

THE ABSENCE OF OXYGEN AND WATER-VAPOR LINES FROM THE SPECTRUM OF VENUS¹

BY CHARLES E. ST. JOHN AND SETH B. NICHOLSON

ABSTRACT

Absence of oxygen and water-vapor lines from the spectrum of Venus.—It has been generally assumed that the atmosphere of Venus is like our own, containing both oxygen and water vapor, but the spectroscopic evidence for this assumption is very doubtful. Recently spectrograms have been made with the Snow telescope and the Littrow grating spectrograph at times when the relative velocity of Venus and the earth was sufficient to separate completely corresponding lines produced by the two atmospheres. Special attention was given to the lines of water vapor near λ 5900 and to the bands α and β due to oxygen. No trace of any line due to the planet's atmosphere was observed. It is estimated that in the path traversed by the solar light through Venus' atmosphere there must be less than the equivalent of one meter of oxygen, less than one-thousandth of that in our atmosphere, and less than one millimeter of precipitable water vapor.

Atmosphere of Venus.—*Various observational facts and theories concerning this atmosphere are discussed.* Although the new data prove that there is no appreciable amount of oxygen or water vapor above the visual surface of Venus, nothing is definitely known about the elevation of this surface above the presumably solid surface of the planet, or whether this reflecting layer is composed of cirro-strati, of haze, or of clouds of dust produced by violent atmospheric circulation.

It has been generally assumed in the literature on planetary atmospheres that the atmosphere of Venus is similar to our own; in particular, that oxygen and water vapor are present. Secchi,² 1868, noted in the spectrum of Venus a nebulous band on the red side of the D line and also one to the violet, the δ of Brewster. He observed these with Venus at a high altitude and when the air was so dry that he assumed that they were not of telluric origin. Huggins³ had previously, 1863, studied the spectrum of Venus, Mars, Jupiter, and Saturn. Of Venus he says:

The light of Venus gives a spectrum of great beauty. The line D was seen double, B, C, and numerous solar lines to a little beyond G, were distinctly visible; and the principal of these were measured and found to agree with corresponding lines in the solar spectrum. Lines other than these, and in the position in which the stronger atmospheric lines present themselves, were carefully looked for, but no satisfactory evidence of any such lines has been obtained.

¹ *Contributions from the Mount Wilson Observatory*, No. 249.

² *Spektre Protuberanze*, p. 24, 1869.

³ *Philosophical Transactions of the Royal Society*, 154, 422, 1864.

The basis of the assumption permeating the literature on planetary atmospheres is found in the observations of Vogel.¹ Of his observations on the oxygen band at λ 6275 and the water-vapor bands at $\lambda\lambda$ 5945 and 5925 he says:

Die Venus stand bei den Beobachtungen so hoch, dass man nicht annehmen kann, dass unser Atmosphäre einen merklichen Einfluss auf das Venusspectrum ausgeübt habe, die Linien oder Streifen sind daher entschieden dem Venusspectrum eigen und deuten auf die absorbierende Wirkung einer Atmosphäre.

Scheiner² in his review of the question sums up as follows:

There seems to be no doubt that the telluric lines appear stronger in the less refrangible portions of the spectrum of the planet than in the solar spectrum. There can therefore be no doubt that the atmosphere of Venus exerts an absorption similar to that of our own, and hence the nature of the two atmospheres must be similar. . . . We may safely assume that the clouds of Venus consist of condensed aqueous vapor, thus again resembling those of the earth.

Arrhenius³ is still more specific and states that:

The humidity (on Venus) is probably about six times the average of that on the earth or three times that in the Congo where the average temperature is 26° C. The atmosphere of Venus holds about as much water vapor 5 km *above* the surface as does the atmosphere of the earth *at* the surface. We must therefore conclude that everything on Venus is dripping wet. The vegetative processes are greatly accelerated by the high temperature. Therefore the life time of organisms is probably short.

The fallibility of these older visual observations, in which conclusions are drawn from estimates of the relative intensities of integrated groups of lines in the spectrum of Venus and of the moon or sky, is shown by comparing Vogel's observations in the green region with our spectrograms of Venus and the sky. Vogel notes, among others, groups at λ 5216 and λ 5251 as strengthened in the spectra of Venus, and Scheiner accepts the observations as definite proof of the similarity of the atmosphere of Venus and the earth. Arrhenius' conception of supertropical moisture and luxuriance of vegetation is founded likewise on these older observations. These groups are resolved on the Mount Wilson spectrogram, Plate XIII, and our

¹ *Untersuchungen über die Spectra der Planeten*, pp. 10-16, 1874.

² *Astronomical Spectroscopy*, pp. 197-198, 1894.

³ *The Destinies of the Stars*, pp. 250-251, 1918.

examination shows no strengthened lines in the spectrum of Venus. The lines of both groups are identified as iron lines of intensity 2 and 3 on the Rowland scale. The degree of dependence that can be placed upon the Mount Wilson spectrograms may be inferred from observations at λ 5293 of some lines which are marked Awv? and oo intensity in the Rowland table. These were clearly displaced in the spectrum of Venus, with no lines visible in the undisplaced positions. An examination of juxtaposed spectra of the east and west limbs of the sun confirms this evidence that the lines are entirely solar and not atmospheric.

These older visual observations depended on estimating the relative intensities of integrated groups of lines in the spectra of Venus and skylight. Lowell¹ suggested measuring the position of the oxygen and water-vapor lines to see whether they were affected by the Doppler shift, and V. M. Slipher obtained spectrograms of Mars and the moon and of Venus and the sky with a dispersion of 50 Å per mm at 6100 Å.² Of the spectrograms of Mars, Lowell says:

The results at first seemed significant. To the writer's eye the shift of the solar lines under the microscope was perceptible though slight and in the shift the α band seemed to share. The lines of water vapor near D though present in both spectra were not strong enough to make much deduction possible.

