No. 95 HIGH ALTITUDE SPECTRA FROM NASA CV 990 JET I: VENUS, 1–2.5 MICRONS, RESOLUTION 20 CM^{-1}

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ABSTRACT

Results from two high-altitude flights in the Spring of 1967 show the Venus atmosphere to be essentially devoid of water vapor and ice crystals. One or two new absorption bands are found, further study of which is deferred until the acquisition of spectra with higher resolution scheduled for late November 1967. The importance is stressed of powerful IR spectral studies from the lower stratosphere.

1. Introduction

Infrared spectral observation of planets and stars from the lower stratosphere presents novel opportunities that have been outlined in *Comm. LPL* No. 93. The present paper deals with the first results of this program. It is based on data obtained during two flights with the NASA CV 990 Jet, on May 14, and June 11, 1967. The principal result is that in the observable part of the Venus atmosphere ($T \leq 320°$ K) water vapor is essentially absent. It followed that the comparatively large amounts of water vapor derived spectroscopically from balloons and at ground-based observatories were spurious; and that atmospheric models of the planet, based on these earlier observations and invoking a large greenhouse effect by water vapor and water clouds, could not be valid. A news release covering these results was issued by the University of Arizona on May 27, 1967, and was printed in the *New York Times* on May 28, 1967. A more precise statement was submitted to *Science News* and published in the July 22 issue (Eberhart 1967). The upper limit of the mixing ratio H_2O/CO_2 there given was 4.10^{-7}.

On both flights the combination of heliostat and 12-in. telescope was used, as described in *Comm. LPL* No. 93. It was equipped with the Block 20 cm^{-1} interferometer kindly lent to us by Mr. L. Mertz, vice president of Block Associates. The 65° window used in both flights was Borosilicate Crown (transmission curve, *ibid.*, p. 167, Fig. 10*b*).

2. Flight Schedules and Elevation Angles of Sources

The pre-computed schedule for the May 14, 1967, flight (without knowledge of wind conditions) and the actual trajectory are found in *Comm. LPL* No. 93, p. 164, Tables 2 and 3; and p. 166, Figure 9. The pre-computed schedule for the June 11 flight is reproduced in abbreviated form in Table 1 and plotted together with the actual trajectory in Figure 1.

In both flights the moon served for calibration of telluric absorptions. On the May 14 flight, the Venus observations extended from 19^h27^m–20^h54^m UT, the moon observations from 21^h00^m–21^h25^m UT. The astronomical coordinates were as follows:

Venus,	May 14, 20^h00^m UT:	$6^h23^m + 25°47'$
Moon,	May 14, 21^h10^m UT:	$7^h48^m + 26°21'$.

Since the moon observations were made about 1 hr after the average of the Venus observations, and since the actual aircraft latitude at the center of the Venus observations was about 45°30′ and for the

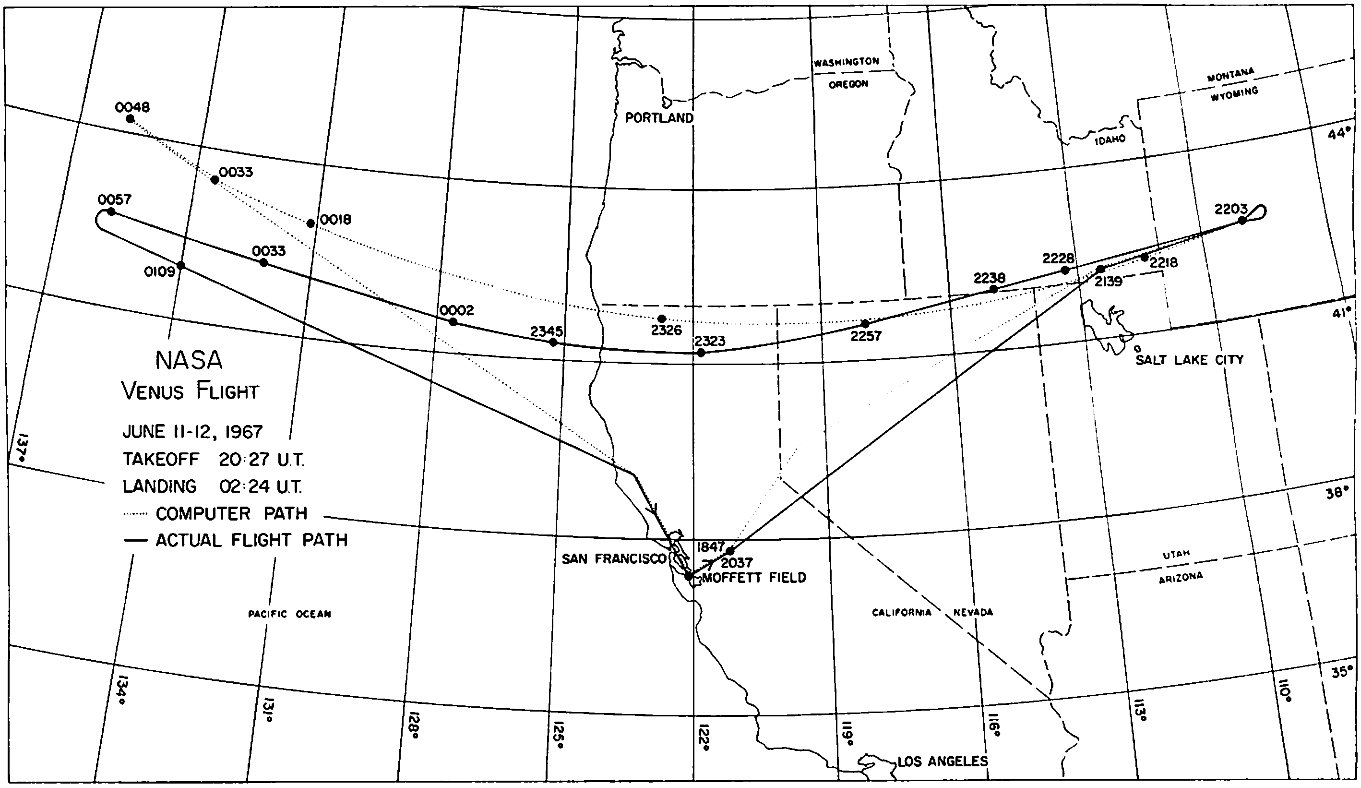

Fig. 1 Flight schedules, precomputed and actual, of the June 11, 1967, Venus Flight.

