No. 100 HIGH ALTITUDE SPECTRA FROM NASA CV-990 JET II. WATER VAPOR ON VENUS*

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ABSTRACT

Venus and Moon spectra obtained with a new interferometer (resolution 8 cm^{-1}) during two flights with the NASA CV-990 Jet on November 27 and 28, 1967, are presented. The ratio spectrum Venus/Moon is also derived which eliminates remaining weak telluric absorptions as well as solar absorption lines of any strength. The ratio spectrum shows Venus essentially as if illuminated in white light, allowing a direct comparison with laboratory spectra.

A lunar spectrum with increased precision was obtained on 5–6 May 1968, allowing the computation of an improved ratio spectrum for Venus (Fig. 13). Finally, ground-based Venus and Moon spectra, and their ratio (Fig. 16), are added for increased precision of the Venus spectrum outside the telluric H_2O bands.

Examination of the effect of the Doppler shift of the planet (V = 12.9 km/sec) shows that, for the 1.4 and 1.9 μ H_2O bands, the telluric and Venus lines are completely separated, so that the ratio spectrum represents Venus correctly; but that the lines of the 2.6 μ H_2O band, many of which are fairly strong and double in the telluric spectrum even at 200 mb, will generally not be separated and will give complex superposition effects with Venus. Under these conditions, the 2.6 μ band in the ratio spectrum will give an apparent H_2O abundance for Venus that is too low. Calibration of the 1.4 μ and 1.9 μ bands, with a 6-meter tube containing laboratory air at 200 mb, shows the amount of H_2O in the Venus spectrum to be about 5 microns precipitable water (2-way transmission). *The resulting mixing ratio* H_2O/CO_2 *is* 1.10^{-6}. This positive identification of water vapor supersedes the upper limit of roughly 2 μ obtained in *Comm. LPL* No. 95. The observed amounts of trace constituents, such as H_2O, will, for constant mixing ratios, vary with the amount of CO_2 observed, known to be variable from day to day as well as systematically with phase. The phases of Venus for the May–June and November 1967 observations were all about 0.6, but the amounts of CO_2 observed in May–June were indeed somewhat less than in November 1967.

In addition to some forty-five absorption features belonging to the 1.4, 1.9, and 2.6 μ bands of H_2O, numerous vibrational bands of CO_2 are identified, as well as the 2–0 band of CO at 4250 cm^{-1}, some rotational lines of the 2–0 band of HCl at 5600 cm^{-1}, and of the 1–0 band of HF at 3950 cm^{-1}.

1. *Introduction*

After the April–June 1967 CV-990 flights, described in *Comm. LPL* No. 93, had established that a rapid-scan Block-type interferometer could be used despite aircraft vibrations, an instrument was ordered having 2.5 times the resolution of the Mertz interferometer, 8 cm^{-1}. The new instrument was received 1 October 1967 together with a 2000-word co-adder and a punch. The reductions could be made on an IBM 1130B computer available on the University of Arizona Campus through the courtesy of the Mathematics Department. The computer reduction program was graciously made available by Vice President Mertz of Block Associates. The interferometer assembly at LPL and the first telescopic observations with it were supervised by Mr. I. Coleman of Block Associates.

The interferometer is an improved version over the original Mertz instrument in that continuous calibration of the mirror displacements is provided by a helium source. During telescopic operations it was found that minor phase shifts occurred in the zero point of the interferogram, possibly resulting from minor temperature variations. These zero point

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drifts were normally not important for runs of 10 minutes or less. Longer runs usually required co-adding the interferograms in 10-min. blocs which would be separately reduced. This was not serious for bright sources with a good signal/noise ratio but was increasingly troublesome as the sources grew fainter. The problem was later solved by Dr. H. L. Johnson with the installation of an auxiliary white light source also reflected by the moving mirror and providing a zero-point calibration on a third channel. For the November 1967 Venus observations, however, the interferometer was used in its original form with the uncooled PbS cells provided by the manufacturer. The reductions were made in blocs that were subsequently added.

2. *Observations*

The observations were made with the heliostat and 12-inch telescope as described in *Comm. LPL* No. 93. The optical window was 1-inch thick, made of GE-105 (dry quartz), provided by NASA's Goddard Space Flight Center. Its transmission curve is given in Fig. 1, measured at NASA-Ames on 6 October 1967. The interferometer was shock-mounted on the telescope. A daytime engineering test flight, made on November 16, 1967, showed that even sharp aircraft vibrations (which the pilot produced with the wing flaps), did not appreciably disturb the performance, as judged by the interferogram from the monochromatic helium comparison source observed on an oscilloscope. The two Venus flights took place on November 27 and 28, 1967, with our notes on times, elevations, outside temperatures, and cabin pressures recorded in Table 1.

The Venus observations on November 27 were made 16:03–17:43 UT, with Moon comparisons both before and after: 15:52–16:02 UT and 17:46–18:03 UT. Some light cirrus passed overhead during brief periods between 16:33–47 UT, as noted in Table 1. On November 28 the Venus observations were made 16:07–17:45 UT, and the moon comparisons 15:55–16:04 UT and 17:46–18:03 UT. Some cirrus was again encountered 16:45–48 UT and 17:03–06 UT. The Venus observations were briefly interrupted around 17:25 UT when a thin film of oil was seen on the optical window, caused by the air-conditioning system. Thereafter the air vent above the optical window was shut off. The trajectories of the November 27 and 28 flights are shown in Fig. 2. Parenthetically, the sunrise views along the Pacific shores of Baja California were profoundly interesting and beautiful, for the topography, the meteorology, and the apparent interactions of ocean and land (semi-circular bays, the flow of ocean fog over low land, etc.). Several photographs were taken from the cockpit. A number of condensation trails, presumably stemming from the Hawaii-Los Angeles jet route, were observed almost intact near flight altitude as far south as 20°–22° North, and around 108° W. These can pose problems for astronomical observations up to 40,000 ft.

The relative positions of Venus and Moon for the mean epochs of the Venus observations are:

Nov. 27, $16^h 53^m$ UT:

Venus	$13^h 14^m$ — 5°38′	Venus was 9°.5
Moon	$12^h 38^m$ — 2°20′	ESE of Moon

Nov. 28, $16^h 56^m$ UT:

Venus	$13^h 18^m$ — 6°01′	Venus was 4°.4
Moon	$13^h 30^m$ — 9°08′	NW of Moon

The latitude of the CV 990 on November 27, $16^h 53^m$ UT, was 23°.0 N; and on November 28, $16^h 56^m$ UT, 23°.2 N (cf. Fig. 2). The *altitudes of Venus* at mid-observation were therefore 61°.4 and 60°.8; whereas the moon altitudes on the two dates were nearly the same, both 61°. It is therefore appropriate to average the two sets of Venus data, and the same for the lunar data; and then take the the ratio Venus/Moon of these averages. This combination was desirable because the electronic noise, with uncooled cells and small telescope, was not negligible.

The spectra of both Venus and Moon, and their ratio, are nevertheless shown for each day separately, as well as their averages, for a better assessment of their degree of consistency. Of special importance is, of course, the strength of the water-vapor absorptions Venus-Moon, on the separate days, as well as in the average. Only the most important section, 3300–7500 cm^{-1}, is shown for the separate days. The full interval, 3000–8500 cm^{-1}, is reproduced for the averages.

Figs. 3–5 are the Venus, Moon, and ratio spectrum for November 27; Figs. 6–8 the same for November 28; Figs. 9–11 the same for the averages. They are paired up in the reproductions for ready reference especially for checking the water-vapor intensities. The identifications are shown in the ratio spectrum of Fig. 13, below.

Since the Moon comparisons before and after the Venus runs were held brief, the noise in the Moon

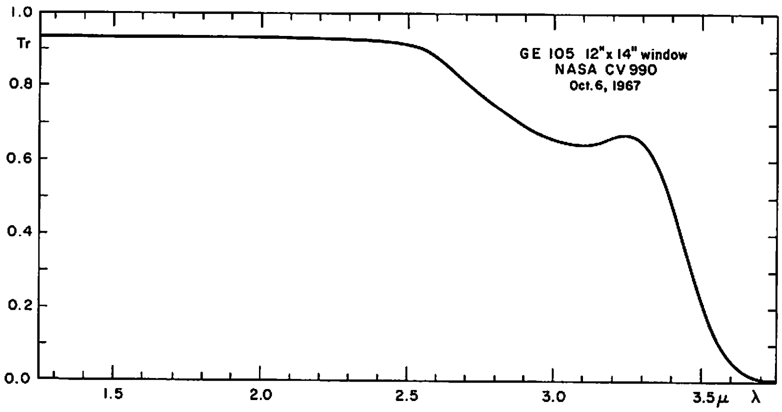


Fig. 1 Measured transmission of GE–105 window used in Venus flights.

