed to 45° resolution. Agreement of this spectroscopic determination of relative differences in altitude with the radar data is quite good. The correlation coefficient is 0.66.

Only a small part of our observations during 1969 opposition has been reduced. These reduced spectra cover roughly a period of one month of observation (about fifteen days of a Martian season) in both 8700 Å and 1.05 μ regions.

To avoid uncertainty in the determination of the pathlength in high Martian latitude, only the central scans of the spectrum were used, and Martian airmass was assumed to be 2.2. Because of the short period of observations, no corrections for seasonal variation of the amount of Martian CO_2 seemed to be necessary. The central thirds of the 8700 Å band spectra (resolution in latitude 20°) were traced in density, and both *R* and *P* branches (calibrated on solar lines) were used in analysis of the curve of growth.

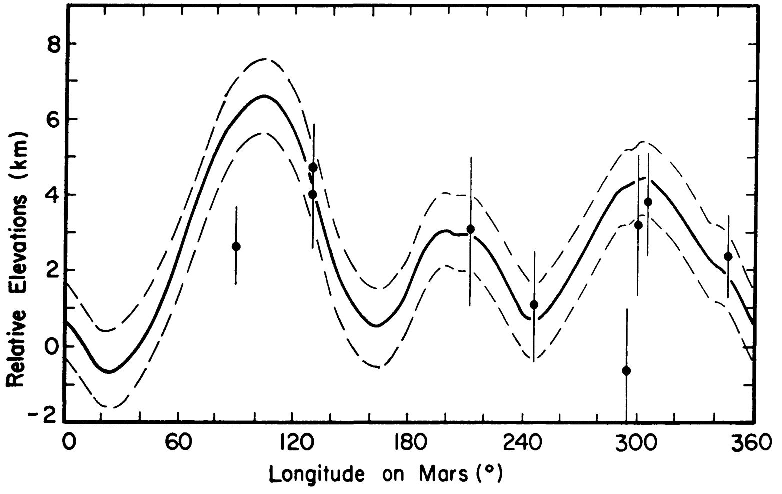

Fig. 2. Relative elevation differences as a function of the longitude from 1967 opposition observations using the CO_2 abundances corrected for seasonal variation. Solid line represents Pettengill's radar profile smoothed to 45° resolution; dashed line, the error limits of ±1 km on the radar profile.

Because of its weakness, this band is unsuitable for temperature determination, and a rotational temperature of 200 K was assumed for all of these plates. The results obtained are shown in Table II and Figure 3 (open circles).

The 1.05 μ band was traced in intensity mode over the central quarter of the Martian disc. The resolution in latitude is about 15° on the planet. Only the *P* branch was used for abundance and temperature determination. In calculating elevation differences,

TABLE II

Relative elevation differences from 1969 observations of 0.87 μ band

Coudé No.	L_s (°)	L_{cm} (°)	ω (m-atm)	CO_2 partial pressure (mb)	Relative elevation (km)
104	184.0	10±7	132±43	9.8	0.0±2.7
70	162.0	40±18	165±68	12.2	−1.8±3.5
74	165.7	353±9	102±55	7.6	+2.4±2.5
80	168.4	252±11	125±39	9.2	+1.4±2.2
82	168.4	281±11	118±32	8.7	+1.2±2.0
84	169.0	266±11	98±37	7.2	+2.6±1.8
87	169.5	213±11	150±57	11.1	−1.2±2.5
88	169.5	240±11	139±61	9.9	+0.5±2.7
89	169.6	264±11	81±32	6.0	+4.0±1.5
91	170.1	243±11	67±23	4.9	+5.1±1.4
96	176.7	135±7	102±33	7.5	+2.4±2.2
98	181.2	92±6	108±66	8.0	+1.8±2.6

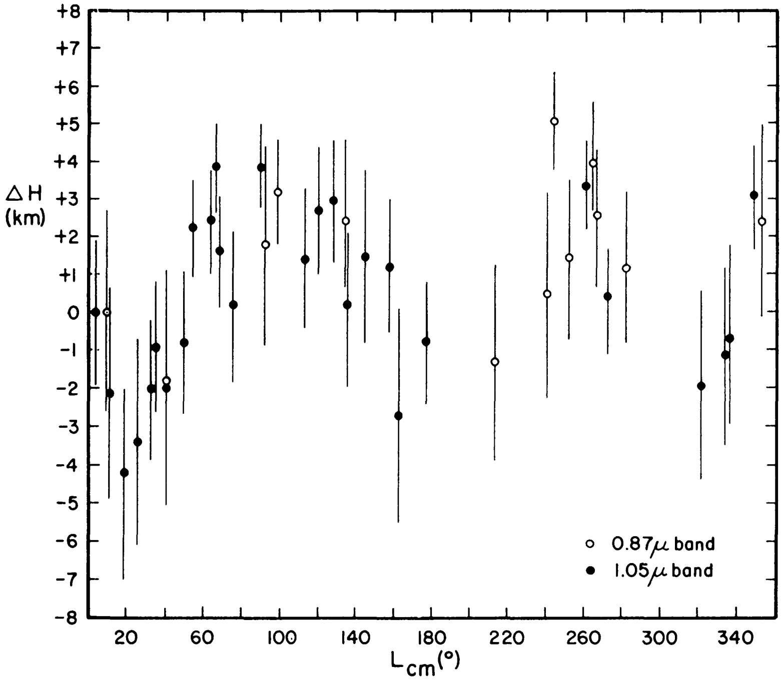

Fig. 3. Relative elevation differences at about 10°N Martian latitude versus Martian longitude from observations of the 0.87 μ (open circles) and 1.05 μ (filled circles) CO_2 bands during the 1969 opposition.

only lines from *P*6 to *P*26 were used in order to be on approximately the same portion of the curve of growth.