Of Venus he says,

Here again eye estimates by the writer subscribed to a shift in the α band, the water vapor lines, very faint, concurring; . . . As regarded differences in density, none was perceptible between either the Martian and the lunar or the solar and Venesian, either in the oxygen α band or the water vapor lines near D. Water vapor is probably non-existent on the illuminated side of Venus and extremely scarce on Mars. As for oxygen the results above show that the spectroscopic method is hardly a delicate enough one in this respect to decide the question.

And Slipher remarks:

Examination and measurement of them led to the same uncertain results as in the case of those of Mars. Although this attempt has failed to detect aqueous vapor in Mars and Venus, the conclusion should not be drawn that it

¹ *Lowell Observatory Bulletin*, No. 17, 1905.

² Campbell and Albrecht in observations on Mars quite independently applied the Doppler-Fizeau method to a planetary atmosphere. *Lick Observatory Bulletin*, 6, 11 (No. 180), 1910.

does not exist in their atmospheres, nor that it will always remain impossible to discover it spectrographically.

This brief account reviews the spectroscopic evidence upon which the current views in respect to the constitution of the atmosphere of Venus were founded when we began our observations in March, 1921, and indicates the extreme detail reached in their interpretation. At the Berkeley meeting of the Astronomical Society of the Pacific in August, when we reported our results, Dr. Slipher also reported results of his recent observations in which he used relative intensity as a criterion, and obtained similar negative results.

INSTRUMENTAL METHODS

The spectrograms were obtained with the Snow telescope and the Littrow grating-spectrograph.¹ To Professor Wood we are greatly indebted for the loan of a large grating very bright in the first order. It was ruled by Anderson and has a surface of 95×170 mm. The dispersion in the first order of the 18-foot spectrograph is 3 Å per millimeter. For the α band and the 5900 region the plates were Seed 23's, sensitized to red light by pincyanol. Ilford Special Rapid panchromatic plates, hypersensitized with ammonia, were used for the B band, λ 6867.

The wave-lengths of eight water-vapor lines near D and of seven oxygen lines in the α band were measured on five spectrograms of Venus and on three of the sky, using I.A. wave-lengths of solar lines, corrected for motions, for standards of reference. On three of the spectrograms of Venus the wave-lengths of the water and oxygen lines were referred also to iron arc lines; the spectrum of the arc was put on intermittently during the long exposures on Venus. On a fourth spectrogram of the sky they were referred to the lines of a simultaneously exposed iron arc. The wave-lengths thus found were compared with the wave-lengths of the same telluric lines, obtained under much higher dispersion, given in Table I.

From the variation among the differences, Rowland *minus* International (R - I in Table I), the relatively low accuracy of measurement of water-vapor and oxygen lines is apparent, even on spectrograms with a scale of 0.72 Å per millimeter. For the

¹ *Mt. Wilson Contr.*, No. 208; *Astrophysical Journal*, 54, 381-382, 1921.

oxygen line λ 6278, which is double on the Mount Wilson plates, the mean wave-length of the two components is used for the comparison with the Rowland value. In such a series of measurements as is presented in this paper, where the scale is 3 A per millimeter, a precision in the final means greater than 0.005 A is hardly to be expected. The results of the measurements are shown in the eighth column of Table II under $\Delta\lambda$, the $\Delta\lambda$ being the difference between the observed wave-lengths and those of Table I.

TABLE I
WAVE-LENGTHS OF THE COMPARISON LINES

Water Vapor* I.A.	R-I	Oxygen† I.A.	R-I
5885.982.....	+0.211	6278.106.....	+0.197
87.227.....	0.218	81.186.....	0.201
87.665.....	0.215	81.963.....	0.201
5909.001.....	0.212	92.171.....	0.202
19.058.....	0.218	92.967.....	0.203
19.646.....	0.214	95.186.....	0.203
24.276.....	0.214	95.968.....	+0.202
32.097.....	+0.219		

* *Mt. Wilson Contr.*, No. 223; *Astrophysical Journal*, 55, 36, 1922.

† Unpublished results by St. John and Babcock.

Because of the dearth of reference lines, a different method of measurement was adopted for the oxygen lines in the B band, λ 6867. The positions of nineteen oxygen lines in the spectra of Venus were compared with their positions in the spectra of the sky taken under similar spectrographic conditions. The scale readings of the solar lines on the spectrograms of the planet were corrected for the relative velocity of Venus and the earth. The average difference between these adjusted scale readings and those of the same lines on the sky spectrograms was then applied to all lines, thus bringing the readings of the solar lines into mean agreement on the two spectrograms. In the absence of absorption by oxygen in the atmosphere of Venus, the oxygen lines should now have the same scale readings in the two spectra; on the other hand, the presence of absorption should register as a displaced component of the oxygen lines, broadening or doubling them, according to the relative velocity. Spectrograms were taken with Venus east and west of the sun, the range in velocity corresponding to a Doppler

TABLE II
 OBSERVATIONAL DATA

Plate	Subject	1921	P.S.T.	z sec. \pm	Velocity E-V km	Doppler Shift	$\Delta\lambda$	Lines Meas.	Refer. Lines	Phase
V 274....	Venus	Feb. 24	5 ^h 36 ^m -9 ^h 00 ^m	{67° 2.56}	-12.87	A {-0.254 -0.270}	+0.015 -0.010	water vapor a, oxygen	arc sun	98°0
275....	Sky	Feb. 25	4 30	{76° 4.13}	.....	.....	{+0.003 -0.001}	water vapor a, oxygen	sun	.....
276....	Venus	Feb. 25	5 40 -9 00	{68° 2.67}	-12.84	{-0.253 -0.269}	+0.014 -0.004	water vapor a, oxygen	arc sun	98°7
277....	Sky	Feb. 27	4 58	{81° 6.39}	.....	.....	{-0.006 +0.001}	water vapor a, oxygen	sun	.....
278....	Venus	Feb. 27	5 37 -9 00	{68° 2.67}	-12.79	{-0.252 -0.268}	-0.012 -0.015	water vapor a, oxygen	arc sun	100°3
279....	Sky	Feb. 28	3 49	{68° 2.67}	.....	.....	{-0.009 -0.013}	water vapor a, oxygen	arc	.....
280....	Sky	Feb. 28	4 10	{71° 3.07}	.....	.....	{-0.014 -0.021}	water vapor a, oxygen	sun	.....
282....	Venus	Feb. 28	7 20 -9 05	{76° 4.13}	-12.76	{-0.252 -0.268}	-0.005 -0.006	water vapor a, oxygen	sun	101°1
285....	Venus	Mar. 1	7 19 -9 00	{76° 4.13}	-12.73	-0.267	-0.005	a, oxygen	sun	101°8
289....	Venus	Mar. 3	6 16 -9 00	{69° 2.79}	-12.69	-0.249	+0.026	water vapor	sun	103°4
301....	Venus	Mar. 24	5 55 -8 ^h 35	{70° 2.92}	-10.99	-0.252	+0.00	B, oxygen	sun	125°1
303....	Venus	Mar. 27	5 45 -8 38	{71° 3.07}	-10.38	-0.238	0.00	B, oxygen	sun	129°0
359....	Venus	Aug. 13	15 0 -23 0*	{31° 1.17}	+12.44	+0.286	-0.00	B, oxygen	sun	67°1