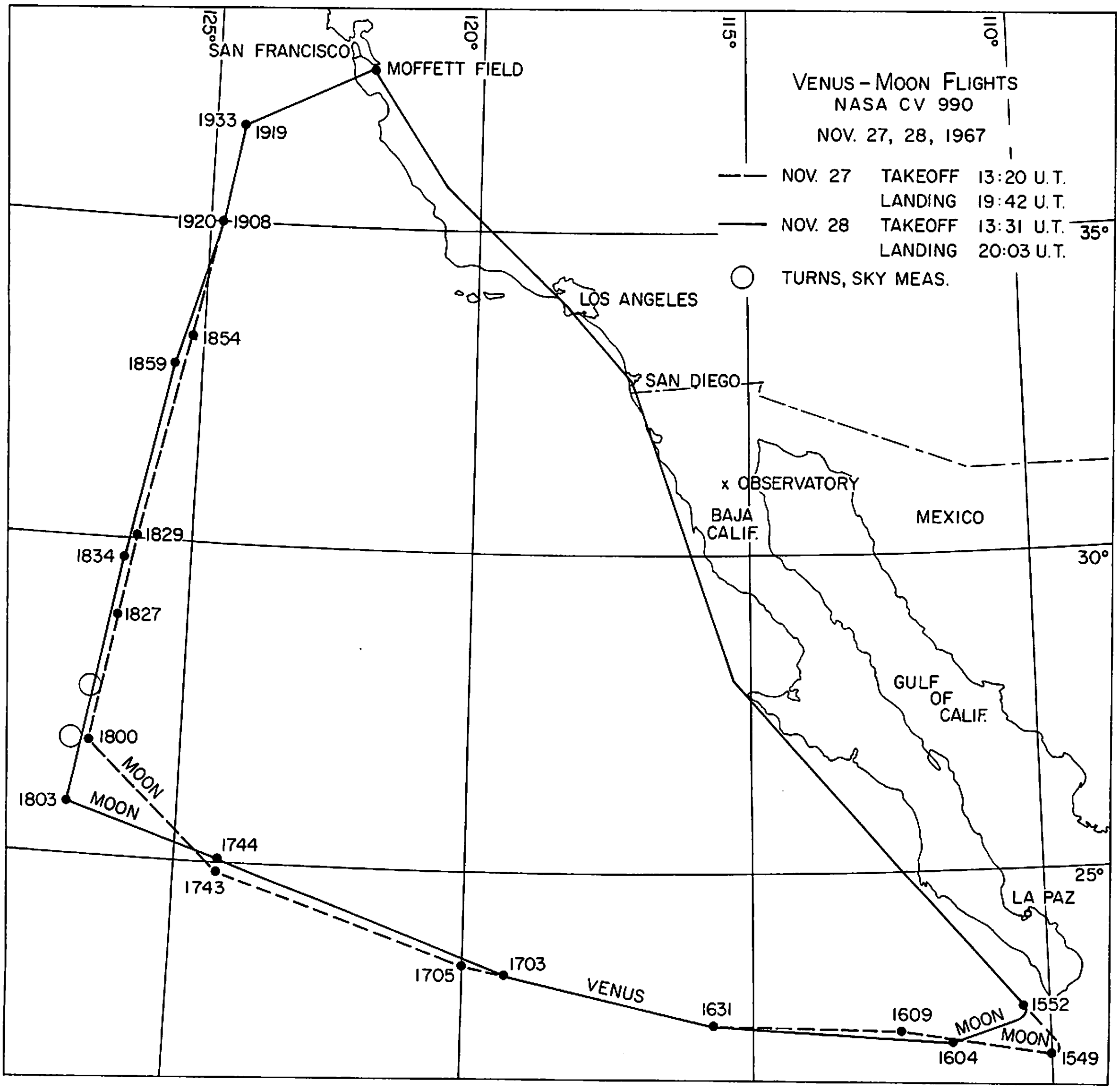


Fig. 2 Flight trajectories, November 27–28, 1967.

TABLE 1

VENUS FLIGHTS, NOVEMBER 1967

Nov. 27				Nov. 28			
UT	Elev. 1000 ft.	T °C (out)	Remarks	UT	Elev. 1000 ft.	T °C (out)	Remarks
13:20	0	—	take off	13:31	0	—	takeoff
13:30	20	−20		13:40	20	−30	cabin 4900′
13:33	25	−30		13:50	25.2	−33	cab. 5600′
13:36	30	−39		13:58	27.2	−37	cab. 5600′
13:40	32	−44		14:25	33.0	−46	cab. 5600′
13:42	33	−47		15:02	33.2	−41	cab. 5600′
13:50	33	−49		15:20	33.2	−41.5	cab. 5500′
14:10	33	−44	sunrise 14:12	15:39	37.0	−48	cab. 8500′
14:35	33	−40		15:55	39.0	−53	start Moon
15:07	33	−39		16:04⁵	39.0	−54	end Moon
15:38	37	−47		16:07	39.0	—	start Venus
15:46	39.0	−54	cabin 8500′	16:24	39.0	−55	W = 4°9, D = 20°3*
15:52	39.0	−54	start Moon	17:00	40.0	−58	W = 4°4, D = 19°9*
16:03	39.0	—	start Venus	17:13	40.1	−59	W = 4°4, D = 19°7*
16:20	39.0	−54		17:25	—	—	window cleaned
16:46	40.0	−57	cab. 8300′*	17:27	40.1	−59	W = 4°7, D = 20°1
17:00	39.9	−58	sky perfect after 16:47	17:44	40.06	−57	W = 4°7, D = 20°3*
17:12	39.9	−58		17:45	—	—	end Venus
17:36	39.9	−57		17:46	—	—	start Moon
17:43	39.9	—	end Venus	17:57	40.06	−56	W = 4°4, D = 20°3*
17:46	39.9	—	cab. 8300′	18:03	—	—	end Moon
17:53	39.9	−57	W = 5°1, D = 21°3	18:21	40.05	−57	
18:03	39.9	−57		19:12	32.9	−50	
19:25	30	−45		19:22	37.0	−52	
19:26	25	−37		19:25	35.0	−51	
19:28	20	−27		20:03	0	—	landing
19:42	0	—	landing				

*Wet bulb, 5°0 C; dry, 21°0 C; or p (H_2O) ≃0.5 mm, or rel. hum. ≃3%, in cabin (but less in ventilated telescope). Light cirrus 16:33–34, 36–38, 39, 47.

* cabin 8300′. Some cirrus overhead 16:45–48, 17:03, 17:06.

spectra is no better (actually somewhat worse) than in the Venus spectra (the disk of Venus filled only a fraction of the interferometer aperture at the focus of the 12-inch telescope, which was about 1 arc minute; but its surface brightness is some 20× larger than that of the bright limb portions of the crescent moon). Therefore, it is important to improve the moon comparison for the study of absorption features other than water vapor (for which comparisons ideally are made on the same night). Two full observing runs with the CV 990 could be made on May 5 and 6, 1968, when the aircraft was based on Wallops Island, Va. The May 5 lunar run was from $22^h\,12^m$–$24^h\,30^m$ UT; the May 6 run, from $21^h\,40^m$–$24^h\,17^m$ UT. The combined lunar spectrum is shown in Fig. 12. Comparison with Fig. 10 shows a major reduction in the noise level, especially beyond 7000 cm^{-1}. For future reference, the absorptions shown in Fig. 12 have been identified with the aid of solar spectra taken with much higher resolution. I am indebted to Mr. L. Bijl for his assistance with these identifications. The ratio Venus/Moon with this new comparison is shown in Fig. 13. For the reasons just stated, its precision is substantially better than that of Fig. 11, based on the same Venus data.

An independent check on the details of the Venus

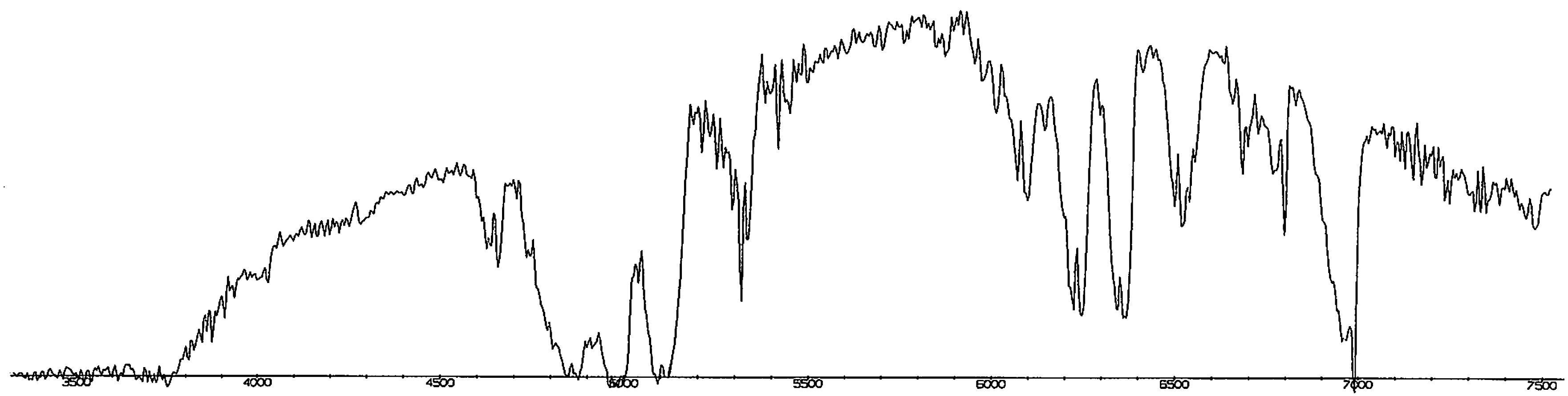


Fig. 3 Venus spectrum, CV 990, November 27, 1967.

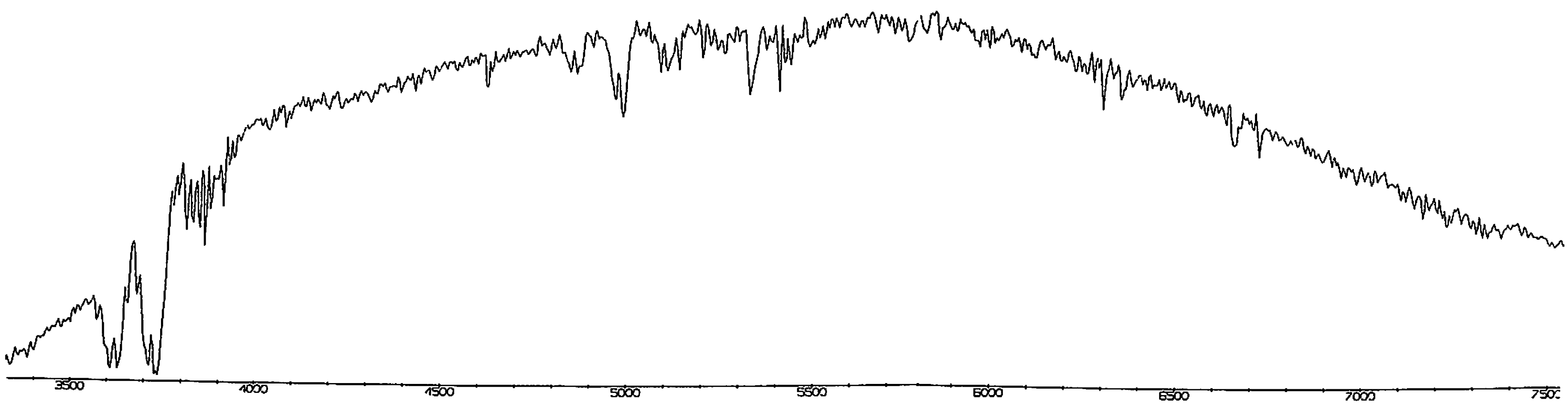


Fig. 4 Moon comparison spectrum, CV 990, November 27, 1967.

