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SPECTROSCOPIC EVIDENCE FOR VEGETATION ON MARS

WILLIAM M. SINTON

Smithsonian Astrophysical Observatory

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ABSTRACT

A new test for the presence of vegetation on Mars depends on the fact that all organic molecules have absorption bands in the vicinity of $3.4\ \mu$. These bands have been studied in the reflection spectrum of terrestrial plants, and it is found that for most plants a doublet band appears which has a separation of about $0.1\ \mu$ and is centered about $3.46\ \mu$. Spectra of Mars taken during the 1956 opposition indicate the probable presence of this band. This evidence and the well-known seasonal changes of the dark areas make it extremely probable that vegetation in some form is present.

The waxing and waning of the Martian dark areas according to the season has long been cited as evidence for the presence of vegetation, although tests for the high near-infrared reflectivity that is characteristic of most plants have all been negative (Slipher 1924; Millman 1939; Tikhov 1947; Kuiper 1949). A few terrestrial plants, such as some lichens, lack this characteristic, however, and it was suggested by Kuiper (1949) that the dark areas may consist of similar plant life.

All organic molecules possess strong absorption bands near $3.4\ \mu$, the wave length of the carbon-hydrogen bond resonance. The resonant wave length depends to some extent on the nature of the molecule to which the carbon atom is attached. In large organic molecules the resonance occurs near $3.46\ \mu$, the precise wave length depending on the neighboring atoms of the molecule. If there are two hydrogen atoms attached to the carbon atom, the band is a doublet with the mean wave length again near $3.46\ \mu$. A convenient chart published by Barnes, Gore, Stafford, and Williams (1948) shows this band and others to be found in organic molecules.

In the gas methane the absorption band is shifted to $3.3\ \mu$ as a result of the lightness of the gas. This shift prevents the absorption band of this gas (a constituent of the earth's atmosphere and a possible constituent of Mars's atmosphere) from interfering with a spectroscopic test for absorption by other organic molecules on Mars.

Unfortunately, only a few papers have been published on the reflection spectrum of vegetation in the infrared. Gates and Tantraporn (1952) made spot measurements of the reflectivity of many different types of plants at discrete wave lengths which did not include the region of the C-H vibration. Coblentz (1913) also made spot measurements, which extended out to $3\ \mu$, where the reflectivity of leaves was decreasing, but not farther into the infrared.

In the visible spectrum, vegetation exhibits body color. Light, in reflecting from the plant, penetrates beneath the surface before emerging and thus shows the ab-

sorption bands of the plant material. If this property continues into the infrared, plants should show the C-H vibration band as absorption in the light reflected from their leaves.

To test this conclusion, spectra were obtained by reflecting the light of an incandescent source from specimens of various plants and re-imaging this light onto the slit of a Perkin-Elmer monochromator. These measurements essentially determined the specular reflectivity. Figures 1*a* and 1*b* show reflectivities for several of the plants.¹ Since the lily of the valley leaf was fresh and thus contained considerable water, the absorption at 3.1 and 3.6 μ is probably due to this water. The organic band is better shown in the spectrum of the dried maple leaf, where it is seen to be a doublet with about 0.1 μ spacing, indicative of the CH₂ group. In fresh but drier plants, such as lichens and mosses, the absorption is pronounced. The doublet structure is still evident, although not so apparent. In all the plants tested, the C-H resonance appeared to some extent. The two lichens of Figure 1*b* were of entirely different appearance; yet the curves are very similar except for the scale. In the region of the band, the upper curve is a constant multiple of the lower curve, within a few per cent. Because the absorption appears with moderate strength in spectra of relatively dry plants, which are the only kinds to be expected on Mars, the presence of this band would apparently be evidence for vegetation, and appropriate tests were carried out during the 1956 opposition of Mars.

At 3.5 μ the largest part of the energy received from Mars is reflected sunlight, but thermal radiation from the planet contributes some. Since the albedo is 0.1 or less, the band will not be expected to appear strongly as emission in the planetary radiation; that is, the emissivity can vary at most between 0.9 and 1.0. The laboratory spectra show that the band appears with moderate strength as absorption of the reflected light. Therefore, the C-H resonance may be expected to have the appearance of an absorption band in the total light.