* Exposure interrupted; total 710^m.

shift of 0.538 Å. The results of the comparison are given in the eighth column of Table II, where the $\Delta\lambda$ for these plates is the difference Venus *minus* sky.

OXYGEN

Five spectrograms of Venus were taken in the region of the α band when the relative velocity of Venus and the earth was -12.8 km, the corresponding Doppler shift being 0.268 Å to the violet, an amount sufficient to separate completely the terrestrial components from those of Venus. Although some solar lines of intensity 000 are faintly visible on these spectrograms, no lines are observable where they should appear if produced by oxygen in Venus' atmosphere. The measured wave-lengths of the oxygen lines present on the spectrograms of Venus and the sky and the magnitude of their deviations from the wave-lengths of Table I show, moreover, that the oxygen lines produced by the earth's atmosphere in the spectrum of the planet are not measurably shifted by blending with lines originating in the atmosphere of Venus and wide enough to overlap those of terrestrial origin.

The B band is producible by a much smaller quantity of oxygen than the α band and therefore furnishes a more sensitive test. King has recently shown that 39.4 m of air at 72 cm pressure, equivalent to 8 m of oxygen, give the lines of the B band faintly.¹ His solar spectrograms indicate that the lines of the B band produced by 39.4 m of air are comparable in intensity with solar lines of intensity 00 on the Rowland scale. On the spectrograms of Venus in this region lines of intensity 1 have about the same visibility as the limiting lines on King's spectrograms. To obtain an estimate of the length of an oxygen column which would produce the lines of the B band with an intensity of 1, we have made use of a valuable paper by Jewell² on the variation of the intensity of water-vapor lines with the quantity of water vapor traversed and of the change in intensity of the oxygen line λ 6287.953 with zenith distance. Jewell determined the intensities of Fraunhofer lines—000 to 6—in terms of the Fe line λ 5930.406. Graphs from these data show that the inten-

¹ *Mt. Wilson Contr.*, No. 232; *Astrophysical Journal*, 55, 411, 1922

² *Astrophysical Journal*, 4, 324, 1896.

sity intervals from 000 to 6 are roughly equal, and that the intensity of the water-vapor line λ 5919.860 is strictly proportional to the amount of water vapor traversed (Figs. 1, 2). A similar proportionality is shown to hold for the oxygen line λ 6287.953 and is assumed to hold for the oxygen lines of the B band. The interval from 00 to 1

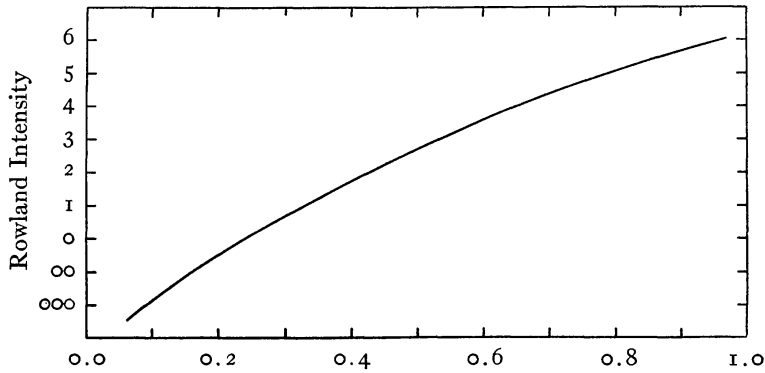


FIG. 1.—Rowland intensities in terms of λ 5930 taken as unity

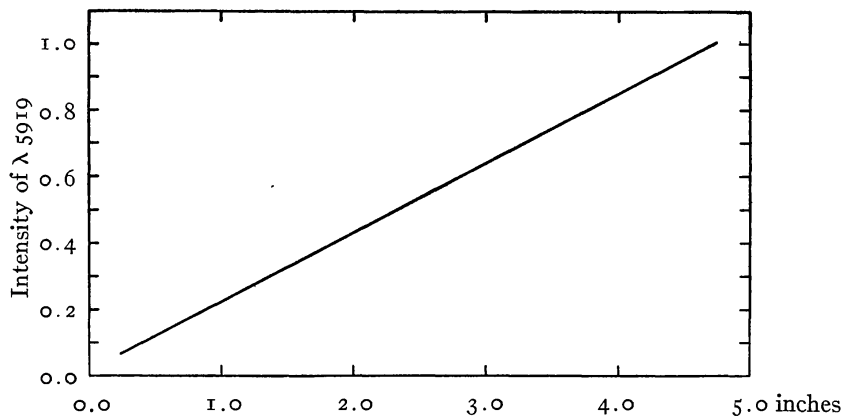


FIG. 2.—Intensity at the zenith of λ 5919 (wv) in terms of λ 5930 (Fe) for various amounts of precipitable water in the atmosphere expressed in inches.

is approximately 0.16 of the intensity of the Fe line λ 5930. This is equivalent to an increase in the length of path of 16 per cent. Hence the lines of the B band would probably appear on the spectrogram of Venus if the absorbing column contained the equivalent of 9.2 m of oxygen under ordinary conditions of pressure.