TABLE 1

UT	LATITUDE	LONGITUDE	OBJECT ELEVATION	OBJECT AZIMUTH	AIRCRAFT HEADING	AIRCRAFT BANK ANGLE	OBJECT BEARING TO FLIGHT PATH
22^{h}40^{m}00^s	41°47′.9	115° 6′.9	69° 4′.7	169°49′.0	264°34′.0	0°4′.1	265°15′.0
22 48 00	41 43.5	116 26.0	69 13.7	171 33.5	266 18.5	0 4.3	265 15.0
22 56 00	41 40.9	117 45.1	69 20.1	173 19.7	268 4.7	0 4.3	265 15.0
23 4 00	41 40.2	119 4.3	69 23.7	175 7.2	269 52.2	0 4.4	265 15.0
23 12 00	41 41.4	120 23.5	69 24.5	176 55.4	271 40.4	0 4.4	265 15.0
23 20 00	41 44.4	121 42.6	69 22.5	178 43.9	273 28.9	0 4.4	265 15.0
23 28 00	41 49.2	123 1.7	69 17.6	180 32.3	275 17.3	0 4.4	265 15.0
23 36 00	41 56.0	124 20.6	69 9.9	182 19.8	277 4.8	0 4.3	265 15.0
23 44 00	42 4.2	125 39.4	68 59.9	184 6.0	278 51.0	0 4.2	265 15.0
23 52 00	42 13.8	126 58.1	68 47.4	185 50.4	280 35.4	0 4.1	265 15.0
24 0 00	42 25.2	128 16.6	68 32.3	187 32.9	282 17.9	0 4.0	265 15.0
24 8 00	42 38.3	129 34.9	68 14.7	189 13.0	283 58.0	0 3.8	265 15.0
24 16 00	42 53.1	130 52.9	67 54.6	190 50.4	285 35.4	0 3.7	265 15.0
24 24 00	43 9.5	132 10.6	67 32.1	192 24.9	287 9.9	0 3.5	265 15.0
24 32 00	43 27.4	133 28.1	67 7.4	193 56.3	288 41.3	0 3.3	265 15.0
24 40 00	43 46.8	134 45.3	66 40.7	195 24.5	290 9.5	0 3.0	265 15.0
24 48 00	44 7.6	136 2.2	66 11.9	196 49.4	291 34.4	0 2.8	265 15.0
24 56 00	44 29.7	137 18.9	65 41.3	198 10.8	292 55.8	0 2.6	265 15.0
25 4 00	44 53.1	138 35.3	65 9.0	199 28.9	294 13.9	0 2.3	265 15.0

moon observations, about 46°0′ (*ibid.*, Fig. 9), the altitudes at observation were close to 70.0° for both objects.

On the June 11 flight the coordinates were:

Venus,	June 11, 23^h00^m UT:	$8^h33^m + 21°07′$
Moon,	June 11, 22^h25^m UT:	$8^h35^m + 23°59′$.

Since the sources were only some 3° apart and the diameter of the finder field was 5°, it was possible without course changes of the aircraft to make alternate runs on them and on the sky near each merely by resetting the heliostat. The interferometer runs are listed in Table 2. Supplementary data for the June 11 flight are found in Appendix A.

3. *Ground-Based Venus Spectrum and Checks on Interferometer*

Prior to the May and June 1967 Venus flights, the interferometer had been tested in a series of observations with the 61-in. NASA telescope of the Catalina Observatory on March 30–31, 1967. The planets Venus and Mars were observed as were the stars Betelgeuse and R S Cancri. The Venus spectrum is reproduced in Figure 2. It is the straight average of two spectra, each of which was based on about 190 interferograms (3.8 min. each run). The solar spectrum is indicated by dots where it differs from Venus; it was taken from *Comm. LPL* No. 94, Figure 1, with minor adjustments of the intensity scale, smooth with wavelength, to fit the Venus continuum. The position of Venus at the time of observation was $2^h41^m + 16° 13′$; it was 5^h05^m past the meridian at the mean epoch 2^h40^m UT, or nearly 20° above the horizon. The large air mass, 2.90, accounts for the heavy telluric absorptions, which roughly match those of the 5000-ft level at unit air mass (*Comm.* No. 94). The identifications have been taken from *Comm. LPL* No. 15.

The spectrum in Figure 2 is comparable to the Venus spectrum recorded with a single-channel spectrometer on the 36-in. telescope of the Kitt Peak National Observatory in 1962 (Kuiper, *Comm. LPL* No. 15, Figs. 1, 2, and 4), both as to resolution (300 at 1.6 μ versus 600 for the one channel) and in signal to noise. The total recording time for the one-channel spectrometer (which used a cooled PbS cell) was about 160 min. Figure 2 was recorded with the 61-in. telescope, the interferometer, and uncooled PbS cells, in 7.6 min. This scanning time would have been reduced to 2 min. however, with the silicon lenses since installed by Mr. Mertz which reduced the image sizes to the detector dimensions, ¼ mm square. The 2-min. figure makes the efficiency of the interferometer just about equal to that theoretically expected (the predicted time is $\frac{1}{4} \times 1/300 \times V_1^2/V_2^2 \times S^2/A^2 \times 160$ min, in which the factor 4 stems from the resolution ratio of 2; 300 is the interferometer resolution at 1.6 μ; V_1/V_2 is the ratio of the planet intensities on the two dates, 1.2; S is the sensitivity ratio of cooled versus uncooled PbS cells, about 10; and A the ratio of the collecting areas of the telescopes, 3). The Mertz design has therefore fully succeeded.

The principal results of Figure 2 are the better definition of the CO_2 absorption from 4400–4600 cm^{-1}, left uncertain in *Comm. LPL* No. 15 because of an unexplained instrumental absorption near 2.2 μ (later found to be due to fuzed quartz); and the Venus absorption near 5850 cm^{-1} (1.709 μ), suspected in 1962, but left open because of inadequate precision.

4. *Results of the Two NASA CV 990 Flights*

Figure 3 shows the average of two traces of the planet Venus taken on the first flight (May 14, 1967) between $20^h 10^m$–40^m UT, each representing 13 min. of observing. The elevation was 37,000 ft (11.3 km). Because sunlight fell on the 65° window through which the Venus observations were made, some scattered radiation entered the interferometer beam. The amount was evaluated through separate observing runs made on the sky close to the planet. The approximate level of the continuous solar spectrum so derived is indicated by the dashed curve in Figure 3. The intensity of the scattered sunlight is 25–30 percent of the total. An independent determination of this ratio is possible from the depth of the strongest CO_2 bands in the planet. Comparison of Figures 3 and 2 suggest how this determination may be made.

In order that the remaining telluric absorptions might be allowed for, a lunar spectrum was obtained under essentially identical conditions, immediately upon completion of the Venus observations. The spectrum is reproduced in Figure 4. It is found to be in general agreement with the solar spectra observed at the 35,000 and 38,000 ft altitudes, reproduced in *Comm. LPL* No. 94. The identifications shown in Figure 4 are taken from the solar spectra. A minor disturbance is noted at 5810 cm^{-1}, which is the third harmonic of 60-cycle hum introduced in the co-adding process. The dotted curve near that frequency indicates the estimated undisturbed profile.

