THE SPECTRUM OF MARS IN THE REGION 1800–3200 cm^{-1}

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Abstract. During the 1971 opposition of Mars, new infrared spectra covering the region 1800–3200 cm^{-1} (3.1–5.6 μ) were taken at a resolution of 0.095 cm^{-1} using a Connes'-type Fourier spectrometer on the 2.7 m telescope, McDonald Observatory. Spectra were obtained near 6° and 33° phase and were calibrated against the Sun, standard stars and an internal black body.

No new trace constituents have, as yet, been found in the spectra, but several previously unobserved combination and isotopic bands of CO_2 are visible. It has also been found possible to fit fairly well defined kinetic temperatures and Bond albedos to the two sets of data. The kinetic temperatures have been determined by a new technique. It is found that the albedo at 33° phase, which was determined a few days after the onset of the great dust storm of 1971, was significantly higher than for the clear atmosphere. The explanation for this phenomenon must await detailed radiative transfer calculations for a dust-laden atmosphere.

1. Introduction

The possibility of finding new trace constituents, particularly of the lighter molecules, has provided much of the impetus to achieve better spectral resolution in the infrared spectra of the planet Mars. All such searches have proven to be negative, even from spacecraft (Beer *et al.*, 1971a; Horn *et al.*, 1972; Conrath *et al.*, 1973). Nevertheless, it was thought worthwhile to pursue the topic somewhat further than before (Beer *et al.*, 1971a), particularly in view of the fact that our earlier spectra (which were only of moderate quality) had suggested that there might be residual, unidentified, lines in the spectrum. Furthermore, our earlier spectra were not flux-calibrated and, as a result, our efforts to determine an albedo at these long wavelengths were subject to gross errors. We, therefore, hoped to produce spectra at better resolution, over a wider wavelength range and flux-calibrated. In this we were successful.

2. Observations

All the observations were made during August and September–October of 1971 using a Connes'-Type Fourier spectrometer at the coudé focus of the 2.7 m telescope, McDonald Observatory, University of Texas. The instrumentation has been described elsewhere (Beer *et al.*, 1971b). Most of the data were taken at 0.095 cm^{-1} resolution but it was found, 7 weeks later, that the power level from Mars had fallen appreciably and, as a consequence, the signal-to-noise ratio was much poorer. Later, of course, we discovered that the great dust storm of 1971 that interfered with the early phases of the Mariner 9 mission was the cause of the surprisingly low temperatures observed.

The spectra are all in the integrated light from the planet and the details of the observations are given in Table I.

Woszczyk and Iwaniszewska (eds.), Exploration of the Planetary System, 229–239.

TABLE I

Conditions of the observations

Run number	Julian Date of Z.P.D. 2441000.000 +	Phase angle (deg)	Longitude of central meridian (deg)	Resolution (cm^{-1})	$\frac{\text{Signal}}{\text{Noise}}$	Air mass at ZPD
304	168.763	6.8	182	0.165	83	1.76
305	169.792	6.3	183	0.095	73	1.84
311	171.729	5.4	144	0.515	130	1.95
315	220.670	32.6	56	0.095	26	1.61
316	221.607	33.0	10	0.129	26	1.71
319	222.611	33.4	2	0.095	20	1.70
322	223.580	33.8	341	0.115	20	1.85
325	227.583	35.3	305	0.095	17	1.73

3. The Spectrum of Mars

Figure 1 is a portion of an average of runs 304 and 305 (taken on successive days) together with a solar spectrum taken somewhat later, with the same spectrometer but not with the same telescope.* Unfortunately, it transpired after the observations in the fall of 1971, that all our solar spectra had digitization errors and only one was at all useful: that presented in the figure. It, too, had errors but could be truncated to produce a satisfactory spectrum at 0.12 cm^{-1}. However the difference both in the date of observation and in the resolution has made the correction for atmospheric transmission quite difficult and full correction must await implementation of the AFCRL atmospheric absorption line catalog (McClatchey *et al.*, 1973).

It is intended to publish the entire series of spectra in the form of an atlas, together with the relevant calibrations in order that other workers may have access to these data. Consequently, no upper limits for possible trace constituents have been determined.

