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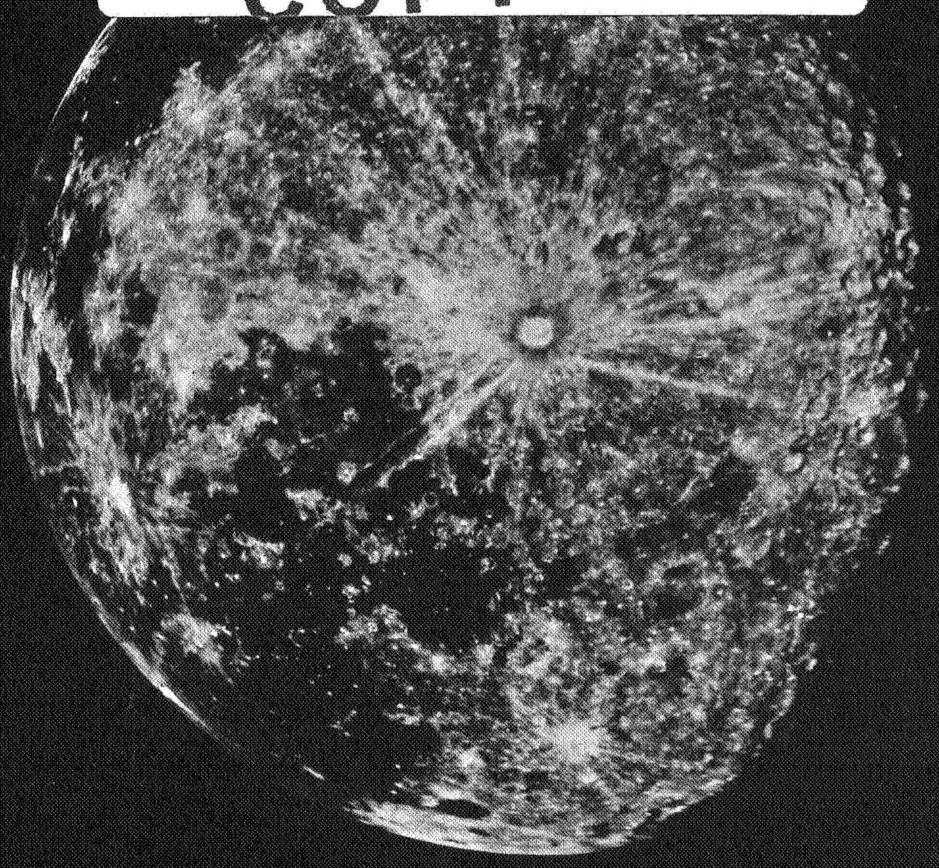

Volume 7 Part 4

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No. 123 ARIZONA-NASA ATLAS OF INFRARED SOLAR SPECTRUM A PRELIMINARY REPORT

by G. P. KUIPER AND D. P. CRUIKSHANK

September 24, 1968

ABSTRACT

This paper shows a sample (about 5%) of a set of photometric tracings of the infrared solar spectrum obtained from the NASA CV-990 Jet during nine flights in July-August 1968. Two 12-inch telescopes were used, one feeding a 4.2-meter spectrometer of special design, the other the LPL B-spectrometer. The 4-meter spectrometer records extend from 0.85-3.3 microns; the B-spectrometer records, from 0.85-5.1 microns. Supplementary flights with the NASA Lear Jet are scheduled to extend the spectrum beyond.

The present paper reproduces the 4.2-meter records between 0.85-0.97 microns. Some runs were made in duplicate because of occasional troubles with the heliostat controls which account for the gaps in the records. The resolution is about 0.3 Å or 30,000 in the region shown. In the remaining 4.2-meter records the resolution varies from 20,000–60,000. In this preliminary paper, matching portions of the Michigan Atlas, "Photometric Atlas of the Near Infrared Solar Spectrum, λ8465 to λ25,242," are reproduced to facilitate comparisons of resolution and in particular to demonstrate the value of high-altitude flights in very nearly eliminating the telluric water-vapor spectrum.

Systematic observations of the infrared solar spectrum with resolutions of 10,000–60,000 were undertaken in conjunction with the ongoing program of infrared spectroscopy of planets and red stars from the NASA CV-990 Jet. Equipment now under development at the Laboratory is designed to achieve resolutions from 1,000–200,000, depending on the intensity of the source. It is obvious that a good set of solar spectra with different resolutions, taken from the same altitude, was essential for purposes of wavelength identification and spectral interpretation.

The present series of high-altitude solar flights were proposed to NASA in "Program of High-Altitude Infrared Spectroscopy of Sun, Planets, and Stars: III," by G. P. Kuiper, J. R. Percy, F. F. Forbes, and H. L. Johnson, dated March 21, 1968, in continuation of a set of experimental flights that took place early October 1967, based on Hickham Field, Hawaii. These earlier flights were limited to the use of the B-spectrometer and owing to the prevalence of high tropical cirrus during the period of observation, yielded only 1–2 hours of net observations. Nevertheless, reasonably satisfactory results were obtained for the interval 1.24–2.04 μ with a resolution of approximately 8000. During these 1967 flights also, a simple method was devised for flushing the spectrometer and the telescope-heliostat area with exceedingly-dry outside air, thereby reducing the remaining precipitable water-vapor content in the instrumental air path to about 1 or 2 μ. For the 4-meter instrument this problem was especially critical since the air path within the spectrometer alone is 17 meters (Ebert design) to which must be added the air path from the optical aircraft window to the spectrometer entrance slit via the Cassegrain telescope, approximately 4 meters. With normal dry laboratory conditions, a 20-meter air path contributes about 120–150 μ precip. H_2O, as compared to only 8–12 μ in the entire atmospheric path above the aircraft. Flushing the equipment with dry nitrogen was attempted in the Hawaii flights but proved cumbersome and less effective than the simple device referred to, of using compressed dry outside air. The outside temperatures at the operating level of 40,000–42,000 ft are normally between $-55°$ and $-60°$ C. The ambient frost point is usually around $-70°$C. By enclosing the optical path, window-heliostat-telescope-spectrometer, with plastic sheets and flushing the air with the compressed dry air from the ventilation system, the ambient dew point within the spectrometer was kept below $-30°$C. After most solar runs, comparison spectra were made under identical operating conditions within the aircraft which gave direct information on the contributions to the telluric spectrum (H_2O, CO_2, N_2O, CH_4) by the spectrometer air. These records are of special interest for the stronger H_2O bands at 1.4, 1.9, and 2.6 μ; and the CO_2 bands at 2.0 and 2.6–2.7 μ.

Figure 1a shows the 4-meter spectrometer in the CV-990 Jet, with the 12-inch feeder telescope situated beyond. The view is looking forward in the aircraft. Figure 1b shows the opposite aspect; the optical window is seen above the heliostat (both above center) and the horizontal Cassegrain telescope beyond. Telescope and heliostat are bolted on a sturdy support frame fastened to both the seat rail (normally used for chairs) and the side rail, by means of shock mounts. The spectrometer was designed by Mr. Ferdinand de Wiess in consultation with the authors; it will be described in a separate publication. The frame design resembles a radio tower, with 8 cables under tension made to keep the end plates of the spectrometer parallel to each other in spite of aircraft vibrations due to engines and air turbulence. The tensions in the cables were made equal within about 1% and kept at about 260 lbs (120 kg.) This high tension served to increase the frequency and therefore the damping of the vibrations, both of which will diminish their amplitude. Since the instrument was normally used with both the entrance slit and the detector only 0.10 mm wide, it was necessary to keep the oscillations in the 17-meter light path to within 1 arc seconds. With the oscillations of the plane sometimes amounting to 2° or more, this requirement was really severe; and it is a tribute to the designer that at no time during the nine operational flights, each lasting 150–170 minutes, did we find evidence of instrumental distortion. Only when the plane turned sideways in a steep bank (which of course did not occur during the level solar runs but only occasionally during comparison runs) would the amplitude of the signal change appreciably, indicating a twisting of the entire spectrometer, which is not surprising because of its four-point support to the fuselage (cf. Fig. 1a).

The detectors used up to 3.3 μ were PbS cells, cooled with dry ice. Beyond 3.3 μ, PbSe cells were used, also dry-ice cooled, which is satisfactory up to about 5.3 μ (beyond this limit we will use liquid-nitrogen cooled PbSe up to about 6.3 μ, and beyond this the Germanium bolometer, liquid-helium cooled). The solar signal was chopped at 60 cps. The preamplifier is seated close to the detector and has a gain of 30. The amplifier was mounted opposite the spectrometer on the starboard side of the aircraft in a rack also containing the power supply and the strip-chart recorder. The signal was synchronously rectified and amplified in the DC mode. The time constant was adjustable. Most records were obtained with $\tau = 0.12$ sec. This rapid response made it possible to record up to four spectral elements per second which was important in the economy of the program, there being some 100,000 spectral elements to record in a necessarily-limited flight time. The recorder used was a Sanborn 7701A, shock-mounted in its rack to minimize the effects of aircraft vibrations. The spectral trace is produced with an electrically-heated stylus on heat-sensitive paper. This ensures extremely low inertia and a very-short time constant of the recorder itself, about 0.01 sec.

The spectral interval selected for reproduction was obtained with a 128 x 154 mm Bausch and Lomb grating having 1200 grooves per mm. The grating was blazed for 1.0 μ and was used as far as 1.43 μ, where the angle of incidence had become about 70°. The resulting resolution in the 1.4 μ region was therefore exceptionally good, about 60,000. The region from 1.22–3.00 μ was obtained with gratings of similar size but 600 lines per mm, the region 2.90–3.30 μ with 300 lines per mm. With the B-spectrometer, designed to use interchangeably the same gratings as the 4.2 meter, the entire interval 0.85–5.1 microns was recorded in a separate, independent installation with its own 12-inch telescope. The part up to 3.0 μ has resolutions 8,000–12,000; the region beyond, 2,000–5,000.

The 4.2-meter spectrometer had 6-inch mirrors to fit the 5 x 6 inch gratings used. The effective F-ratio was therefore F/32, matched by the F/30 Cassegrain telescope. The original secondary mirror was replaced by a newly-produced Cervit mirror. It was found that this allowed the use of the full solar beam from the 12-inch primary (intensity 50–60 times that of normal sunlight), which, of course, improved the quality of the spectral records.

Figures 2–7 give photographic reproductions of all spectral records obtained with the 4-meter spectrometer from $\lambda\lambda$8487–9725. The wavelength scales are based on the catalog by H. B. Babcock and C. M. Moore, "The Solar Spectrum, λ6600 to λ13495" (Carnegie 1947), derived from photographic records obtained at the Mt. Wilson Observatory. Our CV-990 records attain about the same limit at λ9000 A, Rowland intensity −3. At longer wavelengths our records show fainter lines presumably because of the lower photographic resolutions there. The telluric water-vapor lines with Mt. Wilson Rowland intensities < 20 or 30 are usually invisible on our spectra (i.e., have Rowland intensity −3 or less). Only some 3 dozen very strong lines, up to Rowland intensity 150, are recorded here, with intensities corresponding to −3 to 0. These lines are indicated by dots *above* the spectra. If only part of the absorption feature is due to H_2O, the dot is placed in ( ).

For ready orientation we have added the identifications of all solar lines having Rowland intensity 0 or above in the Babcock-Moore catalog, taken from this catalog. Some of these lack identification and other prominent lines are included although they had no Rowland intensity assigned to them (usually because of blending with telluric lines). The very wide solar Paschen lines P_8–P_{10} have not before been recorded without the telluric disturbances. Two small regions show a shallow depression (marked G) due to imperfect guiding (away from the center of the disk).

Table 1 gives descriptive data of the high-altitude spectral records here shown. It includes the wavelength interval, the date and UT, the aircraft altitude during the observations, the outside temperature, the cabin pressure inside the aircraft (which affects the pressure broadening of the residual water-vapor absorption produced in the cabin air path), and the gain-setting of the amplifier. The slit width in the present records was 0.10 mm; the cell width was the same; the time constant of the amplifier, 0.12 sec; the grating was blazed for 1 micron, 1200 lines per mm; the filter used to cut out higher orders, RG 8 (λ>.68 μ). Some gaps occur in the (duplicate) records, due to troubles with the heliostat control (which happened all for λ<1 μ). The absorption lines regarded real on the basis of the records themselves (or, in some cases, by supporting data such as the Liège solar atlas) are marked with a dot, with a running number assigned for each spectral strip to facilitate further reference. In the Atlas, larger-scale reproductions will be used and supporting laboratory and ground-based solar spectra added.

We are making a comparison here with the Michigan Atlas (1950), Figures 2M–7M, rather than with the more recent and improved Liège Atlas (L. Delbouille and R. Roland, 1963), because the former extends to 2.5 μ, nearly as far as our records, whereas the Liège Atlas terminates at 1.2 μ. It is seen that the dots *above* the spectral records in Figures 2–7 all correspond to nearly-saturated telluric lines in Figures 2M–7M.

The wavelength identifications of the weaker solar lines shown in our figures were verified with the aid of the Liège Atlas on which all the Babcock-Moore identifications were entered. Some of these weaker lines are not found in the Babcock-Moore catalog but were recorded in the Liège Atlas. A few puzzling cases were noted, the most striking of which is λ9438.7 listed as "−1N Atm.," while our records show it to be about 5 $\odot$. Numerous uncertainties in identification, sun or Atm., could be settled. These systematic comparisons have brought out clearly the *immense value for subsequent identification work of high-resolution infrared solar spectra* (R >> 100,000) *taken from a very dry mountain observatory.* Preparations have been made for observing the sun in this manner with the 4.2-meter spectrometer as a first step.

The spectrometer tests preceding the solar flights were made by Dr. Cruikshank, assisted by Mr. A. Thomson. They and Messrs. de Wiess and Kuiper optimized the equipment in the CV-990 during an engineering flight on July 2, 1968. The wavelength scales and water-vapor identifications in Figures 2–7 were compiled by Dr. Kuiper, in the manner described above, and verified by him on the basis of post-flight laboratory runs on water vapor, made in collaboration with Dr. Uwe Fink. In the λ9350 region these runs proved indispensable to resolve some remaining ambiguities. A brief report on the

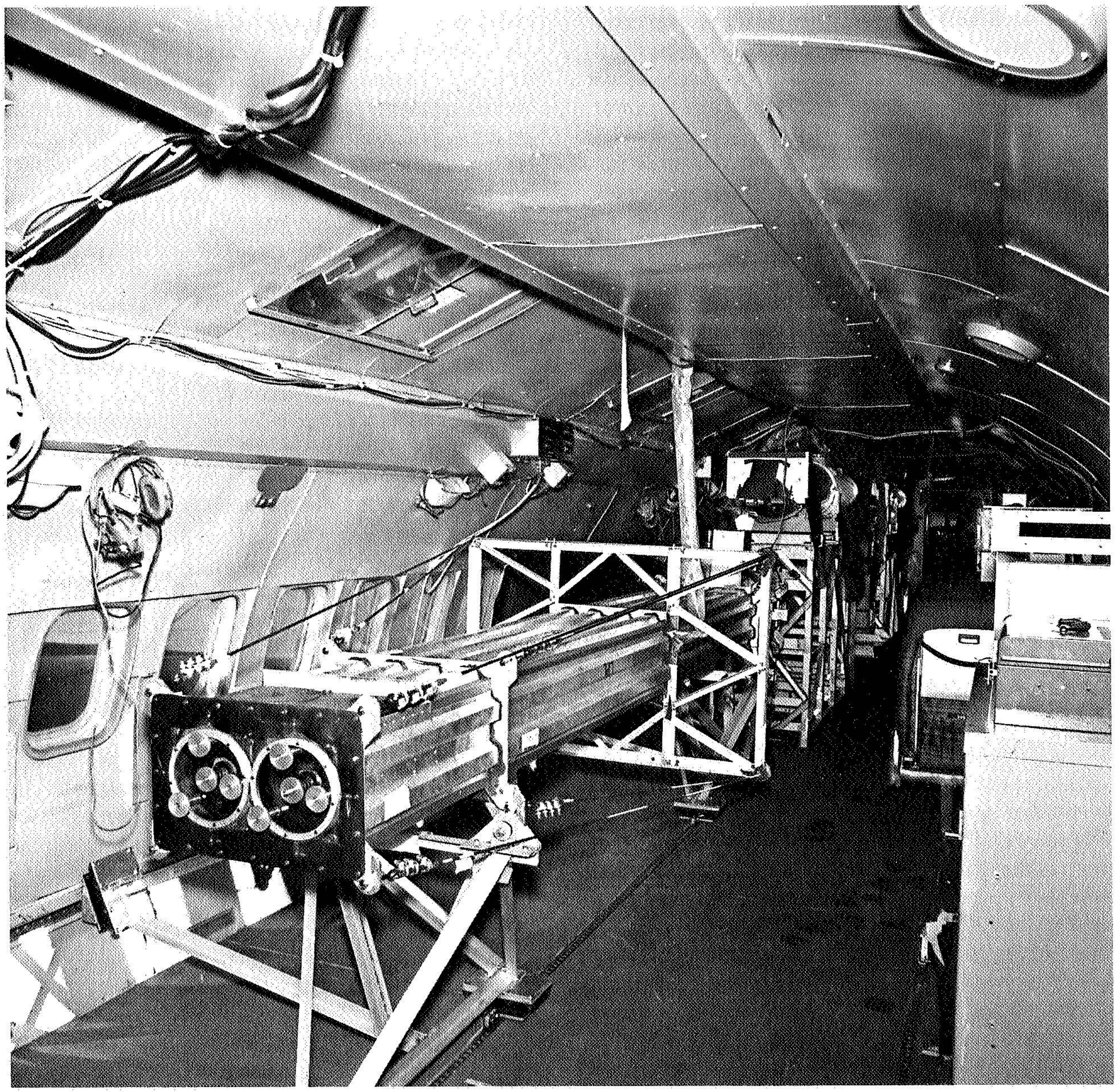

Fig. 1a 4.2-meter solar spectrometer in NASA CV-990 Jet, with 12-inch feeder telescope beyond. Note shock-mount attachments to seat rail; central extended frame with 8 cables for keeping heavy end-plates of spectrometer parallel. Vertical tube supplying dry outside air to spectrometer seen beyond central frame. Adjustment screws at left, control focus and orientation of collimator and camera mirrors. (NASA Photograph)

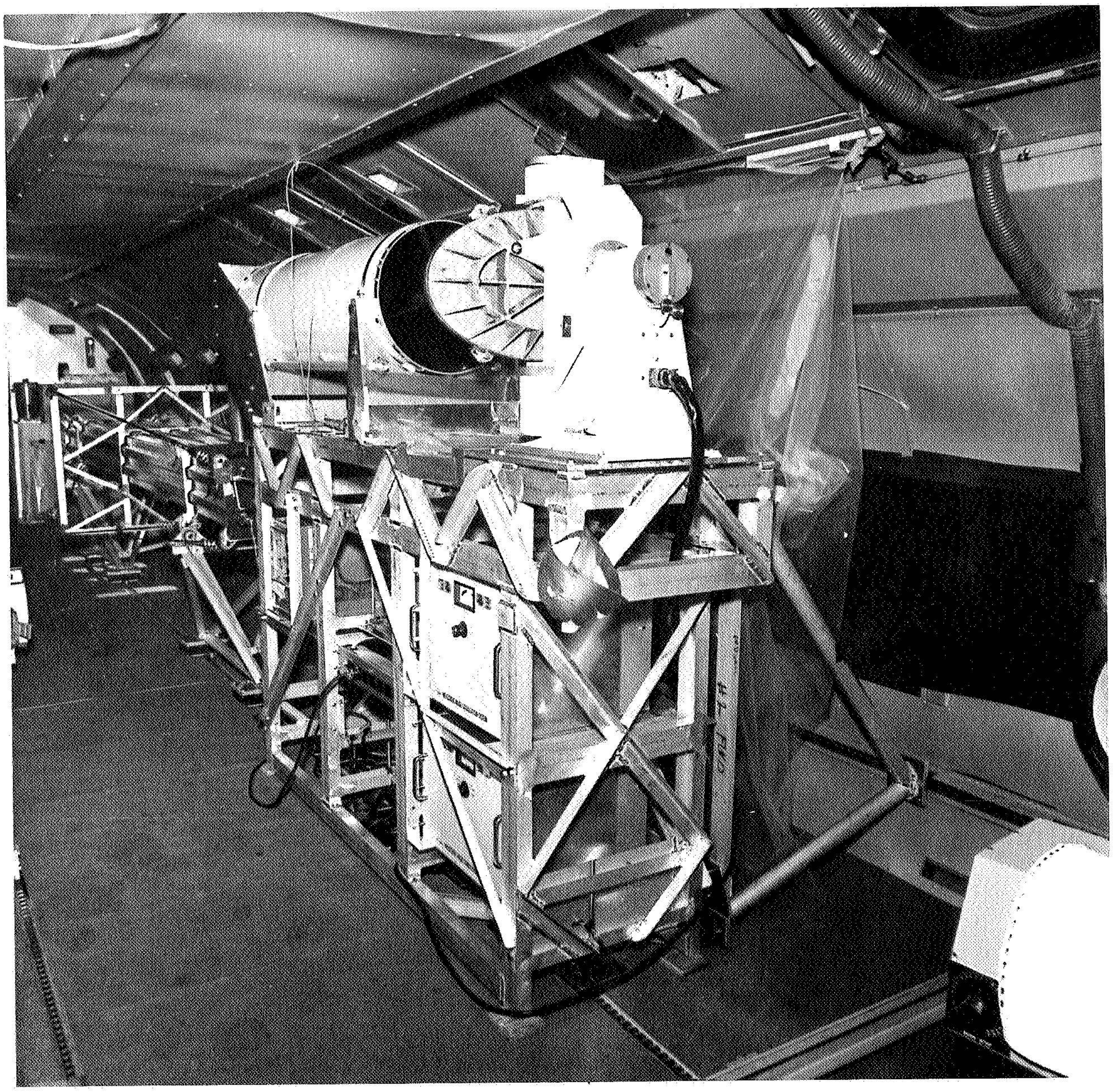

Fig. 1b 12-inch horizontal Cassegrain telescope, fed with heliostat (elliptical mirror in white frame). Control of heliostat gyroscopic, with electronics in rack below. Optical window, with safety covers front and back, above heliostat mount. 4-meter spectrometer beyond, at left. During operations entire unit enveloped in plastic sheet, ventilated with dry outside air. (NASA Photograph)