Table III and Figure 3 (filled circles) show the results. The subearth point of Mars was between 8° and 12°N during these observations.

One can see easily that there are no systematic differences between the results obtained from the 8700 Å and the 0.05 μ bands. The observed altitude differences are on the order of 10 km. A comparison with the latest radar data (Rogers *et al.*, 1969) shows that there is a good agreement of both results in the region from 0° to about 200° in Martian longitude. There is a lowland region at about 20°–30° of longitude, and there is a big highland area at 100°–120°. Regarding the longitudes of about 200°–300°, the correlation is not as good. However, this region is chiefly covered by our 8700 Å plates, with relatively large internal errors. We have good coverage of this region of Martian longitudes by the observations in the 1.03 μ band; these have not yet been reduced.

5. Summary

By improvements in the Struve reflector's coudé spectrograph and construction of the new 107-inch telescope and its large spectrograph, observations of Mars with greater spatial resolution were possible. This allowed the study of the Martian atmosphere

TABLE III

Relative elevation differences from 1969 observations of 1.05 μ band

Coudé No.	L_s (°)	L_{cm} (°)	ω (m-atm)	CO_2 partial pressure (mb)	Rotational temperature (°K)	Relative elevation (km)
6251	168.9	261 ± 7	54 ± 18	4.0	220	$+3.9 \pm 1.3$
6252	168.9	276 ± 7	79 ± 10	5.8	185	$+0.4 \pm 1.7$
6269A	170.5	162 ± 7	113 ± 19	8.3	216	-2.7 ± 2.8
6269B	170.5	177 ± 7	69 ± 10	5.1	173	-0.9 ± 1.8
6301A	176.0	53 ± 3.5	64 ± 11	4.7	205	$+2.2 \pm 1.4$
6301B	176.0	63 ± 3.5	64 ± 11	4.7	214	$+2.5 \pm 1.4$
6301C	176.0	675 ± 3.5	69 ± 13	5.1	228	$+1.5 \pm 1.5$
6302A	176.0	75 ± 3.5	79 ± 15	5.9	225	$+0.2 \pm 1.9$
6302C	176.1	90 ± 3.5	50 ± 15	3.7	230	$+3.9 \pm 1.3$
6302D	176.1	$97 + 3.5$	53 ± 16	3.9	211	$+3.2 \pm 1.4$
6303A	176.1	112 ± 3.5	83 ± 14	6.2	251	$+1.4 \pm 1.8$
6303B	176.1	119 ± 3.5	60 ± 14	4.3	250	$+2.6 \pm 1.7$
6303C	176.1	127 ± 3.5	58 ± 16	4.3	212	$+2.9 \pm 1.7$
6303D	176.1	135 ± 4	85 ± 16	6.3	196	$+0.2 \pm 2.1$
6303E	176.1	144 ± 5	71 ± 32	5.3	281	$+1.5 \pm 2.2$
6358	181.7	157 ± 5.5	64 ± 18	4.7	221	$+1.7 \pm 1.5$
6359A	181.7	10 ± 7	101 ± 27	7.5	225	-2.0 ± 2.7
6359B	181.7	25 ± 7	113 ± 17	8.4	200	-3.5 ± 2.5
6359C	181.7	40 ± 7.5	98 ± 39	7.3	200	-2.0 ± 3.1
6363A	182.2	334 ± 7	91 ± 27	6.7	220	-0.6 ± 2.1
6363B	182.2	348 ± 7	56 ± 17	4.2	237	$+3.1 \pm 1.4$
6363C	182.2	3 ± 7	85 ± 18	6.3	195	$+0.0 \pm 1.8$
6364A	182.2	18 ± 7	118 ± 32	8.7	217	-4.2 ± 2.6
6364C	182.3	32 ± 7	83 ± 23	6.3	275	-0.8 ± 1.8
6371A	182.8	321 ± 7	102 ± 24	7.5	177	-1.9 ± 2.5
6371B	182.8	335 ± 7	95 ± 20	7.0	159	-1.1 ± 2.2
6403	201.5	31 ± 7	87 ± 19	6.4	229	-2.0 ± 1.9
6404	201.5	65 ± 7	52 ± 7	3.8	202	$+3.9 \pm 1.2$

over particular regions of the planet and the detection of large scale irregularities in the surface by means of spectrographic methods. The results presented here, though in agreement with radar data, have a relatively large internal error. The average error of the elevation determinations is about ± 1.8 km for the 1.05 μ band and ± 2.3 km for the 0.87 μ band. One could probably decrease the error for the 1.05 band by including in the solution the lines of the R branch. Furthermore, the spectroscopic elevation profile for the planet will be certainly better defined after reduction of our remaining observations. More precise observations in the future will require better spatial as well as spectral resolution.

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