Two spectrograms of Venus showing the B band, March 24 and March 27, 1921, were taken when the relative velocity was -10.68 km, the equivalent Doppler effect being -0.245 A. A

similar spectrogram was taken August 14, when the relative velocity was +11.36 km, the Doppler displacement being +0.286 Å. With the scale of 3 Å per millimeter, the doublets of the B group are widely separated, but in the interspaces no lines are visible, where lines due to oxygen absorption in the atmosphere of Venus should appear, though solar lines of intensity 0 are present. Whether lines originating in the planet would be completely separated from the terrestrial lines by shifts of 0.264 Å and 0.286 Å depends on the widths of the lines. It is evident that at most only a small amount of oxygen is traversed in the atmosphere of Venus, and lines produced by it would be faint and narrow. On a plate of the B band taken by King with an air path of 39.4 m, the mean width of the single lines is 0.19 Å. The mean width of these lines on plate V 359 is 0.27 Å, and the Doppler shift +0.29 Å, so that the edges of the lines would be separated by 0.06 Å. Spectrograms V 301 and V 303 are not so suitable for this purpose, as the continuous background is fainter and the lines somewhat wider and the Doppler shift smaller than for V 359. When, however, the positions of the oxygen lines in these spectrograms are compared with their positions in the sky spectrograms, the measures show a displacement of 0.003 Å to the red, whereas the Doppler shift would be 0.245 Å to the violet. On V 359, the measured displacement is 0.002 Å to the violet, with a possible Doppler shift of 0.285 Å to the red. If, therefore, for any cause the lines of the B band produced by small amounts of oxygen on Venus are somewhat wider than those produced in the laboratory, the results show that there is no measurable influence of overlapping of the edges of the terrestrial lines by undetected Venus components.

The length of the path traversed through Venus' atmosphere in a layer of a given radial depth depends upon the phase angle of the planet and the position on the disk of the point from which the light is observed. For a point on the line perpendicular to the terminator and limb, whose distance from the limb in units of the length of that line is d , the zenith distances of the earth, z_e , and of the sun, z_s , are given by

$$\sin z_e = 1 - d \cos i,$$

$$z_s = i - z_e$$

where i is the phase angle. Table III gives the total length of the path traversed by the solar beam for different phase angles and different distances from the limb in units of the radial depth. The secant equation used here is of course not applicable just at the limb and terminator.

TABLE III
sec z_e + sec z_s

d		i		
		70°	100°	130°
(Limb)	0.0.....	∞	∞	∞
	0.1.....	3.0	3.7	5.5
	0.2.....	2.6	3.2	4.8
	0.3.....	2.4	3.1	4.8
	0.4.....	2.5	3.2	5.0
	0.5.....	2.6	3.5	5.6
	0.6.....	3.0	4.0	6.6
	0.7.....	3.5	5.0	8.2
	0.8.....	4.7	6.9	11.6
	0.9.....	8.1	12.9	22.9
(Terminator)	1.0.....	∞	∞	∞

At the middle point of the visible disk, corresponding to the center of the spectral band, the path for plates V 301 and V 303 was 5.2 times the radial depth of the layer penetrated, and for V 359 it was 2.5 times the depth. On the basis that lines of intensity 1 would be produced by 9.2 m of oxygen, it follows for V 301 and V 303 that the quantity of oxygen traversed did not exceed the equivalent of a column 2 m long under standard conditions. For light from near the terminator the path traversed in Venus' atmosphere is much longer. With the slit normal to the terminator, as in these observations, one edge of the spectrum corresponds to this longer path. For spectrograms V 301 and V 303 the path for the light at the point halfway between the center and edge of the spectrum was 7.5 times the radial depth of the layer. The edge of the spectrum shows no trace of oxygen lines due to absorption in the planet's atmosphere. Absorption capable of producing lines of intensity 1 would be expected if an oxygen layer equivalent to 1 m under normal pressure had been traversed in the passage through the atmosphere of Venus. As the oxygen in the earth's

atmosphere is equivalent to a column 1500 m long, it follows that the oxygen in the path through Venus' atmosphere was less than one-thousandth of that in the terrestrial atmosphere.

WATER VAPOR

Five spectrograms of Venus taken when the relative velocity of Venus and the earth was -12.8 km, the corresponding Doppler shift being -0.252 Å, form the basis of the investigation on water vapor. The relative velocity was sufficient to separate completely lines produced by absorbing gases common to both atmospheres. No traces of lines due to the planet's atmosphere are discernible on the spectrograms.

An upper limit for the amount of water vapor in the atmospheric layer on Venus penetrated by the solar beam may be found by the following considerations. Spectrogram V 282 was taken at mean zenith distance 76° . The average quantity of precipitable water above Mount Wilson is 0.69 cm¹ (the mean for the days of observation was 0.72 cm). The water-vapor line λ 5919.860 was of intensity about 5 on the Rowland scale, and telluric water-vapor lines of intensity 00 and ∞ can be identified on the spectrum of Venus. Had a like quantity of water vapor been present in the planet's atmosphere above the reflecting surface, the intensity of the component of λ 5919.860 due to Venus should have been about 4 as against 5 for the terrestrial line, since the water-vapor masses traversed would have been 2.5 cm for Venus and 2.9 cm for the earth, the two respective paths being 3.6 and 4.1 times that for zenith distances 0. For the point half-way between the center of the disk and the terminator the water mass traversed would have been 4.2 cm, corresponding to solar intensity 7 for the water-vapor line λ 5919.860. These results are deduced from the graphs of Jewell's data. Terrestrial water-vapor lines of 00 intensity are easily seen on the plate, but no line is visible 0.25 Å to the violet of the terrestrial line λ 5919.860, in which position 0.7 cm of water above the apparent surface of Venus would have produced a line of intensity 7. As the water vapor traversed in the atmosphere of Venus was not sufficient to produce the line λ 5919.860 with intensity 00, there must have been

¹ *Annals of the Astrophysical Observatory*, 3, 189, 1913.

less than 1 mm of water in the layer of the planet's atmosphere traversed by the solar beam, for a line of intensity ∞ is produced by 16 per cent of the water vapor necessary for a line of intensity 7.