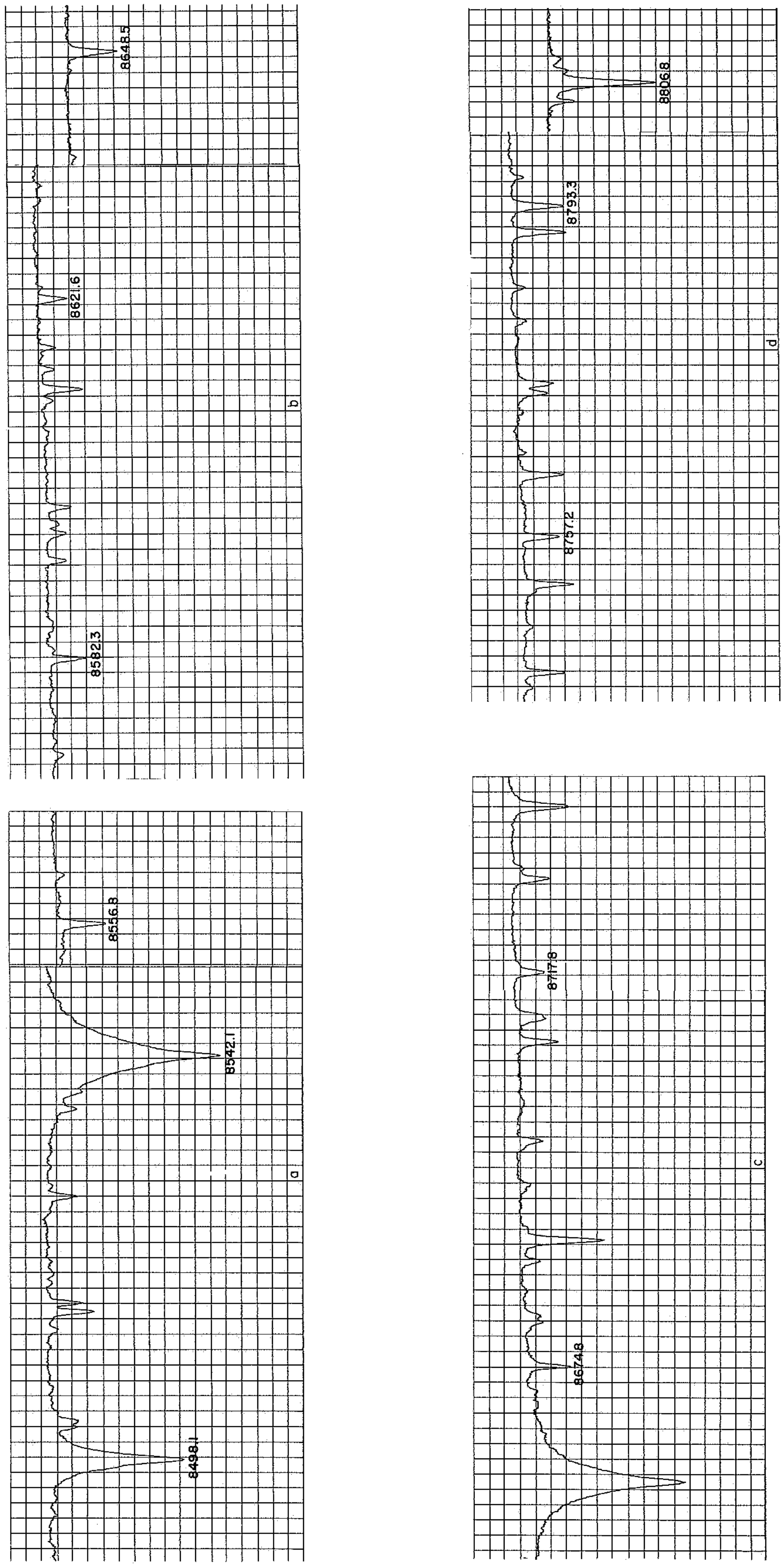

Fig. 2M Part of Michigan Atlas that matches Fig. 2. (2M–7M reproduced with permission)

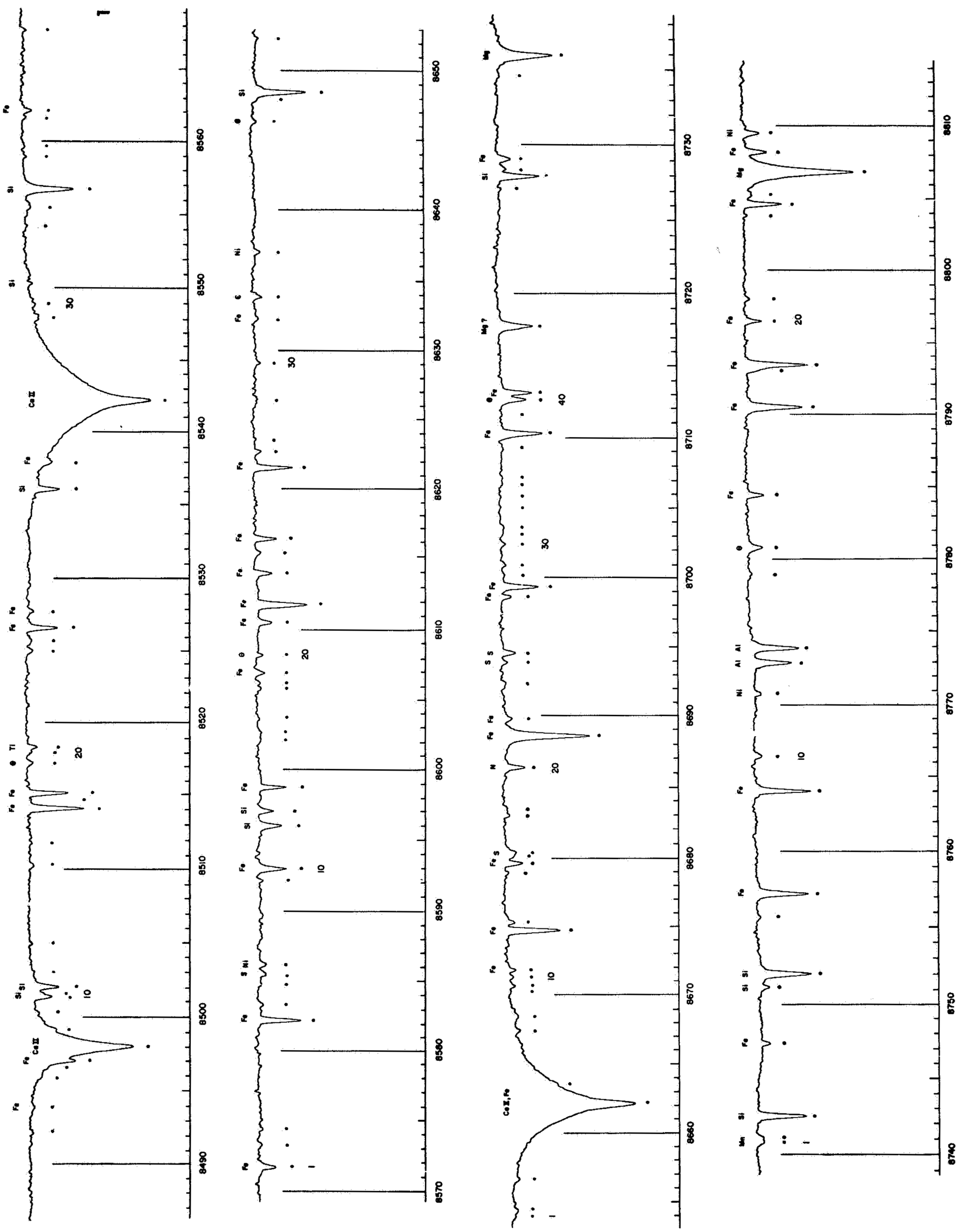

Fig. 2 Solar spectrum λλ8487–8815, in four strips (cf. Table 1).

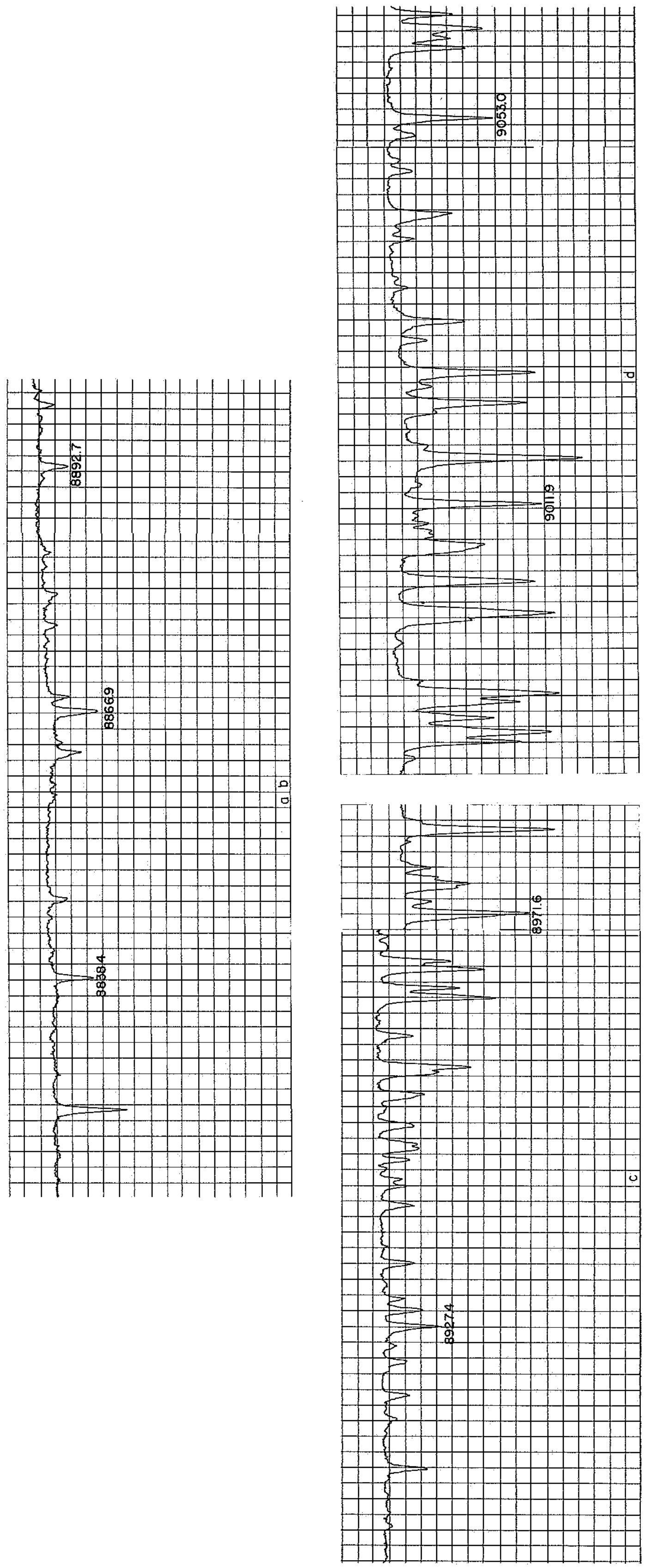

Fig. 3M Part of Michigan Atlas that matches Fig. 3.

Fig. 3 Solar spectrum λλ8814–9064, in four strips (cf. Table 1).

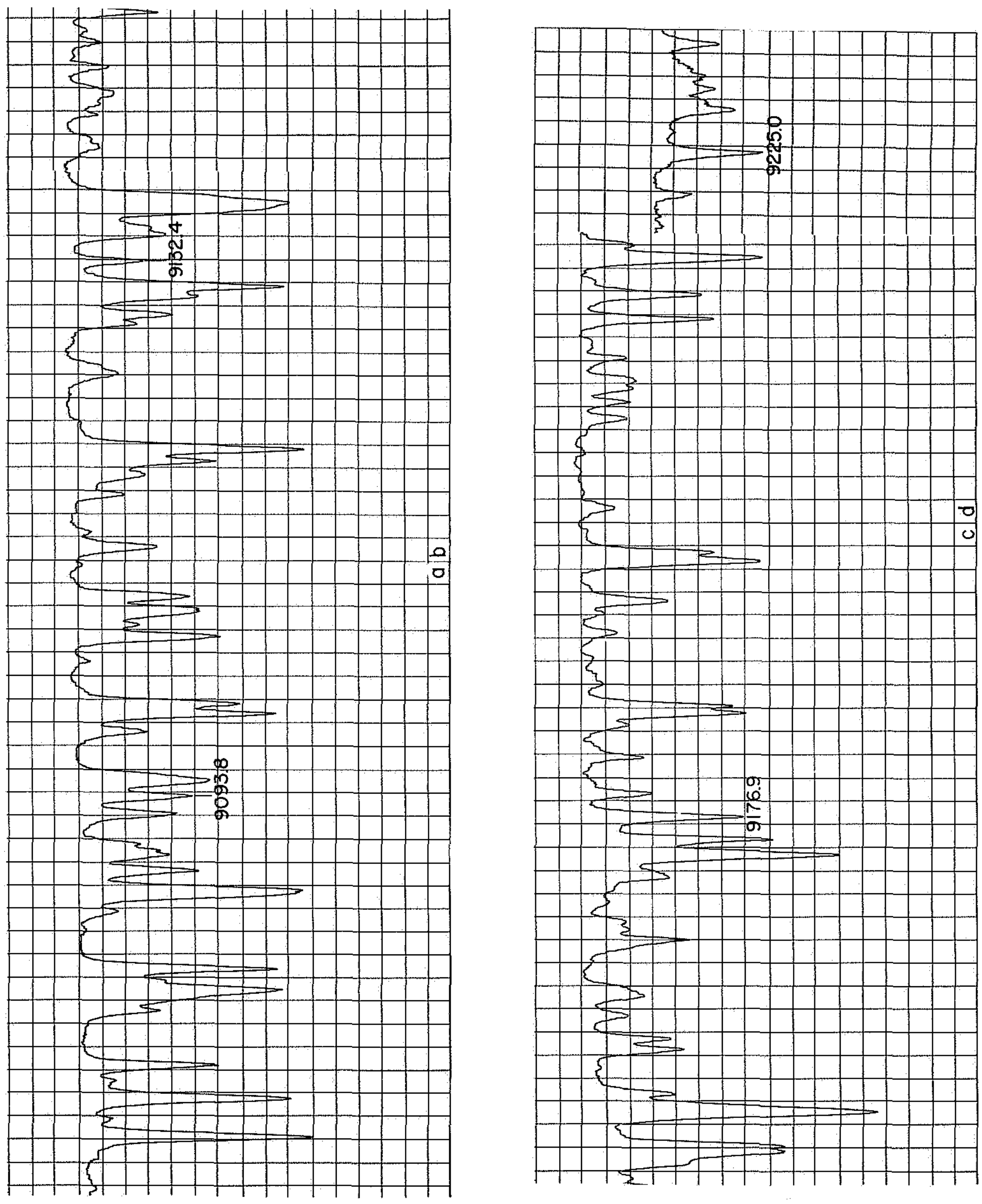

Fig. 4M Part of Michigan Atlas that matches Fig. 4.

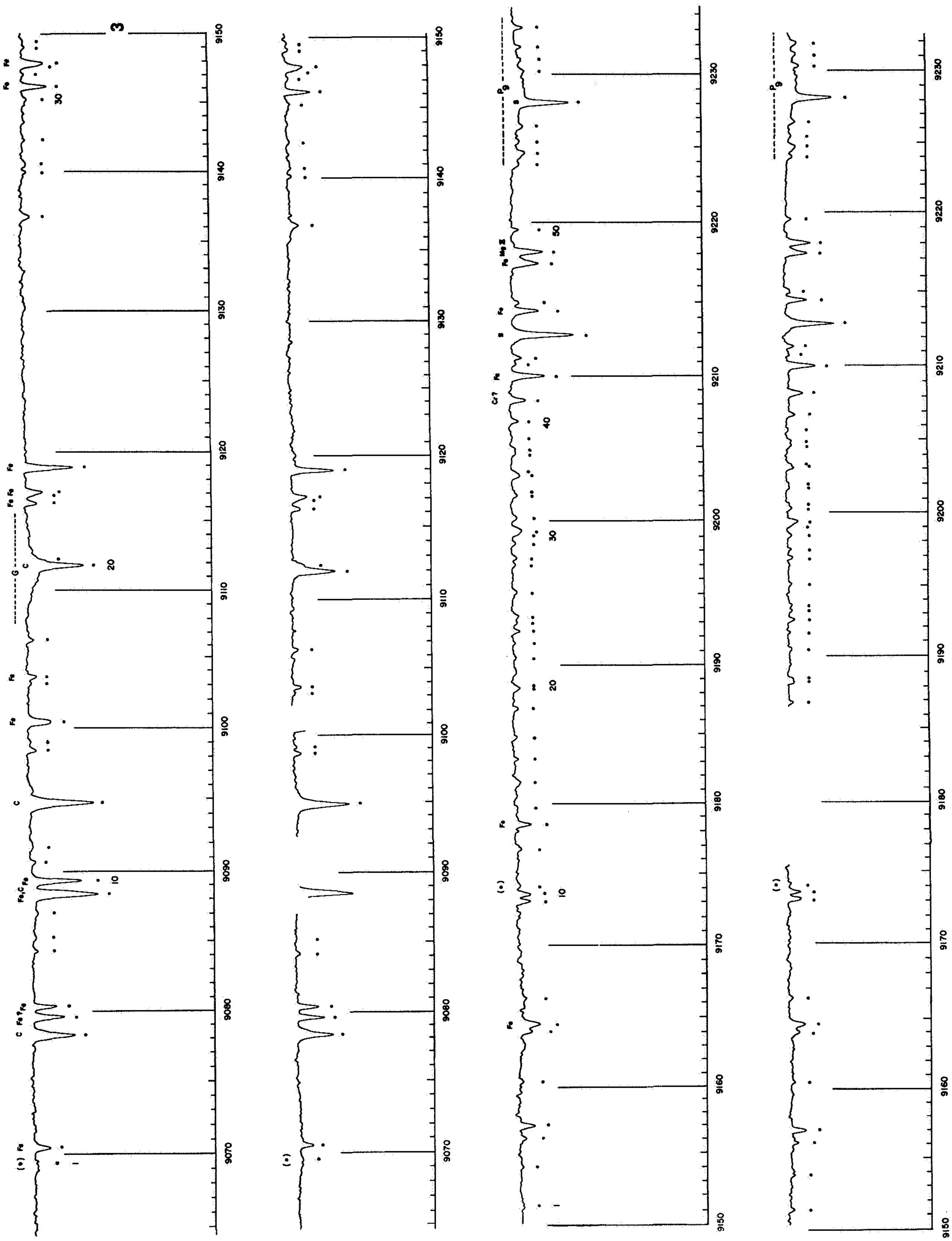

Fig. 4 Solar spectrum λλ9064–9234, in four strips (cf. Table 1).

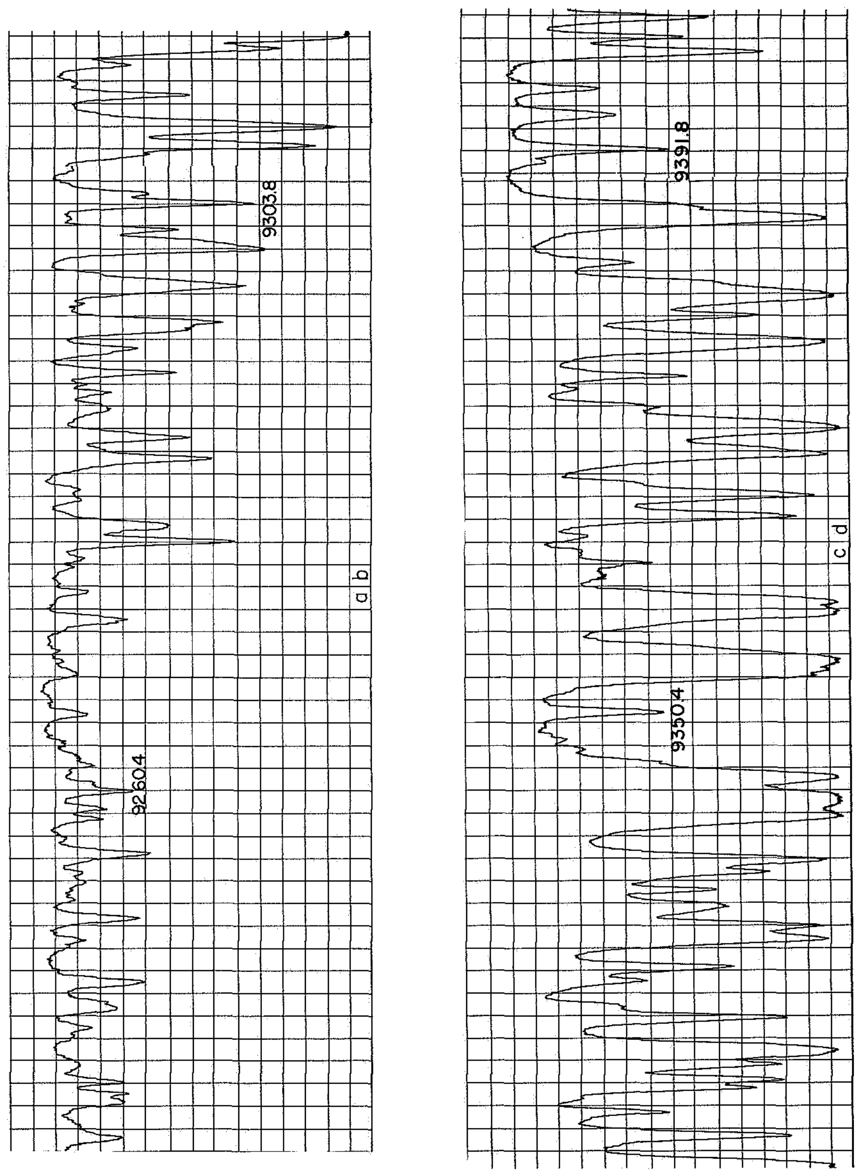

Fig. 5M Part of Michigan Atlas that matches Fig. 5.