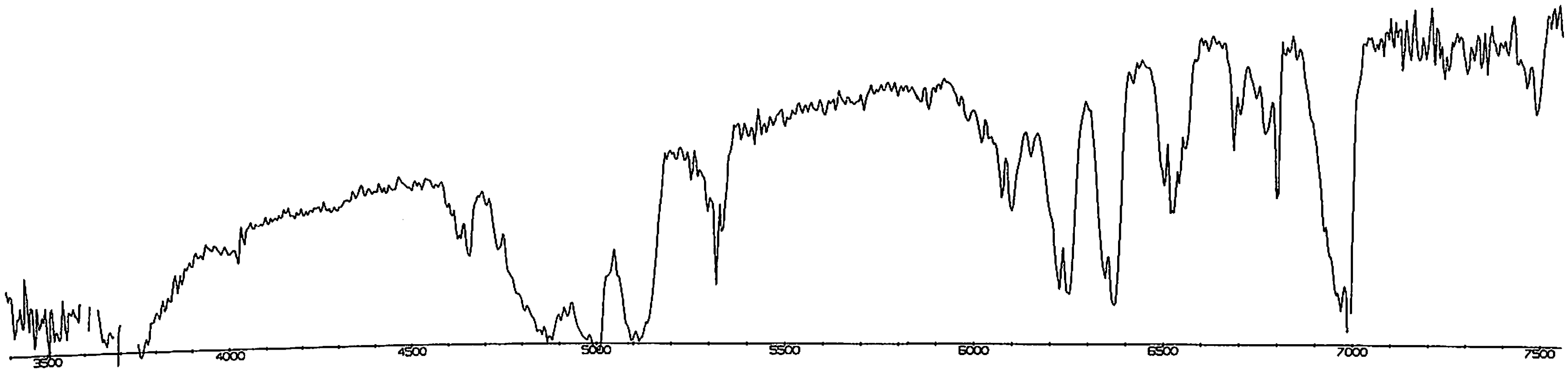


Fig. 5 Ratio spectrum, Venus/Moon, of Figs. 3 and 4.

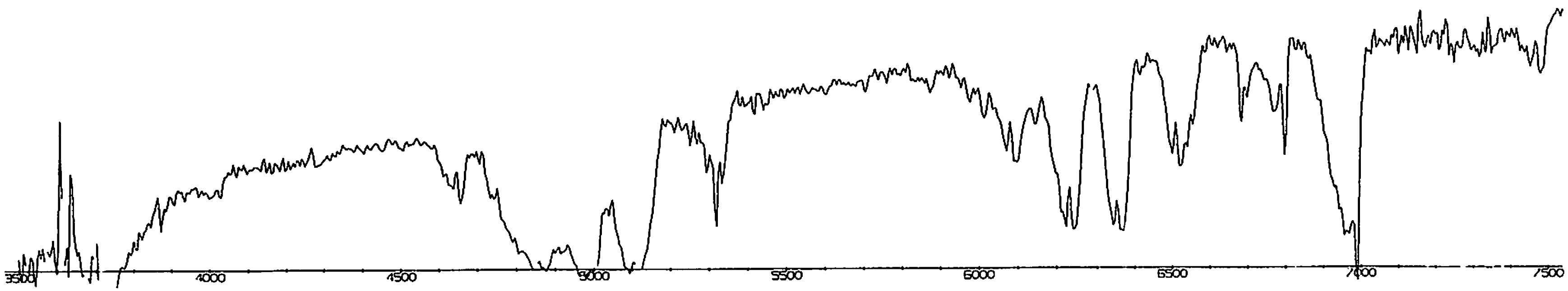


Fig. 8 Ratio spectrum, Venus/Moon, November 28, 1967.

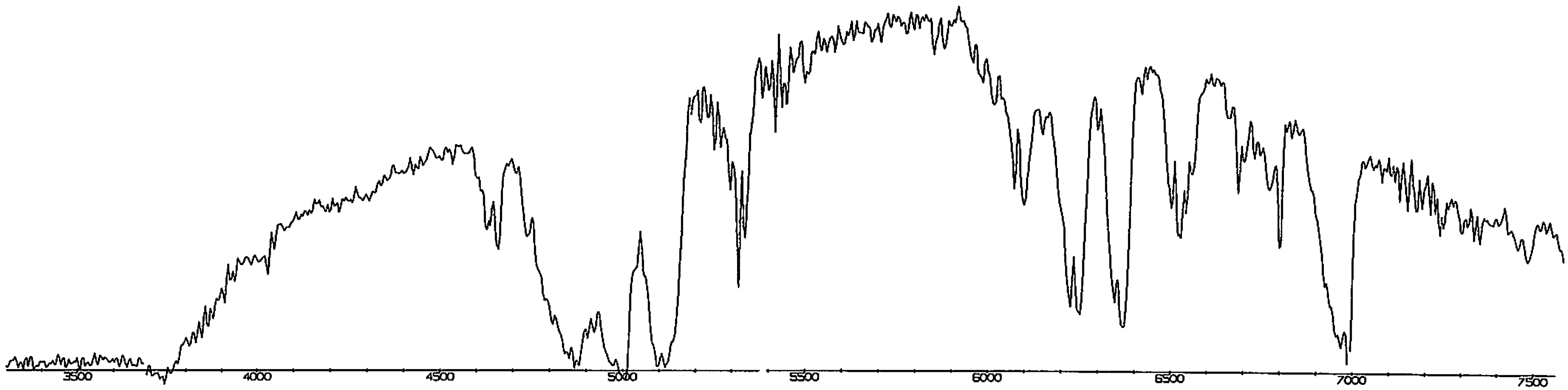


Fig. 6 Venus spectrum, CV 990, November 28, 1967.

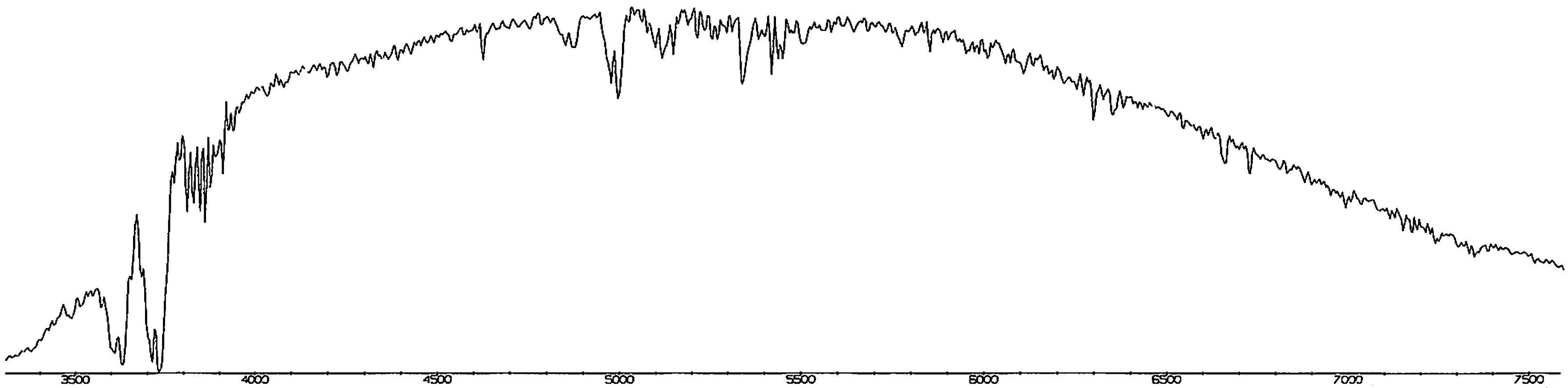


Fig. 7 Moon comparison spectrum, CV 990, November 28, 1967.

