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FLYBY MEASUREMENTS OF THE PROFILES OF WATER VAPOR, PARTICULATE MATTER, AND CARBON DIOXIDE IN THE MARTIAN ATMOSPHERE

by Alfred E. Barrington, Anthony J. Caruso,
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SUMMARY

A study of infrared absorption measurements in the Martian atmosphere for the determination of the profiles of water vapor and carbon dioxide is presented in quantitative detail.

Using the best available data on the Martian atmosphere, it is shown that with state-of-the-art instrumentation the following can be measured: an upper limit of water vapor of 10^{-3} g/cm^2-column (at 6.3 μ), scattering by particulate matter (at 3.5 μ), and the carbon dioxide profile above an altitude of 50 km (at 4.3 μ).

The choice of wavelengths and of experimental instrumentation is based on a realistic appreciation of Martian atmospheric characteristics and experience gained during the Mariner II Venus mission.

INTRODUCTION

The most exciting aspect of Martian exploration is the search for extraterrestrial life. The prerequisite for the formation and sustenance of living organisms is water. So far, the only acceptable evidence of water on Mars is the observation by Kaplan et al (ref. 1) who, with a terrestrial telescope, were able to record rotational absorption lines characteristic of water vapor near 0.82 μ. From their observations they derived a figure of approximately 10^{-3} g/cm^2-column of water vapor in the Martian atmosphere.

It was assumed until recently that the Martian atmosphere consisted mainly of nitrogen. However, the Mariner IV observations of the refractivity and density of the Martian atmosphere have led to the conclusions that carbon dioxide is by far the most abundant constituent (ref. 2). In constructing a Martian model atmosphere based on Mariner IV measurements, Johnson (ref. 3) has indicated an inconsistence between the probable temperature distribution through the Martian atmosphere and the above mentioned spectroscopic determination of water vapor on Mars. The question regarding the water vapor content of the Martian atmosphere is thus of paramount interest to planetary physics as well as to extraterrestrial biology. The earliest opportunity for a measurement in the vicinity of the planet will probably occur during a flyby. The present study was initiated with this purpose in mind.

With the feasibility of a flyby experiment established, a detailed proposal was submitted by the authors to the Office of Space Science and Applications in March 1966.* In essence, it was proposed to measure the absorption of solar infrared radiation by water vapor (6.3 μ) and also to obtain a simultaneous measurement of the carbon dioxide profile (4.3 μ) in order to corroborate the interpretations of the Mariner IV occultation experiment. A suggestion by Ben-Aryeh (ref. 4) to perform a similar measurement for water vapor at 6.3 μ from a Martian orbiter has recently appeared in the literature (September 1966). He also suggested the need for an absorption measurement at 8.4 μ, where the Martian atmosphere should be completely transparent, to determine the effects of scattering on absorption measurements in this portion of the infrared spectrum. However, his discussion of absorption measurements is couched in only very general terms, whereas the authors' earlier study contained considerable quantitative detail. This shows, for example, that, in the infrared, Rayleigh scattering is insignificant in the Martian atmosphere. Only particulate scattering, as perhaps from frozen carbon dioxide or dust particles might be observable. Furthermore, solar radiation at 8.4 μ is insufficient for meaningful measurements with state-of-the-art detectors. For adequate intensity, radiation in the atmospheric window near 3.5 μ should be used instead.

The quantitative evaluation of infrared absorption measurements in the vicinity of Mars as presented here is considered of sufficient interest to warrant distribution among the scientific community.

THEORY

Water vapor and carbon dioxide have strong infrared absorption bands. Therefore, the profiles of these constituents of the Martian atmosphere can be determined by appropriate measurements of absorption of solar radiation during periods immediately prior to or following occultation of the sun by the planet. In this case, absorption of solar radiation will occur along a path parallel with a tangent to the planetary disc and will be a maximum along the tangential path.

The following calculation of the pertinent infrared absorption characteristics of the Martian atmosphere is based on the barometric equation and the best available figures for surface number density, water vapor content, Martian atmospheric temperature, and other well established Martian constants.

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*Water Vapor and Carbon Dioxide Profiles of the Martian Atmosphere, NASA-ERC proposal, 14 March 1966.

Let $n(h)$ = number density at altitude h

n_s = number density at surface (altitude = 0)

H = scale height

k = 1.38×10^{-16} erg/° K

T = average atmospheric temperature

m = mass of molecular particle

g_o = surface value of gravitational acceleration.