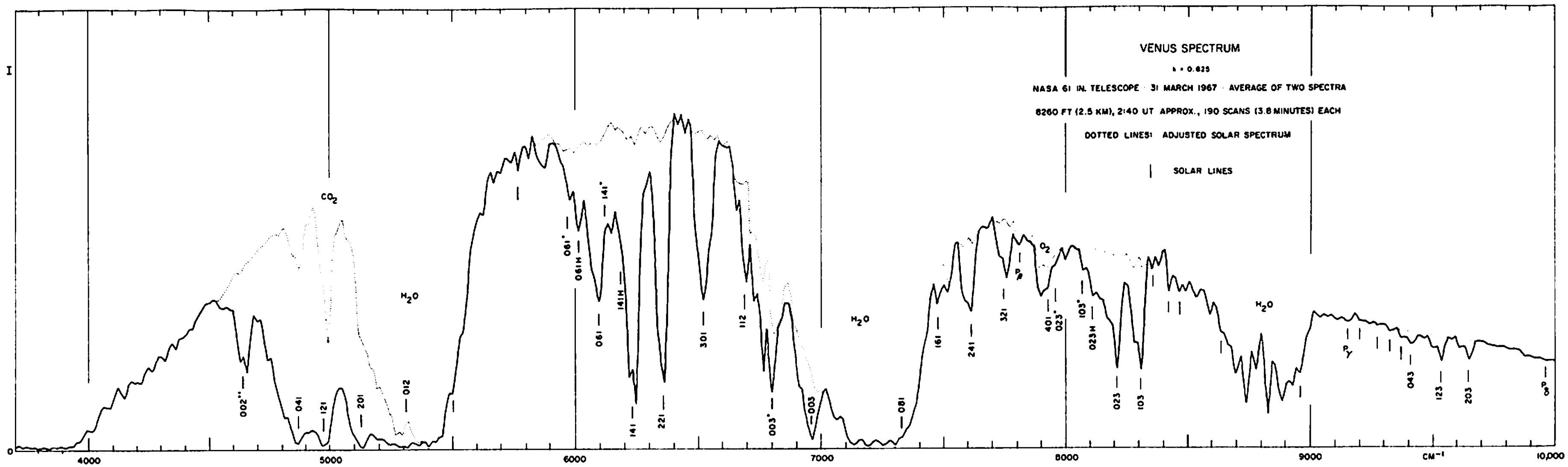

Fig. 2 Spectrum of Venus obtained with Mertz Interferometer, 61-in. telescope, March 31, 1967. Venus absorptions contained between dotted line (adjusted solar spectrum) and full-drawn line (Venus spectrum). Band classifications are of CO_2 molecues; H = hot band; * C^{13} isotopic band, ** oxygen O^{18} isotopic band.

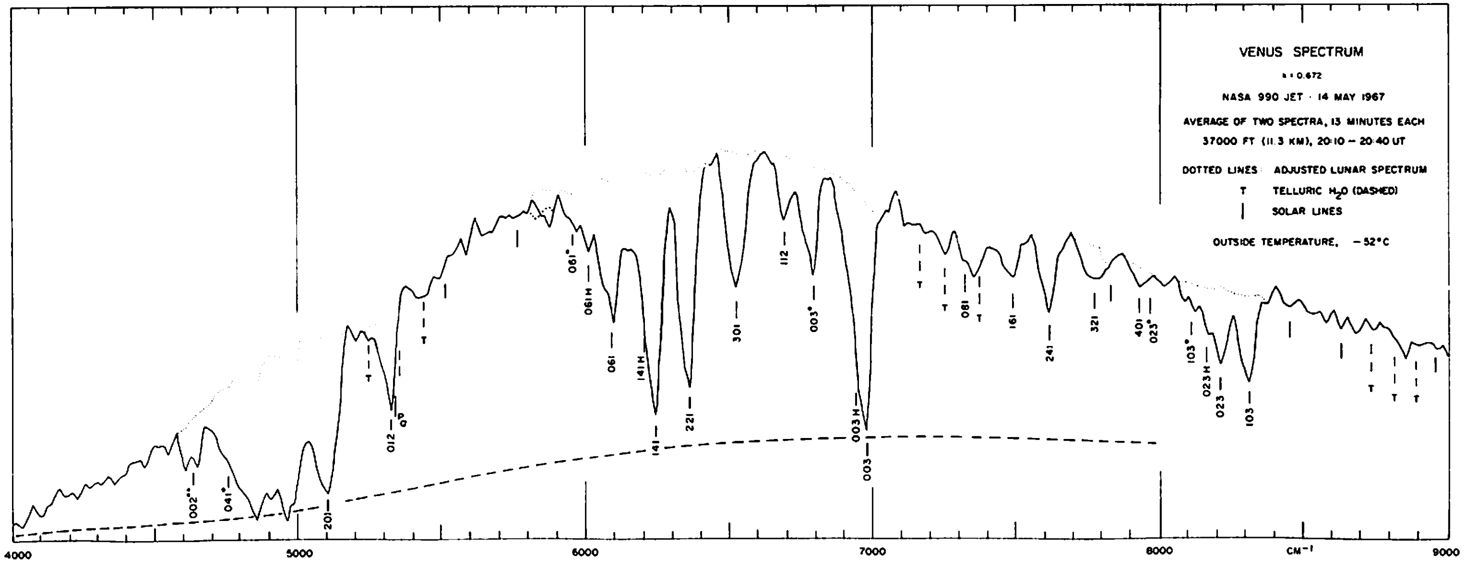

Fig. 3 Venus spectrum, the first obtained at high altitude, May 14, 1967. Venus absorptions are contained between dotted line (adjusted lunar spectrum) and full-drawn line (Venus spectrum). Dashed line near bottom indicates average intensity of scattered sunlight contribution from aircraft window.

The identifications of the CO_2 bands in Figure 3 were taken from *Comm. LPL* No. 15. Of special interest is, of course, the strength of the water-vapor absorptions in the Venus spectrum and any dips in the continuous spectrum attributable to absorptions by ice crystals in the Venus atmosphere. These matters are reviewed in the next section with the aid of laboratory calibrations of water vapor made in *Comm. LPL* No. 96.

As is apparent from Table 2, the circumstances of the June 11 Venus flight were photometrically excellent since the proximity of the moon allowed alternating observations, Moon-Venus-Moon-Venus, in each case supplemented by sky records. Figure 5 shows the first lunar calibration spectrum of this flight. Comparison of it with the high-altitude solar spectra reproduced in *Comm. LPL* No. 94 shows excellent agreement for the 38,000-40,000 ft level.

Figure 6 presents the average of two Venus spectra based on 29 min. and 30 min. observing runs (cf. Table 2). Throughout, the basic spectra were plotted mechanically, directly from the computer output. The averaging of the two spectral traces (each about 1 m long) was done by Mrs. A. Agnieray, by averaging the ordinates for nearly a thousand wavelength points after making minor adjustments of the abscissae so that the sharp spectral features would come into complete coincidence for blocks of 500 to 1000 cm^{-1}. These small adjustments were needed because of a minor scale difference between the spectral plots. It is felt that this averaging has been done with complete objectivity.