SPECTROGRAPHIC EQUIPMENT

Little energy is emitted by Mars at 3.5 μ , and only the most sensitive detector and amplifying scheme should be used for this experiment. The detector selected for this work was a lead sulfide photoconductive cell, manufactured by Electronics Corporation of America, and designed to be cooled with liquid nitrogen. Cooling to 96° K extends the sensitive range of a lead sulfide cell to 3.6 μ . The sensitive area of the cell (0.16 mm square) should have been just large enough for the reduced image provided by the condensing mirror system at the exit slit of the monochromator, but aberrations of the condensing system made the image of the slit somewhat larger. The monochromator was a Perkin-Elmer Model 83 equipped with a lithium fluoride prism. The band pass of the monochromator was 0.056 μ . This equipment was attached at the Newtonian focus of the 61-inch Wyeth reflector of the Harvard Observatory and was oriented so that it was nearly level when the telescope was on the meridian at the declination of Mars. An oscillating plane mirror, arranged in the light-path between the telescope and the slit of the monochromator, chopped the light. The mirror was driven so that it remained parallel in a square-wave motion at 90 cycles/sec. By this motion the image of Mars that fell on an aperture placed in front of the slit was switched to a position beside the aperture, where the aperture prevented the light from entering the monochromator. The amplitude of the image motion was about 1 mm, a little larger than the diameter of Mars.

The signal was amplified and was multiplied by a generated wave which had a shape and phase very nearly the same as those of the signal. This treatment provides

¹ At first sight, these reflectivities appear low, but it must be remembered that much of the light is scattered away from the angle of specular reflection. The diffuse reflectivity, which measures the total scattered light, is probably much higher.

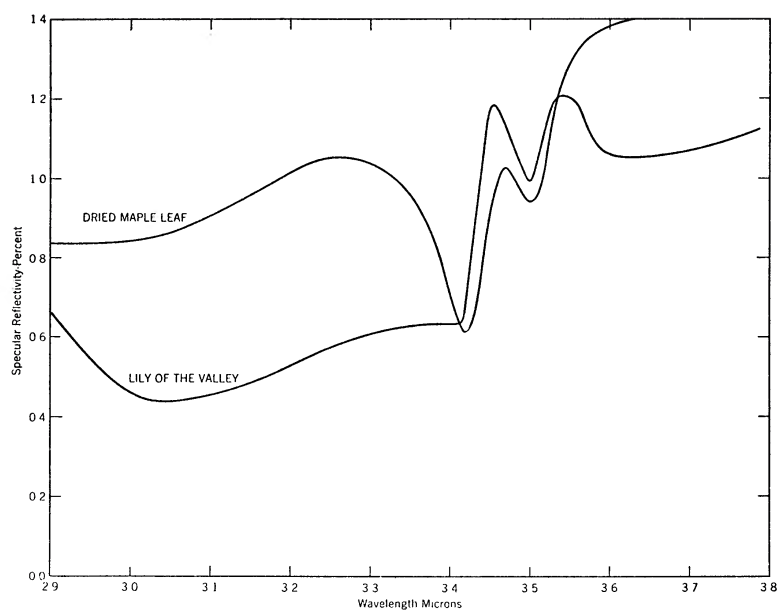
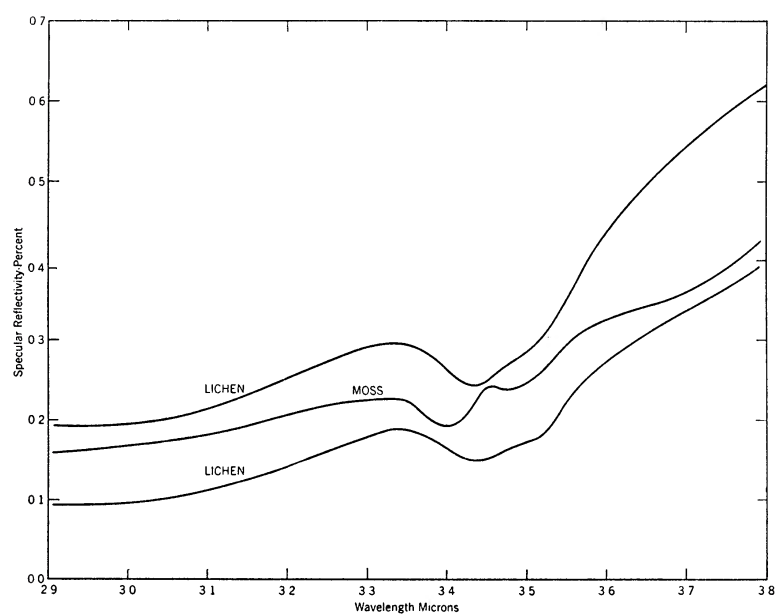
*a**b*

FIG. 1.—Specular reflectivity of several plants. The depressions at 3.1 and 3.6 μ in *a* are probably due to absorption by water. The lichens in *b* were of rather different types but show similar spectra. The double band at 3.4 and 3.5 μ seen in all the spectra is due to C-H absorption.

high discrimination against noise and also takes cognizance of the phase of the measured signal. If the second of the two images formed by the oscillating mirror enters the slit of the monochromator, a negative deflection is obtained. Switching from one image to the other gives doubled deflections and consequently gives twice the signal-to-noise ratio obtained by the usual chopping procedure where reference is made to the sky.