Measurements of the wave-lengths of eight water-vapor lines were made on the five spectrograms of Venus and on four of the sky. The wave-lengths in Table I were obtained from solar spectrograms with a dispersion four times that used in this investigation. For these closely crowded lines the mean excess of 0.008 Å shown by the Venus measures in Table II, when they are compared with the values given in Table I, represent probably the systematic errors associated with the measurement of spectral lines not well separated and varying in intensity from time to time as is characteristic of atmospheric lines. The difference is positive, whereas it should be negative if there were a measurable effect due to partial superposition of lines produced by water vapor in Venus' atmosphere.

DISCUSSION

These observations indicate that the previous spectroscopic evidence for oxygen and water vapor in the atmosphere of Venus, depending upon visual observations of a change in line intensity, is not reliable, that in fact there is no acceptable spectroscopic evidence of the presence of either. On the other hand, they do not show the complete absence of water vapor and oxygen from the planet's atmosphere, but that, to the depth penetrated by the solar beam, they are not present beyond a definite low limit.

Previous to Russell's¹ investigation in 1898 the accepted view as to the extent of Venus' atmosphere made it much denser than our own.² Russell showed that the prolongation of the cusps, formerly attributed to refraction, was mainly due to diffuse reflection of light by the planet's atmosphere. He concluded that the horizontal refraction at the apparent surface cannot exceed 12' as against 34' for the earth, and that there is no satisfactory evidence that the atmosphere of Venus at the apparent surface is more than one-third as dense or extensive as the earth's at sea-level. The entire height above the apparent surface he thinks may be thirty miles as com-

¹ *Astrophysical Journal*, 9, 284, 1899.

² Young, *Manual of Astronomy*, p. 356, 1912.

pared with the earth's forty, thus implying a pressure at this surface of perhaps one-tenth that of the earth's atmosphere at sea-level. He attributes the prolongation of the cusps visible in daylight to a hazy layer of fog or dust lying below the 4100-foot level, a haze-bank whose upper boundary presents a more or less abrupt decrease in haziness, and whose lower portions may at times be obscured by low mountains, evidenced by irregularities in the thin circle of illumination on the side opposite the sun when Venus is at inferior conjunction.

A. W. Clayden¹ makes a strong presentation of the view that Venus has a moisture-laden atmosphere as dense and extensive as that of the earth. He decides on a long period of rotation, but one less than 225 days. He assumes that a high and heavy layer of pillared cumuli covers the cyclonic areas of low pressure and rising vapor, that over the regions of greater pressure the anticyclonic circulation results in lower detached masses of cumuli between which we see perhaps the shaded surface of the planet, and that a filmy veil of cirrus produces the prolongation of the cusps.

If, as suggested by Russell, the pressure at the visible surface is only one-tenth of an atmosphere, then the atmosphere of Venus is much poorer in oxygen than the earth's atmosphere, as the quantity of oxygen in Venus' atmosphere above the visible surface is less than the equivalent of 1 m, while in our atmosphere above the level of similar pressure there are 104 m of oxygen. If the reflection takes place at the upper surface of a 4100-foot haze-bank, which Russell suggests may be partially cut off at times by low mountains and therefore may not be far above the actual surface of the planet, then the oxygen above this low level is less than one-thousandth of that in the earth's atmosphere above Mount Wilson, elevation 1739 m.

If, on the other hand, it be assumed, as by Clayden, that the atmosphere of Venus is similar in composition and extent to ours, it follows that the reflected sunlight has not penetrated to a point less than 43 km from the real surface of the planet and has traversed but an insignificant path through its atmosphere, since in the earth's atmosphere there is above the 43 km level the equivalent of a meter

¹ *Monthly Notices*, 69, 195, 1909.

of oxygen under normal pressure, an amount capable of registering on our spectrograms. The question of the depth to which the solar beam penetrates the planet's atmosphere and the probability that it reaches a point much nearer the real surface than 43 km are considered in detail in the discussion of water vapor.

TABLE IV
AMOUNT OF OXYGEN ABOVE A GIVEN ELEVATION

Elevation	Pressure	Oxygen
km	mm	m
0.....	760	1490
5.....	405	722
10.....	201	324
15.....	90	135
20.....	41	54
25.....	19	23
30.....	8.6	10.0
35.....	3.8	4.2
40.....	1.6	1.76
45.....	0.85	0.73
50.....	0.40	0.30

Any conclusion as to water vapor must rest upon the nature and temperature as well as the elevation of the apparent surface at which diffuse reflection takes place. The high albedo has been considered evidence of a cloudy surface, but the equally high reflecting power of Vesta indicates that this evidence is not definitive, since for Vesta there is no question of a cloudy surface. Russell¹ gives a Bond albedo of 0.59 for Venus. Using 65 per cent as the reflecting power of a cloudy surface, Abbot and Fowle² found 0.60 as the corresponding albedo for a cloud-covered earth. Aldrich³, under more favorable conditions of observation, obtained 78 per cent as the reflecting power of clouds, from which the albedo calculated in the same manner is 0.75 for a cloud-covered earth. Russell says that the Bond albedo A should not be used for comparison with the observed reflecting power of terrestrial substances, but a quantity p , which he defines in an article on the albedo of

¹ *Loc. cit.*, p. 190.

² *Annals of the Astrophysical Observatory*, 2, 161-163, 1908.

³ *Smithsonian Misc. Collections*, 69, 10, 1919.

planets and satellites.¹ For Venus p is 0.49 while for clouds it is 0.78. Both the reflecting power and the Bond albedo are considerably less than would be expected if Venus is completely cloud covered.