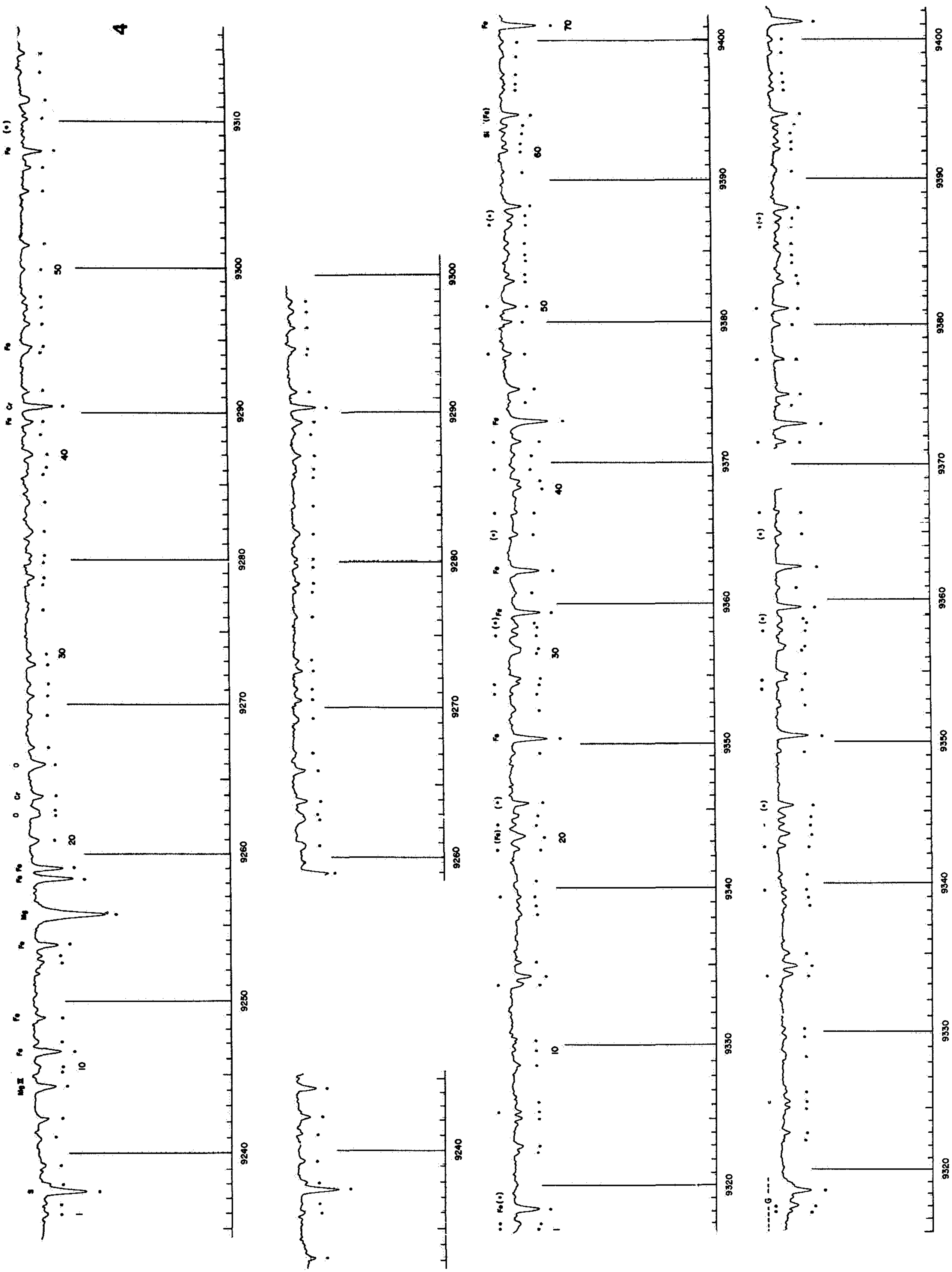

Fig. 5 Solar spectrum λλ9233–9402, in four strips (cf. Table 1).

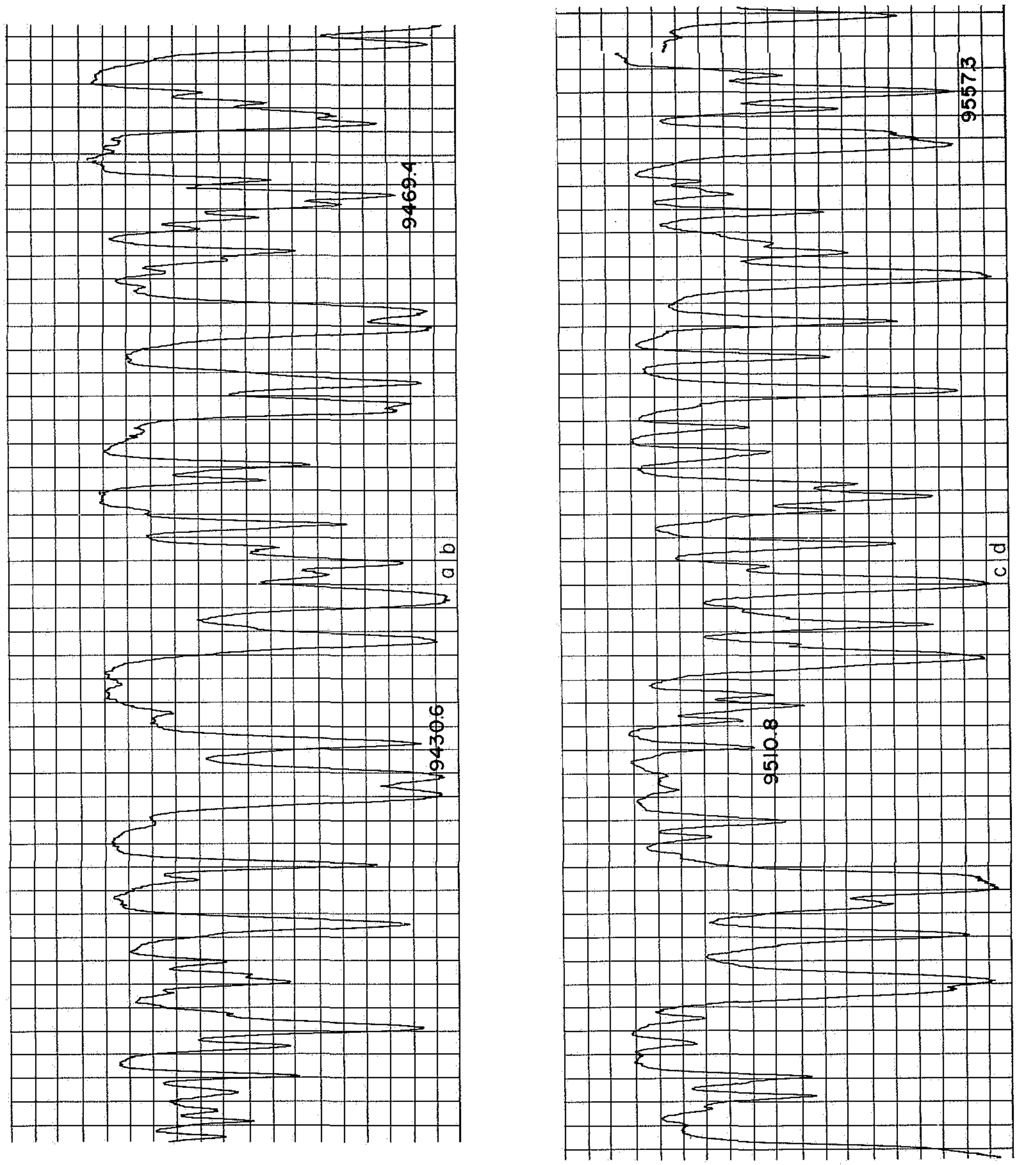

Fig. 6M Part of Michigan Atlas that matches Fig. 6.

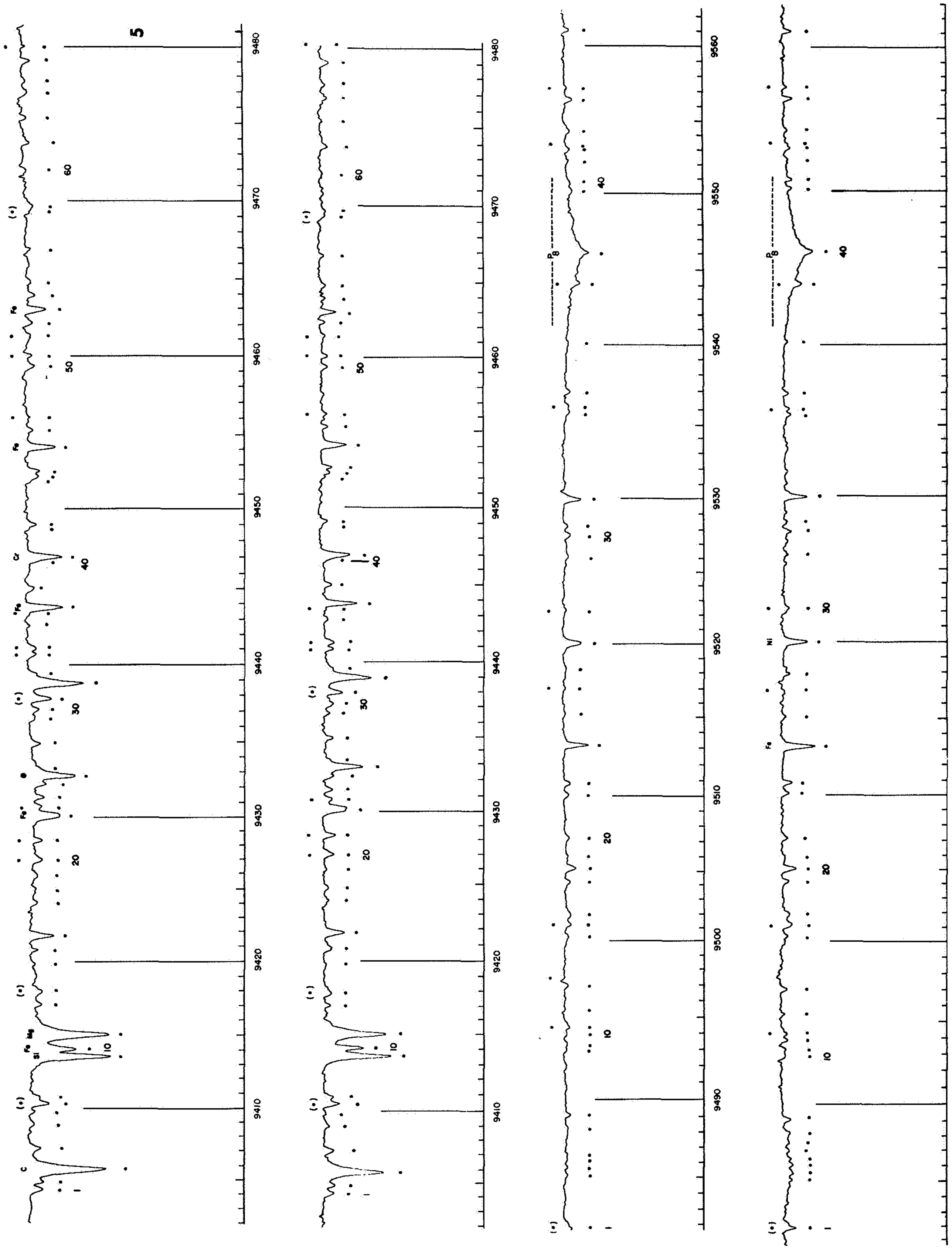

Fig. 6 Solar spectrum λλ9402–9563, in four strips (cf. Table 1).

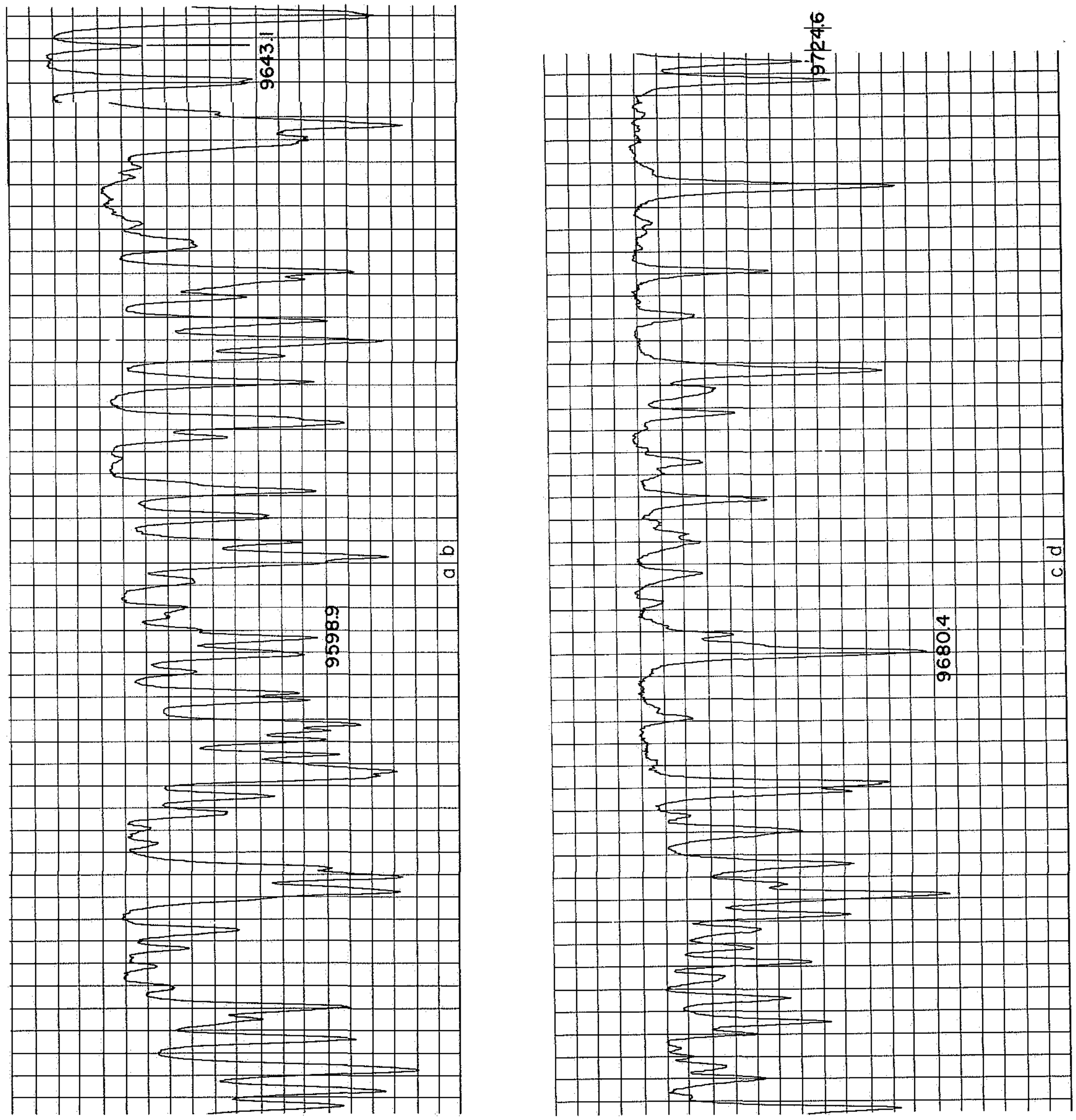

Fig. 7M Part of Michigan Atlas that matches Fig. 7.

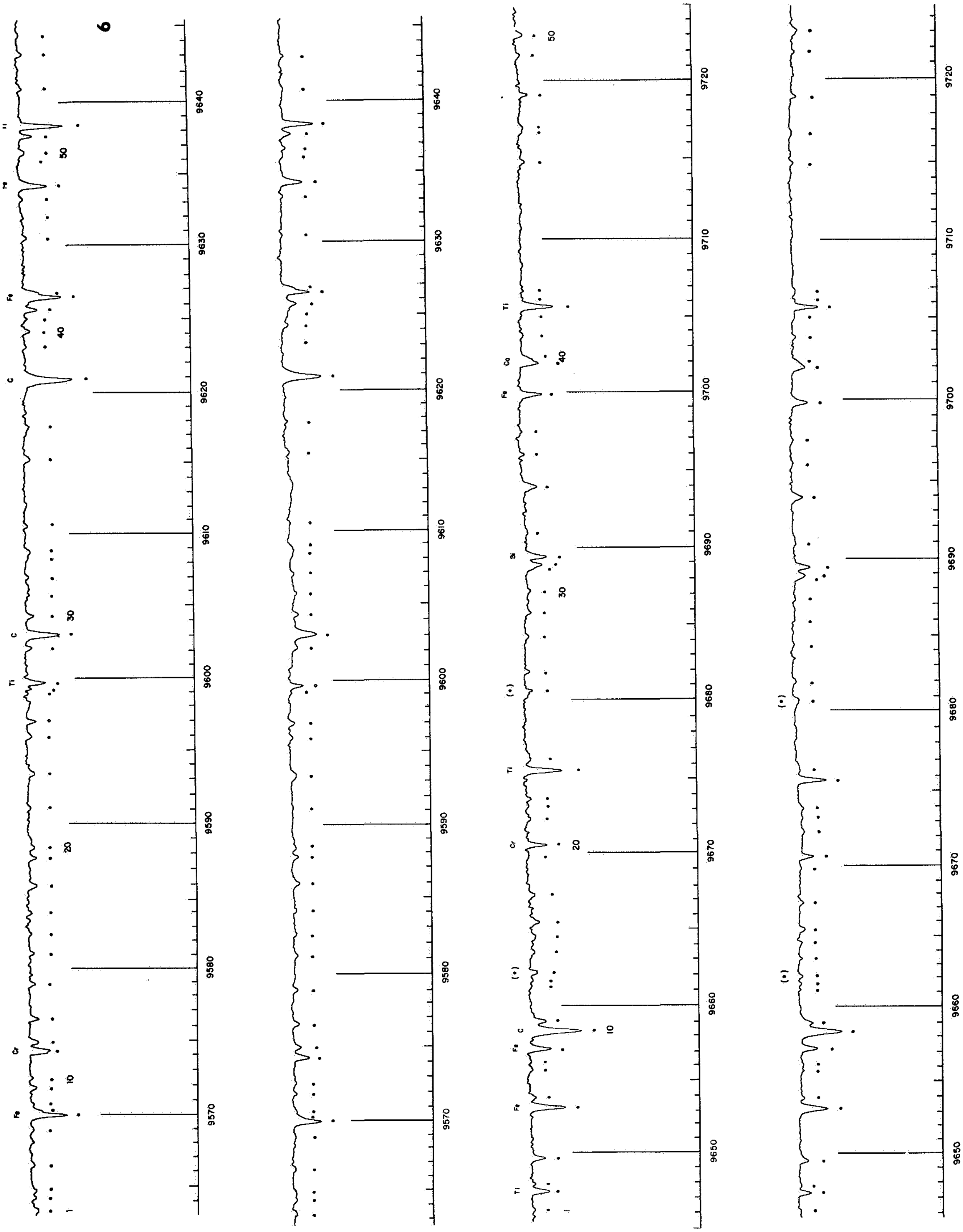

Fig. 7 Solar spectrum λλ9563–9725, in four strips (cf. Table 1).

solar flights is found in *Sky and Telescope,* October 1968, based on a University news release dated August 12, 1968. The nine operational flights were made on July 15, 17, 18, 19, 30, and August 1, 2, 6, and 7. All records were made on East-West flights somewhat south of the Canadian border, between Minnesota and Seattle, Washington, at latitudes to achieve solar elevations of 65° ± 2°.

Acknowledgments — We are greatly indebted to NASA Hq. and NASA-Ames, especially Dr. M. Bader and Mr. R. Cameron, for their interest in the high-altitude program and their invaluable advice and assistance throughout; to Mr. J. Percy for several design features of the electronics system in the vibrating aircraft and for his participation in about half the flights; to Mr. B. McClendon for assistance with the electronics during the other flights; and to Mr. C. Titulaer, Mr. A. Thomson, and Rev. G. Sill of LPL and Mr. D. Olsen of NASA-Ames for their important assistance during the flights in the solar guiding and the taking of spectral records. Mrs. A. Agnieray ably assisted in the preparation of the figures. This research was supported by NASA through Grant NsG 161-61 and the University of Arizona Institutional Grant NGR-03-002-091.

TABLE 1
SOLAR SPECTRUM RECORDS, 4.2-METER SPECTROMETER, NASA CV-990 JET

Fig.	λ(Å)	1968 Date	UT	Alt. (ft)	Temp. (°C)	Alt. (ft) Cabin	Gain
2. a	8487–8569	Aug 2	18:26	41,000	−57	8900	5-4
b	8569–8653	Aug 2	18:29	41,000	−57	8900	5-4
c	8653–8739	Aug 2	18:32	41,000	−57	8900	5-4
d	8739–8815	Aug 2	18:36	41,000	−57	8900	5-4
3. a	8814–8902	Aug 2	18:42	41,500	−57.5	8900	5-4
b	8815–8850	Aug 2	18:39	41,000	−57.5	8900	5-4
c	8902–8983	Aug 2	18:45	41,500	−57.5	8900	5-4
d	8983–9064	Aug 2	18:48	41,500	−57.5	8900	5-(4, 3)
4. a	9064–9150	Aug 6	20:31	41,000	−57.5	8900	5-2
b	9064–9150	Aug 2	18:52	41,500	−57.5	8900	5-3
c	9150–9234	Aug 6	20:34	41,000	−57.5	8900	5-2
d	9150–9232	Aug 2	18:56	41,500	−57.5	8900	5-3
5. a	9234–9316	Aug 6	20:38	41,500	−59	8800	5-2
b	9232–9300	Aug 2	18:59	41,500	−57	8900	5-3
c	9316–9402	Aug 6	20:42	41,500	−59	8800	5-2
d	9315–9402	Aug 2	19:02	41,500	−57	8900	5-3
6. a	9402–9481	Aug 6	20:45	41,500	−59	8800	5-2
b	9402–9480	Aug 2	19:05	41,500	−57	8900	5-3
c	9481–9563	Aug 6	20:48	41,500	−59	8800	5-1
d	9480–9563	Aug 2	19:08	41,500	−57	8900	5-3
7. a	9563–9645	Aug 2	19:11	41,500	−57	8900	5-3
b	9563–9646	Aug 6	20:51	41,500	−59	8800	5-1
c	9645–9725	Aug 2	19:14	41,500	−57	8900	5-3
d	9646–9725	Aug 6	20:55	41,500	−59	8800	5-1

No. 124 ARIZONA-NASA ATLAS OF INFRARED SOLAR SPECTRUM, REPORT II

by G. P. KUIPER, D. P. CRUIKSHANK, AND L. A. BIJL

November 10, 1968

ABSTRACT

This paper is a continuation of *LPL Comm.* 123 covering the interval λλ 10657-12857 Å. The arrangement is the same as in Report I.

In the interest of prompt publication, we are here reproducing Charts 7–15 of the Infrared Solar Spectrum Atlas. *LPL Comm.* No. 123 covers the region λλ 8487–9725 Å, much of it recorded twice. The original observing plan called for a continuous record to the longer wavelengths, but the region λλ 9758–10657 Å, which contains no strong telluric lines and which had been very well recorded in the Liège *Atlas,* had to be omitted when a second run of the important λ 9000 Å region became necessary because of heliostat troubles. Chart 7 begins with two short sections that continue the two parallel records of Chart 6. Thereupon, an unbroken record with the 1200-line grating is available from λ 10657–λ 12857 Å, recorded in two parts that overlap from λλ 12244–12314 Å. A small second gap (about 300 Å) follows, whereupon the 1200-line record continues to about 14400 Å, through the heavy part of the 1.4 μ water-vapor band. (This gap, again, was not planned, but had to be accepted as the flight schedule evolved; both gaps were covered, however, with lower resolution.)

In addition, the 600-line-per-mm grating records start at 12188 Å and continue without break to λ 29000 Å, continued in turn with 300-line/mm grating coverage to about 33000 Å (cf. *LPL Comm.* No. 125).

The present report covers the interval λλ 10657–12857 Å with the 1200-line/mm grating. In this region precise wavelength calibrations did not present major problems. Up to λ 12016 the Liège *Atlas* could be used, supplemented by laboratory spectra of the 11350 Å water-vapor band and of the 12055 and 12206 Å CO_2 bands, roughly matching the intensities in our solar spectra. These laboratory spectra were kindly obtained by Dr. Uwe Fink and Mr. A. Thomson. Beyond the λ 12016 Å limit, the *Table of Solar Spectrum Wavelengths, 11984 Å–25578 Å* by O. C. Mohler (1955) was used almost exclusively.