OBSERVATION PROCEDURE

Because of the small amount of radiation, observations were made by averaging numerous measurements at fixed wave lengths. Five wave lengths, distributed through the region of from 3.3 to 3.6 μ , were used each night. Shifting the net of five wave lengths from night to night gives good coverage over the band.

The procedure consisted of recording each of the five wave lengths for 4 minutes, alternating every minute from one of the two images to the other and then moving the monochromator to the next wave length. The changing zenith distance and a slow decrease in the cell's sensitivity through the night made it advisable to vary the order of the wave-length settings. About three to five complete sets were made each night. All observations were made within 2 hours of meridian passage, to avoid excessive zenith distances and to prevent spilling liquid nitrogen from the cell. A filling of the

TABLE 1
LOG OF OBSERVATIONS OF MARS, SUN, AND MOON

Date	Times	Object	Central Meridian	Secant of Zenith Angle
Sept. 30	2 ^h 39 ^m –4 ^h 12 ^m	Mars	178°5	1 669–1 725
Oct. 6	2 05 – 4 56	Mars	125 5	1 660–2 005
Oct. 11	3 03 – 5 54	Mars	94 4	1 647–1 759
Oct. 20	2 06 – 4 05	Mars	351 7	1 616–1 996
Oct. 8	15 25 –16 22	Sun		1 512–1 587
Oct. 20	15 07 –15 25	Sun		1 753–1 805
Oct. 20	4 25 – 7 38	Moon		1 132–1 417

cell lasted for about 30 minutes, which was ample time for a run, with allowance for changing wave lengths and moving the telescope from one image to the other.

It had been hoped that the spectrum of a dark area could be obtained and compared with that of a bright area, but measurements of areas less than the entire disk were valueless because of insufficient energy. Instead, the aperture in front of the slit passed the entire disk of Mars, and the C-H band was sought in the spectrum of the total light.

Four nights, all after the time of opposition, yielded good observations. Table 1 shows the dates and times of the observations, the central meridian of Mars at the middle of the observing period, and the range of zenith distances.

Unfortunately, there is some absorption in this part of the spectrum by water vapor in the earth's atmosphere. The strongest absorption occurs at the short-wave-length end of the observed range. The spectrum of the sun was observed on 2 days, and the zenith distances for these are also given in Table 1. The solar spectrum was obtained by using the sunlight reflected from a clean aluminum wire. Aluminum should not have any wave-length effect in this range. The spectral distribution of the sun is shown in Figure 2. For comparison, four spectra of the limb of the nearly full moon were obtained on October 20.

REDUCTION

Figure 3 presents the observations of Mars after division by the spectrum of the sun. They have been brought to the same relative scale, since differences in gain settings, cell sensitivity, and apparent size of Mars made relative deflections different for the 4 nights. As indicated by the curve, it appears that the dip is actually present, but scatter of the points, caused by the poor signal-to-noise ratio of the measurements, makes any interpretation uncertain without performing a statistical analysis.

The presence of thermal radiation from Mars might have caused the rise at the long-wave-length end of the curve and the upward concavity. To find out whether the dip in the observed points is significant in the face of this alternative explanation,