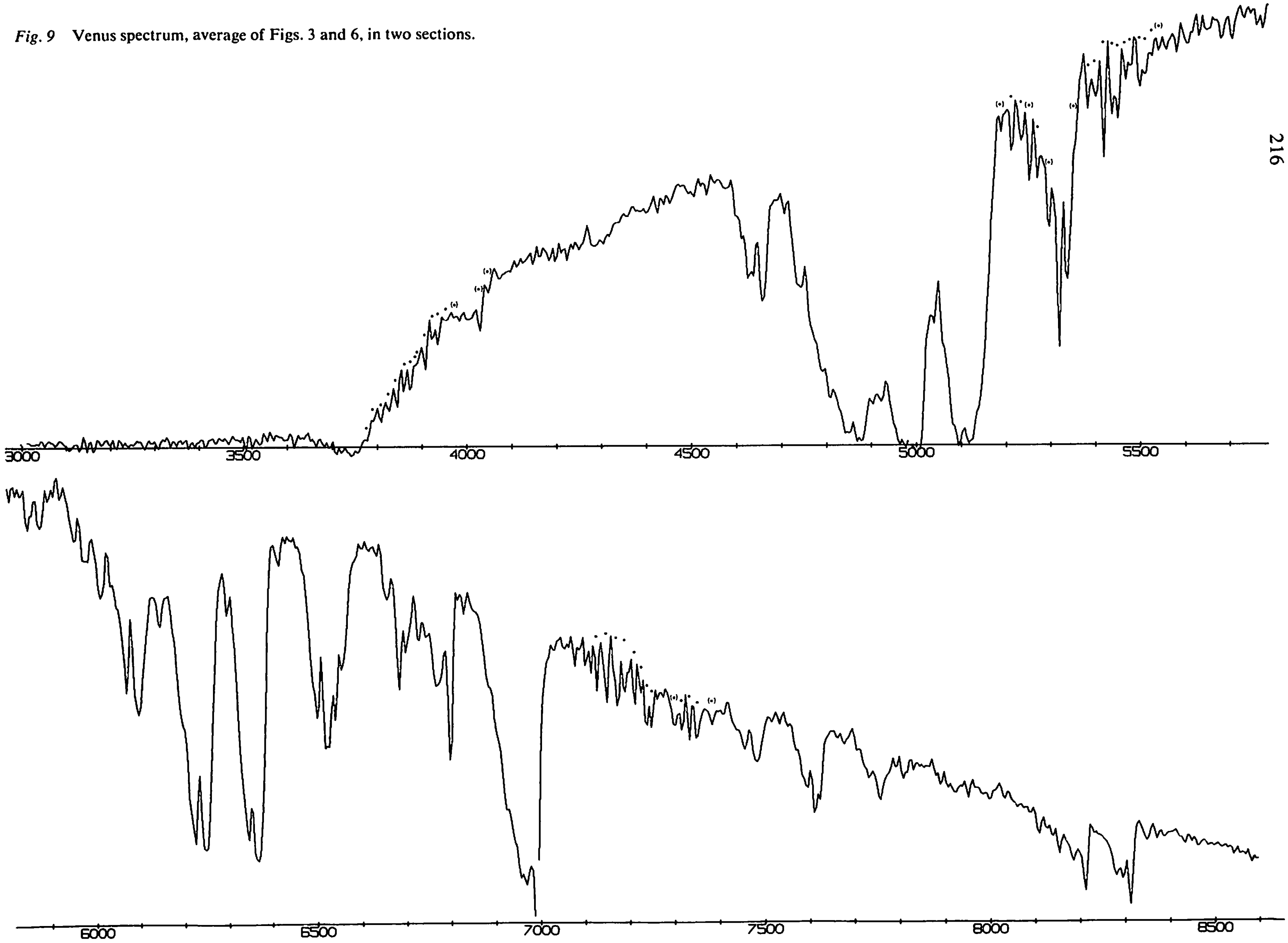


Fig. 9 Venus spectrum, average of Figs. 3 and 6, in two sections.

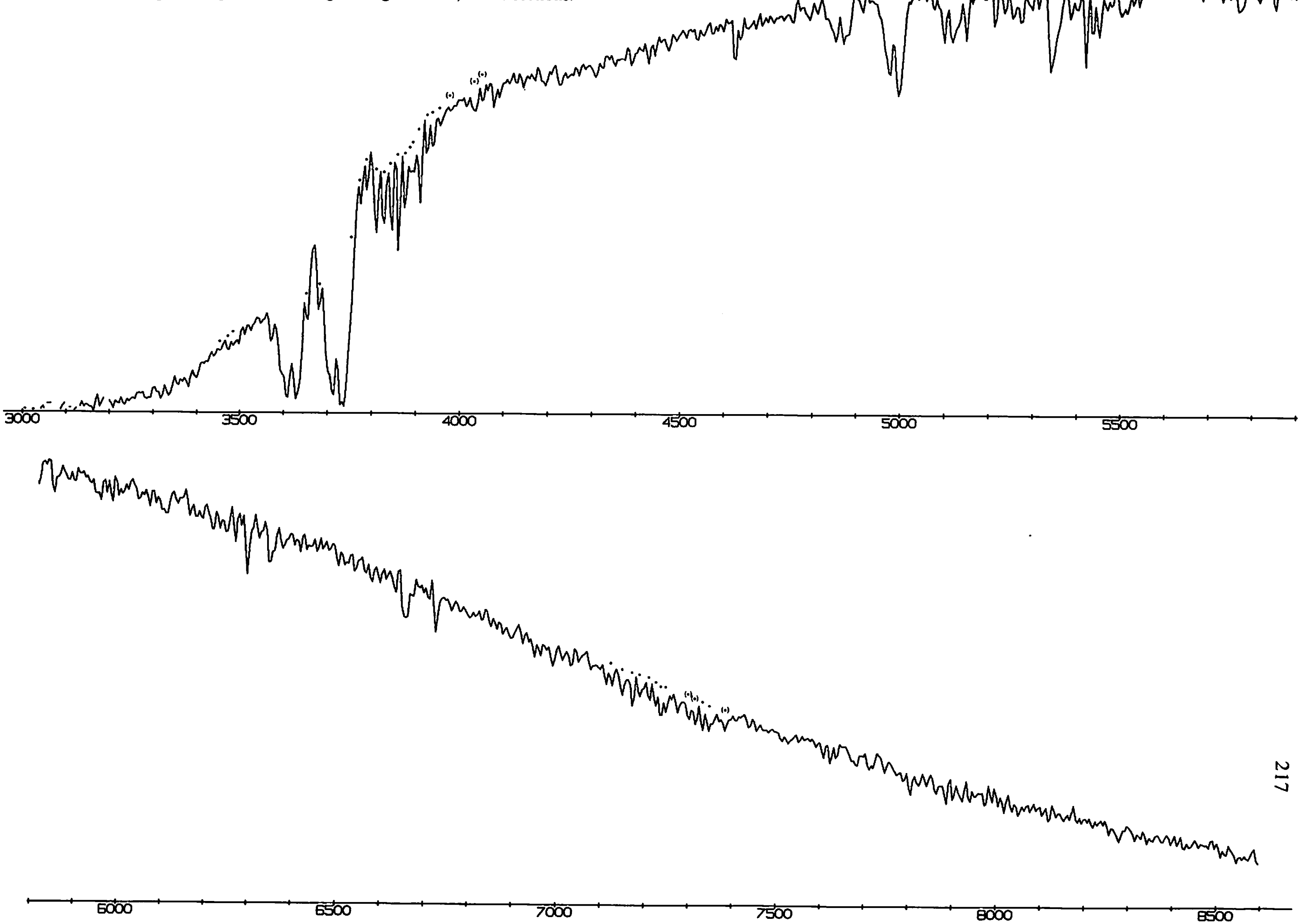


Fig. 10 Moon comparison spectrum, average of Figs. 4 and 7, in two sections.

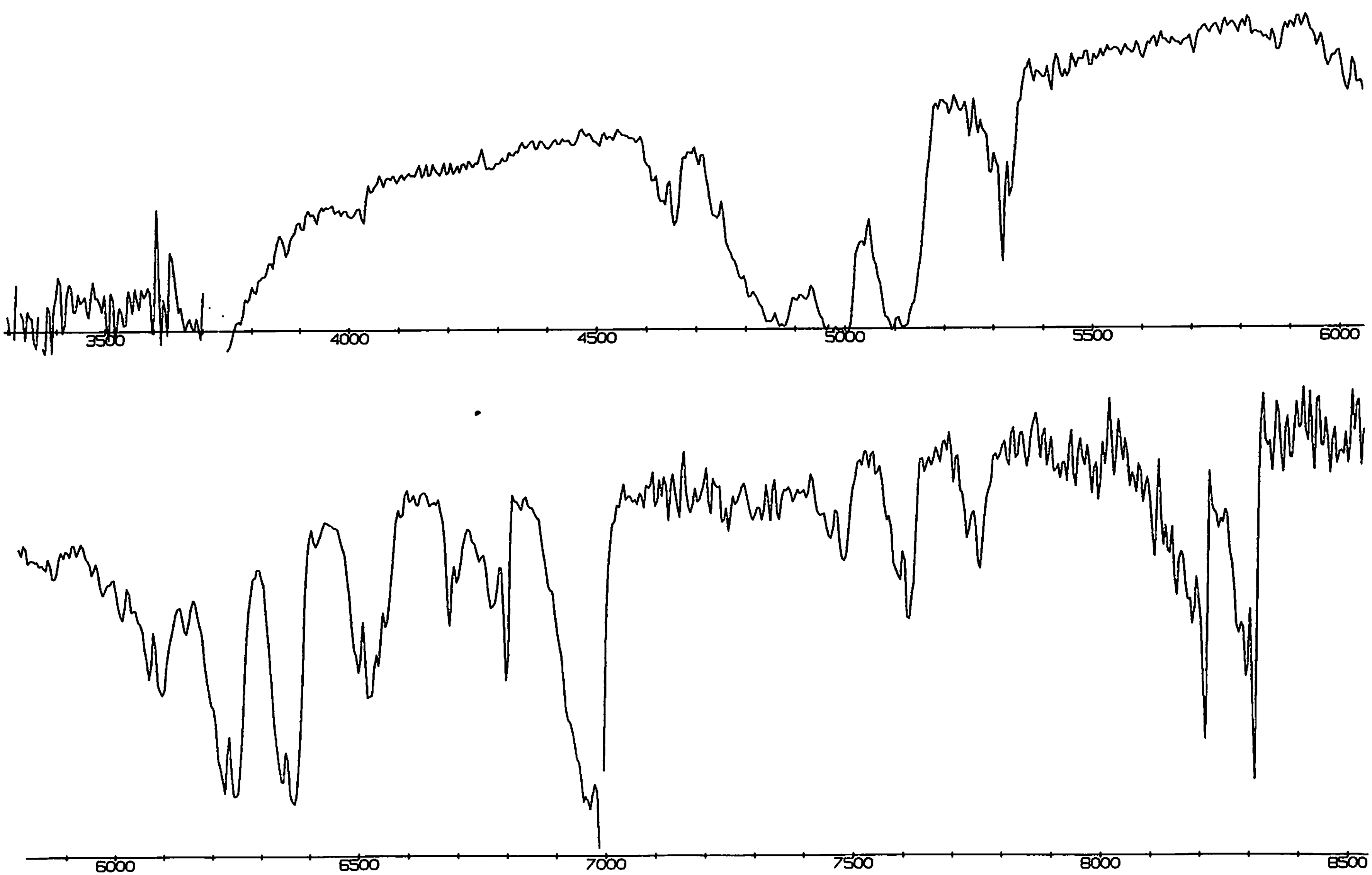


Fig. 11 Ratio spectrum, Venus/Moon, average of Figs. 5 and 8, in two sections.