Clearly visible in the spectra are the 'hot' 10°1–02°0 band of normal CO_2, centered on 2429.36 cm^{-1}, the 00°0–04°0 band of $^{12}C^{16}O^{18}O$ centered at 2500.74 cm^{-1} and the 00°0–12°0 band of $^{12}C^{16}O^{18}O$ centered on 2614.24 cm^{-1}, a portion of which is shown in Figure 1. The 'hot' band is of particular interest because some strengths have been measured for this band (Plyler *et al.*, 1962) and, consequently, it will be possible to deduce a kinetic temperature from the relative population of the lower state. The band is exceedingly weak. For example, the strength of the $P16$ line is listed by Plyler *et al.* as 5.5×10^{-5} cm^{-1} cm A and yet this line, having an equivalent width of about 0.005 cm^{-1}, is quite clearly visible in the spectrum, indicating the great power of high resolution spectroscopy for the measurement of weak absorptions.

4. The Flux Calibrations

For flux calibration purposes, we deliberately operate at truncated resolution (2 cm^{-1})

* All our solar spectra are obtained with an auxiliary 15 cm telescope which can feed sunlight to our interferometer.

https://doi.org/10.1017/S007418090002547X Published online by Cambridge University Press

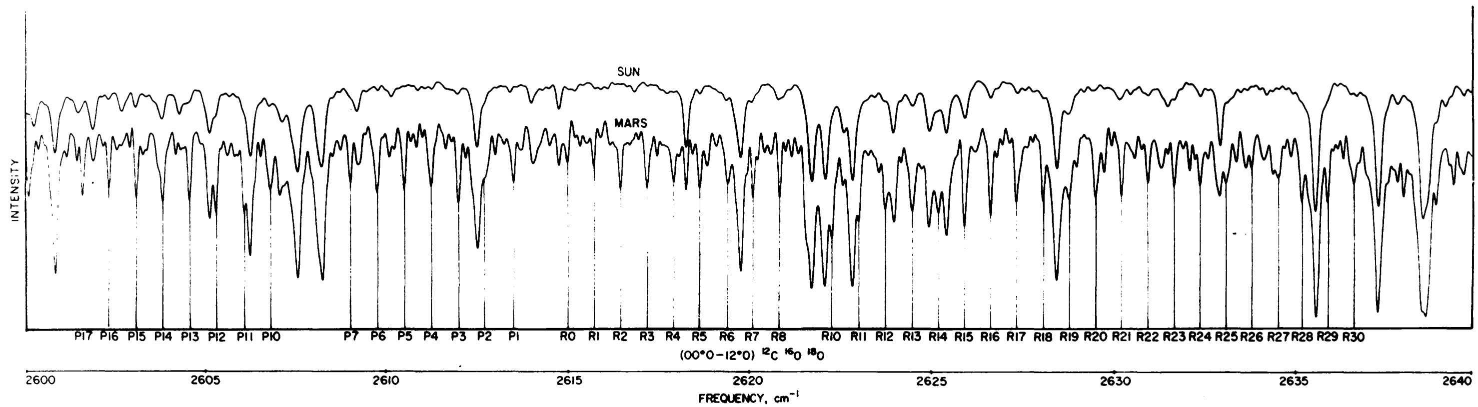

Fig. 1. A portion of the spectrum of Mars and of the Sun near the center of the (00°0–12°0) $^{12}C\,^{16}O\,^{18}O$ band. The upper curve is of the Sun at a resolution of 0.125 cm^{-1}. The lower curve is of Mars at a resolution of 0.095 cm^{-1}.

in order to avoid difficulties with variable airmass during a given observation. The instrumental response is determined by observation of an internal black body and the external transmittance by observation of the Sun and standard stars (Betelgeuse, in this instance). The solar flux distribution is obtained from the data of Labs and Neckel (1968) and the L and M magnitudes for Betelgeuse from various sources (Johnson, 1966, 1967; Gillett *et al.*, 1968; Low and Krishna Swamy, 1970). There is significant disagreement between the authors as to the absolute calibration for Betelgeuse. However, the most complete study is that of Gillett *et al.* (1968), who also give an energy distribution over the entire 3–6 μ region. Their values are:

$$L(2940\ \mathrm{cm}^{-1}) = 1.655 \times 10^{-22}\ \mathrm{W\ m^{-2}\ Hz^{-1}}$$
$$M(2000\ \mathrm{cm}^{-1}) = 8.25 \times 10^{-23}\ \mathrm{W\ m^{-2}\ Hz^{-1}}$$