The identifications in Figure 6 are based on *Comm. LPL* No. 15 supplemented by solar lines of Figure 5, present also in Figure 6.

The remaining Venus and moon spectra, obtained during the last two runs (cf. Table 2), are reproduced in Figures 7 and 8. Figure 7 is again an average, derived by Mrs. A. Agnieray from two mechanically-plotted spectral traces based on 10- and 13-min runs, respectively. The noise level in Figure 7 is somewhat greater than in Figure 6, partly because of the shorter observing run and also apparently because of increased engine vibrations at the ceiling altitude of the aircraft. Thus, the lunar spectrum of Figure 8 is also noisier than Figure 5 although the observing run was slightly longer.

Referring to the general program described in *Comm. LPL* No. 93, it was initially considered quite uncertain whether the interferometer could be used at all, since obviously even minute displacements of the moving mirror due to vibration would lead to spurious results. Even with the telescope and heliostat-stand shock-mounted to the aircraft, the initial interferometer results were indeed found "vibration-limited." This was overcome by shock mounting the interferometer on the telescope as well. It was, of course, attempted to obtain Venus records with lunar comparisons at ceiling altitude. This, however, resulted in increased engine vibrations (and one of the cabin compressors to blow out just upon termination of the last Venus run). In addition to an increase in noise level, the lunar spectrum showed minor spurious peaks at $n \times 1935$ cm^{-1}, the 60-cycle hum. The peaks at n equals 2, 3, 4, and 5 are within the range of Figure 8 and since their cause was known, they have been deleted (leaving small gaps). Ultimately a more definitive reduction of the Venus spectra here reproduced may become feasible.

TABLE 2

INTERFEROMETER RUNS ON THE JUNE 11 VENUS FLIGHT

OBJECT	JUNE 11/12 UT	NO. OF SCANS	ALTITUDE (FT)	FIG. NO.
Moon	$22^{h}20^{m}$–29^{h}	471	38,900	5
Sky n. M	22 30 –35	251	38,900	—
Venus	22 41 –10	1418	38,900	6
Sky n. V	23 11 –16	267	38,900	—
Venus	23 30 –00	1493	41,050	6
Venus	24 03 –13	491	41,400	7
Sky n. V	24 13 –20	312	41,400	—
Moon	24 21 –31	500	41,400	8
Venus	24 37 –50	600	41,400	7
Sky n. V	24 50 –55	230	41,400	—

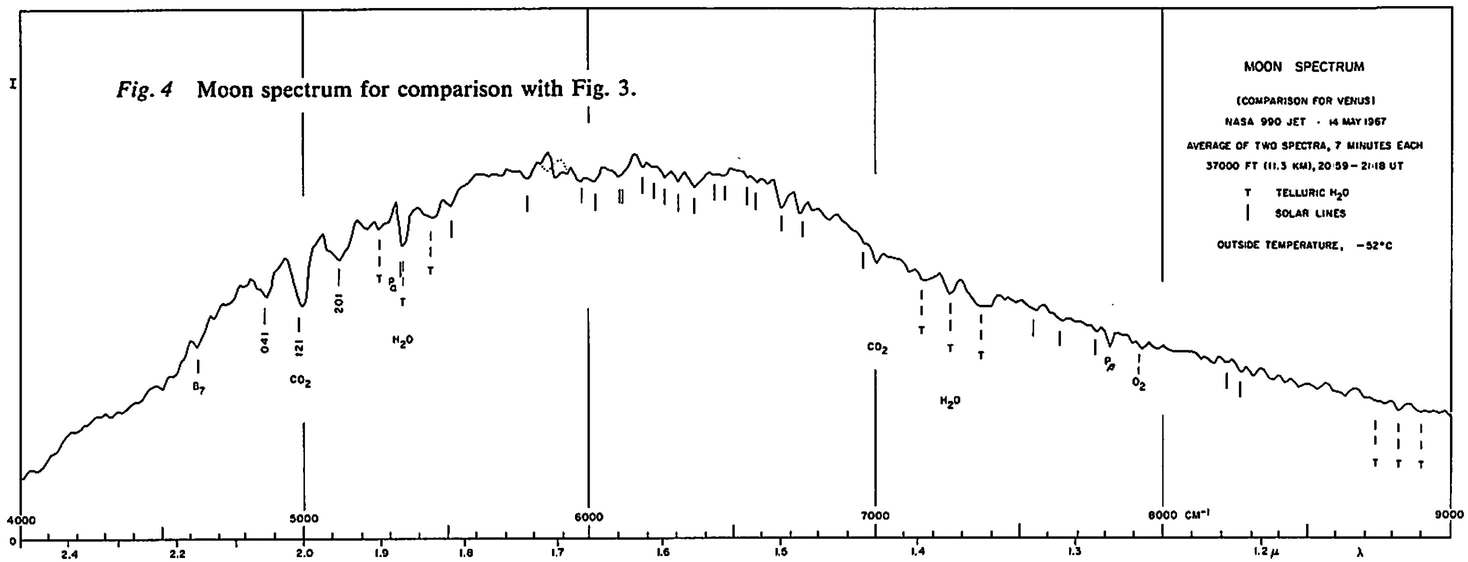

Fig. 4 Moon spectrum for comparison with Fig. 3.