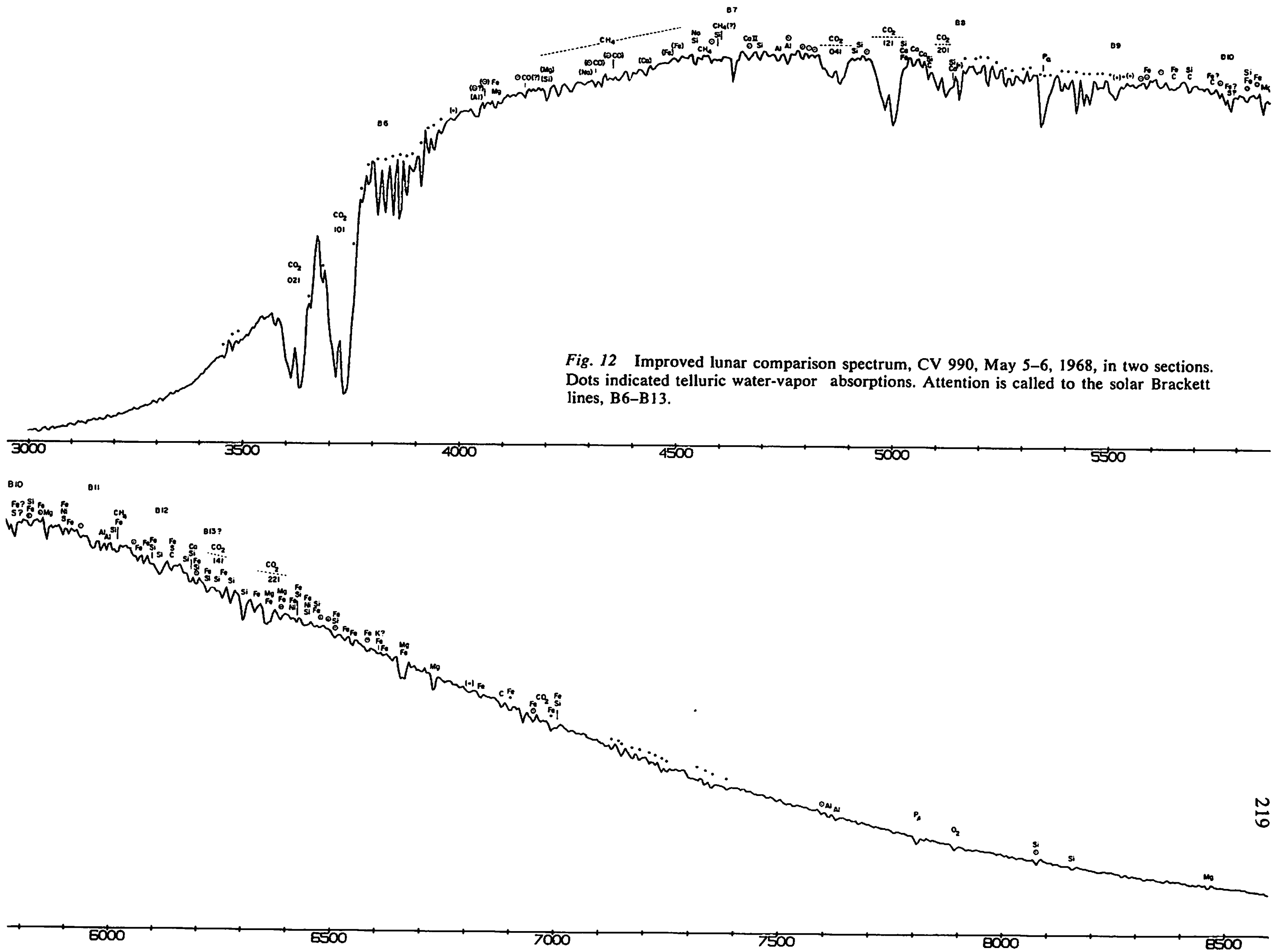


Fig. 12 Improved lunar comparison spectrum, CV 990, May 5–6, 1968, in two sections. Dots indicated telluric water-vapor absorptions. Attention is called to the solar Brackett lines, B6–B13.

Fig. 13 Ratio spectrum, Venus/Moon, based on spectra of Figs. 9 and 12, with identifications. CO_2 designations as in *LPL Comm.* No. 15, Table 1. Venus H_2O absorptions are open circles. HCl, HF absorptions marginally recorded. Identifications $\lambda < 3680$ cm^{-1} uncertain (omitted).

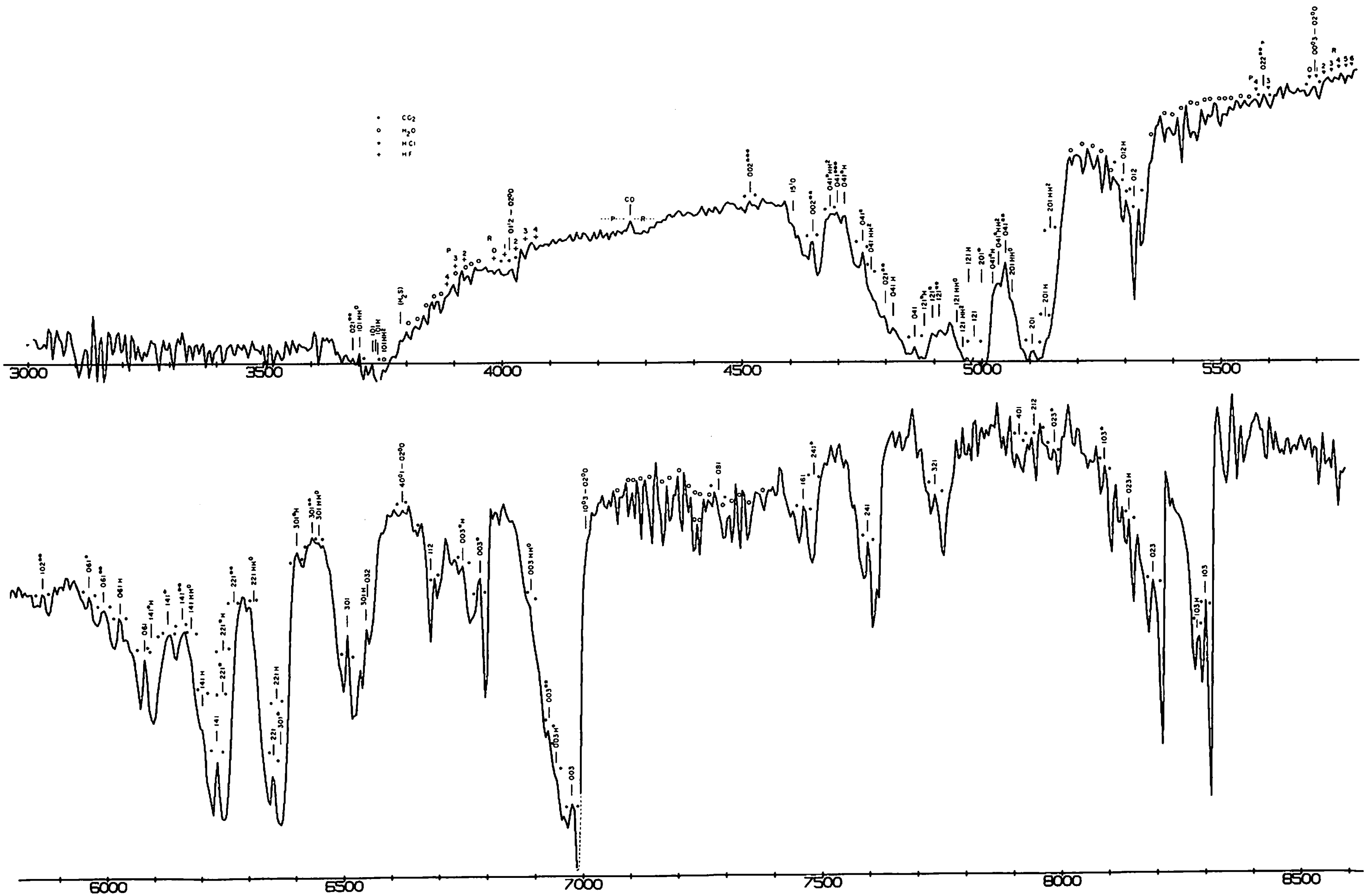


Fig 14 Venus spectrum, 60-inch, Catalina Observatory, Site II, (elev. 8450 ft, 2580 meters), November 7, 1967. (Zero intensity line slightly adjusted here, but not in Fig. 16).