Then (see ref. 5):

$$n(h) = n_s e^{-\frac{h}{H}} \tag{1}$$

where

$$H = \frac{kT}{mg_o} \; . \tag{2}$$

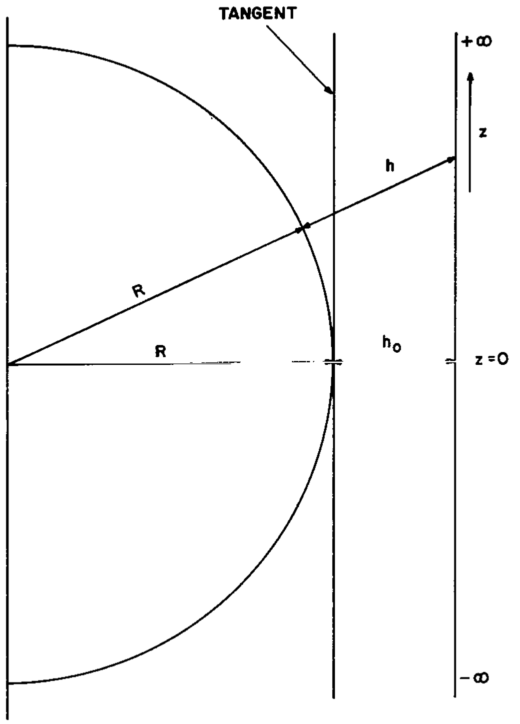
The number of molecules N_H/cm^2-column above the surface is obtained by integrating equation (1), i.e.:

$$N_H = n_s \int_o^\infty e^{-\frac{h}{H}} \, dh = n_s H \; . \tag{3}$$

The mass M_H/cm^2-column above the surface is given by

$$M_H = n_s mH \; . \tag{4}$$

The number of molecules N_z and the mass M_z/cm^2-column along a path z through the Martian atmosphere, parallel with a tangent to the planetary disc (radius R) and spaced from it by a distance h_o, is found from Figure 1 as follows:



TANGENT AND z COORDINATE PARALLEL

Figure 1.

$$z^2 = (R + h)^2 - (R + h_o)^2 \simeq 2R(h - h_o) \text{ for } h \ll R,$$

or

$$h = h_o + \frac{z^2}{2R} . \tag{5}$$

The path extends from $z = -\infty$ to $z = +\infty$.

Substituting equation (5) in equation (1):

$$n(z) = n_s \, e^{-\left[\frac{h_o}{H} + \frac{z^2}{2RH}\right]} \tag{6}$$

and

$$N_z = n_s \, e^{-\frac{h_o}{H}} \int_{-\infty}^{\infty} e^{-\frac{z^2}{2RH}} dz . \tag{7}$$

Let

$$\frac{z^2}{2RH} = t^2 . \tag{8}$$

$$\text{Therefore, } dz = \sqrt{2RH}\, dt \tag{8a}$$

Substituting equations (8) and (8a) in equation (7):

$$N_z = n_s \sqrt{2RH}\, e^{-\frac{h_o}{H}} \int_{-\infty}^{\infty} e^{-t^2} dt = n_s \sqrt{2\pi RH}\, e^{-\frac{h_o}{H}} . \tag{9}$$

Maximum absorption occurs when the path is along the tangent, i.e., when

$$h_o = 0 .$$

Equation (9) then reduces to

$$N_{z,\,max} = n_s \sqrt{2\pi RH} = 2.5 n_s \sqrt{RH} \tag{9a}$$

$$M_{z,\,max} = 2.5\ mn_s \sqrt{RH} \tag{10}$$

In order to utilize published values of infrared absorption of water vapor and carbon dioxide, we can use the following information (see ref. 2):

For water vapor: $M_H = 10^{-3}$ g/cm^2 - column

For carbon dioxide: $n_s \simeq 2 \times 10^{17}$ mol/cm^3

Surface pressure: $P_s \simeq 5$ mb

Scale height: $H_{CO_2} \simeq 10$ km

Martian radius: $R = 3360$ km .

Absorption by Water Vapor

From equation (4), for water vapor:

$$mn_s = \frac{10^{-3}}{10 \times 10^5} = 10^{-9}\ \text{g/cm}^3 .$$

Substituting this value in equation (10):

$$M_{z,\,max} = 2.5 \times 10^{-9} \left(3360 \times 10 \times 10^{10}\right)^{1/2} = 0.046\ \text{g/cm}^2\text{-column} \tag{11}$$

This latter quantity is also the amount of precipitable water, W (pr-cm). The transmittance T_λ at 6.3μ of precipitable water vapor can be calculated according to the following expression (see ref. 6):

$$T_\lambda = \exp\left\{\frac{-1.97\ W/W_o}{\left[1 + 6.57\ (P_o/P)\ (T/T_o)^{1/2}\ (W/W_o)^{1/2}\right]^{1/2}}\right\} \tag{12}$$

where

W_o = water vapor concentration for 50% transmittance at 6.3μ (0.002 pr-cm)

at

P_o = 740 mm Hg

and at

T_o = 273° K .