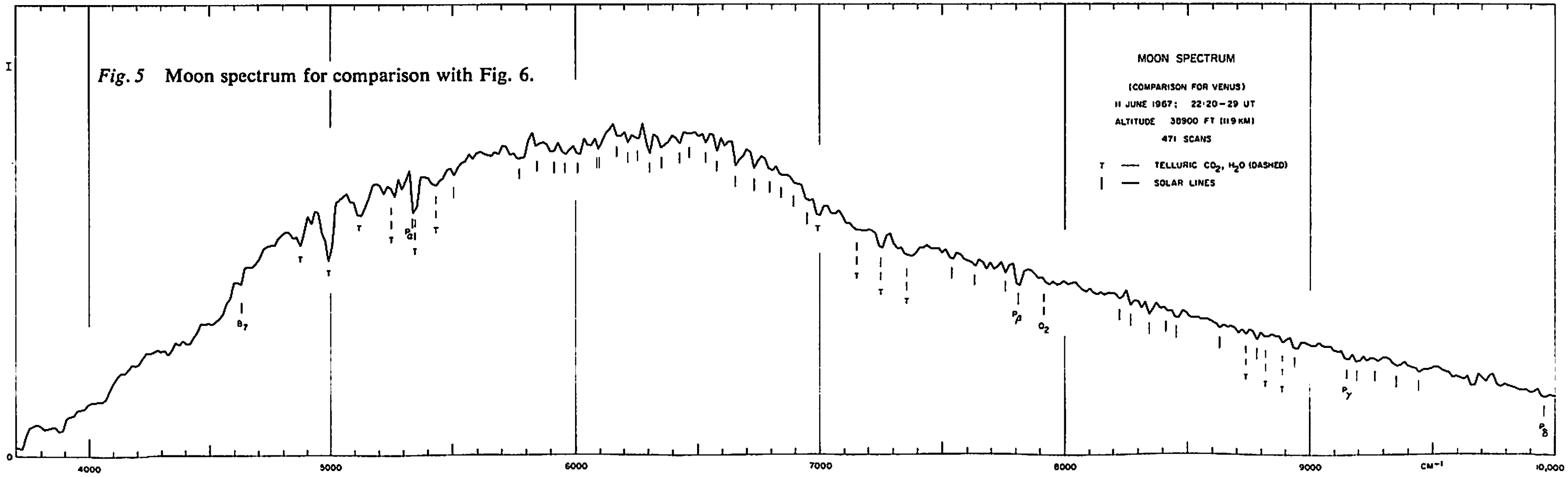

Fig. 5 Moon spectrum for comparison with Fig. 6.

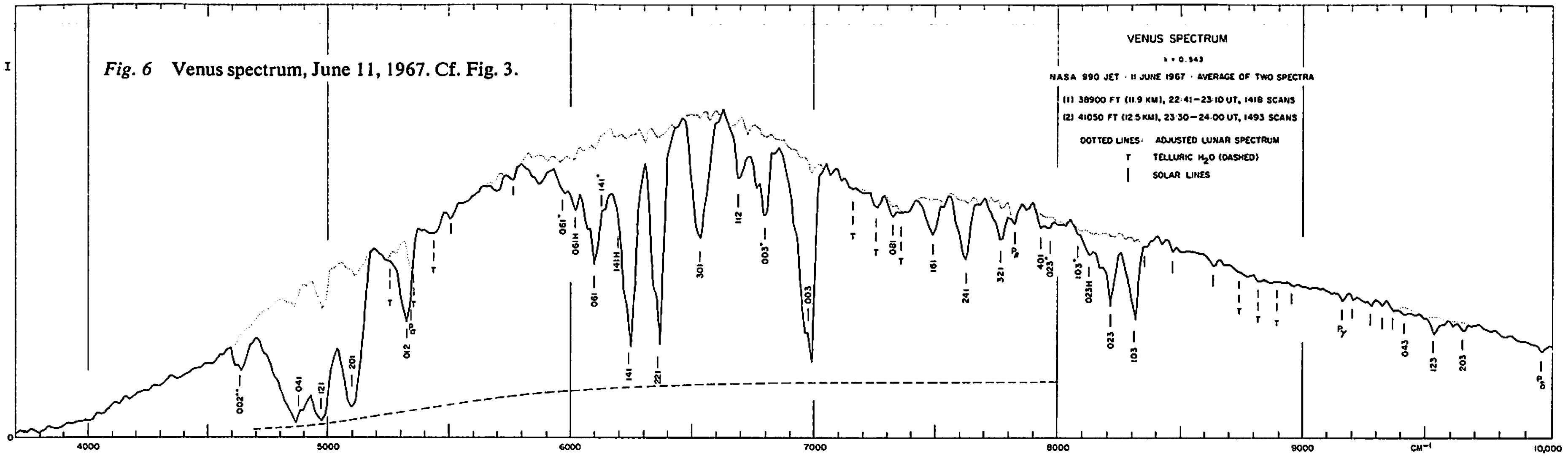

Fig. 6 Venus spectrum, June 11, 1967. Cf. Fig. 3.

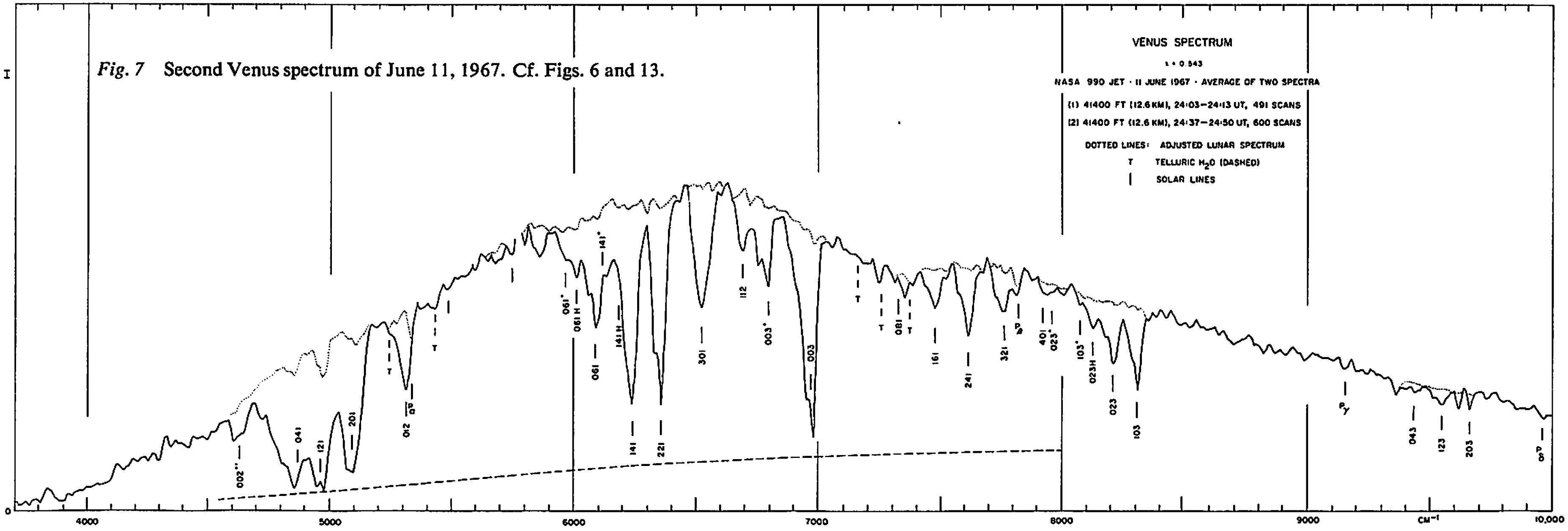

Fig. 7 Second Venus spectrum of June 11, 1967. Cf. Figs. 6 and 13.

5. *Water-Vapor Content of Venus Atmosphere*

Two moderately strong water-vapor bands, at 1.4 and 1.9 μ are present in the spectral range covered as well as the weaker band at 1.13 μ.