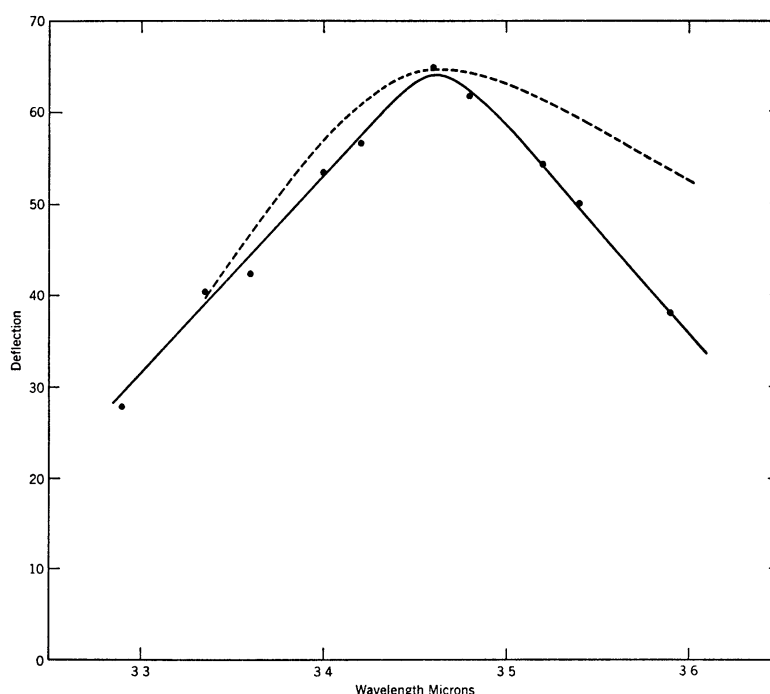


FIG. 2.—Low-resolution solar spectrum in the region of investigation. The solid curve is that determined directly from the sun on two days. The dashed curve is determined as explained in the text from the moon on one of the nights on which Mars was observed.

a statistical treatment of the data was made. The observed points may be fitted by the sum of three curves with arbitrary coefficients. That is, the observed reduced reflectivities R_o are assumed to be equivalent, except for accidental errors, to the sum $R_o = C + K_i f_i + K_o F_o$, where C , K_i , and K_o are arbitrary coefficients. The first coefficient, C , represents merely a constant reflectivity, to be expected for rocks or dust in this part of the spectrum. The second term, f_i , is the expected thermal emission of Mars divided by the sun's spectrum, since the other terms in the foregoing equation have this division implicitly within them. The third term, F_o , is the average of the two lichen curves of Figure 1.

The three coefficients were adjusted to give a least-squares solution to the original observations, that is, equation (1) was multiplied through by the solar spectrum before the solution was made. The significance of the coefficient of the vegetative term was then examined by means of the "t-test" of Gauss. This method takes cognizance of the two ways in which it seems most likely that the observations can be explained—

by thermal emission or by the presence of vegetation. The observations themselves then decide whether the vegetative term is necessary.

The thermal emission from Mars was calculated by first finding an effective temperature, T_e , which a black disk the same size as Mars would have in order to yield the same amount of radiation at 3.5μ as Mars does. This calculation requires a model for the distribution of temperature over the surface, since the actual distribution is very complex. The calculation is made for opposition, and the model is one in which the total radiation emitted by a given area is assumed to depend only on the cosine of the angle between the normal to the surface and the sun. The temperature variation is found from the Stefan-Boltzmann law and by assuming that the temperature of the subsolar point is 300°K . This temperature is close to the maximum observed on the

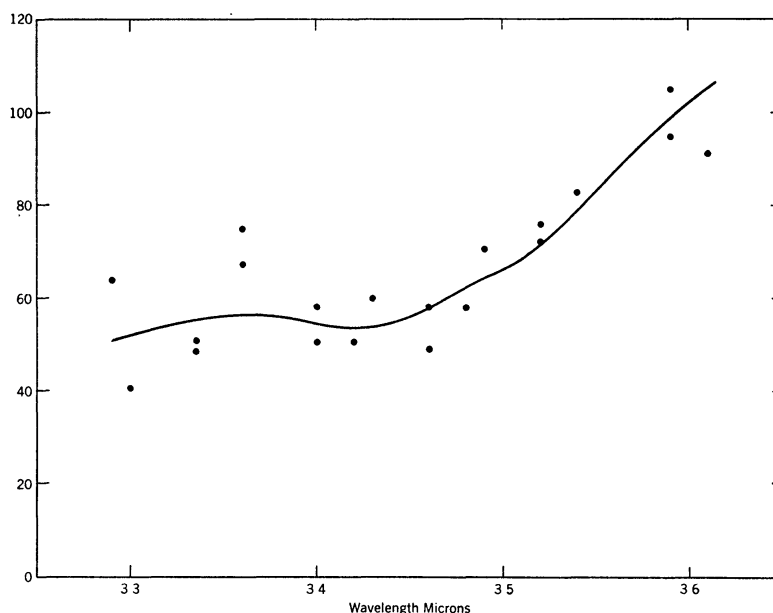


FIG. 3.—Observations of the spectrum of Mars obtained on four nights and after division by the solar spectrum (solid curve of Fig. 2).