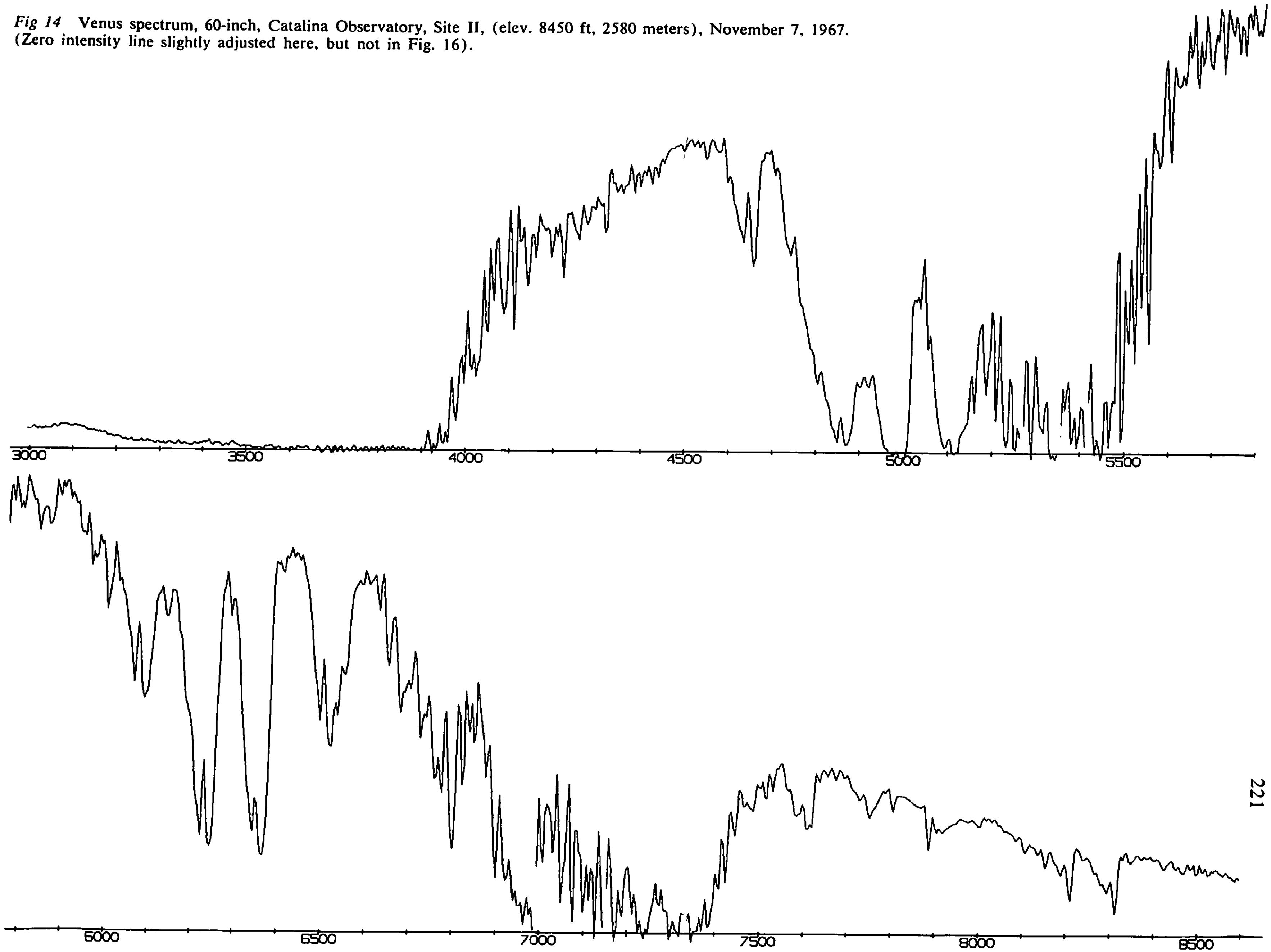
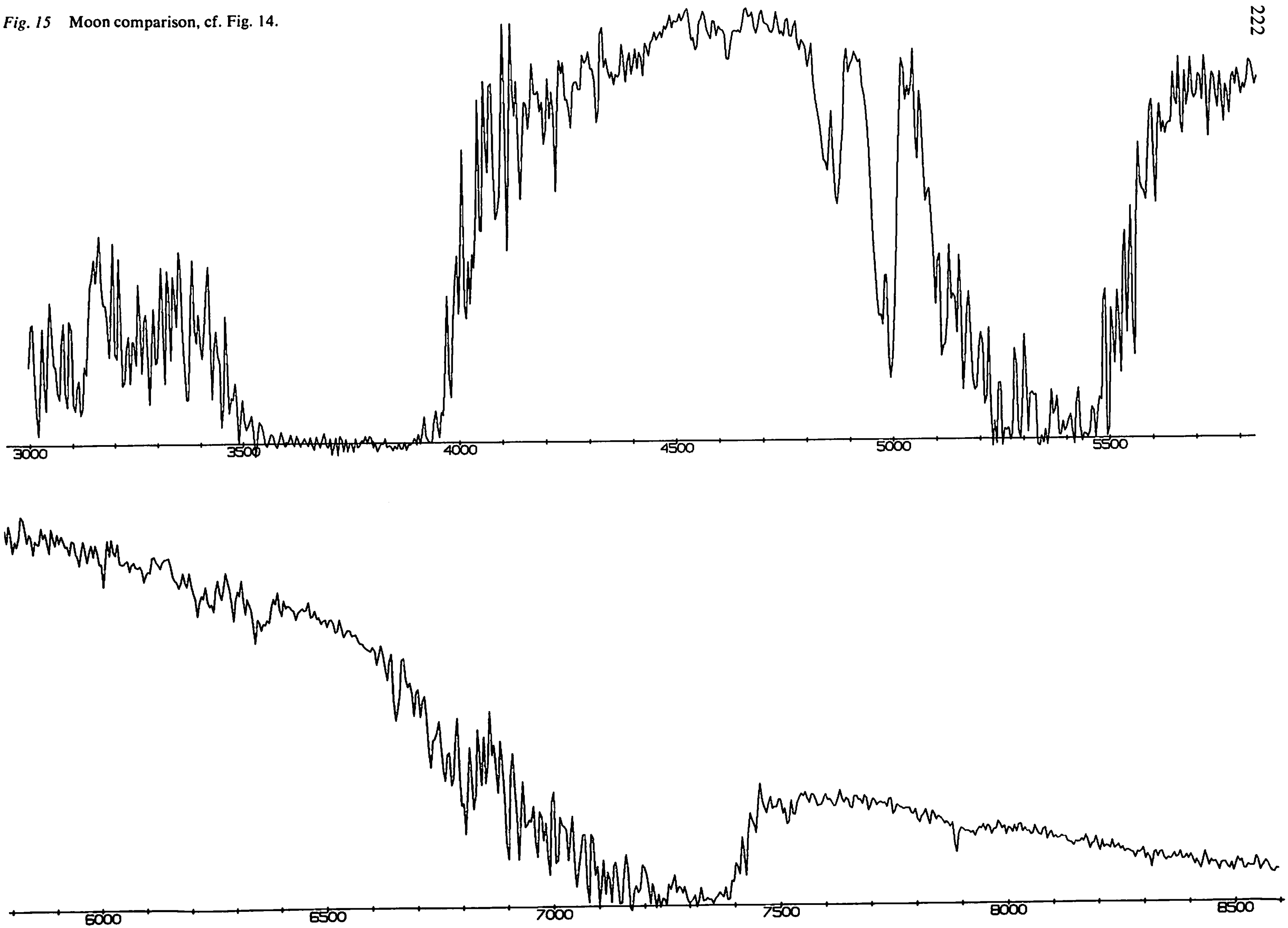


Fig. 15 Moon comparison, cf. Fig. 14.



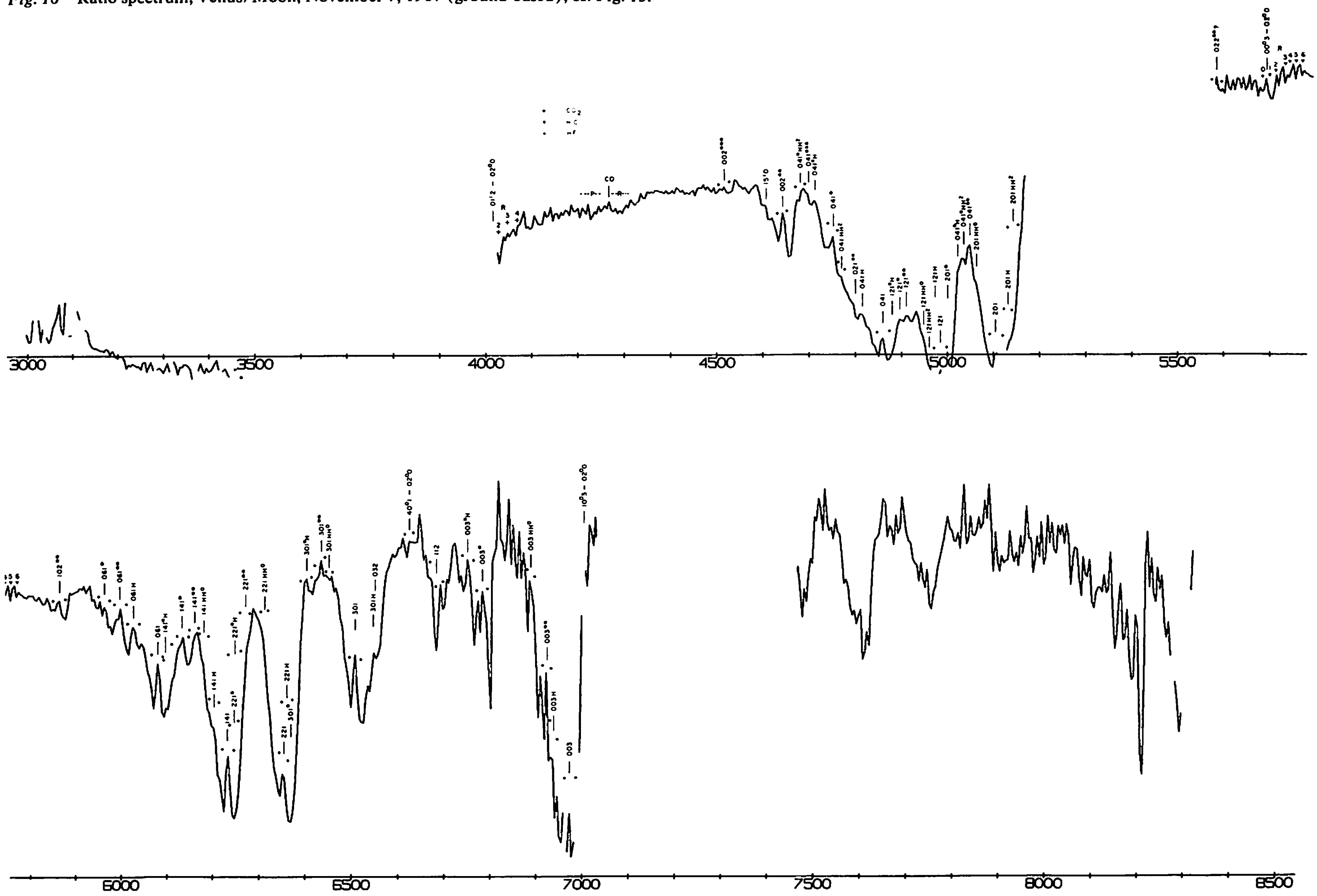


Fig. 16 Ratio spectrum, Venus/Moon, November 7, 1967 (ground-based), cf. Fig. 13.

spectrum may be made by comparison with Fig. 14 which was obtained at the Catalina Observatory with a 61-inch telescope on November 7, 1967, prior to the observations on the CV 990. (This telescope collects at least 30× as much radiation as the 12-inch aboard the CV 990, with its window and heliostat mirror in the beam.) Since the Moon was not up, no lunar comparison could be obtained on the same day, but one which matches the H_2O absorptions approximately is reproduced in Fig. 15. The ratio spectrum is shown in Fig. 16, which, of course, cannot be used in the regions of the heavy water-vapor absorptions. It is stressed that all Fourier Transform reductions used in the spectra shown are somewhat provisional. E.g., one suspects that the amplitudes of the sharp features shown in Fig. 14 near 4100 cm^{-1} are somewhat exaggerated. An attempt will be made to obtain a more definitive reduction in conjunction with additional Venus observations made 1968–69.