Each of the three pairs of Venus and Moon spectra contain water-vapor bands of very nearly equal strength, showing that the Venus contribution is zero or very small. Nonetheless, it is necessary to calibrate the intensities in terms of precipitable water in order that the difference and its precision may be made quantitative. The curves of growth needed for this calibration are found in *Comm. LPL* No. 96, Figure 3. Two pressures were used, ambient laboratory air ($p = 70$ cm) and $p = 15$ cm, corresponding to the atmospheric 200 mb level from which the Venus and moon observations were made (since the water vapor is concentrated toward the lower levels even at that altitude, $p = 200$ mb rather than the average of 100 mb was regarded appropriate).

As explained in *Comm. LPL* No. 96, the 200 mb calibrations suffered from a minor complication due to a short (37 cm) air path in ambient laboratory air. The Venus and moon records likewise had a short air path at higher pressure. The cabin altitude for most of the observations was around 9700 ft (cf. Appendix A), corresponding to a pressure of 706 mb; and the air path 4 m (mirror-heliostat-Cassegrain telescope-interferometer). Thus, as found from the measured water-vapor pressures, listed in Appendix A, the cabin contribution to the optical path was 1.5–2 microns of water. The total amount may actually have been less since the measures were made with a sling psychrometer in the open cabin area near the telescope, not within the plastic sheet loosely enclosing the optical train, shielding it from the proximity of the three observers, and allowing fresh compressed outside air to enter directly. Since the outside frost point must have been around −70°C, the actual water-vapor content within the enclosure may have been only a few tenths of the amount measured in the cabin at large. In any case, during the Venus and moon observations the cabin contributions will have been almost identical. During the second Venus flight the manpower aboard the aircraft was limited to the flight personnel and the three observers, so the spectral records were made under optimal conditions.

Table 3 lists for each of the records, Figures 3–8, the average UT of observation, the aircraft position (taken from *Comm. LPL* No. 93, Fig. 8 and Fig. 1), the local time (computed from the UT and the aircraft longitude), the hour angle of the source at the mid-time of observation, the declination of the source, its computed zenith angle, and the corresponding air mass (secant Z). Since about 30 percent of the continuum in Figure 3 is due to sunlight on the aircraft window, the effective air mass determining the strength of the telluric absorptions is $0.3 \times 1.55 + 0.7 \times 1.064 = 1.21$. The lunar spectrum, Figure 4, which was not appreciably diluted by sunlight, corresponds to the air mass 1.085.

For each of the records, Figures 3–8, the percent absorptions in the 1.4 and 1.9 μ water vapor bands were measured. The results are contained in Table 4. The branch designations are the same as used in *Comm. LPL* No. 96. It was found that in spite of the efforts to retain feature 1.9a, this could not be done since the Venus absorption was uncertain due to the blending with one of the CO_2 bands. A similar but less serious complication exists for

TABLE 3

FLIGHT DATA AND AIR MASSES FOR SPECTRA

FIG. NO.	OBJECT	MEAN UT	AIRCRAFT POSITION	LOCAL T	HOUR ANGLE	DECLINATION	ZENITH ANGLE	AIR MASS
3	Venus	$20^{h}25^{m}$	78°30′W,45°50′N	$15^{h}11^{m}$	$0^{h}15^{m}$ W	+25°47′	20°.0′	1.064
	Sun	— —	— — —	— —	3 15 W	18 36	49.50	1.550
4	Moon	21 08	83 20 W,46 22 N	15 35	0 56 W	26 21	22.1	1.085
5	Moon	22 25	112 45 W,42 19 N	14 54	0 20.5 E	24 00	19.0	1.058
6	Venus	23 20	121 22 W,41 14 N	15 15	0 00	21 06	20.08	1.065
	Sun	— —	— — —	— —	3 15.5 W	23 06	44.29	1.402
7	Venus	24 26	131 26 W,42 06 N	15 40	0 25 W	21 06	21.8	1.077
	Sun	— —	— — —	— —	3 40.5 W	23 06	49.12	1.531
8	Moon	24 26	131 26 W,42 06 N	15 40	0 31 W	23 42	19.9	1.064

TABLE 4

MEASURED PERCENT ABSORPTIONS OF H_2O BANDS

ABS.	FIG. 3 (V)	FIG. 4 (M)	FIG. 5 (M)	FIG. 6 (V)	FIG. 7 (V)	FIG. 8 (M)	$\frac{5+8}{2}$
1.9c	8.8	7.9	7.3	7.2	9.4	8.1	7.7
1.4a	5.0	6.1	6.9	5.3	5.2	6.2	6.5^5
1.4b	9.4	6.9^5	9.8	8.9	11.0	7.9	8.6^5
1.4c	8.2:	7.3	8.4	6.8	6.1	5.4^5	6.9

feature 1.4c which was retained in the table with half weight. Feature 1.4b (the central Q branch) was given half weight also because of its narrow profile.

The absorption depths of Table 4, converted into microns of water vapor, give for the difference Venus-Moon, based on Figure 3 and 4, the amount $20\ \mu - 17\ \mu = 3\ \mu$. If the lunar comparison is scaled up to the larger effective telluric air mass of Venus (cf. above) the amount would be $(1.21/1.085) \times 17\ \mu = 19\ \mu$, leaving 1 μ for the two-way transmission in the Venus atmosphere.

The 17 μ of vapor in the lunar spectrum is interpreted as follows. As stated earlier in Section 5, an amount not over 1.5–2 μ was contained in the cabin air path, which will correspond to roughly double this amount when reduced to $p = 200$ mb. This leaves 13–15 μ for the outside atmosphere, or 12–14 μ at unit air mass. According to *Comm. LPL* No. 93, Table 1, the amount expected above the 37,000 ft = 11.3 km level is 8 μ from 11.3–19.5 km and a somewhat uncertain amount of 2–6 μ above, making a total of 10–14 μ. The amount measured on the May 14 flight is therefore consistent with the table.

Another verification of our calibrations comes from the observations in the 6.3 μ band of H_2O made by Dr. Peter M. Kuhn of ESSA, Boulder, Colorado, on the same flights of the total overlying water-vapor content made from an instrument attached to the wall of the aircraft (no cabin contribution). These accord well with the amounts derived here. The telluric amounts vary from approximately 15 μ for a flight at 37,000 ft to about 10 μ for a flight at 40,000 ft.

Since Figure 6 is the average of two records obtained at slightly different altitudes, it should be compared to the average of the lunar spectra, Figures 5 and 8, making a strictly comparable pair. This comparison is the strongest of the three and should receive double weight. The reduced measures of Table 4 give $-2\ \mu$ for the difference Venus−Moon. It is estimtaed that the contamination of the Venus spectrum by sunlight on the aircraft window requires the Venus figure to be corrected by $-1\ \mu$, to $-3\ \mu$.

The third comparison is between Figures 7 and 8, given weight 1 because of the shorter run and increased noise level. The measures yield Venus − Moon = + 4 μ, which again requires small negative correction for blending to about +3 μ.

The weighted average of the three determinations is $-0.5 \pm 1.3\ \mu$ (mean error). With allowance for possible small systematic effects, we adopt:

water-vapor content, two-way transmission, $0 \pm 2\ \mu$.