Both sources proved invaluable also in the verification of some of the *weaker lines* shown on our spectra. Normally, duplicate records would have served that purpose, and some regions were indeed recorded twice. In general, the flight schedules did not permit this, however. (Before the final *Atlas* is issued, it is expected that new solar spectra will have become available taken on a very dry mountain.) The weakest lines recorded in the present solar spectra have about 0.005 Å equivalent width.

The *resolving power* may be tested on Chart 14 where narrow lines occur. The pair at λ 12648, $\Delta\lambda = 0.30$ Å, is well separated; the pair at λ 12621, $\Delta\lambda = 0.21$ Å, is seen as a pair; the pair at λ 12680, $\Delta\lambda = 0.15$ Å, is seen only as a blend. Hence $\Delta\lambda = 0.21$ Å is the limit of resolution; or $R \simeq 60{,}000$.

On Charts 7, 9, 10, and 15 five small regions occur (marked *g*) where the continuum was slightly depressed by minor guiding errors, noted at the time when the observations were made (due to drift of the solar image on the slit). On Chart 13 during a few brief moments overhead cirrus was noted, as indicated on the Chart, and apparently responsible for a few weak spurious absorptions.

The observing procedures have been described in *LPL Comm.* No. 123. The chart numbers used here, 7–15, continue from LPL 123 so that they can be retained in the final *Atlas*. The relevant data are listed in Table 1. The observations were made by the first two authors, assisted by Mr. A. Thomson and Rev. G. Sill. The wavelength scales were derived independently by Mr. Bijl and Dr. Kuiper. The laboratory H_2O records mentioned proved so useful in the identification work (because of the line intensities) that they are reproduced in the *Addendum*. Comparison charts of the Michigan *Atlas* are again included, to clarify the gains obtained at the 200-mb level; though the precision of the 1950 records has obviously been greatly improved upon in the unpublished traces used in O. C. Mohler's 1955 *Table* (which includes lines too weak to be seen in our spectra).

The comparisons with the ground-based records have shown some classifications in the Babcock-Moore catalogue (1947) to require revision. Since identification work on solar lines is proceeding, we are listing in Table 2 some of the stronger "solar" or "probably solar" lines from that catalogue that are absent from our spectra and are therefore telluric. On the other hand, strong solar (not "atmospheric") lines, not recorded before, are found at $\lambda\lambda$ 11018, 11130, 11188, 11197, 11251, 11253, 11255, 11290, 11299, 11330, 11486, and 11700 Å; and numerous weaker lines, as indicated by the dots on our charts.

On the bottom strip of Chart 8, very faint water-vapor lines have been indicated to assist comparisons with ground-based records. Normally, we have omitted reference to the telluric component of a blend *if its contribution is less than one-fourth of the equivalent width of the combined feature*. Exceptions are $\lambda\lambda$ 11127, 11134, and 11149, where the water-vapor contribution is less than one-fourth, but where its presence is nevertheless indicated above the spectrum to facilitate comparisons with the Liège *Atlas*. There is a question about λ 11276; it is possible that it is *all* due to H_2O (Dr. Kuhn of ESSA, who recorded the integrated water-vapor content of the atmosphere above the aircraft, reported changes during our observations).

In the Charts, we have identified telluric absorptions by symbols *above* the records: H_2O by *dots*, O_2 (1.07 μ, 1.25–1.28 μ) and CO_2 (1.20 and 1.22 μ) by lines. The identifications by element were taken from the Babcock-Moore catalogue, as before, and the Mohler *Table*.

After the August 2, 1968 solar observations had been completed, a comparison record was made of H_2O absorption in the spectrometer itself. The conditions were not entirely identical, since for safety reasons (brittle optical windows) the flight altitude had already been decreased from 41,500 ft to 35,000 ft and the cabin pressure changed from 9900 ft to 6900 ft. Both changes will have increased the H_2O intensities. Nevertheless, the absorptions in the λ 11300 band were negligible. *The water-vapor intensities in the solar Charts are therefore almost entirely (> 90%) due to the overlying atmosphere, not the cabin.* For CO_2 and O_2 the cabin contribution (path $\sim$22 meters, p $\sim$750 mb) is about 1 percent in the number of molecules and about the same in the absorptions (the lines being weak).

It is noted that the H_2O absorptions are *narrower* than those in the laboratory spectra in the Addendum, apparently because of the much lower atmospheric pressure (< 200 mb) and temperature ($T \sim -54°C$).

Acknowledgments. As before, we wish to record our indebtedness to NASA Hq. and NASA-Ames for their interest in the high-altitude program; to Messrs. J. Percy and B. McClendon for assistance with the electronics during the flights; to Mr. A. Thomson and Rev. G. Sill of LPL and Mr. D. Olsen of NASA-Ames for their important assistance during the flights in the solar guiding and the taking of spectral records. Mrs. A. Agnieray again assisted in the preparation of the figures for publication. This research was supported by NASA through Grant

TABLE 1

SOLAR SPECTRUM RECORDS, 4.2-METER SPECTROMETER, NASA CV-990 JET
1 μ GRATING (1200 LINES/MM), SLIT AND CELL 0.10 MM, $\tau = .12$ SEC.

FIG.	CHART	λ (Å)	1968 DATE	UT	ALT. (FT)	TEMP. (°C)	CABIN ALT. (FT)	GAIN
1	7. a	9725– 9758	Aug 2, 6	19:18, 20:57	41,500	−57, −59	8900	5–3, 1
	b	10657–10731	Aug 2	19:27	41,500	−57	8900	5–3
	c	10731–10807	Aug 2	19:31	41,500	−57	8900	5–3
	d	10807–10880	Aug 2	19:34	41,500	−57	8900	5–3
2	8. a	10880–10955	Aug 2	19:38	41,500	−56	8900	5–3
	b	10955–11031	Aug 2	19:41	41,500	−56	8900	5–3
	c	11031–11104	Aug 2	19:45	41,500	−56	8900	5–3
	d	11104–11177	Aug 2	19:49	41,500	−56	8900	5–3
3	9. a	11177–11250	Aug 2	19:52	41,500	−54	9900	5–3
	b	11250–11321	Aug 2	19:55	41,500	−54	9900	5–3
	c	11321–11393	Aug 2	19:58	41,500	−52	9900	5–3
	d	11393–11467	Aug 2	20:01	41,500	−52	9900	5–3
4	10. a	11467–11539	Aug 2	20:04	41,500	−54	9900	5–3
	b	11539–11613	Aug 2	20:07	41,500	−54	9900	5–3
	c	11613–11686	Aug 2	20:11	41,500	−54	9900	5–3
	d	11686–11757	Aug 2	20:14	41,500	−54	9900	5–3
5	11. a	11757–11832	Aug 2	20:18	41,500	−54	9900	5–3
	b	11832–11904	Aug 2	20:21	41,500	−54	9900	5–3
	c	11904–11975	Aug 2	20:25	41,500	−54	9900	5–3
	d	11975–12047	Aug 2	20:28	41,500	−54	9900	5–3
6	12. a	12047–12114	Aug 2	20:31	41,500	−54	9900	5–3
	b	12114–12179	Aug 2	20:35	41,500	−54	9900	5–3
	c	12179–12247	Aug 2	20:39	41,500	−54	9900	5–3
	d	12247–12314	Aug 2	20:42	41,500	−54	9900	5–3
7	13. a	12244–12306	Aug 6	18:13	41,500	−58	8900	5–2
	b	12306–12369	Aug 6	18:16	41,500	−58	8900	5–2
	c	12369–12431	Aug 6	18:19	41,500	−58	8900	5–2
	d	12431–12494	Aug 6	18:22	41,500	−58	8900	5–2
8	14. a	12494–12556	Aug 6	18:25	41,500	−58	8900	5–2
	b	12556–12619	Aug 6	18:29	41,500	−58	8900	5–2
	c	12619–12678	Aug 6	18:32	41,500	−58	8900	5–2
	d	12678–12736	Aug 6	18:35	41,500	−58	8900	5–2
9	15. a	12736–12797	Aug 6	18:38	41,500	−58	8900	5–2
	b	12797–12857	Aug 6	18:41	41,500	−58	8900	5–2

TABLE 2

TELLURIC LINES PREVIOUSLY CLASSIFIED ☉ OR ☉?

λ	INT.	λ	INT.	λ	INT.	λ	INT.
10677.01	−1	11246.95	2	11569.96	0	11876.32	10 NN
10718.08	1	11278.21	−1	11605.31	7 *	11886.24	−2 N
10816.03	1 N	11280.03	0	11623.06	0 N	11897.22	−2 N
10858.36	−1	11285.05	0	11624.76	−1 N	11903.17	1 n
10890.13	−1	11364.08	−2 N	11630.50	1 N	11906.82	1 N
10909.20	1	11369.15	1 N	11671.80	−2	11916.25	−2
10910.97	−2	11508.00	3 N	11676.40	2 N	11916.85	−1 N
10917.14	1 N	11542.92	−1	11685.89	1	11918.02	0 N
10921.34	−1 N	11556.92	−1 N	11703.32	−1	11928.98	1 N
10950.86	1	11557.08	−1 N	11732.34	−1 N	11938.41	−2 N
10961.18	−2	11558.09	−1 N	11742.80	−2 NN	11943.90	0 n
11076.15	1	11559.00	−1 Nd	11744.78	−1 N	11951.72	0 n
11206.25	−1 N	11560.98	4	11746.09	0 N	11954.47	0
11230.17	−3 N	11562.90	−2 d	11797.55	0	11982.97	0 N
11239.9	−3 N	11563.69	0 N	11822.91	0 N		

*A solar line of −3 intensity is nearby.

Some intensity corrections are noted: λ 9753 Fe, + 1 (not −2); λ 10667 Cr, −1 (not +2); λ 11448, −1N (not 5N); λ 11645, −3 (not 0N). For 11633 Atm, read 11635. No corrections given beyond 11984 Å where the Mohler *Table* begins. Numerous classifications can now be added to this *Table* as well; the only serious correction found in the present spectral interval is at λ 12239.50, given as ☉Fe, but found to be atmospheric.

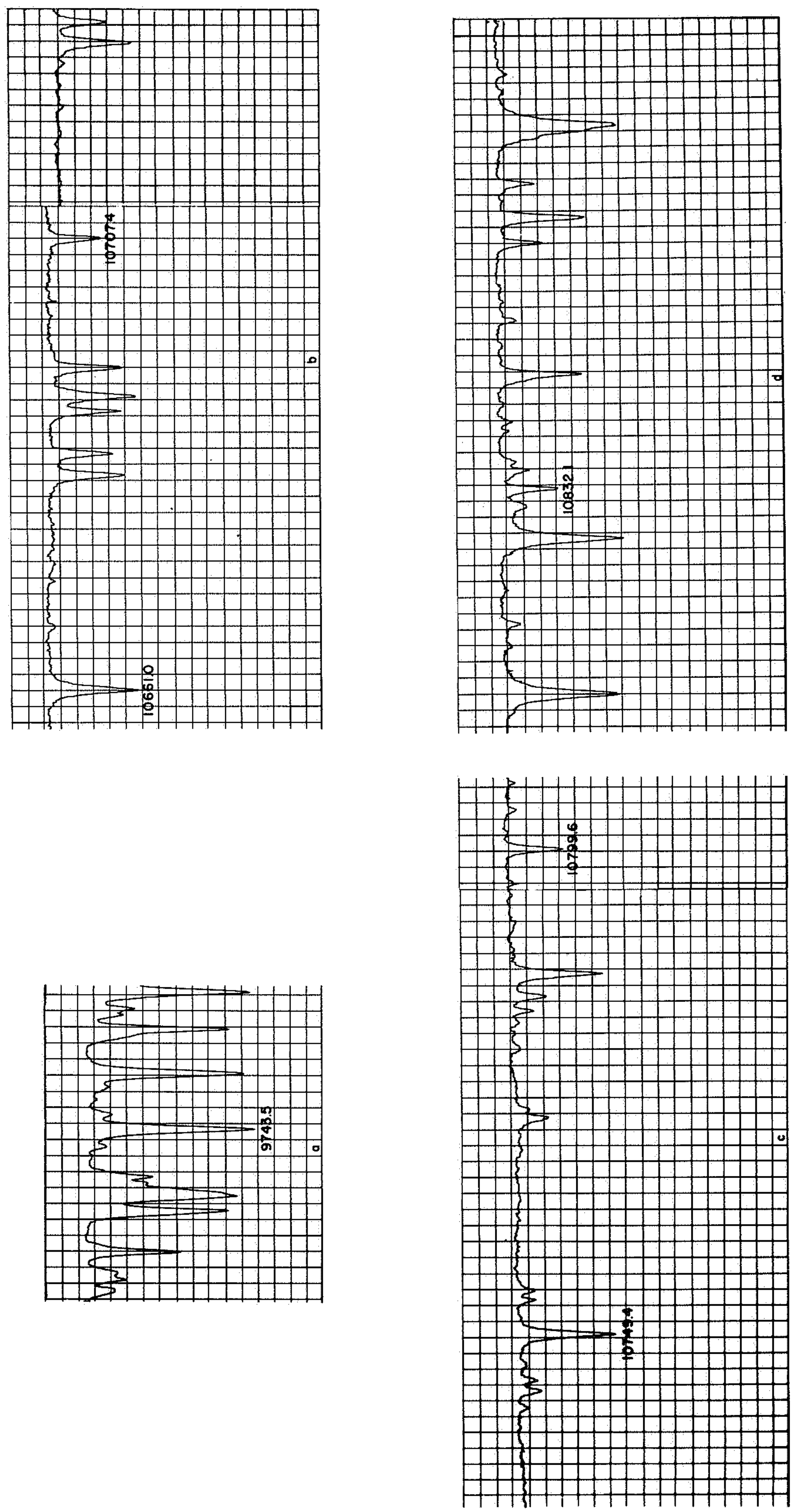

Fig. 1M Part of Michigan Atlas that matches Fig. 1 (1M–9M reproduced with permission).

Fig. 1 Solar Spectrum λλ 9725–9758 and 10657–10880, in four strips (cf. Table 1).

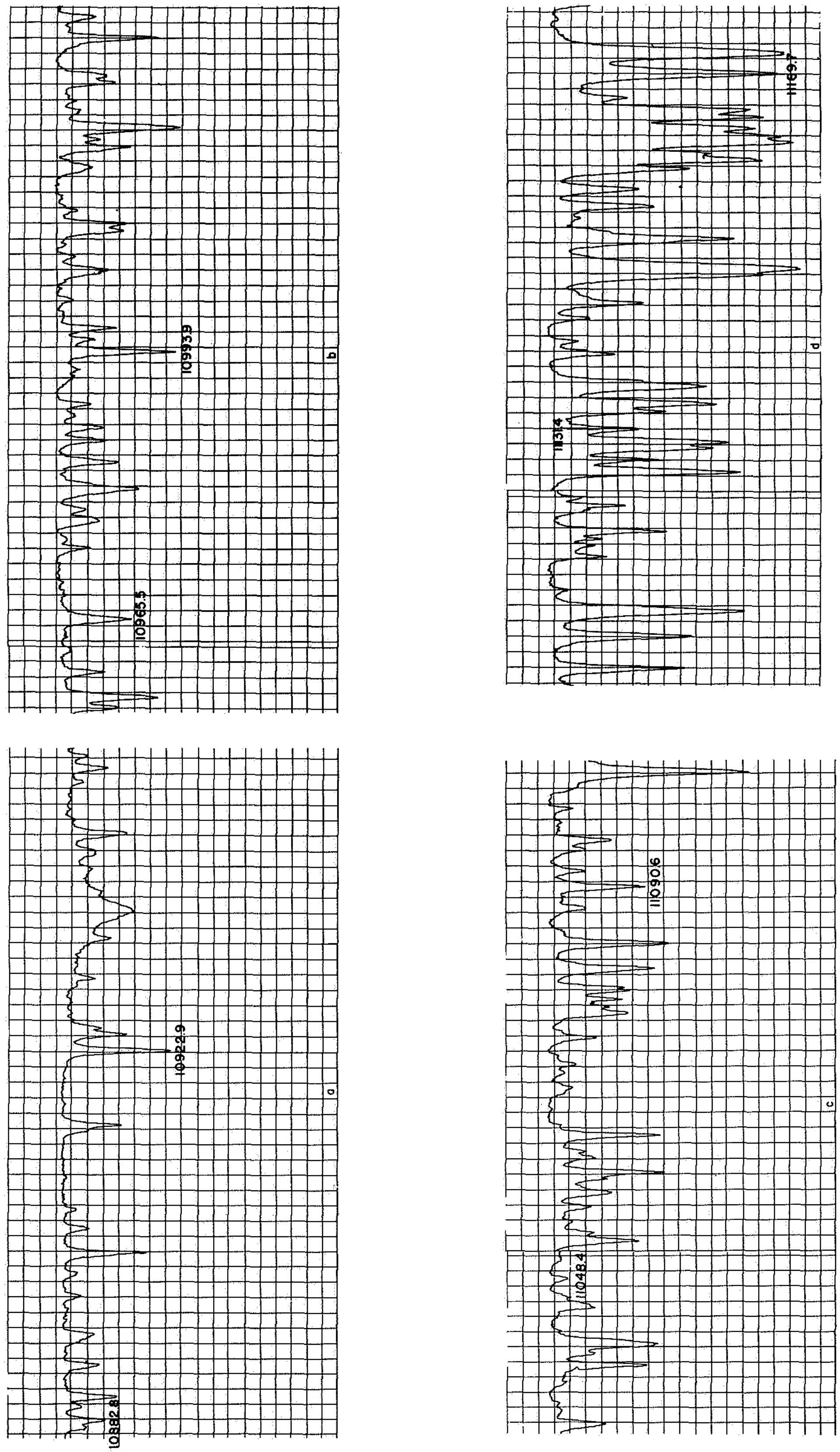

Fig. 2M Part of Michigan Atlas that matches Fig. 2.

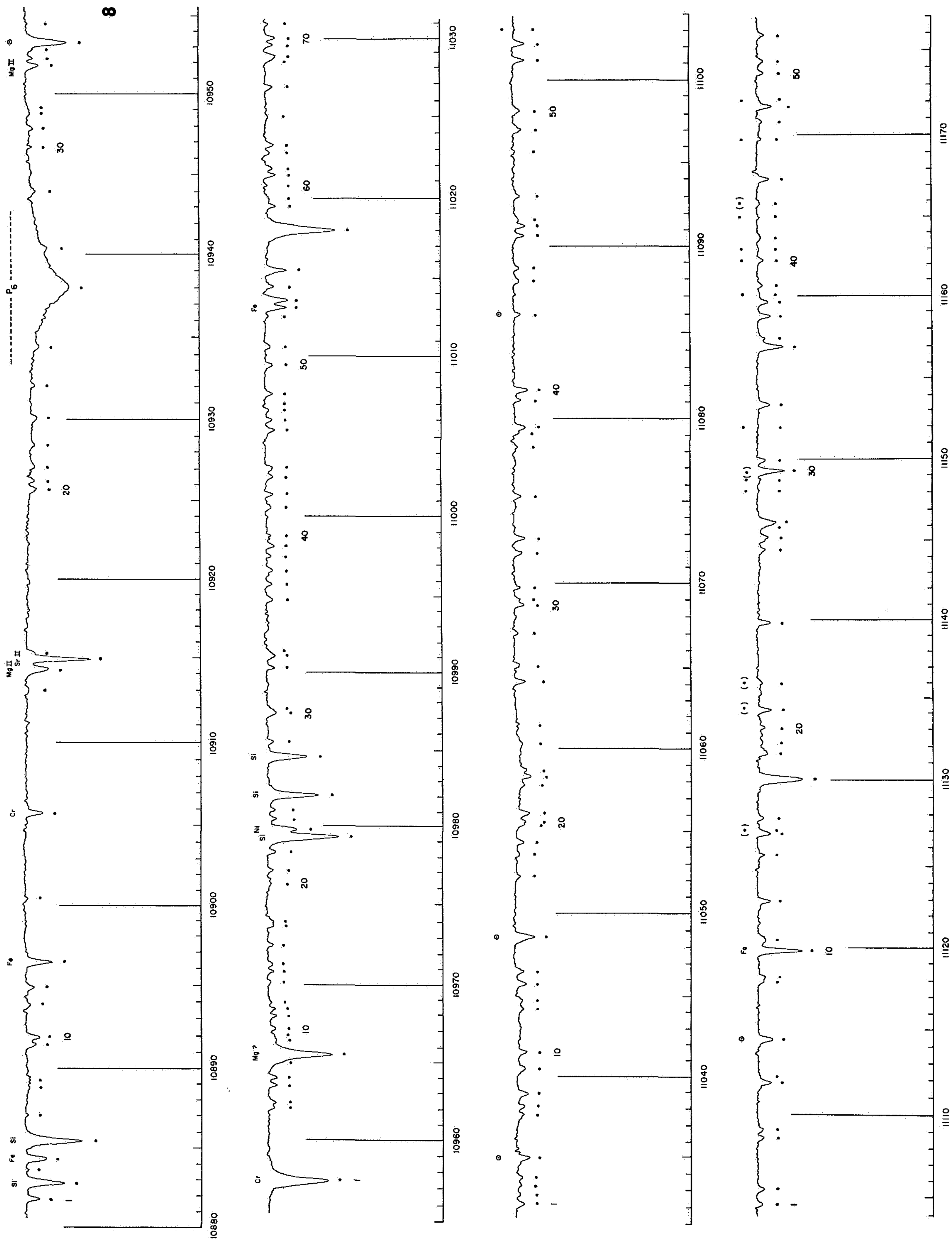

Fig. 2 Solar Spectrum λλ 10880–11177, in four strips (cf. Table 1).