The conditions of Venus' atmosphere depend in large measure upon the period of rotation, the temperature, and the temperature gradients, all undetermined quantities. The period of rotation is quite probably not less than fifteen days, the limit shown by Slipher's observations with which our own agree. With a period of rotation equal to that of the orbital revolution, it is reasonable to assume, as Arrhenius suggests,² that water vapor and all other constituents of an atmosphere would collect and be congealed on the side of the planet turned away from the sun where a temperature near absolute zero would prevail. But the illumination of the whole circumference of the disk when Venus is at inferior conjunction, attributed to scattering and refraction, shows the presence of an atmosphere of considerable extent. These considerations give grounds for assuming that the period of rotation is shorter than that of the orbital revolution and hence is between the extremes of 15 and 225 days. For an intermediate period of rotation, an atmosphere would be present over the region of insolation, subject probably to violent disturbances near the terminator. This would be in harmony with Quenisset's³ observations, both photographic and visual, of extensive and rapid changes in the obscuring envelope, indicating a shallow atmosphere.

The region of maximum cloudiness in the terrestrial atmosphere is mainly below 4000 m,⁴ coinciding roughly with the average altitude of the zero isotherm, which is 3000 m.⁵ The corresponding region of cloudiness in the atmosphere of Venus would be where the temperature and humidity conditions are similar. According to Abbot and Fowle,⁶ the mean temperature of the earth's surface is

¹ *Astrophysical Journal*, 43, 191, 1916.

² *Worlds in the Making*, p. 61, 1908.

³ *Comptes Rendus*, 172, 1645, 1921.

⁴ Humphreys, *Physics of the Air*, p. 309, 1920.

⁵ Hann, *Handbook of Climatology*, p. 250, 1903.

⁶ *Annals of Astrophysical Observatory*, 2, 173-175, 1908.

287°2 A, but the temperature of the true radiating surface of the earth as a planet is 263° A, this surface being chiefly the water-vapor layer at an elevation of 4000 m or more above sea-level. The elevation of a water-vapor radiating surface on Venus, however, would probably be greater owing to higher temperature. Using 2.5 calories as the solar constant, Poynting¹ gives the average temperature of an ideal planet at Venus' distance from the sun as 342° A, and at the earth's distance as 290° A. With 287°2 A for the temperature of the earth the temperature of Venus becomes 337° A.

If the surface temperature of Venus be taken as 337° A and a temperature gradient of 6° per kilometer be assumed in Venus' atmosphere, such as obtains on the earth, the elevation of the zero isotherm would be 11 km, that of a water-vapor radiation surface 12 km, and that of the isothermal layer 19 km, which are to be compared with 3, 4, and 11 km for the earth.

The conditions at Mount Wilson offer favorable opportunities to study the increase in the relative humidity of the air above a cloudy surface. The velo cloud,² as the Spanish called the "high fog" of southern California, often covers the valleys to a height of 1200-3000 feet, especially during the months of May and June. For nine clear days in May and eight in June, 1921, the mean vapor pressure on Mount Wilson was 3.25 and 4.05 mm, respectively, while for nine days in May and twenty-one in June, with clear sky above and the velo cloud 4000 feet below and two to five miles distant, the respective vapor pressures were 4.65 and 5.28 mm, about 35 per cent greater. In the case of Venus' atmosphere with a water-vapor content sufficient to form a continuous layer of cumulus clouds exposed to nearly twice the intensity of the solar radiation at the earth, the water vapor above the dense cloud layer would probably exceed the increase at Mount Wilson when velo clouds are 4000 feet below and several miles away. This increment is two or three times the quantity our spectrograms should record. Granting the probable circulation in the planet's atmosphere suggested by Clayden, it seems also probable, especially over the anticyclonic

¹ *Collected Scientific Papers*, p. 315, 1920.

² Carpenter, *The Climate and Weather of San Diego*, 1913.

areas, that the solar beam would penetrate a region of the atmosphere where water vapor would be encountered in detectable quantity. The spaces not only above, but especially between the columnar cloud masses, must be more or less moisture laden, since, under the powerful solar radiation, evaporation and convection into the neighboring drier regions would take place as over the velo clouds, and under the downward anticyclonic flow, the clouds would be carried into regions of higher temperatures and more or less dissipated. The results would be an atmosphere of high humidity over extensive areas more or less open to observation, as the high cirrus assumed by Clayden would offer little obstruction.

If the dusky markings upon which investigators have based the observations interpreted as showing short rotation periods are actual surface features of the planet, or if they are a transient thinning of a cloudy envelope, it is probable that we there see down to levels at which the humidity would be high in an atmosphere so heavily moisture laden that the planet is enveloped in a blanket of clouds. Spectrogram V 274 was taken eight hours later than Quenisset's photographs showing extensive dusky areas, but no traces of water-vapor lines are discernible on any part of the spectral band.

If the brilliant white spots from which the long rotation period has been deduced really belong to the planet's surface, and, as suggested, are snow-covered mountain peaks extending into the upper atmosphere, it seems probable that water vapor would be spectroscopically detectable by its absorption lines were they to stand free from the corresponding terrestrial lines, as they would in our spectrograms. It is to be considered also that the spectrograms were taken in light of long wave-length, for which scattering is relatively small and the consequent penetration into a hazy atmosphere great. In the case of the oxygen lines, near λ 6900, the depth from which the light is reflected is well below the apparent visual surface.

If, however, the reflecting surface consists of a permanent layer of cirro-stratus, the quantity of water vapor traversed by the reflected beam would be small, as cirro-strati are formed in the upper troposphere where the temperatures are very low. These low temperatures practically insure that cirro-strati consist of ice crystals, but as at such low temperatures there is little water to con-

dense, their structure is necessarily more or less tenuous and fibrous and consequently the reflected light will have penetrated the layer to a great depth. Above such a cloud-surface there would be the thinner cirrus to which the prolongation of the cusps is due, and the still higher atmosphere which produces by refraction the illumination around the planet's circumference observed at inferior conjunction.