According to Johnson (ref. 3), there is little, if any, water vapor above 20 km. We assume an average pressure P of 1 mm Hg and an average temperature T of 180° K (ref. 2) over the altitude range of interest.

Using these values of P and T and the value of W from equation (11), we obtain:

W/W_o = 23

P_o/P = 740

T/T_o = 0.66 .

Upon substituting these quantities in equation (12), we obtain:

$$T_\lambda = \exp\left[\frac{-45.5}{(1 + 6.57 \times 740 \times 0.814 \times 4.8)^{1/2}}\right]$$

$$= \exp\left[\frac{-45.5}{138}\right] = \exp(-0.33) \simeq 0.72$$

Thus, approximately 28 percent of the incident radiation at 6.3 μ will be absorbed by water vapor along a tangential path, whereas carbon dioxide, the major atmospheric constituent, is transparent at this wavelength.

Attenuation by Scattering

Attenuation of radiation at 6.3 μ other than by water vapor absorption should be due only to scattering. Accordingly, Ben-Aryeh (ref. 4) has suggested that the resulting signal reduction be monitored with a second spectral channel at 8.4 μ, where atmospheric absorption is expected to be negligible.

Even under the most adverse condition, Rayleigh scattering can be shown to be negligible. The Rayleigh scattering cross section σ of carbon dioxide at 0.5890 μ is 9.18×10^{-28} cm^2 (ref. 7). Assuming it varies as the inverse fourth power of the wavelength, it decreases to 7×10^{-32} cm^2 at 6.3 μ. Therefore, even in traversing a tangential path, where the quantity of carbon dioxide is a maximum, i.e., 9.2×10^{24} mol/cm^2-column [equation (13) below], the fractional decrease of intensity by Rayleigh scattering is given by (ref. 8):

$$I_s = \sigma N_{z,\max} = 7 \times 10^{-32} \times 9.2 \times 10^{24} = 6.45 \times 10^{-7} ,$$

a quantity too small to affect the proposed measurement. Loss by Mie scattering therefore appears to be the most likely mechanism of attenuation. It might be caused, for example, by dust clouds (ref. 8) or by frozen carbon dioxide particles, which have been suggested as an almost permanent feature of the Martian atmosphere (ref. 9). Specifically, therefore, a scattering measurement in the infrared would indicate the presence of particulate matter in the Martian atmosphere.

Absorption by Carbon Dioxide

From equation (9a), for carbon dioxide:

$$N_{z,\max} = 2.5 \times 2 \times 10^{17} \left(3360 \times 10 \times 10^{10}\right)^{1/2}$$

$$= 9.2 \times 10^{24} \text{ mol/cm}^2\text{-column} \qquad (13)$$

Since 1 cm^3 at STP contains 2.68×10^{19} mol, the above amount of carbon dioxide corresponds to

$$\frac{9.2 \times 10^{24}}{2.68 \times 10^{19}} = 3.34 \times 10^5 \text{ atm-cm.} \tag{13a}$$

Infrared absorption of carbon dioxide in terms of atm-cm is tabulated in the literature (ref. 7).

Measurement of attenuation at 4.3μ will permit an estimate of the carbon dioxide profile in the Martian upper atmosphere. Extinction occurs when the total amount of carbon dioxide is slightly less than 2000 atm-cm (ref. 6). This quantity is exceeded by more than two orders of magnitude along the tangential path as deduced in equation (13a).

The extinction altitude (total number of mol/cm^2-column along path tangential to surface equal to 2000 atm-cm) is readily calculated from equation (9), i.e.:

$$\begin{aligned} h_o &= H_{CO_2} \log_e \left[n_s N_z^{-1} (2\pi RH)^{1/2} \right] \\ &= 10 \log_e \left[\left(2 \times 10^{17} / 2 \times 2.68 \times 10^{22} \right) \left(2\pi \times 3360 \times 10 \times 10^{10} \right)^{1/2} \right] \\ &= 51 \text{ km} . \end{aligned}$$

INSTRUMENTATION

The experiment requires the spacecraft to travel on a trajectory behind the dark side of Mars and for the infrared sensors to point at the Sun. We assume a flyby distance of 10,000 km and a spacecraft velocity of 10 km/sec.

Since, as discussed previously, a measurable indication of infrared absorption by water vapor cannot be expected beyond 20 km from the Martian surface, an altitude resolution of at least 1 km is desirable. At 10,000 km, this requires a field of view of 20 by 20 sec.

To show that adequate signal strength can be obtained with existing state-of-the-art instrumentation, the most adverse case of optical design will be considered. This consists of a 0.1 by 0.1 mm thermistor flake and a collimator with a field of view of 20 by 20 sec, which simply consists of two 0.1 by 0.1 mm slits, 1 meter apart, with a suitable infrared filter.