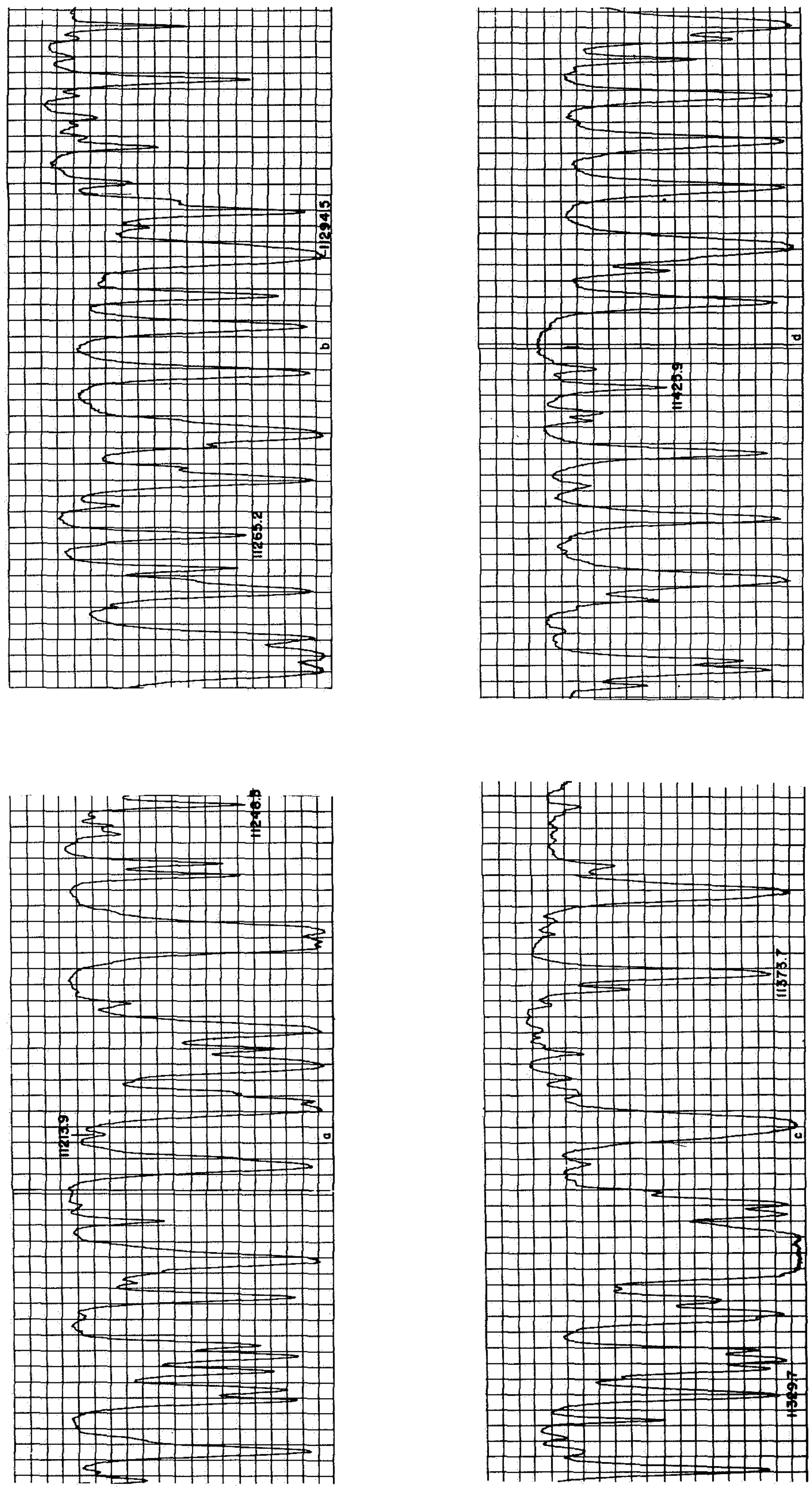

Fig. 3M Part of Michigan Atlas that matches Fig. 3.

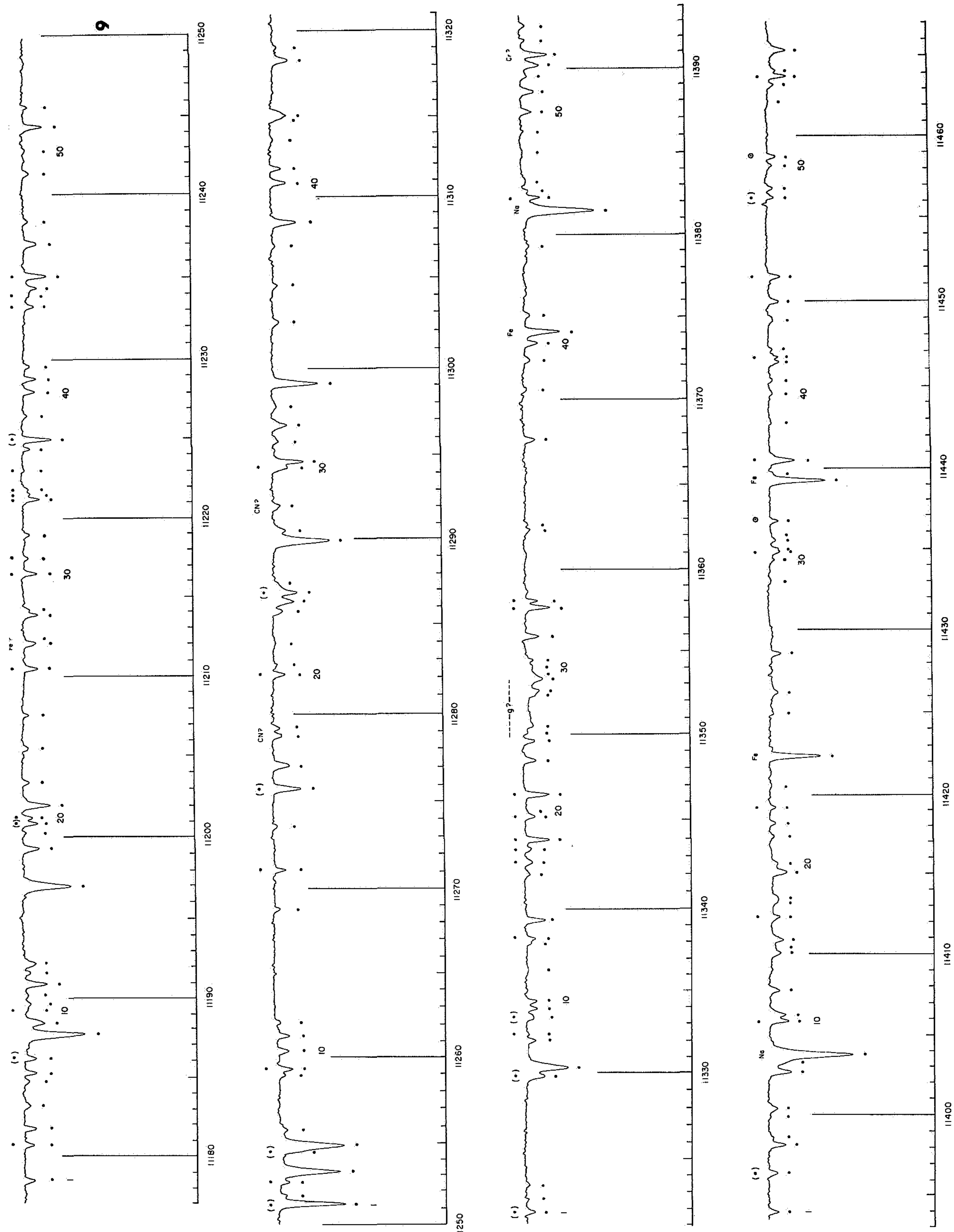

Fig. 3 Solar Spectrum λλ 11177–11467, in four strips (cf. Table 1).

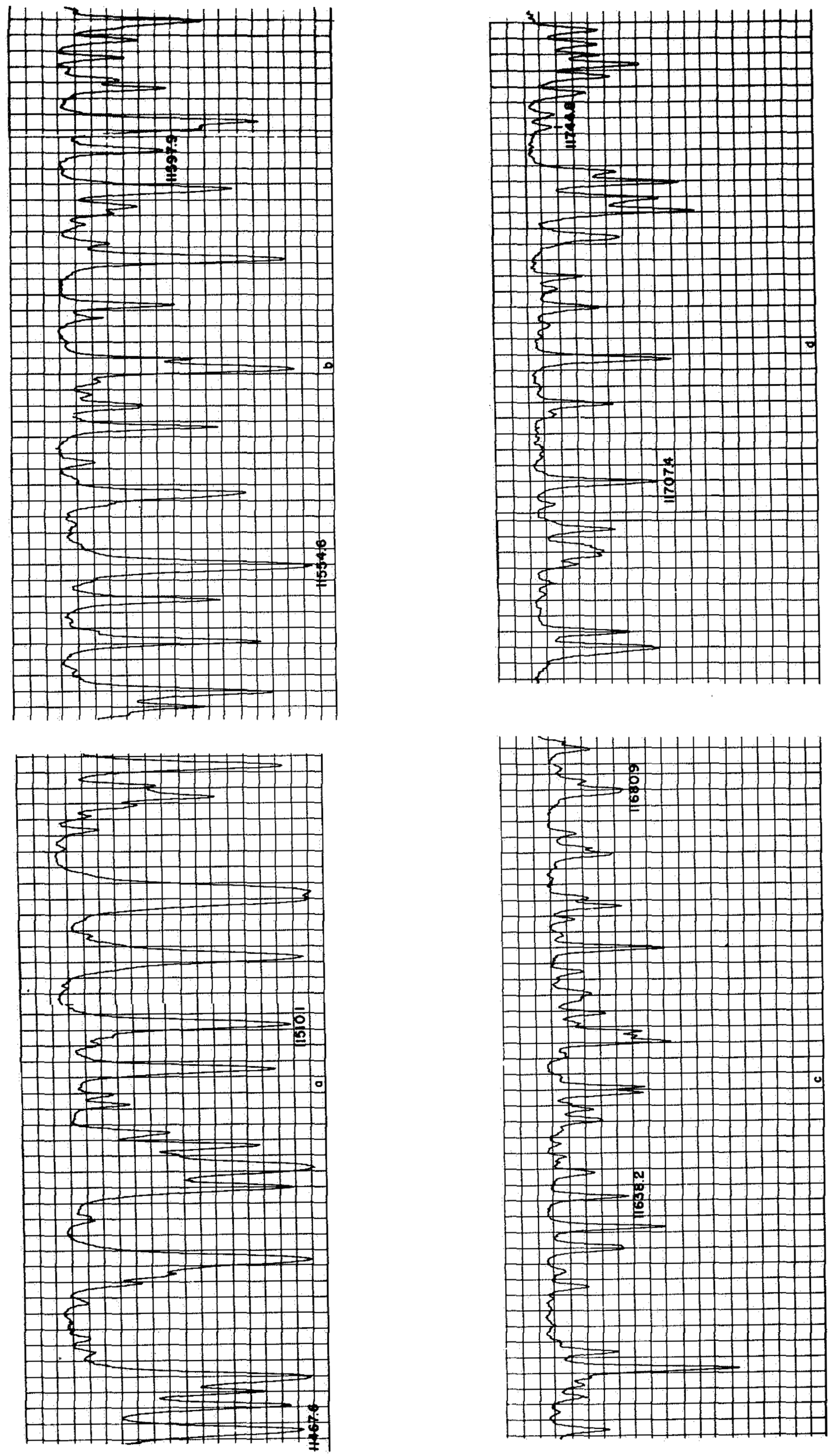

Fig. 4M Part of Michigan Atlas that matches Fig. 4.

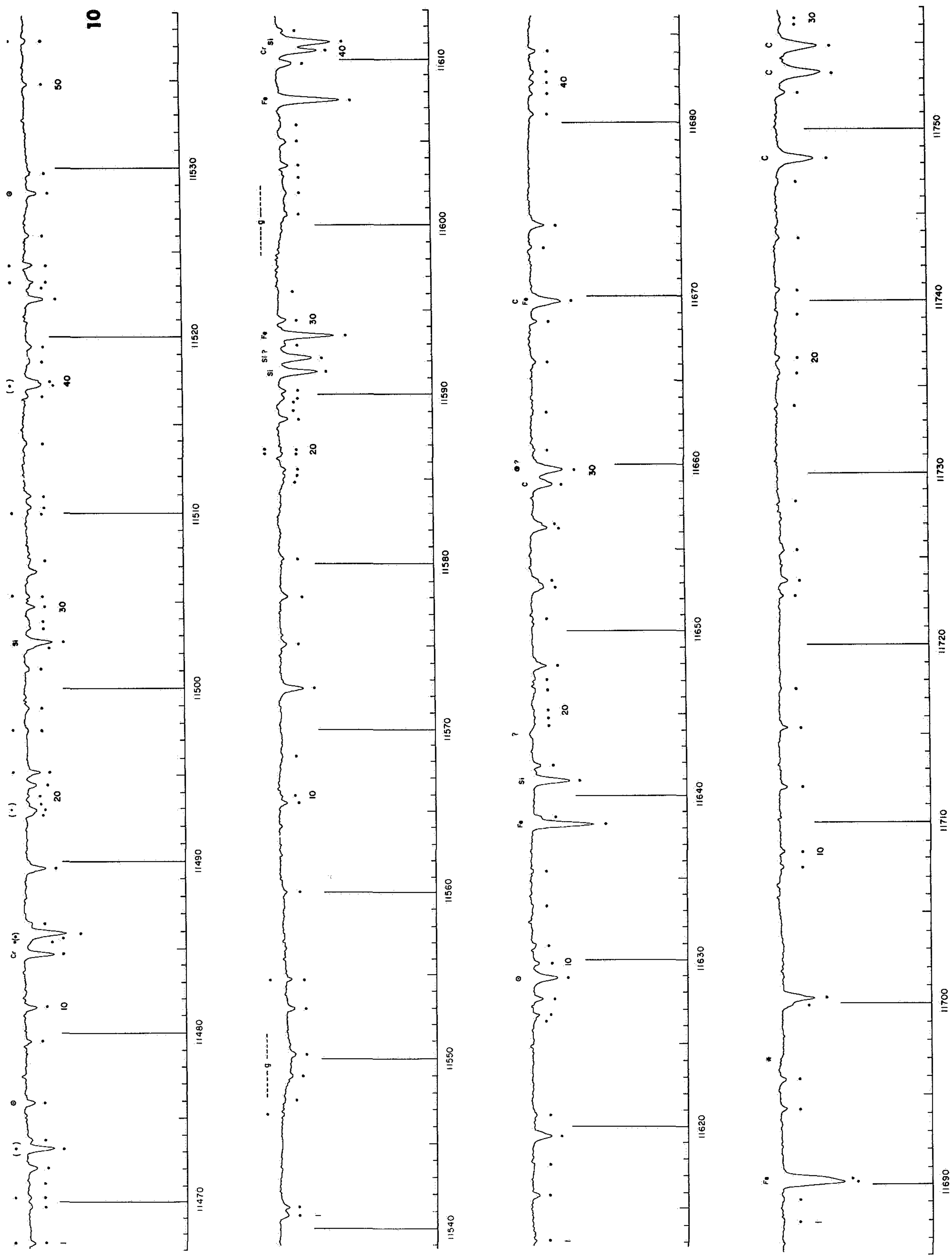

Fig. 4 Solar Spectrum λλ 11467–11757, in four strips (cf. Table 1). Asterisk indicates minor course change in aircraft (some vignetting).

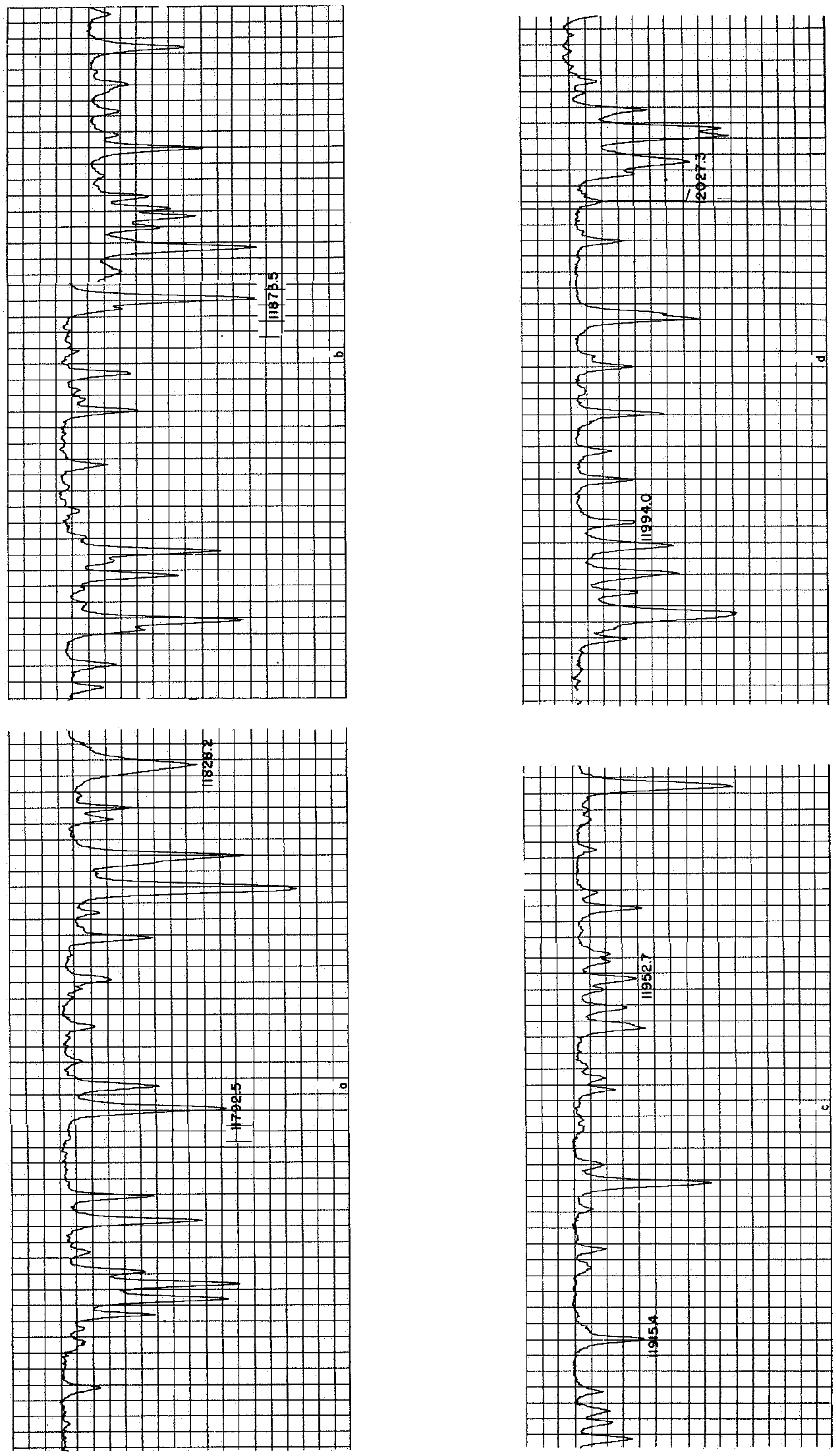

Fig. 5M Part of Michigan Atlas that matches Fig. 5.

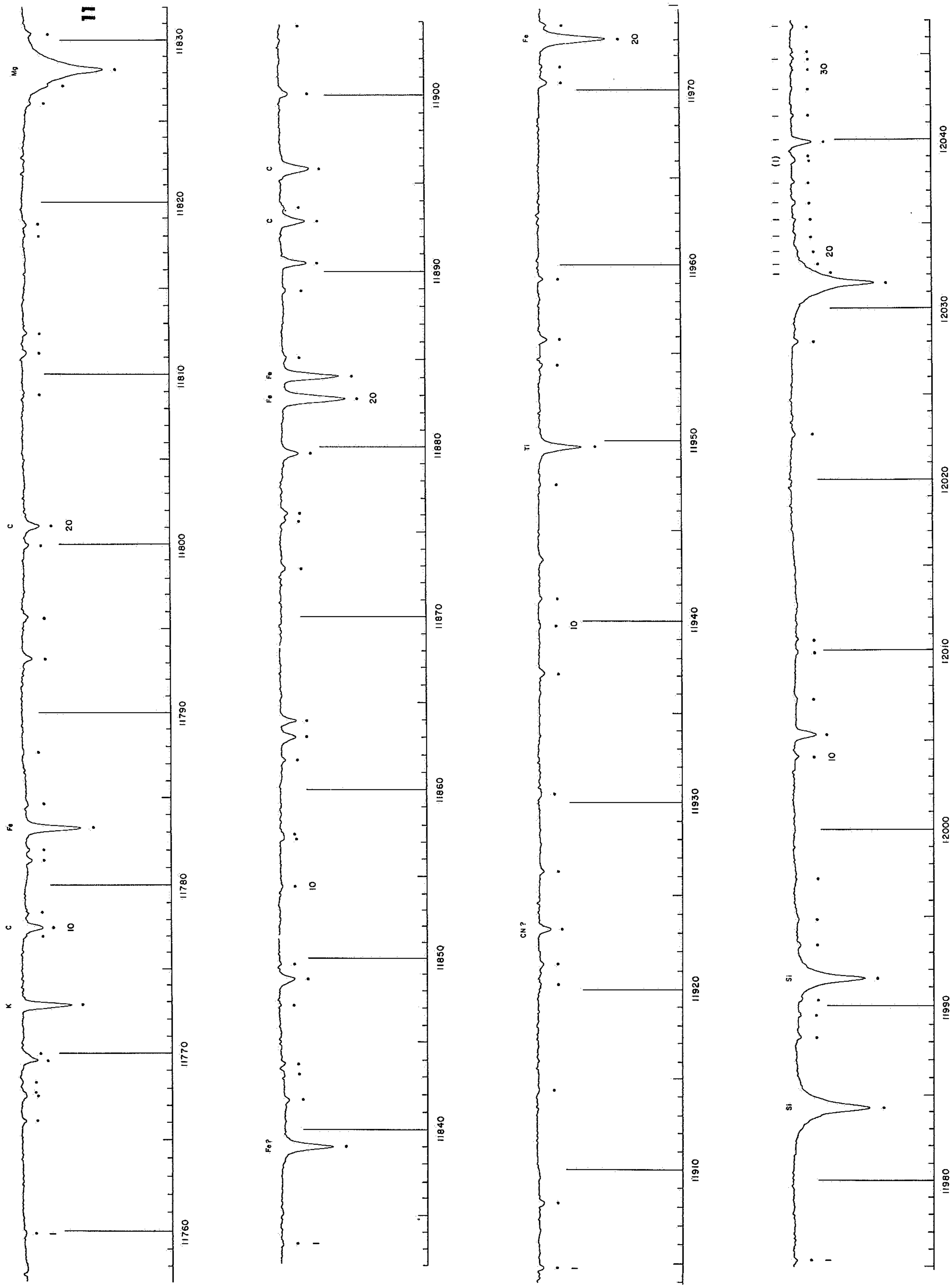

Fig. 5 Solar Spectrum λλ 11757–12047, in four strips (cf. Table 1).