Reflection from a layer of cirri gives the shortest possible path for the light in the planet's atmosphere. The water vapor above the cirrus level may be insufficient for detection by observations on the lines in the rain-band. The spectrographic test for oxygen by observations on the B band is, however, much more sensitive. In the earth's atmosphere above the cirrus level there is the equivalent of 274 m of oxygen at sea-level; above 19 km, the elevation assumed for the cirrus level on Venus, there is still the equivalent of 65 m, but our observations show that oxygen on Venus above the reflecting surface is less than 2 per cent of this amount.

It is of interest to consider some alternatives to water-vapor clouds. It is possible that a very small quantity of water vapor would produce an impenetrable haze-bank if the atmosphere of Venus contained minute hygroscopic centers of condensation capable of producing cloud particles in an atmosphere where the humidity is much below that which otherwise would be essential to cloud formation.¹ With such a hazy atmosphere on Venus, analogous to but denser than the dry-weather haze that sometimes obscures the valley or lies along the lower reaches of the distant mountains viewed from Mount Wilson, the surface of the planet might appear much as we see it. To an observer on the planet's surface transmitted light would be rich in long wave-lengths, as to us when the earth's atmosphere is laden with volcanic dust. To an outside observer the color would depend upon the proportion of the light scattered in its atmosphere to that reflected from its surface.

Under the probable extremes of temperature on the opposite hemispheres of Venus it is conceivable that the violent atmospheric circulation would cause clouds of dust to be permanent features of

¹ Humphreys, *Physics of the Air*, p. 92, 1920.

the planet's atmosphere, dust composed of highly reflecting material such as that to which the high reflecting power of Vesta is due. Wilsing and Scheiner¹ give for liparitic pumice a reflecting power of 0.56, for rock salt 0.44, and for granular limestone 0.42. These are comparable with 0.49 for Venus and 0.48 for Vesta. It is to be observed, however, that the presence of two of these substances would imply the action of water at the time of their production or segregation. The dust storms that sometimes prevail for days over the deserts and occasionally sweep through the mountain passes suggest vividly the possibilities on a dry and wind-swept planet.

Whether or not light reflected from the continually evaporating surfaces of clouds produces sufficient water vapor to give its absorption lines with observable intensity is a question whose answer would aid greatly in determining the character of the apparent surface of Venus and in solving the puzzling problems of its atmosphere. We hope later to obtain more observational data as to the humidity around and above clouds, and to extend the spectrographic observations to the water-vapor band near λ 7200, as the lines of this band are producible by smaller amounts of vapor and would furnish a more sensitive test of its presence. Other and quite as important information would be obtained from the relative color indices of Venus and terrestrial clouds and from direct photographs through violet and infra-red filters² as used by R. W. Wood for Jupiter and Saturn. These would show the apparent surfaces at widely different levels and offer the possibility of reaching the actual surface through the thinner portions of the atmospheric veil.

It has been too easily assumed, perhaps, that the atmospheric conditions on our nearest planetary neighbors are similar to those on the earth, and that on Venus development has followed along similar lines and by like stages as on the earth. It was long ago suggested by Koene,³ of Brussels, that all free oxygen may have been formed from carbonic acid in the air. Arrhenius says that we may take it as established that the masses of free oxygen in the air and of free carbon in the sedimentary strata approximately corre-

¹ *Potsdam Publications*, 20, Part IV, 1909.

² *Mt. Wilson Contr.*, No. 113; *Astrophysical Journal*, 43, 310, 1916.

³ *Mémoires de Chimie*, 1856.

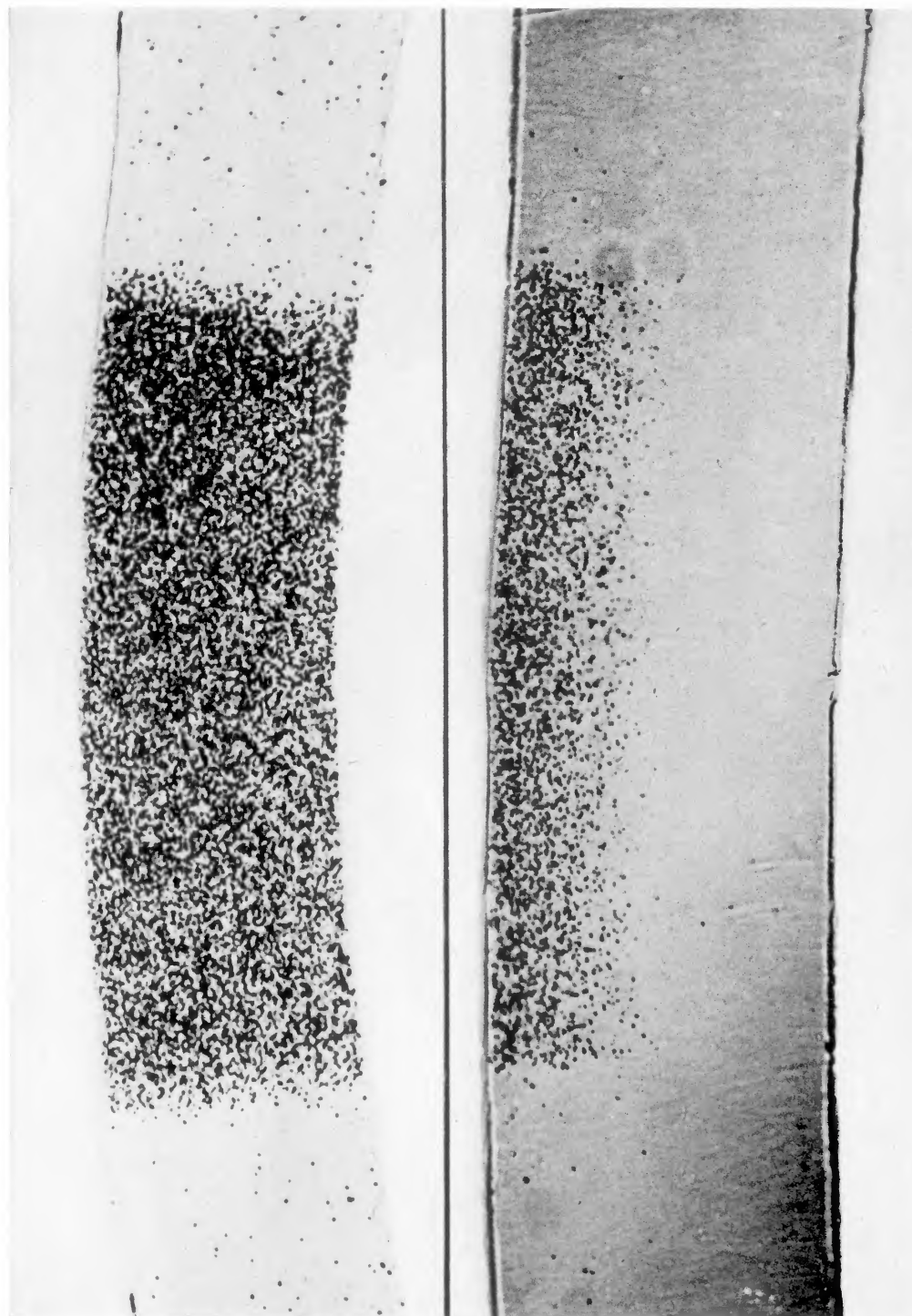
spond to each other, and that probably all the oxygen of the air owes its existence to plant life.¹ That a similar production of oxygen has apparently not taken place on Venus suggests that some condition is wanting. Possibly a deficiency of water has prevented or hindered the freeing of oxygen through vegetation, or it may be that the exacting conditions for the origin of life have not been satisfied so that the existing atmosphere may consist of other permanent or semipermanent gases such as nitrogen or carbon dioxide.