and these are the values employed in the present study. Observations of Betelgeuse extending over many months give absolutely consistent results, so that we are satisfied as to the stability of the system. Much less satisfactory is the correction for atmospheric transmission. It is, operationally, very difficult ever to obtain enough data under identical conditions in a program of high-resolution spectroscopy to insure that the transparency has not altered. That is, a typical high-resolution run requires 2–4 h for completion, but, for flux-calibration purposes, we abstract only the first 10–20 min worth of data. Consequently, at best, there is likely to be a 2–4 h delay before the acquisition of a calibration spectrum. In this interval, there can have been drastic changes in the atmospheric conditions. We believe that the final solution must await implementation of an extensive atmospheric transmission program using the, recently-

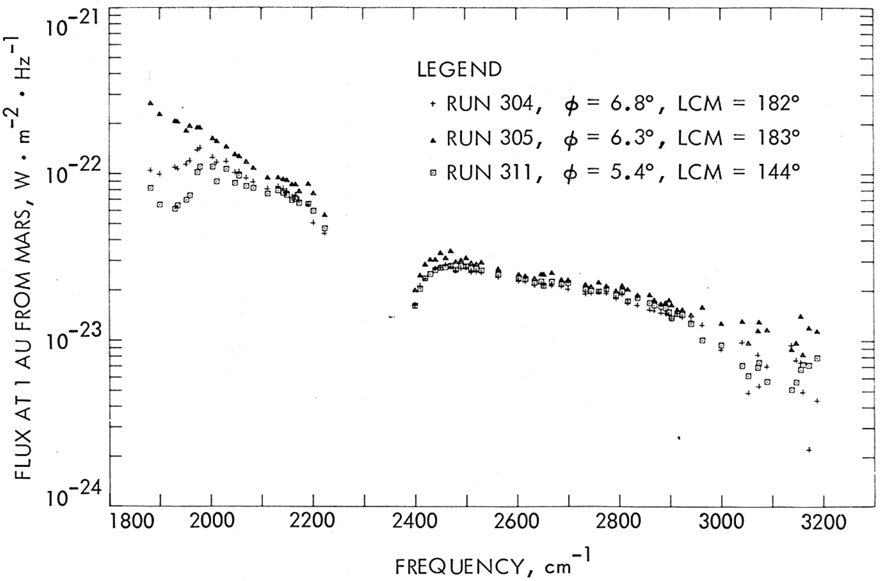

Fig. 2. The absolute, integrated-disk, spectrum of Mars near opposition (mean phase angle ~ 6.2°).

available, AFCRL line parameter tape (McClatchey *et al.*, 1973). However, there is no doubt that production of such transmissions at sufficient resolution will be exceedingly expensive in terms of computing costs.

In order to reduce the problem, somewhat, we chose to sample the spectra only in regions where the transmission of the atmosphere is high (in 'micro-windows') and the errors in applying the correction are not too great. Figures 2 and 3 show the result of this for the two series of spectra. As may be seen, the scatter is fairly small except at the end-points, where the 6.3 and 2.7 μ telluric water vapor bands become dominant.