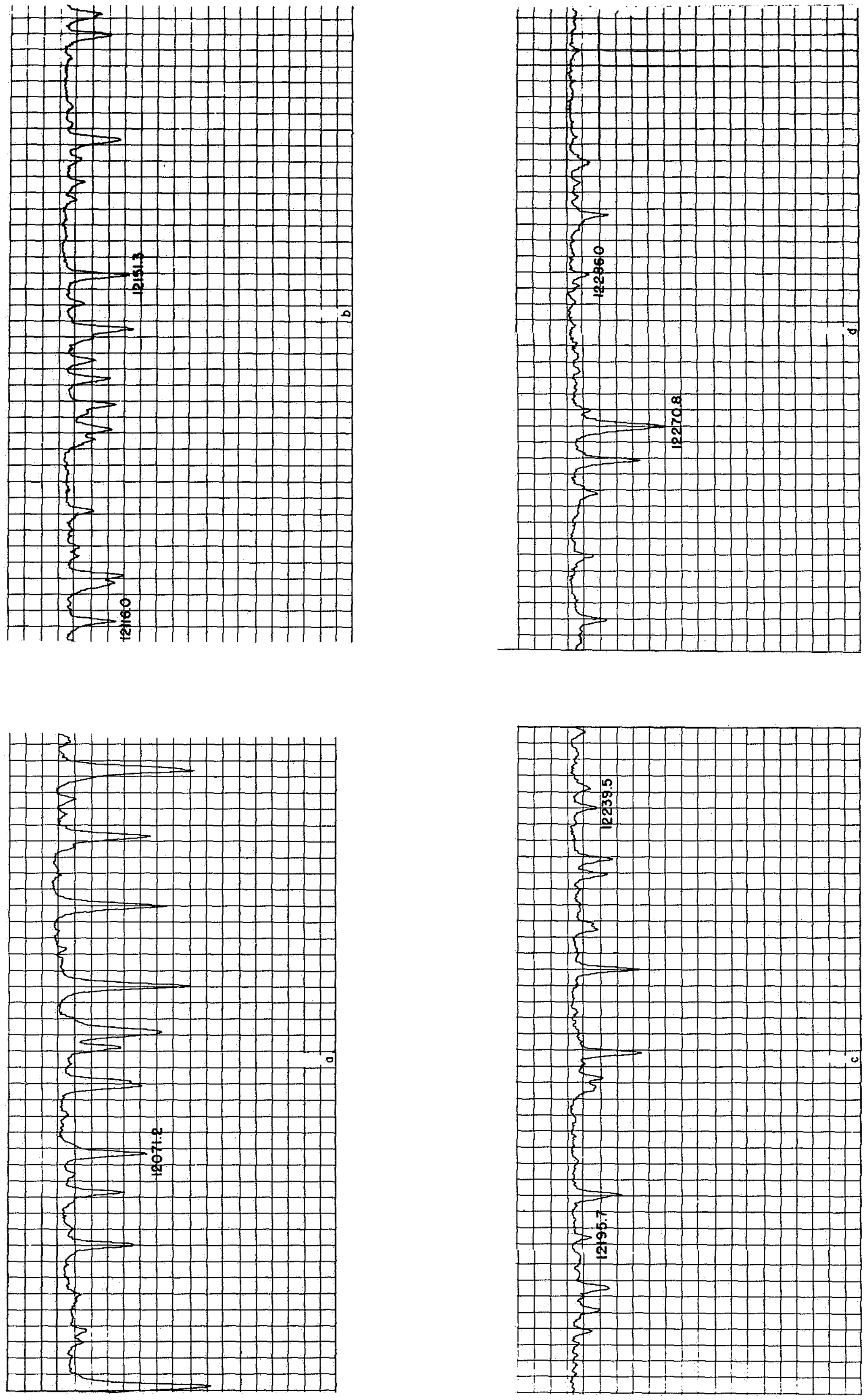

Fig. 6M Part of Michigan Atlas that matches Fig. 6.

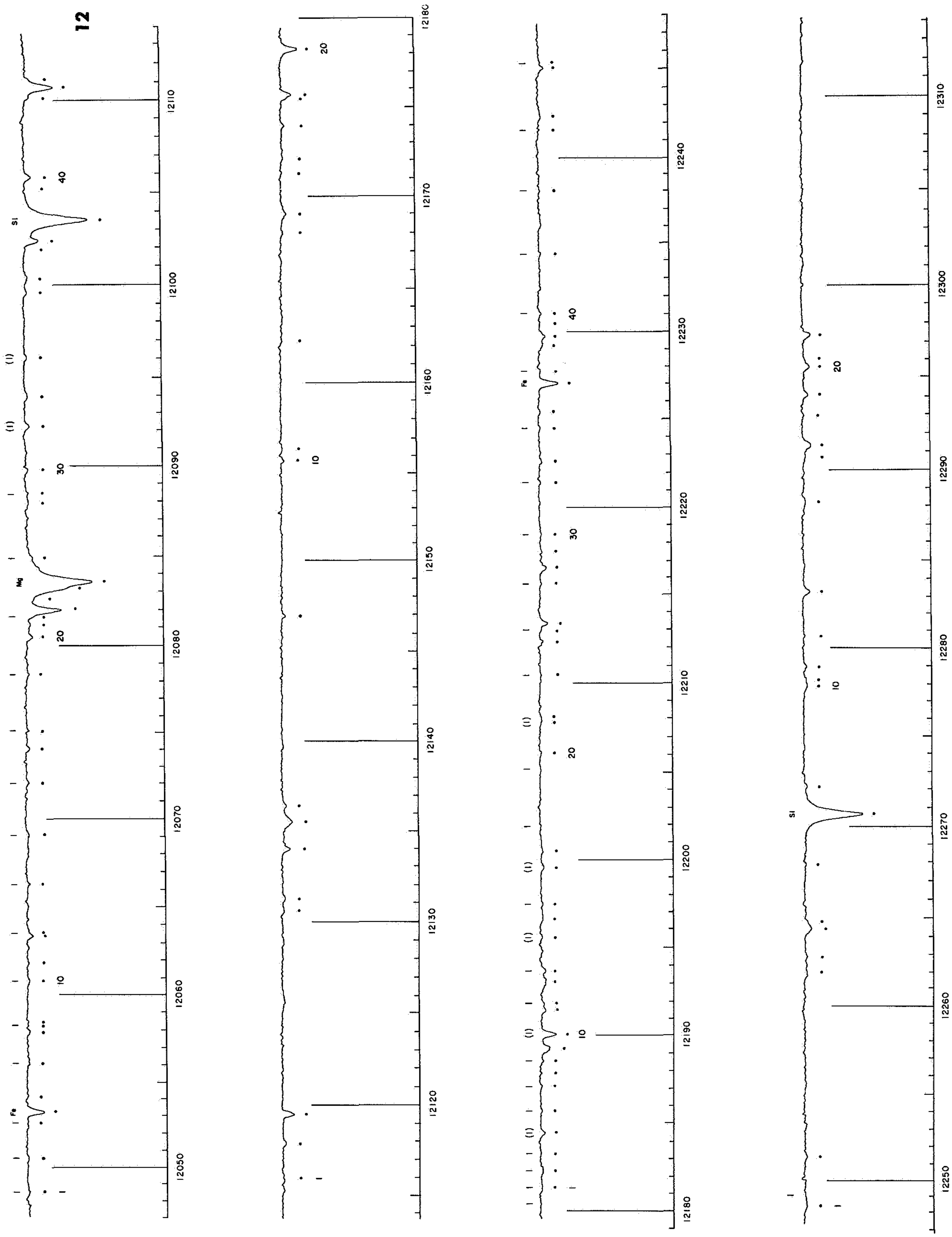

Fig. 6 Solar Spectrum λλ 12047–12314, in four strips (cf. Table 1).

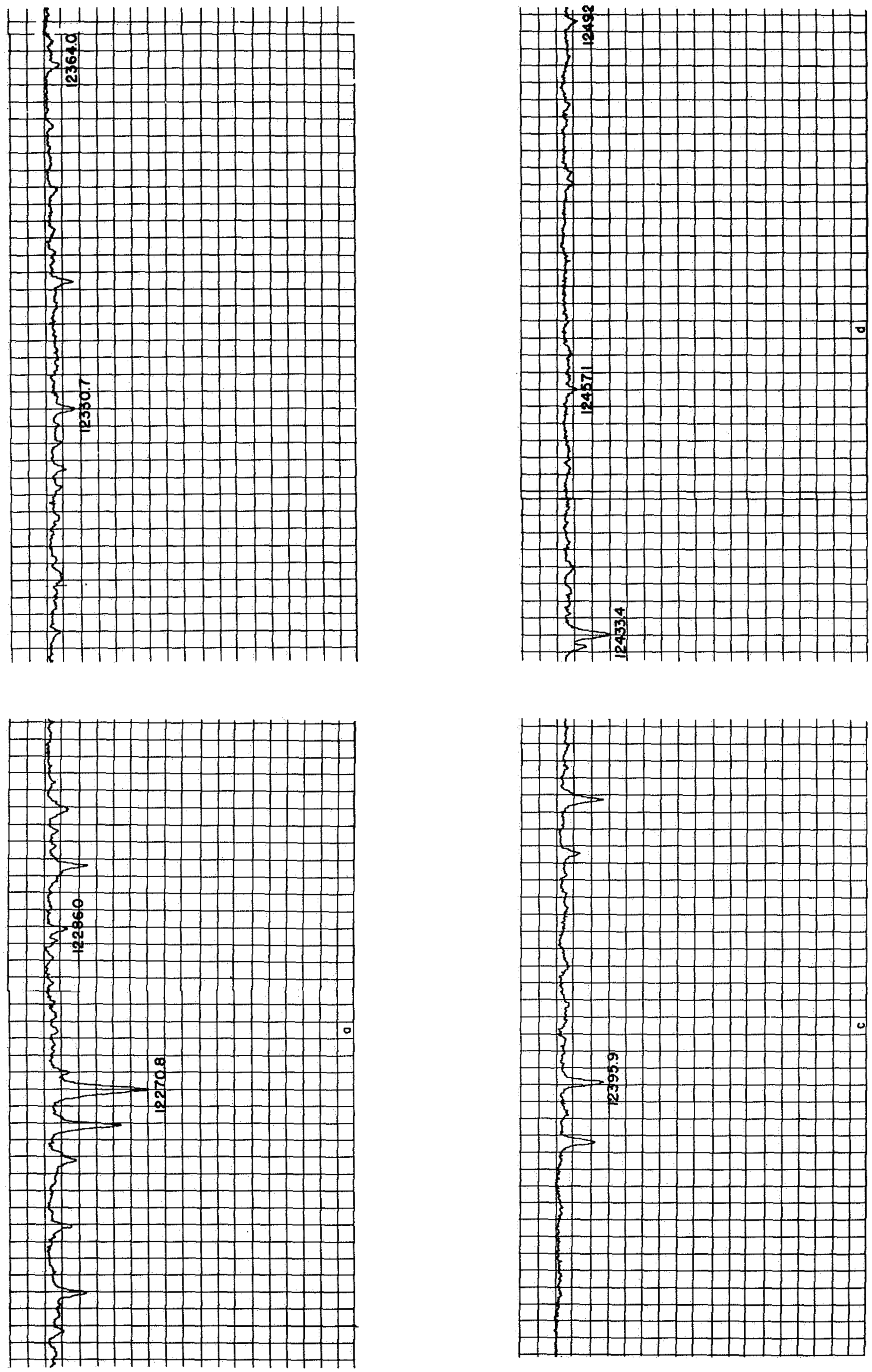

Fig. 7M Part of Michigan Atlas that matches Fig. 7.

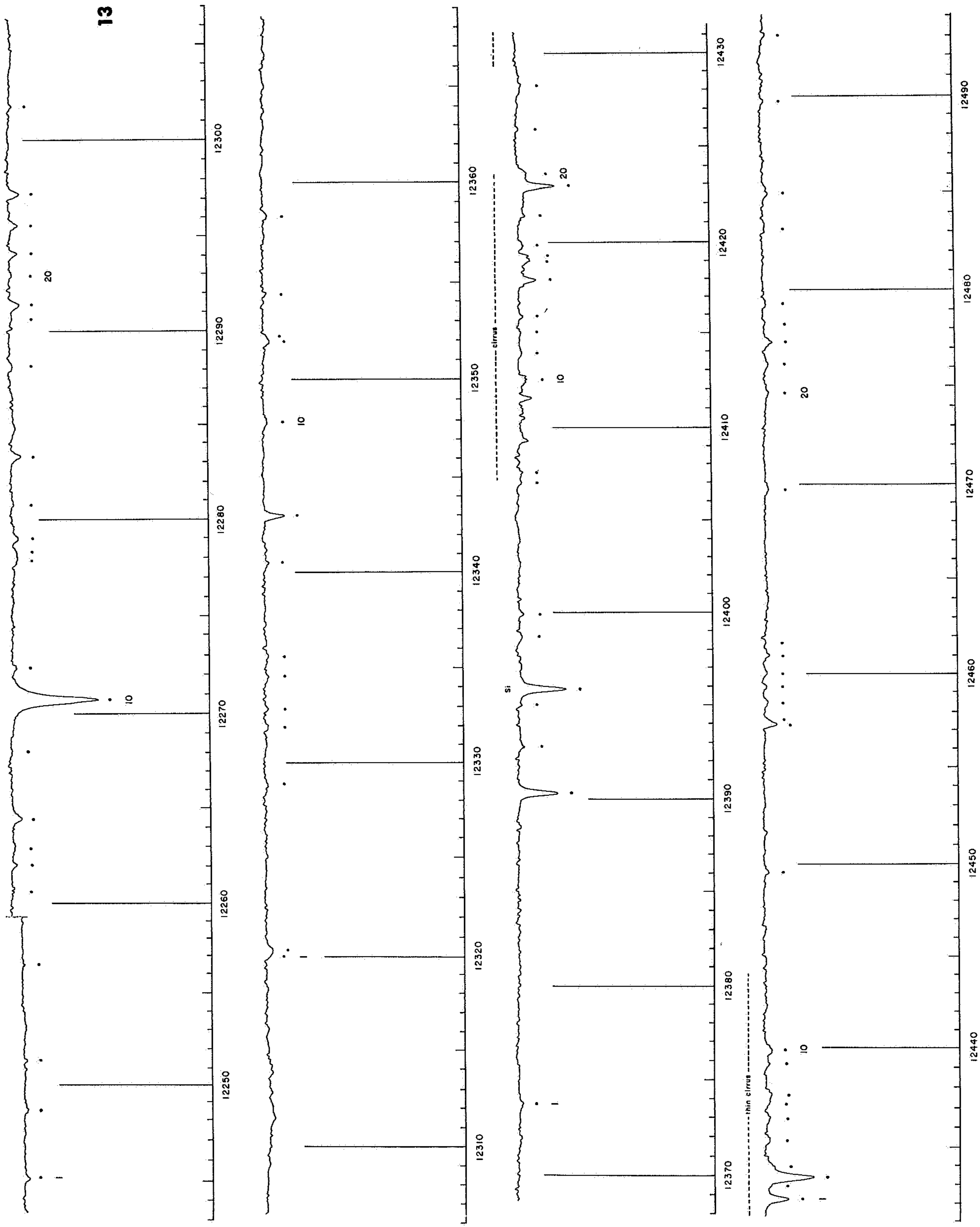

Fig. 7 Solar Spectrum λλ 12244–12494, in four strips (cf. Table 1).

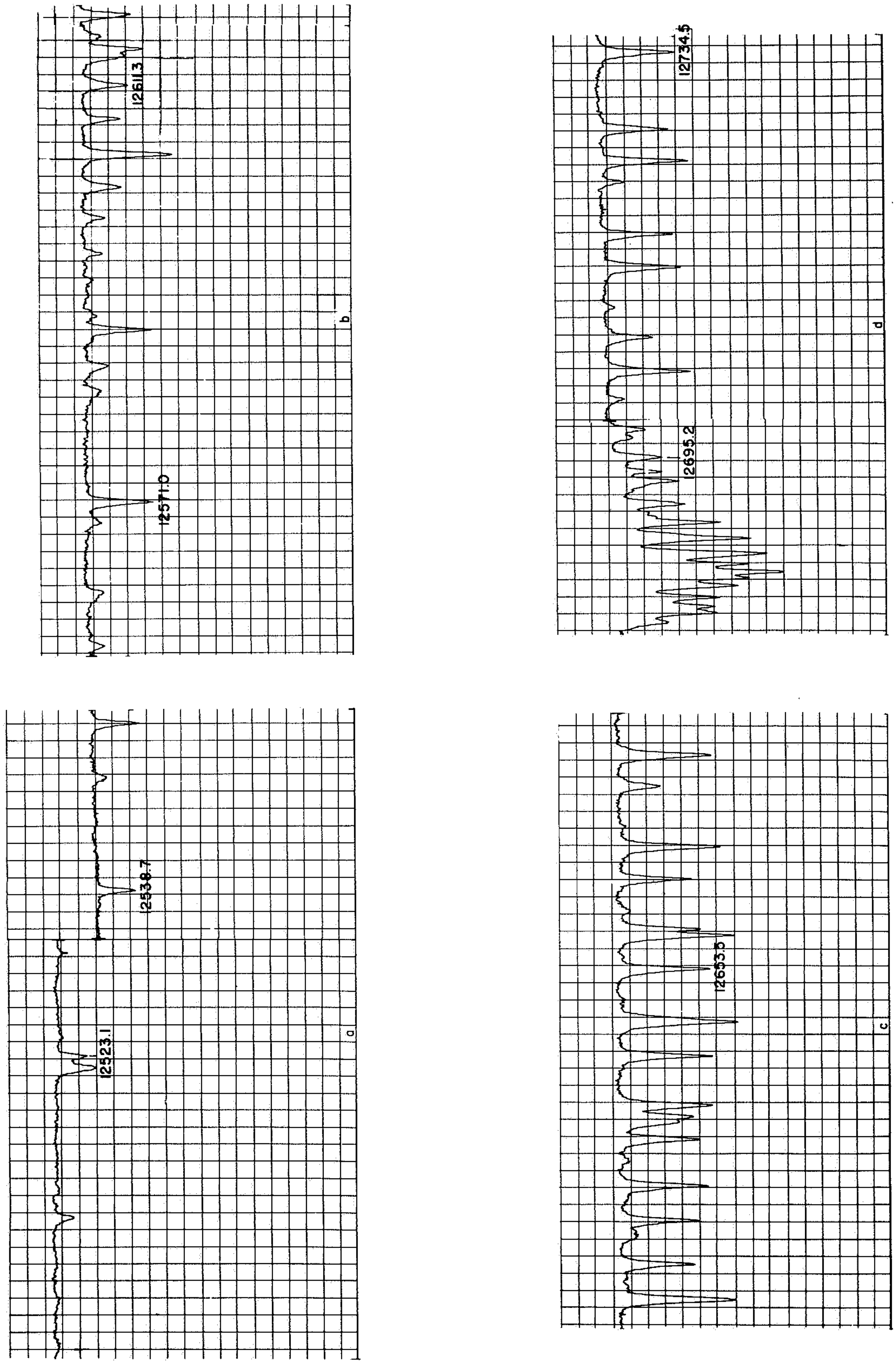

Fig. 8M Part of Michigan Atlas that matches Fig. 8.

Fig. 8 Solar Spectrum λλ 12494–12736, in four strips (cf. Table 1).

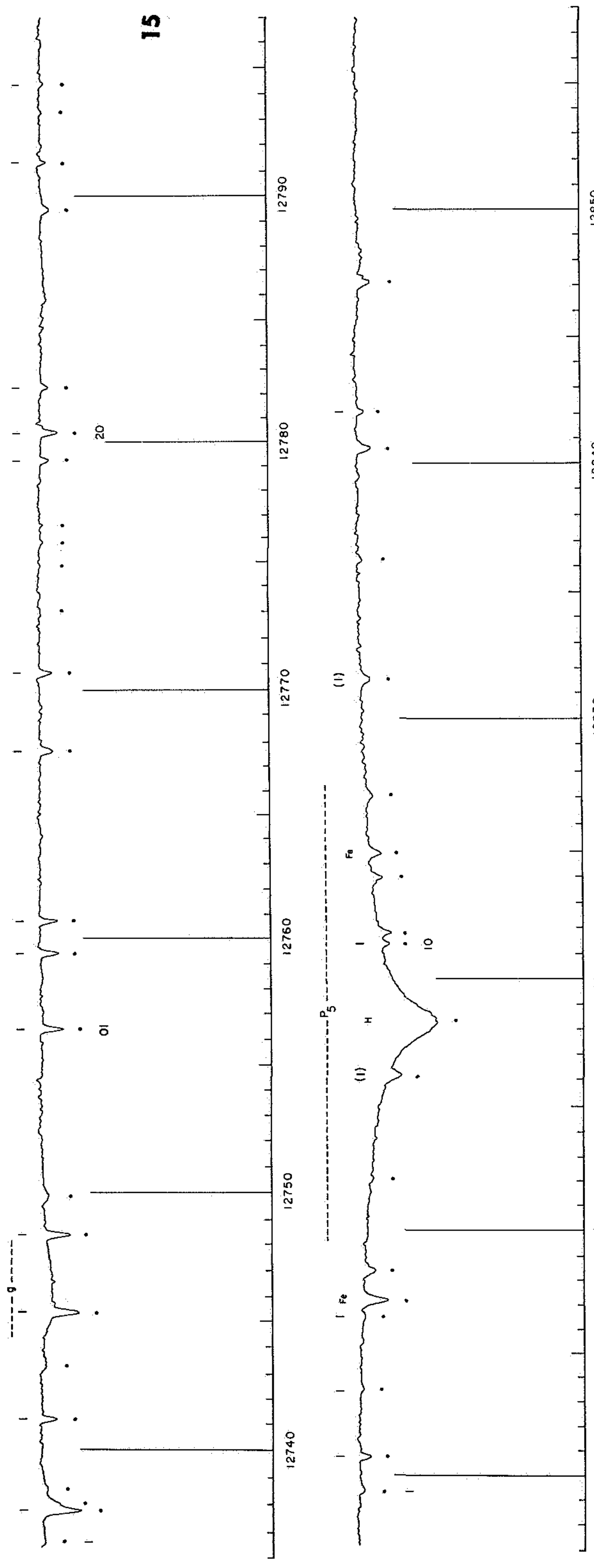

Fig. 9 Solar Spectrum λλ 12736–12857, in two strips (cf. Table 1).

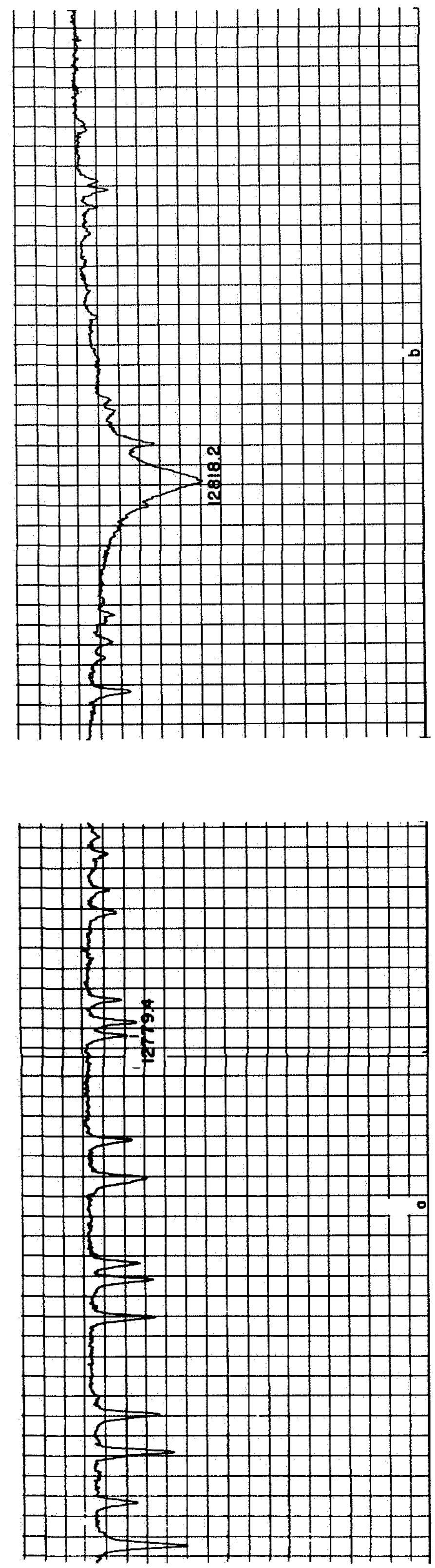

Fig. 9M Part of Michigan Atlas that matches Fig. 9.