Water Vapor Measurement

Since the average distance between the Sun and Mars is 1.52 A.U., the value of the solar constant at Mars' distance is 0.06 w/cm^2.

The spectral region between 5.5 and 6.5μ contains 0.17 percent (ref. 10) of the total irradiance, i.e., 1.02 x 10^{-4} w/cm^2. Assuming a filter efficiency of 35 percent, the radiative power passing through the collimator is 3.57 x 10^{-9} w. With a typical solid-backed bolometer infrared detector, for a sensitive area of 0.1 by 0.1 mm, the sensitivity is 2500 V/w. The resulting detector output will be 8.95 μV, whereas the Johnson noise of the bolometer resistors and the noise level of the preamplifier can be kept below 1 μV (ref. 11). The predicted 28 percent change of the incident radiation caused by absorption by water vapor will produce a signal of approximately 2.5 μV. Thus, a detection scheme of this type will be capable of establishing an upper limit of 10^{-3} g/cm^2-column of water vapor in the Martian atmosphere. This figure might well be lowered by a more efficient optical design (ref. 12) or by relaxing the altitude resolution of the radiometer.

Scattering Experiment

The spectral region between 8 and 9 μ contains less than 0.05 percent (ref. 10) of the total irradiance. Following the above procedure, a 28 percent change of incident radiation under identical conditions would not be detectable. On the other hand, the spectral region between 3.4 and 3.6 μ contains 0.22 percent (ref. 10) of the total irradiance. In this case the unattenuated signal will be 12 μV and a change of less than 20 percent will be readily detectable.

Carbon Dioxide Measurement

The spectral region between 4.1 and 4.5 μ contains 0.2 percent (ref. 10) of the total irradiance. Under identical conditions of collimation, transmittance, and detector response, the unattenuated signal will be 10.5 μV. Because of the high abundance of carbon dioxide in the Martian atmosphere, the carbon dioxide profile will be readily measurable.

The basis of the instrumented package will be a radiometer design developed for the Mariner II mission (ref. 12) with an optical system considerably more sophisticated than the one outlined above. Except for certain modifications, such as the addition of a third channel and filters for different portions of the infrared spectrum, the equipment is already fully flight-qualified.

A comparison of a Martian radiometer with that flown on Mariner II is given in Table I.

TABLE I

	Mariner II	Mars
Channel A: spectral range	8 - 9 μ	5.5 - 6.5 μ (Water Vapor)
Channel B: spectral range	10.4 μ	3.4 - 3.6 μ (Scattering)
Channel C: spectral range	-	4.1 - 4.5 μ (Carbon Dioxide)
Channel B: amplifier	logarithmic	all channels linear
Field of View	1.2° x 1.2°	20 x 20 sec
Chopper Frequency	20 Hz	100 Hz
Power at 400 Hz	1.9 w	6 w
Reference Optics	essential	redundant
Reference Amplifier	essential	redundant

Except for the chopper frequency, the above changes do not require further explanation. The figure for the chopper frequency is derived as follows: Assuming the most adverse case, the scan-speed will be equal to the spacecraft velocity, i.e., 10 km/sec. (A reduction of the scan speed is, of course, possible by a suitable change in orientation of the velocity vector of the spacecraft relative to the Sun-Mars position vector.) The time constant of the bolometer is 3 msec; for 99 percent response, at least five time constants are required, namely, 15 msec. For a 50 percent duty cycle, 30 readings per second can thus be obtained. The chopper frequency should be at least three times the readout frequency, i.e., approximately 100 Hz. This can be obtained with a modest increase in chopper power from 1.9 to approximately 4 w.

Readings can thus be obtained every 0.33 km. Regarding data acquisition, for an accuracy of 1 percent full-scale, seven binary bits are required; the bit rate is 210 per second per channel. Scanning from 100 km to the planetary surface requires a bit-storage capacity of 2100 per channel, i.e., a total of 6300. This number is doubled if the scan can be performed on both sides of the Martian disc.

CONCLUSIONS

The underlying theory of the proposed experiment relies on the best presently available data on the Martian atmosphere. No unreasonable assumptions have been made in the calculations. In essence, the instrumentation has been qualified on Mariner II (ref. 13) and the proposed modifications will not affect performance of reliability. Where necessary, the equipment will have to be updated in the light of advances made since 1962.

Successful functioning of the equipment can be anticipated with confidence with the following tentative characteristics of the radiometer:

Size:	6 by 6 by 6 inches
Weight:	5 lb
Power:	0.5 w - 12 V dc, 6 w - 400 Hz, 26 V rms.

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