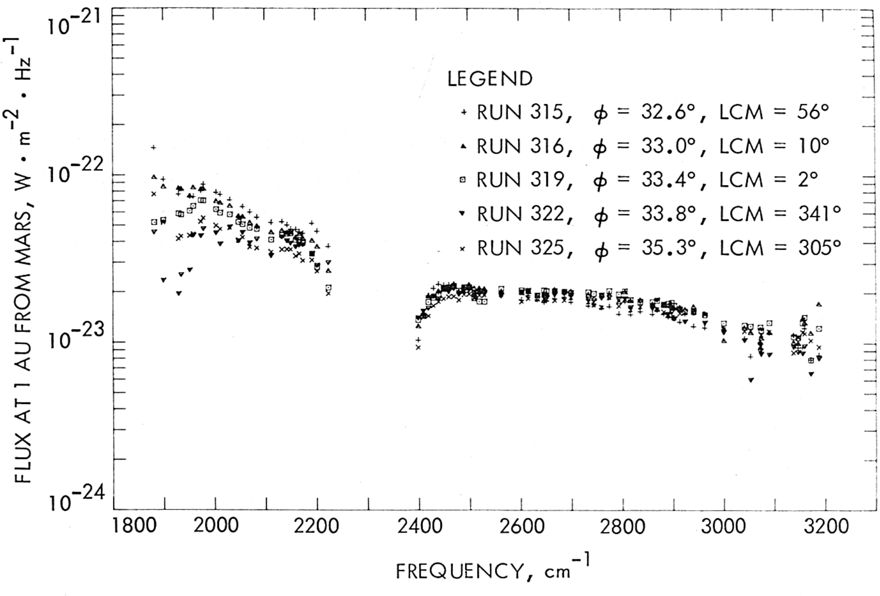

Fig. 3. The absolute, integrated-disk, spectrum of Mars about 1 week after the onset of the great dust-storm of 1971 (mean phase angle = 33.6°).

The gap in the middle is due to the telluric 4.2 micron CO_2 bands. However, the 'turn-down' at the edges of the gap is real and a consequence of the, even stronger, Martian CO_2 bands. That is, in these wings, the observed flux is probably due to atmospheric emission, rather than flux from the surface.

5. The 3–6 μ Albedo of Mars

It is easily verified that, for any reasonable temperatures, there is almost no point in the 3–6 μ region wherein either the thermal emission from the surface or the solar reflection become negligible. It was therefore necessary to construct a model for the combination of reflection and emission.

It may be shown that

$$L_1(v) = \Omega_1 [(1-A)\, B_M(v, T) + A\bar{B}_s(v)\, F(\phi)\, \Omega_s]\ Wm^{-2}\ Hz^{-1},$$

where

$L_1(\nu)$ = the flux at 1 AU from Mars
Ω_1 = the solid angle subtended by Mars at 1 AU
A = the Bond albedo
$B_M(\nu, T)$ = the Planck function at temperature T [W m^{-2} ster^{-1} Hz^{-1}]
$\bar{B}_s(\nu)$ = the mean brightness of the Sun [W m^{-2} ster^{-1} Hz^{-1}]
Ω_s = the solid angle subtended by the Sun at Mars
$F(\phi)$ = a function of the phase angle ϕ and for a Lambert surface (the model assumed here)

$$F(\phi) = \frac{2}{3\pi}[(\pi - \phi)\cos\phi + \sin\phi].$$

Under normal circumstances, one is faced with an insoluble problem: that of finding both T and A from a single observation. Consequently, the temperature normally reported is a *brightness temperature* which can only be related to the true, kinetic, temperature if the albedo is otherwise determinable. However, it can be seen that, in the above expression, if

$$B_M(\nu, T) = \bar{B}_s(\nu)\, F(\phi)\, \Omega_s$$

then the terms in A cancel and

$$L_1(\nu') = \Omega_1\, B_M(\nu', T)$$

independent of any unknown parameters. *That is, the kinetic temperature T may be found explicitly.* A similar effect occurs even if the surface is non-Lambertian (Beer, 1973).

Fortunately, this cross-over condition occurs within our spectral region. The principal sources of error are as follows:

(a) If $F(\phi)$ does not have the simple Lambertian form assumed here, the 'cross-over' point between the emitted and reflected energy will move. Michaux and Newburn (1972) have made a critical study of all the available empirical phase data and conclude that the 'opposition effect' on Mars is certainly small (less than 0.1 mag.) and may be zero. In our region, at some ten times longer wavelengths, we might reasonably expect such effects to be even smaller. Even if the effect is the same, it will affect only the 6° phase data by 10%, an amount much smaller than the scatter in the data at the cross-over region, and the 33° data by a negligible amount.

(b) Systematic errors in either our flux calibration or in the solar flux tables of Labs and Neckels (1968). The Labs and Neckels' data is based upon a model fit to all known flux measurements from the ultra-violet to the sub-millimeter region and is entirely self-consistent. The error is unlikely to exceed 1%. Our calibrations are, of course, subject to errors of 10–20% but again, the scatter of the data is much greater than this.

(c) The principal source of error is in the telluric transmission correction and the errors are as great as a factor of 2 in the relevant region.