NsG 161-61 and the University of Arizona Institutional Grant NGR-03-002-091.

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Addendum

Spectrum of the 1.13 μ H_2O Band

by UWE FINK, L. A. BIJL AND A. THOMSON

Figures 1–4 reproduce two sets of spectra of the 1.13 μ water-vapor band, covering the interval from λλ 11111–11613 Å. They were obtained with the 4-meter spectrometer as used in the solar spectrum observations, mounted in the LPL laboratory. The upper spectrum refers to a laboratory air path at ambient pressure (705 mm), totaling 18.5 meters, 17 meters of which was within the spectrometer. The lower spectrum was obtained with the spectrometer flushed with dry nitrogen gas, and refers essentially to the outside air path of about 1.5 meters. The water-vapor contents are estimated from a wet-and-dry bulb hygrometer and correspond to about 7 microns precip. water per one meter air path. The upper spectrum therefore represents approximately 130 microns of precip. water, the lower spectrum 10 microns, both at p = 705 mm.

The slit width and the detector width were both 0.10 mm, the time constant of the amplifier 0.12 sec. and the filter RG-8, all as in the solar observations. Also, the scan and recorder speeds were the same as in the solar records.

The wavelength scale was derived by one of us (L. A. B.) and corresponds accurately to the scale shown in the solar records, both being based on that of the Liège *Atlas*. Owing to slight irregularities in the grating drive, the dispersions in the two water-vapor spectra are not quite identical.

The width of the water-vapor lines in the laboratory records is somewhat larger than that of the telluric lines in the solar spectra, presumably due to the higher pressure in the laboratory (930 mb vs < 200 mb).

Mrs. A. Agnieray assisted in the preparation of the figures.

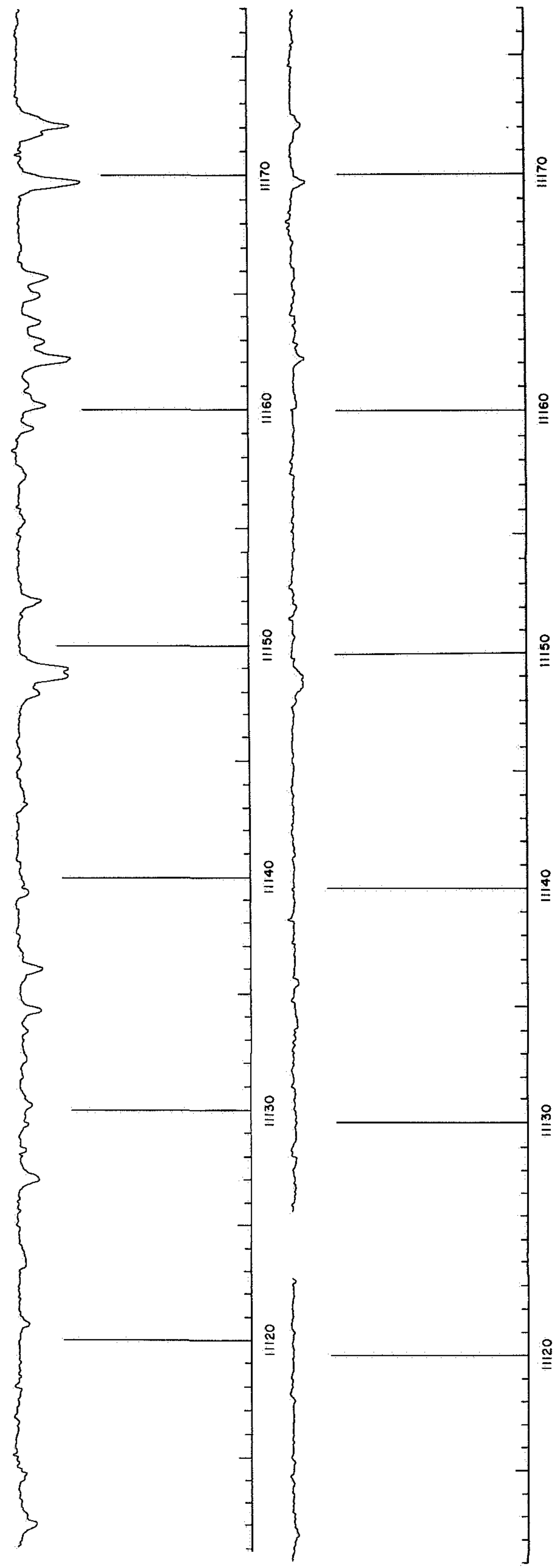

Fig. 1A Laboratory spectrum of water vapor, λλ 11111–11177 Å.

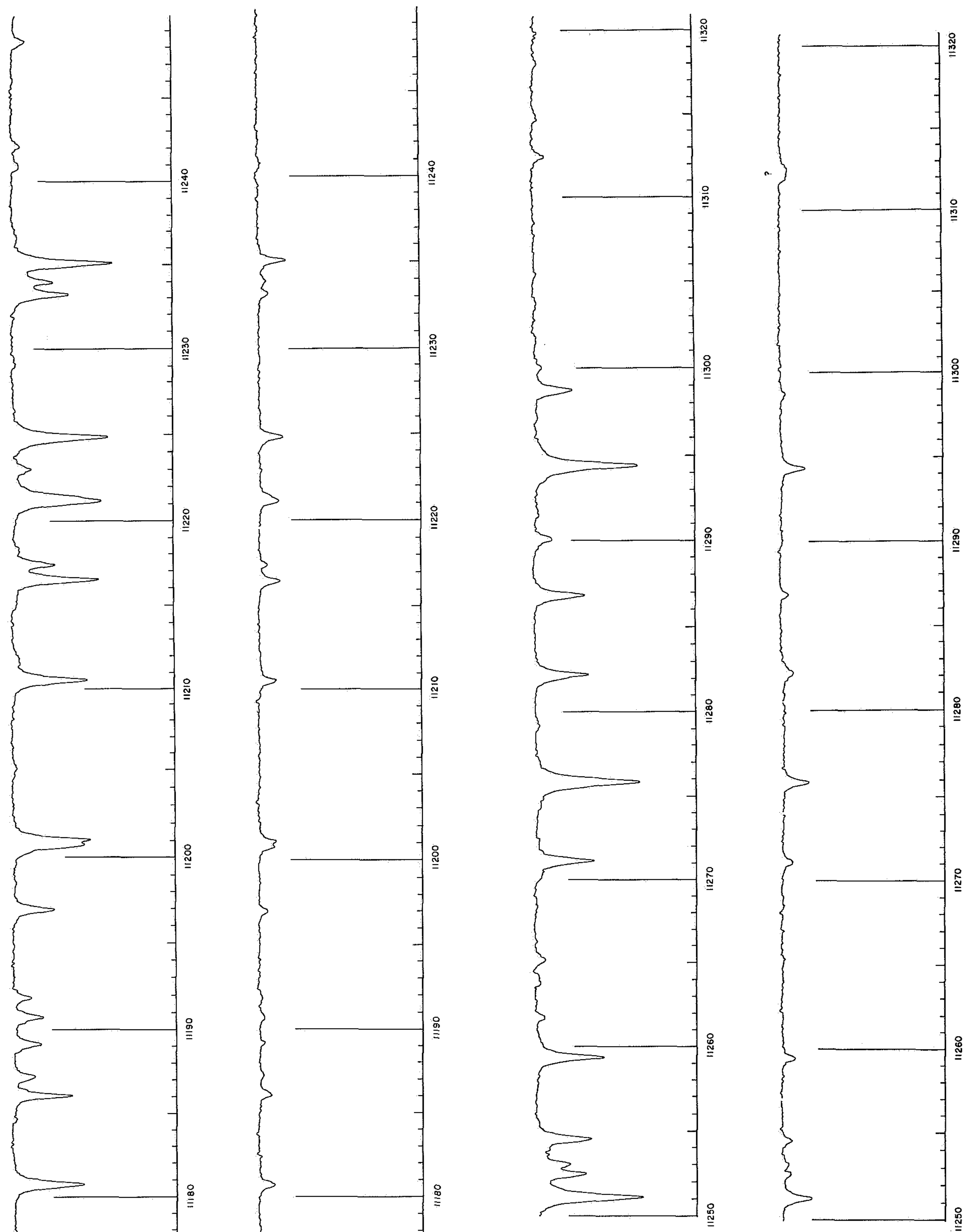

Fig. 2A Laboratory spectrum of water vapor, λλ 11177–11321 Å.

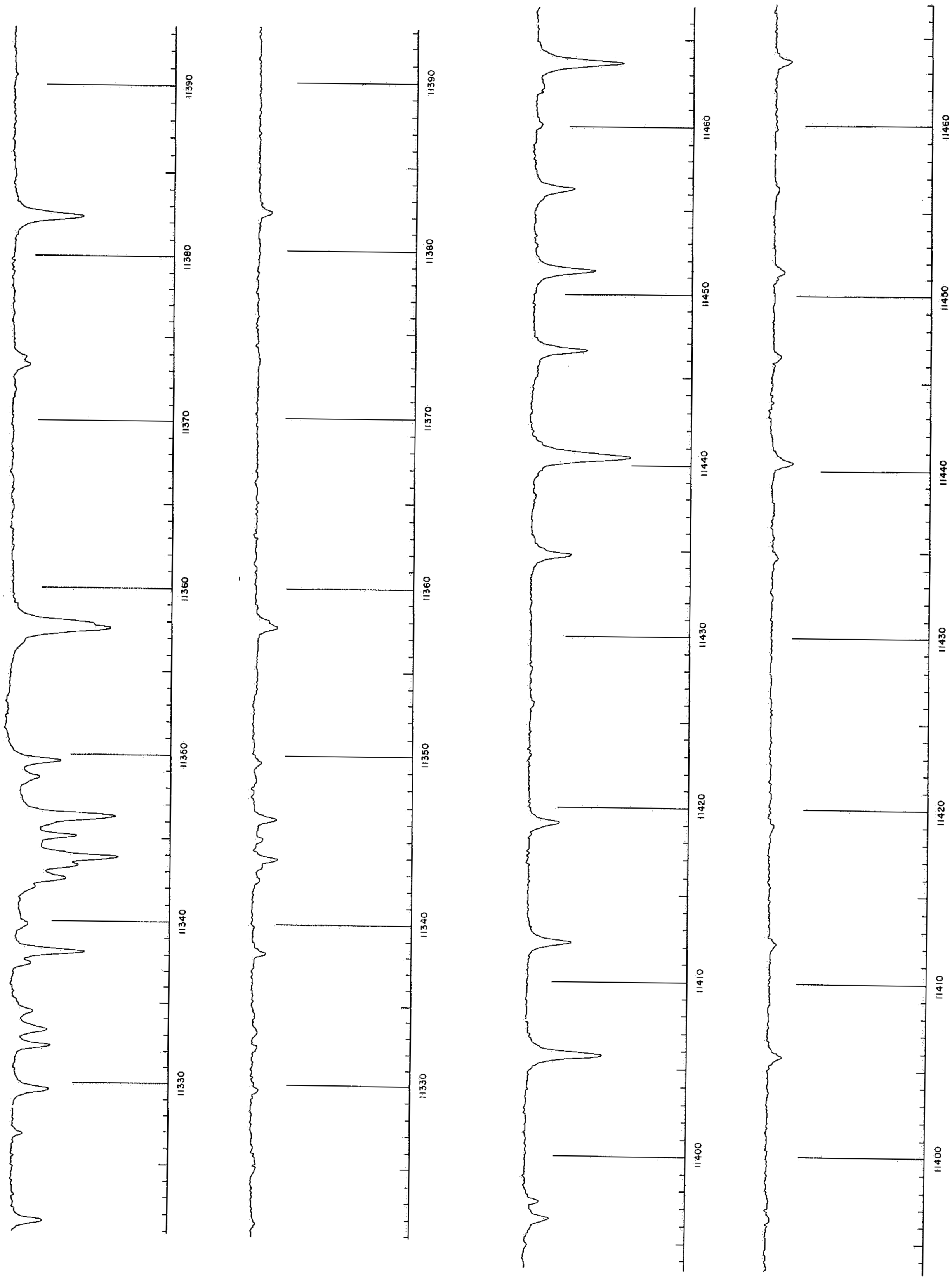

Fig. 3A Laboratory spectrum of water vapor, λλ 11321–11467 Å.

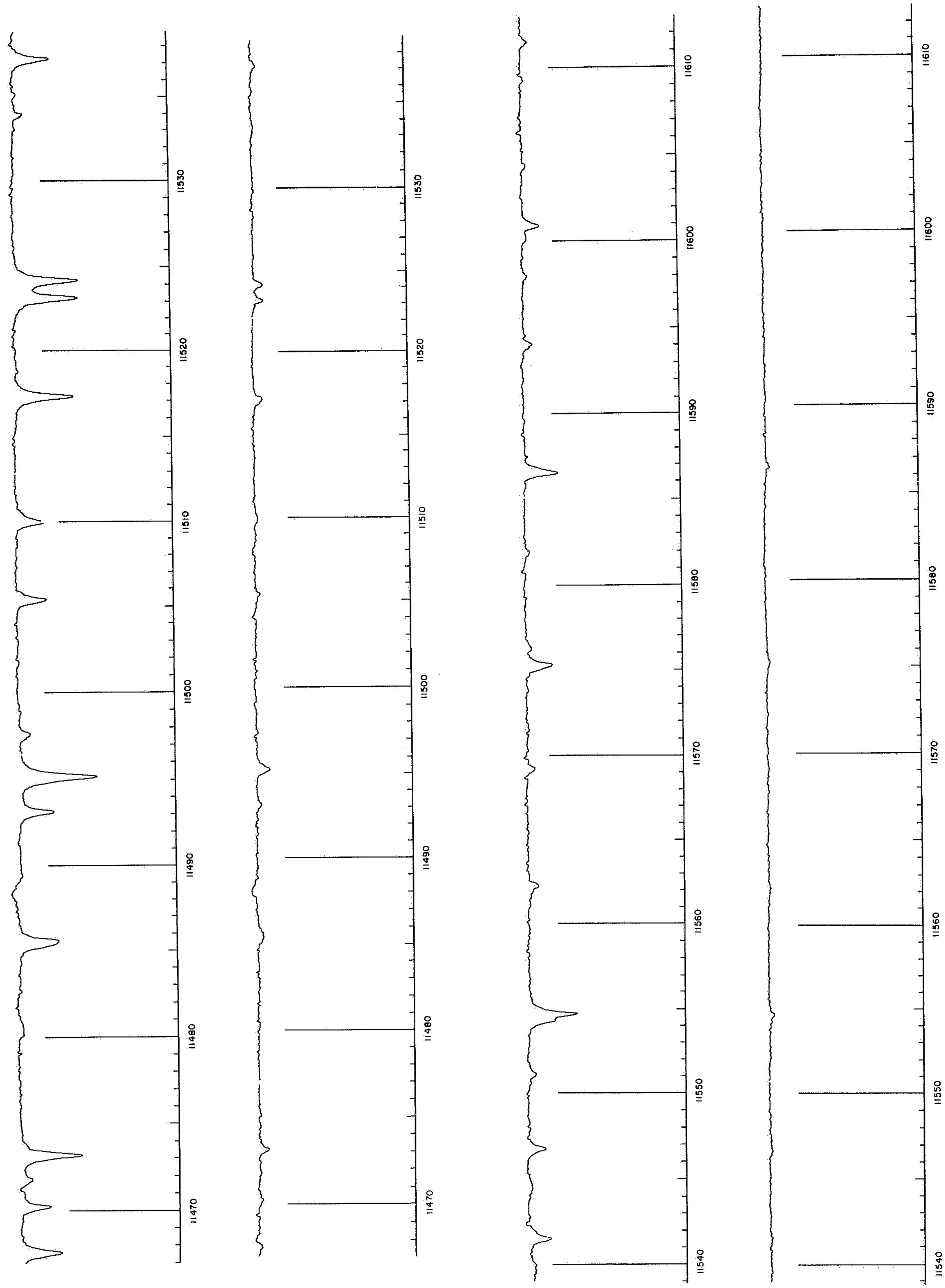

Fig. 4A Laboratory spectrum of water vapor, $\lambda\lambda$ 11467–11613 Å.

No. 125 NASA ATLAS OF INFRARED SOLAR SPECTRUM, REPORT III

by GERARD P. KUIPER

November 16, 1968

ABSTRACT

The region of the solar spectrum containing the ν_3 band of methane, λ 3.12–3.46 μ, is shown as it appears essentially freed from telluric water vapor. Records taken with both the B- and the 4-meter spectrometer are included. The 4-meter results are somewhat degraded by a modulation due to filter interference and are regarded provisional. The Coriolis fine structure for some of the rotational lines is resolved. The remarkable paucity of solar absorption lines in this region is noted.

In addition to the solar spectrum itself, the available observations from the NASA CV 990 illustrate one further aspect: the telluric absorptions other than by H_2O are standing out much more clearly. For, while the H_2O abundance is cut by 100–1000 $\times$ over a mountain observatory, other telluric absorptions (CO_2, CO, N_2O, CH_4) are cut by only 4 $\times$, while O_3 is hardly cut at all. Thus, other minor atmospheric constituents might be still found spectroscopically, as CH_4, CO, and N_2O were discovered in the recent past. This report considers the region of the ν_3 band of CH_4 around 3.3 μ, from records that are regarded quite provisional.

The upper two strips of Fig. 1 show one of the four traces of the 3.12–3.46 μ region taken with the B-spectrometer and a PbSe cell, dry-ice cooled. Two small dips due to guiding errors have been reconstructed in accordance with the other traces. The rotational lines of the *P* and *R* branches have been numbered. The *Q* branch is just beginning to show structure. The resolution is 7–8 Å or about 4500, or 0.7 cm^{-1}. The strength of the ν_3 band may cause surprise with only 3-mm atm. of CH_4 at $p < 200$ mb in the beam.

The lower two strips of Fig. 1 show two separate runs with the 4-meter spectrometer of the region of the *Q* branch, and well as *P*(1), and *R*(0) and *R*(1). The other members of the *R* branch, up to *R*(15), are seen in Fig. 2. Unfortunately, an instrumental interference effect put a rough sine wave on the continuum and the flight schedule did not allow tracing and eliminating the source. (This region will soon be re-observed from the NASA Lear Jet.) From the appearance of *R*(4) *R*(5), *R*(6), *R*(7), *R*(10), *R*(12), the resolution of the 4-meter records is found to be 1.0–1.2 Å or $R \simeq 30{,}000$ (or 0.1 cm^{-1}), close to the theoretical limit of the optics used. The times and other flight data are found in Table 1. Above the spectral traces in Figs. 1 and 2 water-vapor lines are indicated by *dots,* and methane absorptions by *lines.*

The atlas, *The Solar Spectrum from 2.8–23.7 Microns* (Migeotte et al, 1956) and its companion Catalogue (Ibid. 1957) previously provided coverage of this spectral interval, based on observations from the 3500-meter high Jungfraujoch International Scientific Station in Switzerland. The wavelength system and identifications there adopted have been used here also, with additional consultation of the *Atlas of Nitrous Oxide, Methane, and Ozone Infrared Absorption Bands* (Migeotte et al, 1957). The spectral resolution of the Migeotte Solar Atlas in the 3.3 μ region is 0.27 cm^{-1} (*op. cit.,* Table II), intermediate between our two resolutions. Fig. 3 reproduces the 5 sections of the Migeotte Atlas that correspond to the 4-meter records of Figs. 1 and 2. The Addendum shows laboratory spectra of methane in the ν_3 band region taken with the 4-meter spectrometer, matching Figs. 1 and 2. (The resolution of 0.1 cm^{-1} is sufficiently higher than that of the Liège records that a matching laboratory run was needed.)

Attention is called to the Coriolis multiplicity of the rotational "lines." The Q branch in Fig. 1 and the Addendum has great complexity which, however, is minor compared to that shown by truly high-resolution records (Plyler *et al,* 1960, p. 202, and especially Hecht, 1960, p. 399). Since each "line" of the Q branch has numerous Coriolis components and since several of the features shown in Fig. 1 and the Addendum are blends caused by 2–4 overlapping multiple "lines," no classifications have been entered for the Q branch. Reference is made to the interpretations by Hecht (*op. cit.*).

As stated, the present records are merely provisional; but they suffice to show a paucity of solar lines on this region.

Acknowledgments. I am indebted to NASA Hq. and NASA-Ames for their support and interest in the high-altitude program; to Messrs. J. Percy and B. McClendon for assistance with the electronics during the flights; to Messrs. A. Thomson, G. Sill, and D. Olsen for their assistance in the operations; and to Mrs. A. Agnieray for her assistance in the preparation of the figures. This research was supported through NASA Grant NsG 161-61 and the University of Arizona Institutional Grant NGR-03-002-091.

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TABLE 1

SOLAR SPECTRUM RECORDS, NASA 990 JET

4 μ GRATING (300 LINES/MM), 2.4 μ FILTER, SLIT 0.23 MM, $\tau = 0.24$ SEC.