disk at the 1954 opposition by Strong and Sinton (1956). The expression giving effective temperature is

$$e^{-C_2/\lambda T_e} = 2 \int_0^{\pi/2} \exp \left(-\frac{C_2}{\lambda T_0} \cos^{-1/4} \theta \right) \sin \theta \cos \theta d\theta, \quad (1)$$

where T_0 is the subsolar temperature, λ is the wave length chosen to be 3.5μ , C_1 and C_2 are the usual constants in the Planck formula, and θ is the angle between the normal to the surface and the sun. The integral may be transformed by substitution and integration by parts to an exponential integral. The resulting value for T_e is 279°K . The reduced spectral distribution of the emission from Mars is obtained by using the effective temperature in the Planck formula and dividing this by a Planck curve for the temperature 6000°K . The result given is the f_i to be used in the least-squares computation.

Table 2 gives the wave lengths of the observed points; the values of f_i , in relative units only, since the coefficient K_i is arbitrary; the averaged spectra of the lichens, f_o ; the computed spectrum of Mars, R_c , after the least-squares adjustment; the observed spectrum, R_o ; and the residuals, $R_o - R_c$. The values determined for the con-

stants, together with their standard deviations, are $C = -1.2 \pm 10.3$; $K_i = 22.9 \pm 7.8$; and $K_o = 143.4 \pm 47.2$. The relative contributions of the three terms may be seen in Figure 4, where the organic term is the largest, the constant term is slightly negative but not significantly so, and the thermal term is appreciable, as was expected.

The quantity $t = K_o/S(K_o)$, where $S(K_o)$ is the standard deviation of K_o , is a measure of the certainty of the existence of a positive K_o . With the computed K_o and its standard deviation, t is 3.04. The twenty observed points provide a seventeen fold redundancy in the solution for the three coefficients. The table of values of t for different levels of significance shows that the probability that the true K_o is negative is less than 0.01. The probability is therefore very high that an organic spectrum is required to account for the data.

TABLE 2
OBSERVED AND COMPUTED SPECTRA OF MARS

Date	Wave Length	f_i	f_o	R_c	R_o	$R_o - R_c$
Sept. 30	{ 3 30	0 509	0 290	52 0	40 7	-11 3
	{ 3 36	0 655	299	56 7	75 3	+18 8
	{ 3 43	0 875	246	54 1	60 0	+ 5 9
	{ 3 49	1 114	278	64 2	70 6	+ 6 4
	{ 3 61	1 756	458	104 6	91 2	-13 4
Oct. 6	{ 3 34	0 591	302	55 6	50 0	- 5 6
	{ 3 40	0 775	268	55 0	58 2	+ 3 2
	{ 3 46	0 988	256	58 1	49 2	- 8 9
	{ 3 52	1 259	306	71 5	76 0	+ 4 5
	{ 3 59	1 650	430	98 2	105 0	+ 6 8
Oct. 11	{ 3 29	0 481	286	50 8	64 2	+13 4
	{ 3 36	0 655	299	56 7	67 6	+10 9
	{ 3 42	0 843	250	54 9	50 6	- 4 3
	{ 3 48	1 072	272	62 3	58 1	- 4 2
	{ 3 54	1 356	337	79 5	82 8	+ 3 3
Oct. 20	{ 3 34	0 591	302	55 6	50 0	- 5 6
	{ 3 40	0 775	268	55 0	50 5	- 4 5
	{ 3 46	0 988	256	58 1	58 5	+ 0 4
	{ 3 52	1 259	306	71 5	72 3	+ 0 8
	{ 3 59	1 650	0 430	98 2	94 8	- 3 4

Several checks may be made on the foregoing result. First, when the data of each night are used separately for a least-squares solution, they all give positive values of K_o . Another check determines whether the magnitude of the thermal emission required is physically tenable. We can determine the albedo (assuming a Lambert reflecting surface) from the ratio of the reflecting terms to the emissive term, since we can calculate the energy reflected if the albedo is 1 and the energy emitted if the albedo is zero. The albedo is given by the formula

$$A = \frac{E(K_o f_o + C)}{R(K_i f_i) + E(K_o f_o + C)}, \quad (2)$$

where E is the energy emitted by a black body at 279° K and R is the sunlight reflected by a white reflector. The values given above for the constants yield an albedo of 0.06 at 3.52 μ , which would seem to be reasonable.