Notwithstanding the large scatter, we have succeeded in making acceptable fits only over quite narrow temperature ranges:

$$6^\circ \text{ phase}: \bar{T} = 270 \pm 5\,\text{K}$$
$$33^\circ \text{ phase}: \bar{T} = 253 \pm 7\,\text{K}.$$

$\bar{T}$ is a global mean temperature which will be, of course, strongly weighted towards the hottest point on the disk. The values are entirely consistent with other workers, both from Earth and from spacecraft (Kieffer *et al.*, 1973; Conrath *et al.*, 1973; Michaux and Newburn, 1972).

Using these temperatures, we proceeded to fit a large series of albedo models, graphically, to the data in Figures 2 and 3. For each temperature $\bar{T}$ within the range permitted above, an upper and lower bound and a central value was calculated as a function of frequency. Some representative results are presented in Figures 4 and 5, superposed upon the data of Figures 2 and 3. The fit is quite surprisingly good.

However, by the same token that the flux from Mars at the low-frequency end is independent of albedo, it is also true that the albedo, here, is virtually indeterminate. We can do little more than bound the values at frequencies not far removed from the cross-over and assume that it changes little or not at all at the cross-over.

We present the results in Figures 6 and 7 for two mean effective temperatures, 270 K and 253 K. If it should transpire that the 'correct' values differ from these, the correction for the mean Bond albedo may be determined from Figure 8, which contains plots of $-\mathrm{d}A/\mathrm{d}T$ for the two cases. The corrections are substantially linear for a few degrees on either side of the mean. The error bounds move with the mean and do

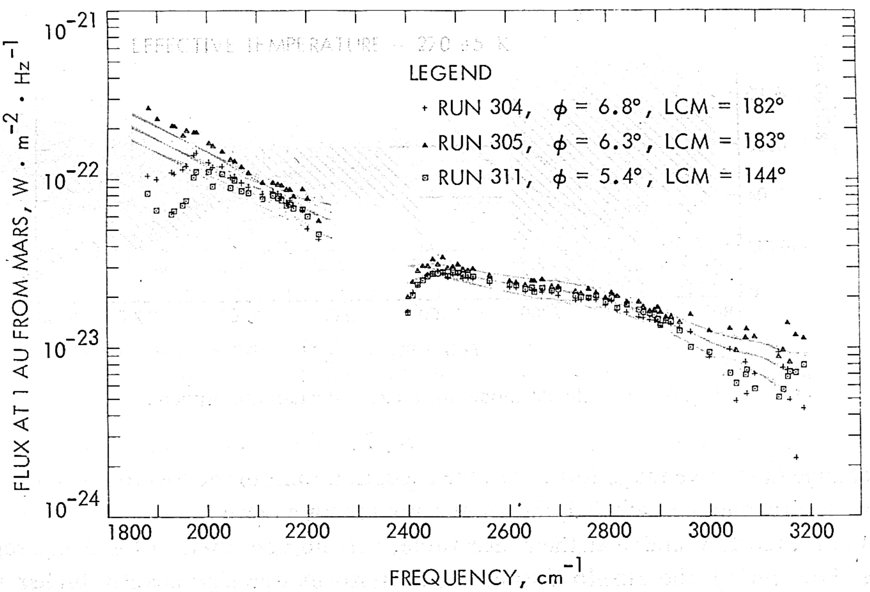

Fig. 4. The same data as Figure 2 with some representative temperature-albedo models superposed.

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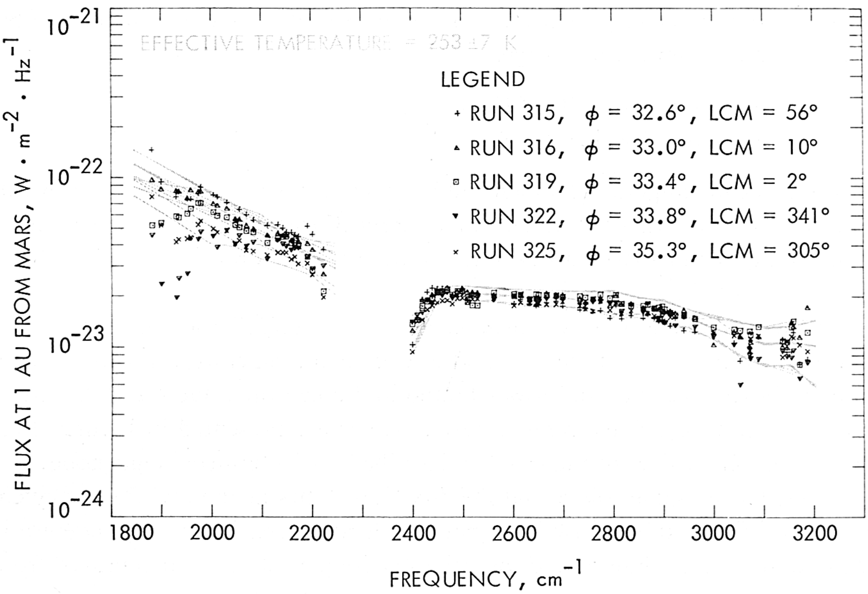