In order that the mixing ratio H_2O/CO_2 may be derived, the depth of penetration into the Venus atmosphere must be estimated. This penetration is probably larger than corresponds to visual observation. The hot bands of CO_2 in the $\lambda = 1$–$2\ \mu$ region seem slightly stronger than those obtained in laboratory spectra taken at 295° K, as may be seen from a comparison of the 023H band with 241 which is nearly of equal intensity (*Comm. LPL* No. 15, Figs. 8, 9, 17a, 18a, and 23), and indicate that in $\lambda = 1$–$2\ \mu$ the penetration occurs to about 300°K. For the 0.8 μ region Spinrad (1967) has just published a temperature for the $5\nu_3$ hot bands and found surprisingly, 400°–450° K. Since it has been assumed that the fractional water-vapor content in the Venus atmosphere increases with depth, the CO_2 hot bands are especially relevant for the interpretation of H_2O absorptions. For a two-way transmission to the level defined by the hot bands of CO_2, the estimated CO_2 content is 4–8 km-atm. The *upper limit* of the mixing ratio, H_2O/CO_2, is therefore (2.5–5) 10^{-7}. This figure is the same as the upper limit, 4.10^{-7}, published in *Science News*, July 22, 1967, on the basis of a provisional analysis.

Our result on the near absence of water vapor (amount < 2 microns in 2-way transmission) is in marked contrast with the observation of Dollfus

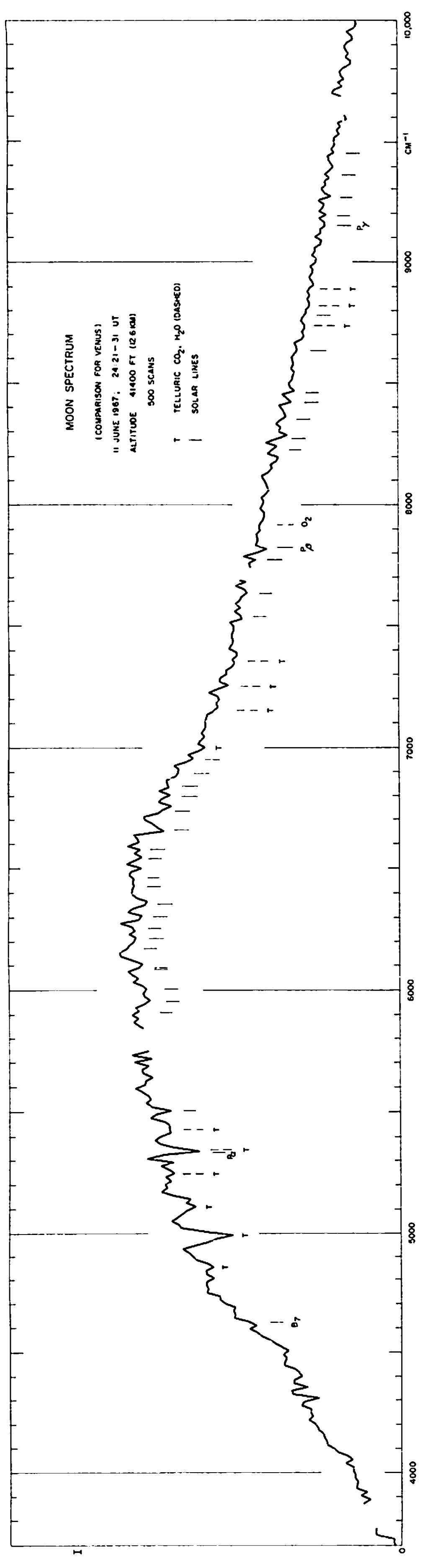

Fig. 8 Moon spectrum, comparison for Fig. 7.

(1963), who found 280 microns for the 2-way transmissions from the 1.4 μ band of H_2O; of Bottema, Plummer, and Strong (1964), who found 110–470 microns from the 1.13 μ band; of Belton and Hunten (1966), who found 317 microns from the .82 μ band; and Spinrad (1966), who found 250 microns also from the .82 μ band. The Dollfus result might be due to residual Venus CO_2 absorption entering his 1.4 μ filter. T. Owen (1967) has suspected that the results based on the .82 μ band are due to a solar line in the wing of the observed telluric water-vapor line, λ 8189 A, because other telluric lines of equal strength lack the corresponding Venus companion.

After the results of the May 14 flight were announced, we have become aware of several new ground-based observations of Venus made during 1967 which have also given zero results, with uncertainties of 20–40 microns, as is inevitable from spectral observations made from existing observatory sites.

6. Ice Crystals in the Venus Clouds

A strict absence of water vapor from the Venus atmosphere would, of course, preclude the presence of H_2O ice crystals in the upper layers. Since the presence of ice crystals has been claimed on empirical grounds, we examine both theoretical expectation, using the upper limit for the water-vapor content found in Section 5, and the direct empirical evidence.

The fractional H_2O vapor content was found $< 4.10^{-7}$. If at the radiometric level of 220° K the atmospheric pressure is about 0.3 bar (cf. *Comm. LPL* No. 101), the H_2O vapor pressure there would be $< 10^{-7}$ bar or $< 10^{-2.4}$ of the saturation pressure at that temperature. No saturation could occur even if the adiabatic gradient extended upward to 200° K, at which level the pressure would be 0.63 that of the 220° K level and the H_2O vapor pressure $< 10^{-1.4}$ of the local saturation pressure. It is therefore not possible for water condensations (liquid or ice) to occur anywhere in the Venus atmosphere (unless there were a zone with $T << 200°$ K).

Direct evidence on the occurence of H_2O ice crystal absorption was considered by Kuiper (1962) who concluded that his evidence in the 2 μ region was negative; and by Bottema, Plummer, Strong, and Zander (1965) and by Strong (1965), who concluded that their evidence was positive. The 1965 results were extensively used by Sagan and Pollack (1965) in their discussion of "Properties of the Clouds of Venus." The conclusions by Bottema *et al.* (adopted by Sagan and Pollack) were based on a balloon flight made on October 28, 1964, during which a low-resolution (0.1 μ) spectrum of Venus was obtained between 1.7 and 3.4 μ. This spectrum is reproduced here in Figure 9 and may be compared with Figures 3, 6, and 7. As seen from Figure 9, Bottema *et al.* attribute about 0.8 of the dip at 2 μ to ice absorption in the Venus cloud. Our Figures 3, 6, and 7 show that instead the Venus CO_2 absorptions are wholly responsible. The small island of the continuum at 1.93 μ (5180 cm^{-1}) left between the (012) band and the triad at 2 μ, which occurs close to the deepest point of the ice absorption (Kuiper 1962, Fig. 7*b;* and Bottema *et al.* 1965) is precisely in line with the continuum on either side (cf. Figs. 3, 6, 7). The identification of the H_2O ice absorption on Venus is therefore incorrect.