3. *Discussion*

The principal topic of this paper is the determination of the water-vapor content of the Venus atmosphere with the increased resolution provided by the new airborne interferometer. As a first step toward this end, the H_2O absorptions shown in Figs. 9 and 10 were identified and marked. The next question is to what extent the ratio spectrum of Fig. 11 shows the correct H_2O absorptions in the Venus spectrum. The radial velocity on Venus on November 27, 28, 1967 was about 12.9 km/sec, which corresponds to Doppler shifts of 0.6 Å at 1.38 μ, 0.8 Å at 1.87 μ, and 1.1 Å at 2.6 μ. The line widths of H_2O telluric lines observed from 40,000 ft are about 0.3–0.4 Å at 1.38 μ, 0.7–0.8 Å at 1.87 μ, and, for the stronger lines, $>$ 2 Å at 2.6 μ. The Venus spectrum is produced at pressures even somewhat less than at the 200-mb flight level of the CV 990, so that the weak Venus H_2O absorptions are narrower (and weaker) than those in the lunar spectrum of Fig. 10. Therefore, in the 1.4 and 1.9 μ H_2O bands the Venus and telluric absorptions are separated, and thus independent and additive; but in the 2.6 μ band the addition is complex. Indeed, the 2.6 μ band of Fig. 11 would give substantially less H_2O than the 1.4 and 1.9 μ bands, if simple additive absorptions were to be assumed. The ratio spectrum of Fig. 11 will therefore give the correct H_2O content for the 1.4 and 1.9 μ bands and it yields, with laboratory calibrations at 200 mb, 5 microns of precipitable H_2O in the 2-way transmission.

Since the corresponding figure for CO_2 is about 4 km atm., the mixing ratio H_2O/CO_2 (after conversion of liquid H_2O to vapor at NPT) is close to 1.10^{-6}. A 2-decimal precision in this mixing ratio will be attempted when additional Venus observations become available, and after appropriate CO_2 calibrations (for bands having lines of equal intensity to the 1.4 and 1.9 μ H_2O bands in Venus) have been made (which is necessary also because of the appreciable variations in the observed CO_2 abundance).

Absorptions others than H_2O have been marked in Fig. 13, but a detailed discussion of them is withheld pending the acquisition of additional Venus spectra. Attention is called to Addendum 2 (Figs. 19A–19C) for laboratory spectra of CO_2 which roughly match the weaker bands in Venus but which of course show much greater absorptions for the medium and strong bands, resulting from the peculiar intensity ratios observed in radiation scattered by an absorbing atmosphere.

Acknowledgments. The Venus flights were made possible through support by NASA Hq. and NASA-Ames. We are deeply indebted to NASA for the courteous cooperation and assistance extended throughout. The purchase of the interferometer was made possible through the NASA Institutional Grant NGR 03–002–091. The continuing LPL high-altitude program is supported by NASA Grant NsG 161–61. We wish to thank Dr. W. S. Benedict for a discussion during the Kitt Peak Conference on identifications of the weaker CO_2 bands; Mr. L. A. Bijl for the identifications in Fig. 12; and Mrs. Alice Agnieray for assistance in the preparation of the figures.

ADDENDUM 1

LABORATORY SPECTRA OF H_2O AND HCl

Fig. 17 shows an interferometer spectrum of 6 meters of air at 200 mb (p = 15cmHg) containing 11 microns of precipitable water, used to calibrate the water-vapor content of the Venus spectrum (*Comm. LPL* Nos. 100, 101).

Fig. 18 shows a spectrum of the 2–0 band of HCl at 1.7 μ, obtained with the A-spectrometer, used in the identifications on Figs. 13 and 16. The isotope band HCl^{37} is well resolved from HCl^{35}. The wavenumbers are based on Rank et al. *J. Opt. Soc.* **52**, 4, 1962.

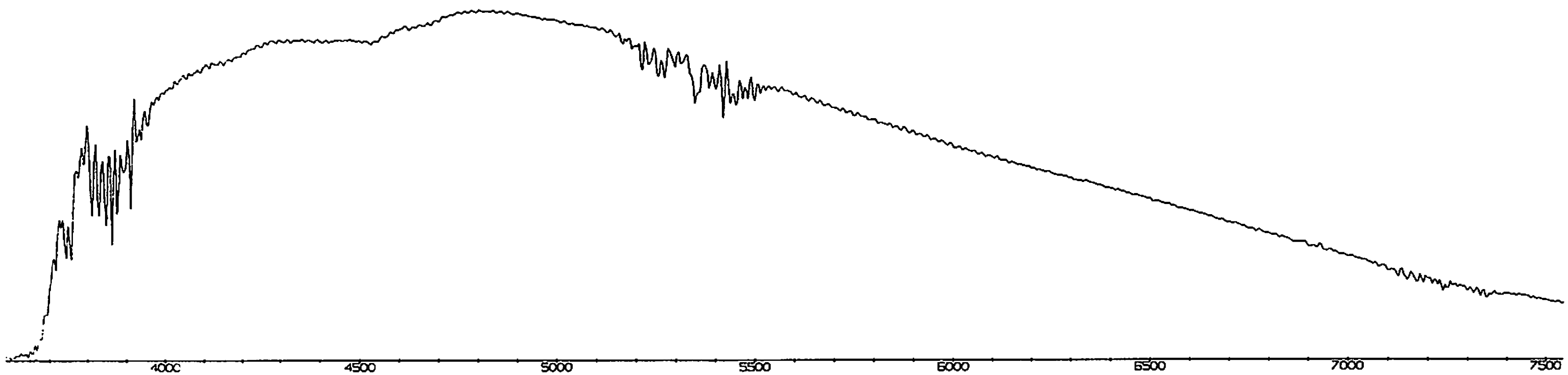


Fig. 17 Interferometer spectrum of H_2O, 3600–7500 cm^{-1}.

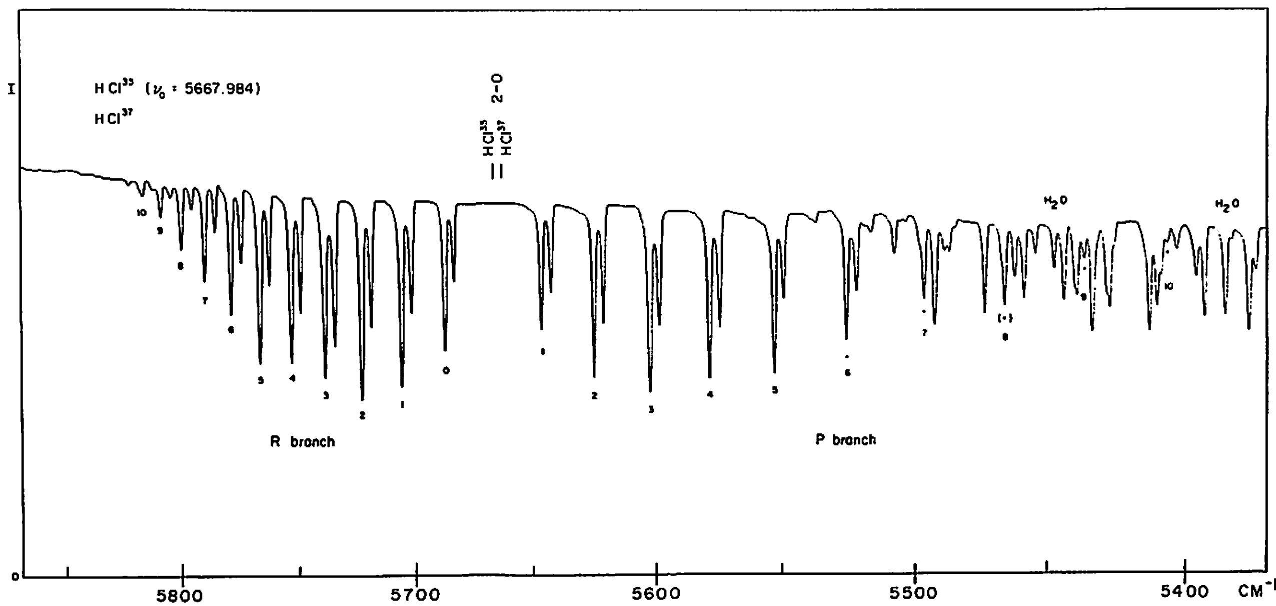


Fig. 18 The 2–0 band of HCl 1.7 μ.

ADDENDUM 2

LABORATORY SPECTRUM OF CO_2

by U. FINK AND G. P. KUIPER

June 11, 1969

An effort was made to obtain CO_2 spectra that would reasonably match the weaker bands shown in the Venus spectrum as a check on the assignments made in the above paper.

The spectra were obtained with the 40-meter-long LPL White tube, recently completed, used so far with 2, 16, 32, and 64 traversals, at pressures 0.5 and 1.0 atm. Ultimately, a greater range will be covered.

The CO_2 used in these runs supplied by the Matheson Company of Cucamonga, California, was unusually free of CH_4 and H_2O; the H_2O absorption was mostly due to the path outside the tube, although the spectrometer was being flushed with dry nitrogen.

The B-spectrometer was used in these runs (with resolutions up to about 5000), rather than the interferometer, for ease of operation and check on the absence of interference fringes, etc.

Figures 19A-C show sample records taken with the 2500-meter path, p = 1 atm., and resolutions matching roughly the interferometer spectra. The scale is roughly constant in λ, but the abscissae are given in cm^{-1} for comparison with the Venus spectra.