Fig. 5. The same data as Figure 3 with some representative temperature-albedo models superposed.

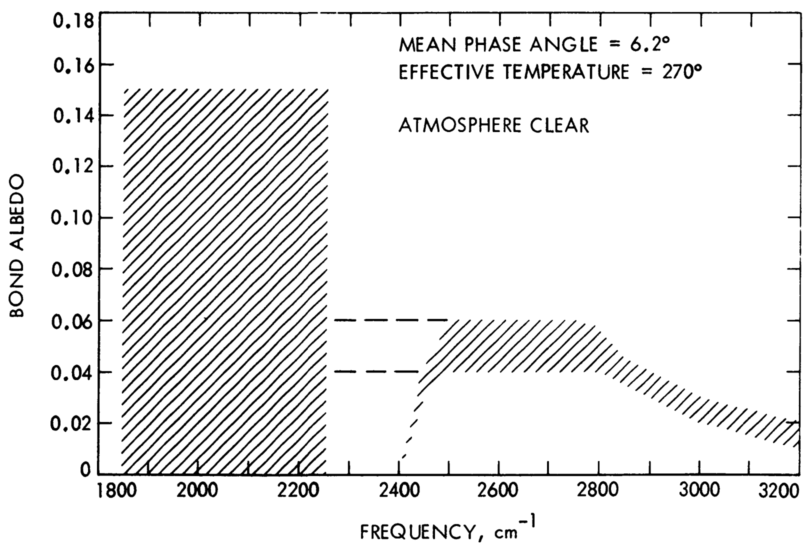

Fig. 6. The albedo model for a clear Martian atmosphere.

not change in relative magnitude, with the exception that, in the low frequency region where $A = 0$ cannot be excluded, the lower bound remains zero.

Taking Figures 6 and 7 at their face value, it is notable that, in the 3–4 μ region (2500–3200 cm^{-1}), the albedo during the dust storm was significantly higher than during the 'clear atmosphere' period. At no possible temperature does the 6° albedo

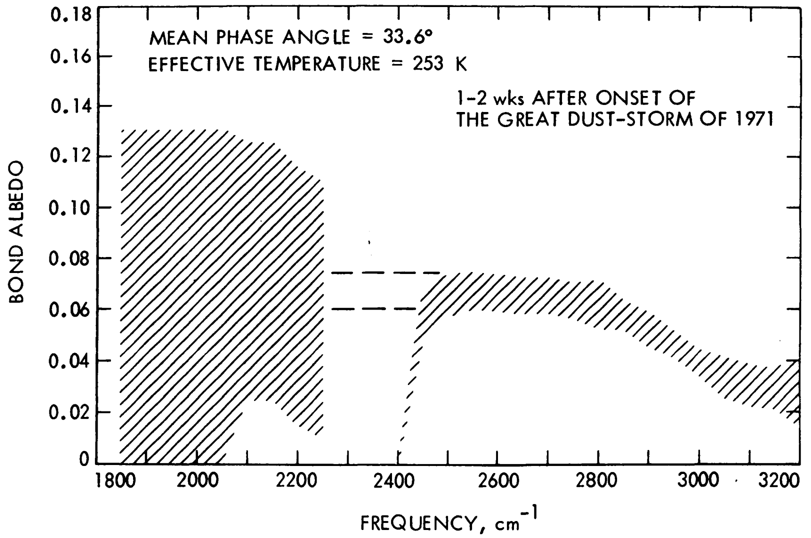

Fig. 7. The albedo model for a dusty Martian atmosphere.