It is noted in passing that the total water-vapor content in a column above an ice-cloud layer on Venus was computed by Menzel and Whipple (1955) to be 130 microns (one-way transmission), or 300–400 μ in two-way transmission. This amount is 200 times the upper limit found in this paper for the much *deeper* atmosphere observed at $\lambda = 1–2\ \mu$.

7. Concluding Remarks

The observed limits on water vapor and ice absorptions show that the Venus clouds are not water, solid or liquid. The only reservation is obviously the formal possibility that somewhere high in on the planet a layer exists of such low temperature ($< 180°$ K) that condensation of H_2O can occur in spite of the very low upper limit of the mixing ratio, H_2O/CO_2, derived in this paper. Even then it would still be necessary to require that the absorption near $\lambda = 2\ \mu$ be negligible; i.e., that the particles be very small ($< 0.2\ \mu$). Whether such a possibility actually exists will be examined in a later paper which will also review the atmospheric composition on the basis of present results augmented by data from two flights made after the completion of this paper with a new interferometer whose resolution is 8 cm^{-1}.

The present study shows the advantages of a major reduction in the strength of the telluric spectrum, even at the very modest resolution used. Major gains may be expected from a large increase in spectral resolution and an extension to longer wavelengths; present technology and the airborne facilities allow both. Ultimately, a larger beam than the present 12 in. will be needed to capture the full potential of the NASA CV 990 platform.

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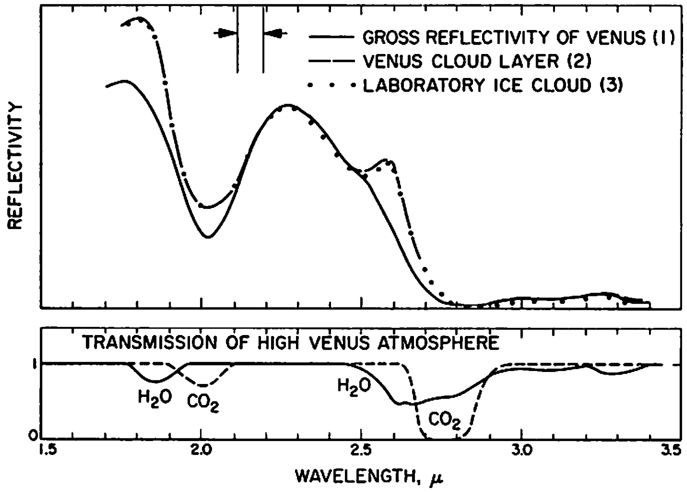

Fig. 9 High-altitude balloon spectrum of Venus and its interpretation according to Strong (1965). The observed spectrum is the full-drawn line. (Reproduced by permission of California Institute of Technology.)

ance throughout the program. We are personally indebted to Mr. Lawrence Mertz for the loan of his interferometer, to Mr. I. Coleman of Block Associates for making the reductions of the interferograms; and to the University of Arizona Space Sciences Committee for a grant in aid. We wish to thank Mr. D. Steinmetz for his collaboration during the flights, Mrs. A. Agnieray for her assistance in preparing the figures, and Dr. T. Owen for helpful discussions of the text. The planetary program at this Laboratory is supported by the National Aeronautics and Space Administration Grant NsG 161-61.

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APPENDIX A

LOG OF JUNE 11 VENUS FLIGHT
(For geographic positions, cf. Fig. 1)

UT	ALT. 1000 FT	ATM T °C	CABIN WET BULB	CABIN DRY BULB	CABIN ALT.	CABIN $P(H_2O)$ MM	REMARKS
20:45	24.2	−20	—	—	—	—	
21:30	32.9	−46	—	—	—	—	
21:38	32.9	−46	7.0	23.1	8400	1.47	
21:45	34.1	−48	—	—	8400	—	
21:50	35.7	−52	—	—	8400	—	
21:53	37.1	−54	—	—	8350	—	
21:56	38.7	−54	—	—	8350	—	
21:57	39.0	−52	3.3	17.0	8350	0.68	
22:00	39.0	−52	—	—	8350	—	
22:05	39.0	−54	—	—	8350	—	Excellent; solid clouds below 30,000 ft.
22:10	39.0	−52	—	—	8350	—	
22:18	39.0	−52	—	—	8350	—	Start moon run.
22:27	39.0	−51	4.7	19.7	8350	0.79	
22:29.5	39.0	−51	—	—	8350	—	End moon run; start sky.
22:35	39.0	−51	—	—	8350	—	End sky.
22:41	39.0	−51	4.7	19.7	8350	0.79	Start Venus run.
23:02	39.0	−52	4.3	19.6	8350	0.40	Clear!
23:11	39.0	—	—	—	8350	—	End Venus, start sky.
23:16	39.0	—	—	—	8350	—	End sky.
23:17	39.0	−53	4.7	20.4	8350	0.52	Started to climb. Some black tape on windows to suppress small reflections.
23:19	39.7	−52	—	—	9750	—	
23:20	40.1	−52	—	—	9750	—	Start Venus run.
23:26	40.7	−52	—	—	9750	—	Clear! 50% cover below 20,000 ft.
23:32	41.1	−52	4.4	20.7	9750	—	
23:37	41.1	−53	—	—	9750	—	Crossing Pacific Coast.
23:49	41.1	−52	4.3	20.4	9650	0.38	Solid layer of low fog over ocean.
24:00	41.1	−52	—	—	9650	—	End Venus run, reverse tape.
0:03–10	41.1	−53	—	—	9650	—	Venus
0.12	41.1	−52	4.4	20.4	9650	0.47	Sky spectr.
0.19	41.1	−55	—	—	9650	—	To Moon ,some turbulence
0:24	41.1	−56	4.3	20.3	9650	0.42	Moon, sea fog below.
0.31	41.1	−57	—	—	9650	—	To Sky.
0.36	41.1	—	—	—	9650	—	End sky, to Venus (last run).
0:40	41.1	−58	4.1	20.3	9650	0.37	
0:45	41.1	−59	—	—	9700	—	
0:50	41.1	−60	4.2	20.3	9750	0.44	End Venus; to sky.
0:54	41.1	−60	3.9	19.7	9650	0.42	End sky; end observations.
0:55	41.1	−60	—	—	9650	—	

Very clear throughout. On the return flight the tropopause was at 40,200 ft, 1:02 UT at −60°C.

The water-vapor reductions are based on *Smithsonian Physical Tables*, 9th Ed., 1954, Tables 634 and 635, Part 3. For the extremely low humidities involved these may not be quite accurate. They lead to a dew point of about −27°C, higher than expected for compressed outside air having a frost point of about −70°C. The amounts in microns per meter are numerically almost the same as the vapor pressure in mm, since $(p/760) \times (18/29) \times 0.001255 \times 10^6 \simeq p$.