The spectra of the moon, obtained on October 20, were used to check for a possible systematic error. The spectrum obtained at the largest zenith distance was reduced by dividing by the solar spectrum and showed a slight dip. Spectra at smaller zenith distances show larger dips at the position of the C-H band. The dip appears to be due only to effects of atmospheric absorption at the short-wave-length end. When the lunar spectrum is extrapolated to air masses similar to those at which Mars was observed, the dip disappears.

Alternatively, the moon spectrum can be used to reduce the Mars observations to relative reflectivity. The reflected solar component of the lunar radiation has to be separated from the observed spectrum, which contains emitted radiation. This is done by multiplying the observed spectrum of the moon by the calculated ratio of

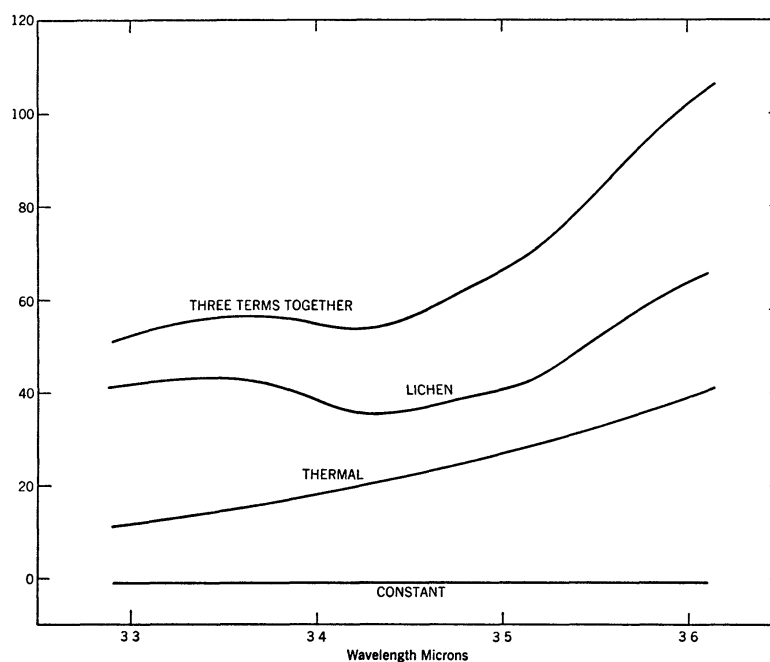


FIG. 4.—Least-squares adjustment of three terms to the observed spectrum. The large “lichen-term” significantly indicates the presence of organic molecules. The constant term, although slightly negative, is not significantly so.

reflected to total light based on an albedo of 0.07. This product, assumed to be the spectrum of the sun after transmission by the earth’s atmosphere, is only a small part of the observed quantity. The dashed curve in Figure 2 shows the spectrum found in this manner. It has a peak at the same wave length as the directly observed curve, but it does not decline so rapidly at long wave lengths. If this curve is used to reduce the Mars observations to reflectivities, the band at 3.46μ is still apparent in the resulting spectrum.

CONCLUSIONS

Unless a fortuitous error occurred (this probability is calculated to be less than one in a hundred), there appears to be a depression at the wave length of the organic band. The spectrum of the moon indicates that no systematic error occurred large enough to explain the greatest part of the dip. The dip could conceivably be caused by a corresponding depression in the reflectivity of inorganic material that might be present. This circumstance seems unlikely.

Although the lichen spectrum was used for the comparison, the agreement does

not, of course, imply that lichens are present on Mars; it indicates only that organic molecules are present. It seems unlikely, however, that organic molecules would remain on the Martian surface without being covered by dust from storms or being decomposed by the action of the solar ultraviolet, unless they possessed some regenerative power. The dip at the significant wave length is therefore additional evidence for vegetation. This evidence, together with the strong evidence given by the seasonal changes, makes it seem extremely likely that plant life exists on Mars.

This research has been made possible only by the considerable help and co-operation of many people. Specifically, I should like to thank Dr. John Howard, of Air Force Cambridge Research Center, who made much of the equipment available; Mr. Norman Anderson, of Electronics Corporation of America, who manufactured the lead sulfide cell to specification; and Dr. G. R. Miczaika, who kindly expedited appropriate parts of the reconstruction of the 61-inch telescope so that it would be in operating condition in time. Others who helped in innumerable ways are Dr. Theodore E. Sterne, Mr. Lionel U. Caron, Mr. Russell Anderson, Mr. Fred Franklin, and Mr. Donald J. Lovell, and Dr. V. Z. Williams and Dr. Horace Siegler of the Perkin-Elmer Corporation.

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