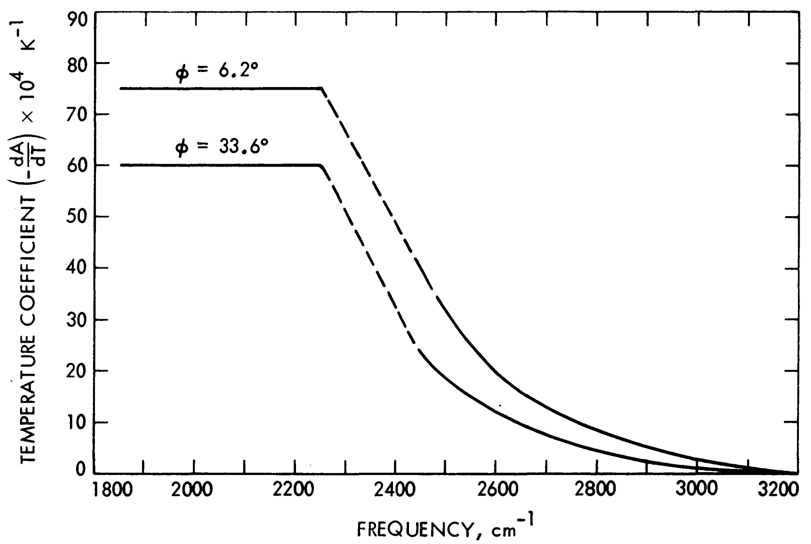

Fig. 8. Curves for the correction of the albedo models in Figures 6 and 7 for other global mean temperatures. The horizontal branches are approximate only.

curve fit the 33° data so that the difference is probably real. It is also worthy of note that the visual albedo appeared to be higher during the dust storm, based on evidence of the shorter exposure times required by the Mariner 9 cameras during this period as compared to later in the mission (Briggs, 1973). The turn-down to 2400 cm^{-1} is probably spurious in both cases and a consequence of the Martian 4.2 μ CO_2 band. However, the decay from 2800 to 3200 cm^{-1} is real and has been noted by several observers, previously (Sinton, 1967; Beer *et al.*, 1971; Houck *et al.*, 1973). It is commonly held that this is due to water of hydration in some form bound in the Martian surface material. It is interesting to note that the character of the band remains substantially the same in the two series of spectra. If the dust cloud was optically thick at these wavelengths (as it certainly was at visible wavelengths), we may draw the conclusion that the 'water band' is intimately associated with the surface material and is not due to either free water at the surface or some other volatile species. That is, the absorbing agent is, almost certainly, molecularly bound to the surface material.

The absolute values for the Bond albedos are also of interest: they are extremely low. In no circumstance wherein the albedo is reasonably bounded does it exceed about 7%. That is, the surface material is absorbing at least 93% of the incident energy, a remarkably high value. The values in the 5 μ (2000 cm^{-1}) region are much more poorly known. Even here, however, values in excess of 15% are excluded and a value of zero is possible, howbeit unlikely.

The explanation for the rise in albedo during the dust storm must depend upon a detailed analysis of the radiative transfer under conditions of particulate matter being suspended in the atmosphere. This, in turn, would demand detailed knowledge of the optical constants, size and distribution of the material, most of which information is conjectural in advance of Martian lander missions.

6. Conclusion

We have presented evidence stemming from the highest resolution spectra yet obtained in the 3–6 μ region that demonstrates the power of high resolution in observing weak absorptions and, for the first time, have succeeded in determining albedos and kinetic temperatures from such data.

Acknowledgements

Our thanks are due to Dr Harlan J. Smith of the University of Texas for observing time on the 2.7 m telescope, McDonald Observatory, and to T. G. Barnes, D. L. Lambert, J. V. Martonchik, and R. H. Norton for unstinting aid in the observations and analyses. Without their aid, this paper would not have been possible.

This paper presents the results of one phase of research in the joint Jet Propulsion Laboratory-University of Texas Infrared Astronomy Program, supported, in part, by National Science Foundation Grant GP-32322X with the University of Texas at Austin and, in part, by National Aeronautics and Space Administration Contract NAS7-100 with the Jet Propulsion Laboratory, California Institute of Technology.

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