MOUNT WILSON OBSERVATORY

July 1922

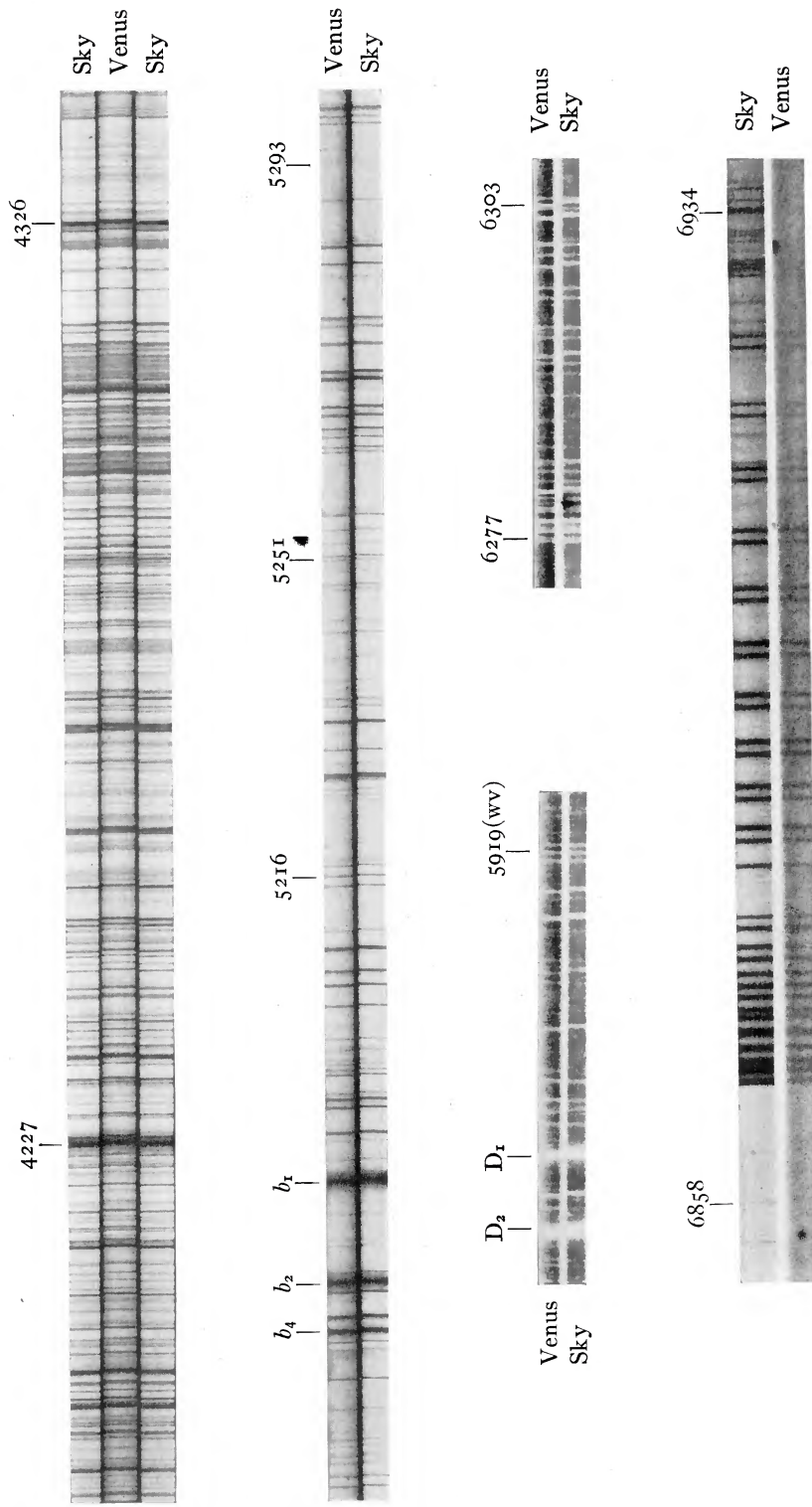
¹ *Worlds in the Making*, pp. 58, 59.

PLATE XII



MAGNIFIED SECTIONS OF A SHARP SLIT IMAGE
Upper, fully exposed; lower, light exposure

PLATE XIII



SPECTRA OF VENUS AND SKY