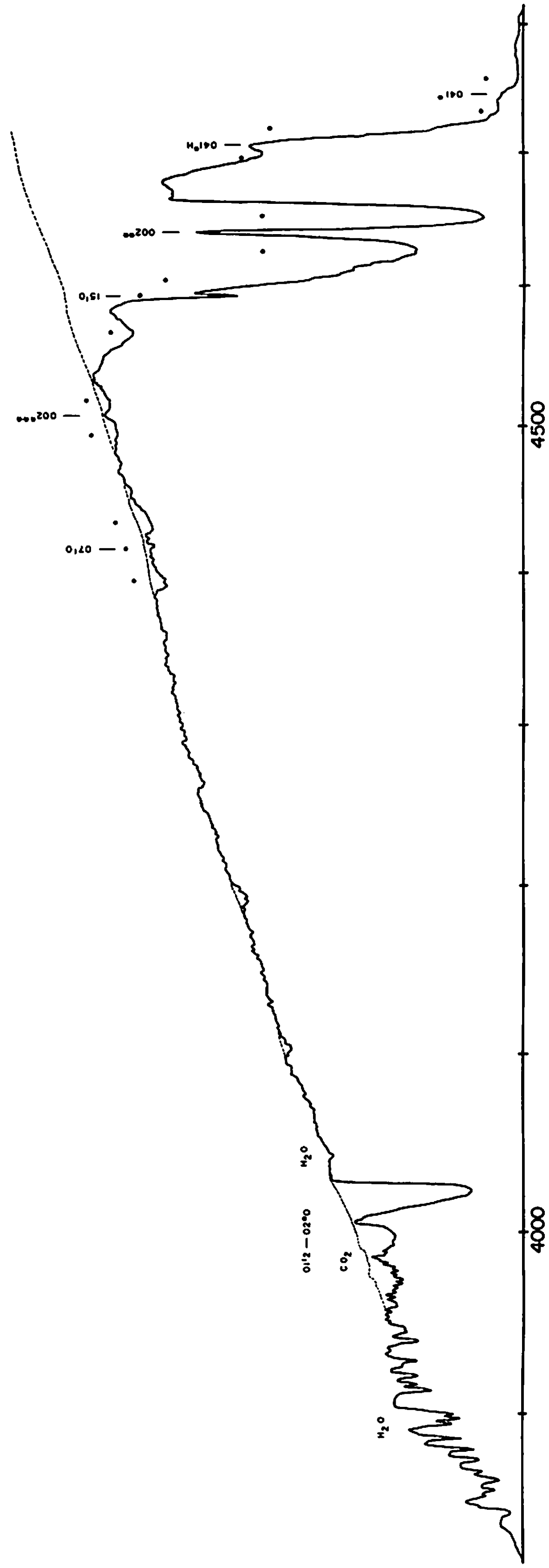


Fig. 19A Laboratory spectrum of CO_2, 2500-meter path, p = 1 atm., 3900–4800 cm^{-1}. Dotted line, blank run, showing laboratory H_2O.

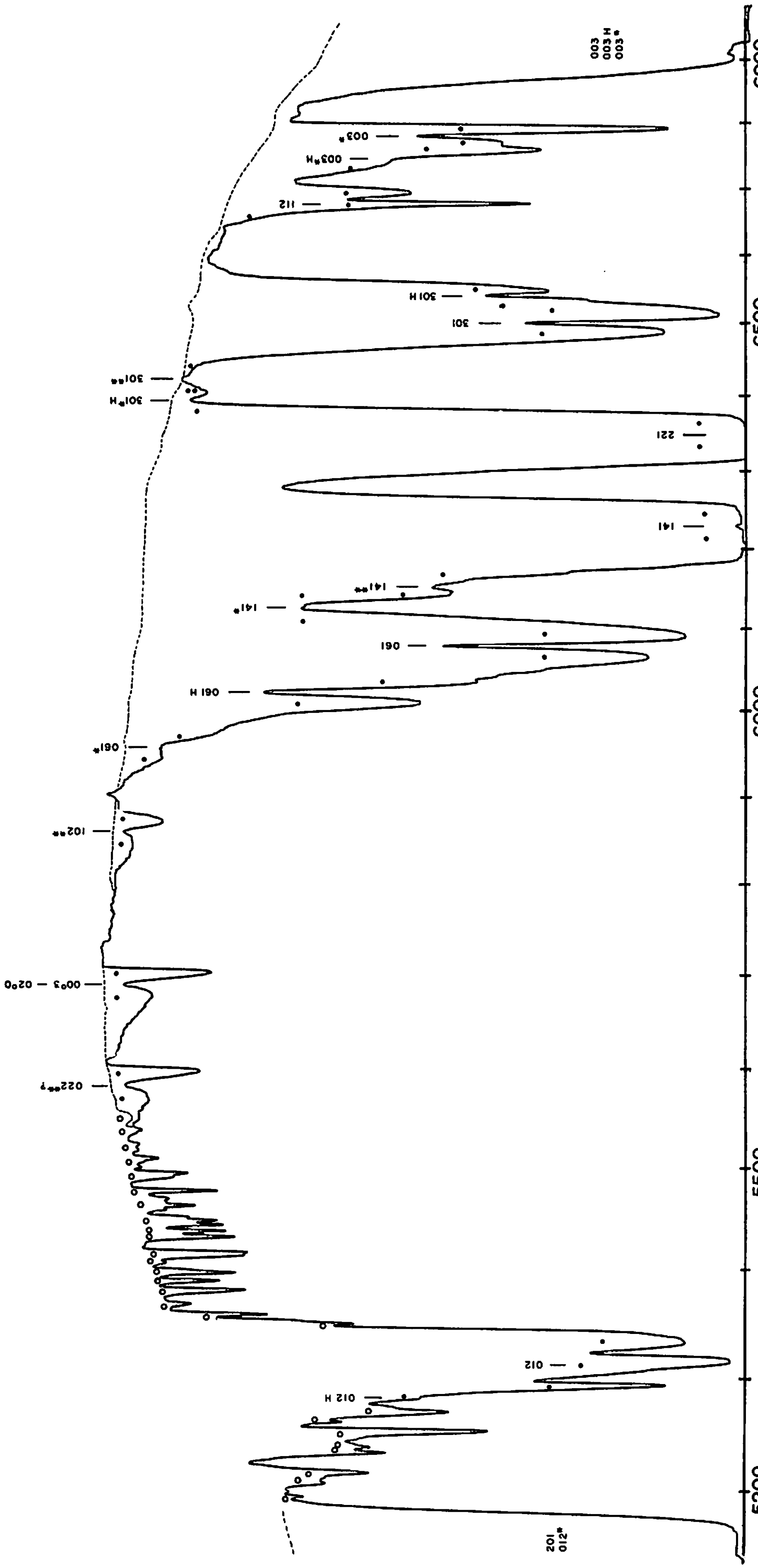


Fig. 19B Continuation of Fig. 19A, 5200–6900 cm^{-1}.

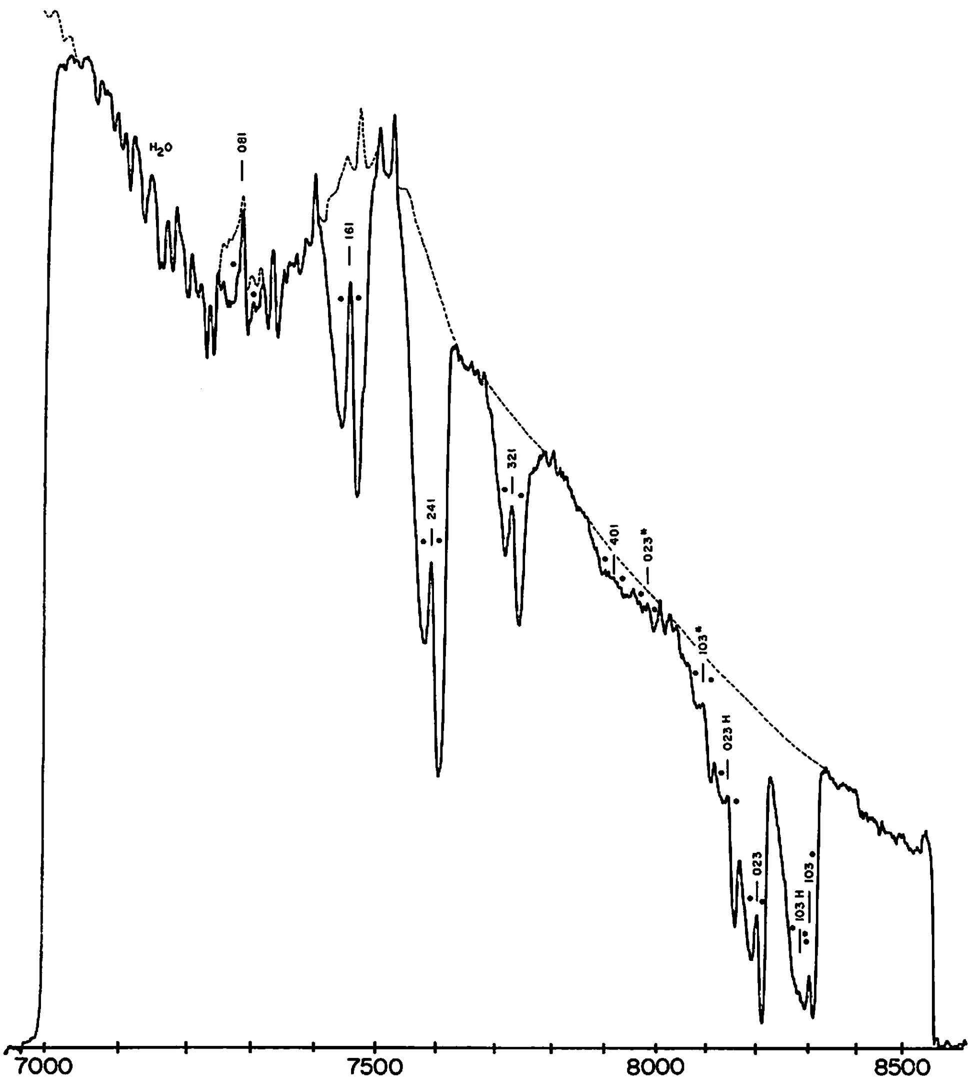


Fig. 19C Continuation of Figs. 19A, B, 7000–8500 cm^{-1}; a few Ar emission lines shown are in lab. source.