FIG.	SPECTR.	λ (Å)	1968 DATE	U.T.	ALT. (FT)	TEMP °C	CABIN ALT.	CELL (−78°C)	GAIN
1a	B	31190–32950	July 19	20:26	39,000	−53	8500	PbSe	5–5
1b	B	32950–34678	July 19	20:29	39,000	−53	8500	PbSe	5–5
1c	4.2 m	32898–33265	Aug 7	19:24	41,000	−57	8900	PbS	6–3
1d	4.2 m	32898–33265	Aug 7	19:27	41,000	−57	8900	PbS	6–(3, 4)
2a	4.2 m	31487–31843	Aug 7	19:10	41,000	−57	8900	PbS	6–2
2b	4.2 m	31843–32190	Aug 7	19:13	41,000	−57	8900	PbS	6–2
2c	4.2 m	32190–32549	Aug 7	19:17	41,000	−57	8900	PbS	6–(2, 3)
2d	4.2 m	32549–32898	Aug 7	19:20	41,000	−57	8900	PbS	6–3

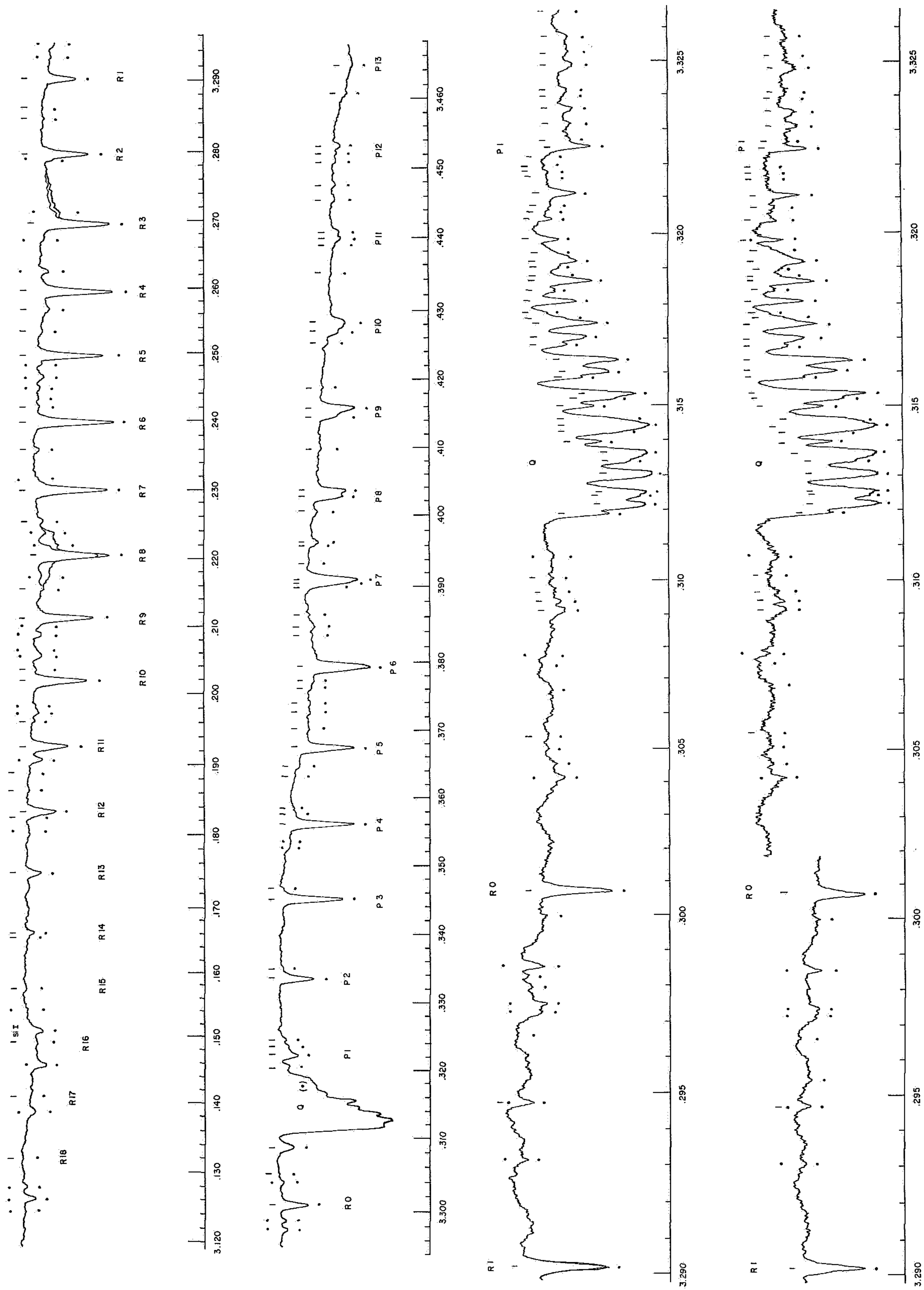

Fig. 1 (a) (b) B-Spectrometer record of Solar Spectrum, λ 3.12–3.46 μ.
(c) (d) Two runs with 4-meter Spectrometer, λ 3.290–3.326 μ (cf. Table 1).

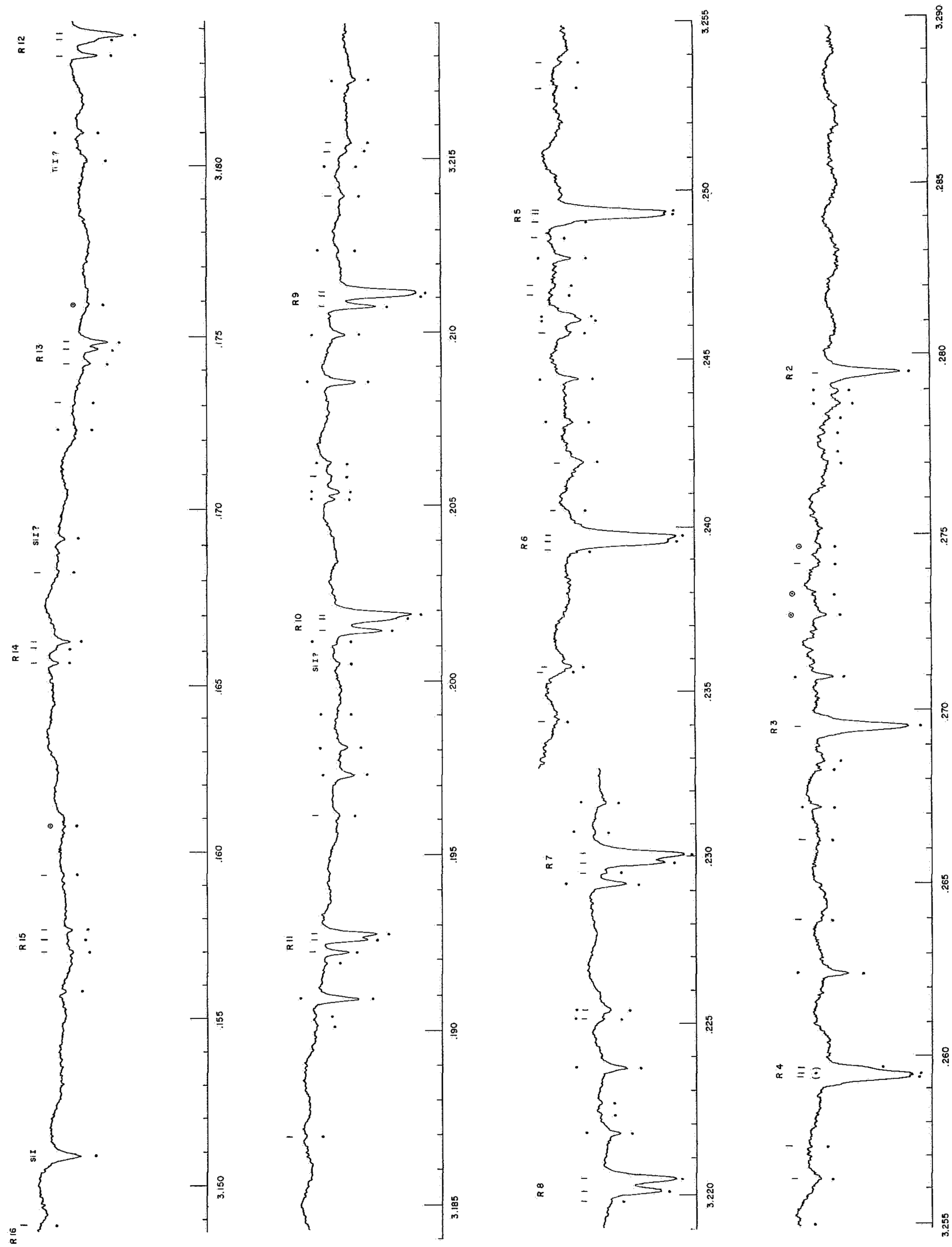

Fig. 2 Solar Spectrum, λ 3.149–3.290 μ, in four strips, with 4-meter Spectrometer (cf. Table 1).

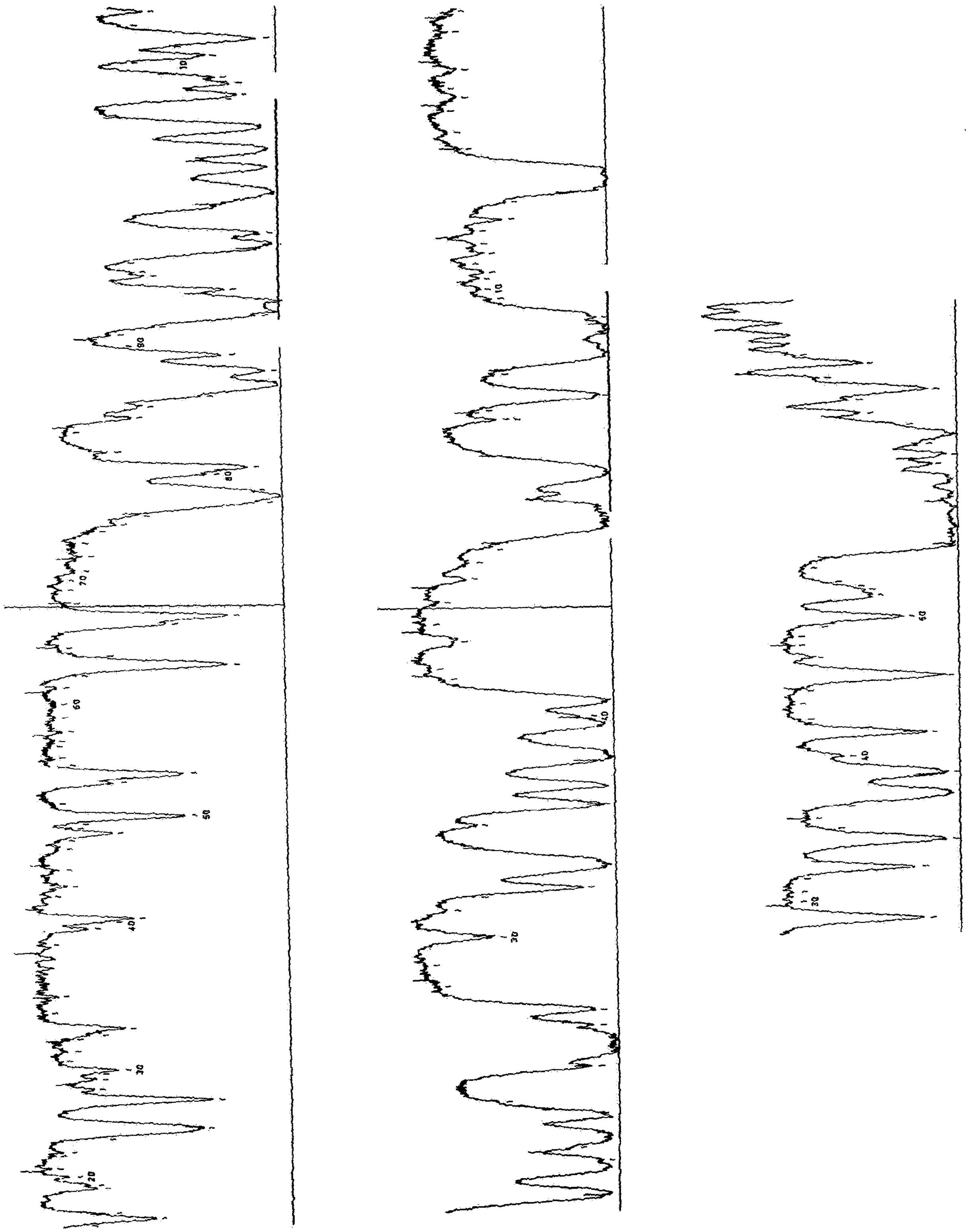

Fig. 3 Five sections of Migeotte *Atlas* (1956) matching 4-meter records of Fig. 1 (bottom) and Fig. 2 (upper four).

ADDENDUM

Laboratory Spectra of the ν_3 Band of CH_4

by LAURENS A. BIJL

Figs. 1A–6A reproduce two sets of laboratory spectra which nearly match, in resolution and in the intensities of the methane and water-vapor absorptions, the solar records shown in Figs. 1 and 2, above. Specifically, Figs. 1A and 2A are the laboratory counterparts of the first two strips of Fig. 1, although they were obtained with the 4-meter spectrometer. A wide slit was used to obtain the desired resolution. Figs. 3A–6A were obtained with the same instrument but normal slit width, approximately corresponding to the conditions used in the solar observations. Table 1 gives the details for all 24 spectral records contained in the six figures.

With ambient air the water-vapor content of the spectrometer would have been 10–15 times the amount desired. Since a 70-cm path outside the spectrometer gave the desired strength of the water-vapor absorptions, the spectrometer itself was flushed with dry nitrogen during the operations. The amount of water vapor in Figs. 1A*d* and 2A*d* is the same as in Figs. 1A *a, b, c,* and 2A *a, b, c;* whereas, the amount in Figs. 3A *b, d,* 4A *b, d,* and 5A *b, d* was made higher than in the corresponding methane spectra, to show the lines more clearly. The water-vapor absorptions have been marked with dots above the spectra as in Figs. 1 and 2. The water-vapor absorptions in Fig. 6A are negligible.

The methane absorptions were obtained with a 10-cm cell placed between the laboratory source and the spectrometer slit. The pressure in the cell was adjusted to values recorded in Table 1 which resulted in total absorptions of the amount required. E.g., Figs. 1 and 2 were obtained with pressures of $p = 9$, 4, and 2 cm corresponding to amounts of methane of 12, 5.3, and 2.6 mm atm, whereas the anticipated amount of the gas in the solar beam is approximately 3 mm atm. The records in Figs. 3A–6A were obtained with $p = 8$ cm corresponding to 10.5 mm atm of methane. In order to facilitate the comparison between the solar and laboratory records, the methane absorptions in Figs. 3A, 4A, and 5A have been marked with short vertical lines, as in the solar spectra.

Comparison with the solar records shows that a reasonably good match in resolution was indeed obtained. The most striking difference is the intensity distribution in the P, Q, and R branches, clearly the result of the higher laboratory temperature (about 295° K vs. 220° K for the stratospheric absorptions). The wavelength scale used was based on *An Atlas of Nitrous Oxide, Methane and Ozone Infrared Absorption Bands* (Migeotte, *et al*). The scale differs slightly from the one adopted in the solar records, Figs. 1 and 2.

Mrs. A. Agnieray assisted in the preparation of the figures.

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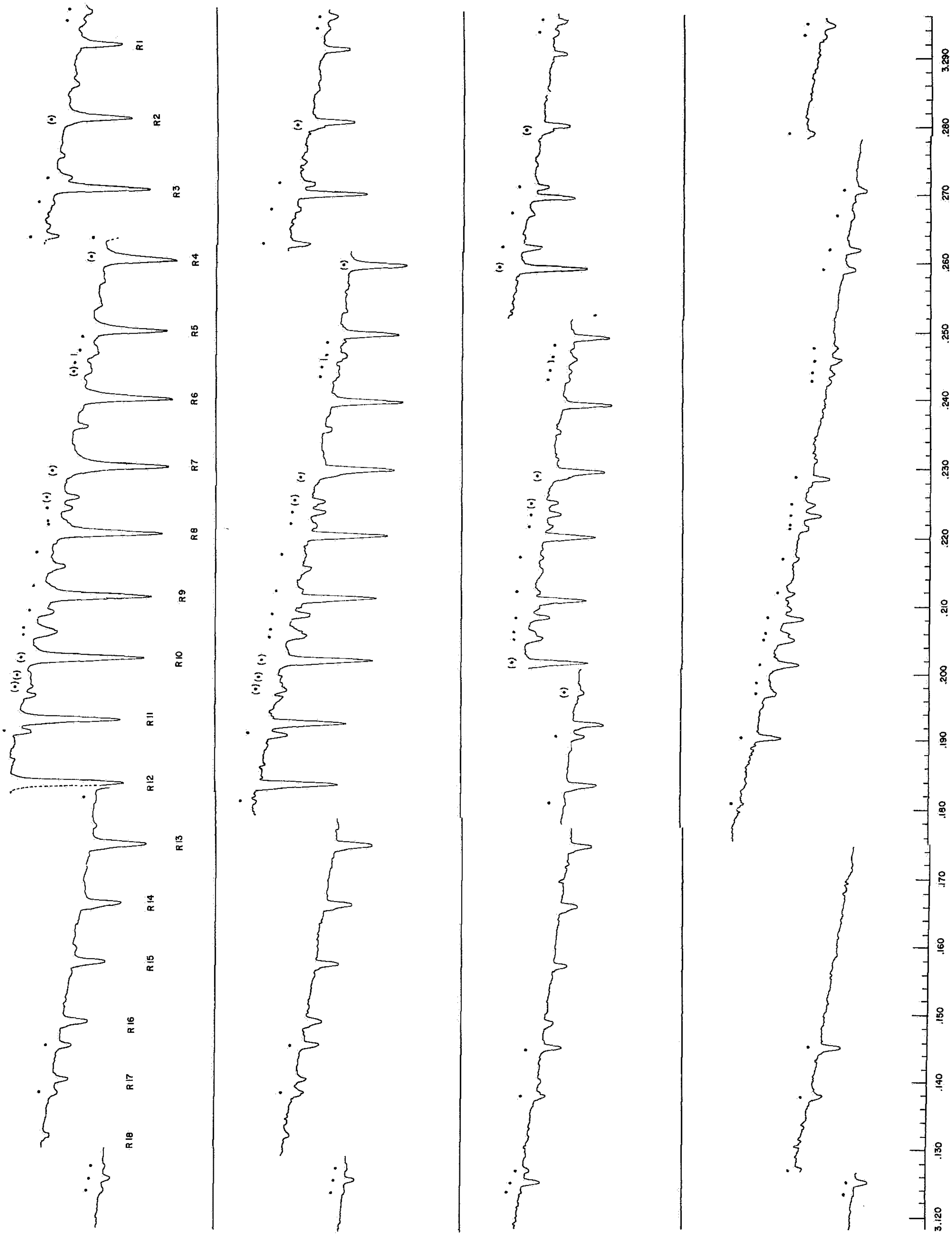
TABLE 1
LABORATORY RECORDS OF ν_3 BAND OF CH_4
4-M SPECTROMETER, 4-μ GRATING (300 LINES/MM), 2.4-μ FILTER, PbS DETECTOR (—78°C)

FIG.		CH_4 P(CM)	GAIN	SLIT (MM)	τ (SEC.)
1A	a	9	4–5, 4–6, 5–2, 5–3	1.0	0.24
	b	4	4–5, 4–6, 5–2, 5–3	1.0	0.12
	c	2	4–6, 5–1, 5–2, 5–3	1.0	0.12
	d	0	4–5, 4–6, 5–2, 5–3	1.0	0.12
2A	a	9	5–3, 5–4, 5–5, 5–6	1.0	0.24
	b	4	5–4, 5–5, 5–6	1.0	0.12–0.24
	c	2	5–3, 5–4, 5–5, 5–6	1.0	0.12–0.24
	d	0	5–3, 5–4, 5–5, 5–6	1.0	0.12–0.24
3A	a	8	6–1, 6–2	0.10	0.24
	b	0	6–1, 6–2	0.10	0.24
	c	8	6–2	0.10–0.15	0.24
	d	0	6–2	0.10	0.24
4A	a	8	6–2	0.15	0.24
	b	0	6–2	0.10–0.20	0.24
	c	8	6–2	0.15	0.24
	d	0	6–2	0.20	0.24
5A	a	8	6–2, 6–3	0.15	0.24
	b	0	6–2, 6–3	0.20	0.24
	c	8	6–3	0.15	0.24
	d	0	6–3	0.20	0.24
6A	a	8	6–4	0.17	0.36*
	b	0	6–4, 6–5	0.17	0.36*
	c	8	6–5	0.17–0.30	0.36*
	d	0	6–5	0.30	0.36*

*Actually, $\tau = 1.8$ sec. used at one-fifth of normal scan rate, thus corresponding to $\tau = 0.36$ sec. at usual scan rate.

Fig. 1A Laboratory spectrum of methane, matching Fig. 1*a* and 1*b* in resolution, 3.119–3.296 μ. Three amounts are used: *a*, 12 mm atm; *b*, 5.3 mm atm; and *c*, 2.6 mm atm. The corresponding water-vapor spectrum is found in *d*.


R1
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.150
.140
.130
3.120

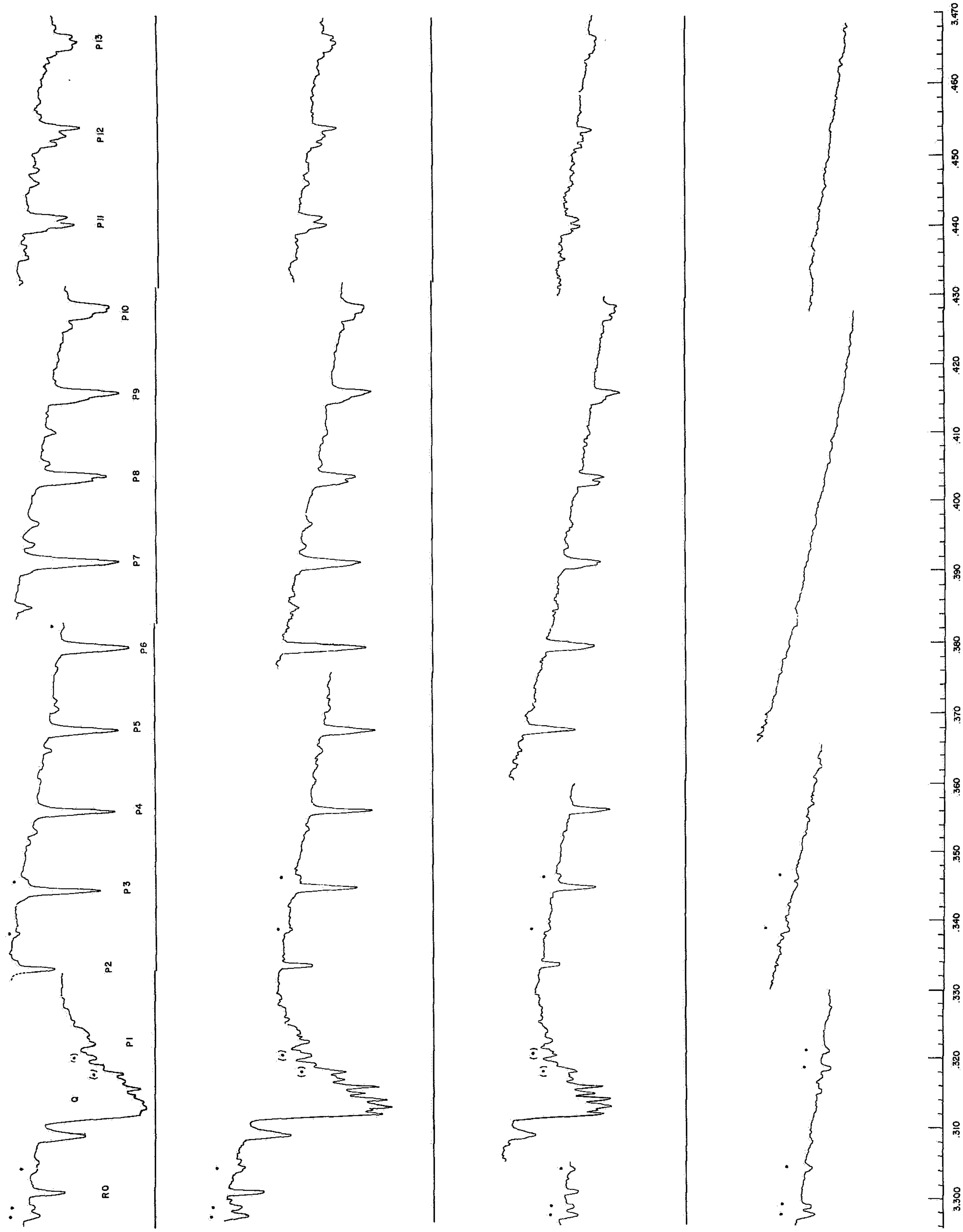

Fig. 2A Laboratory spectrum of methane, matching Fig. 1*a* and 1*b* in resolution, 3.296–3.469 μ. Three amounts are used: *a*, 12 mm atm; *b*, 5.3 mm atm; and *c* 2.6 mm atm. The corresponding water-vapor spectrum is found in *d*.

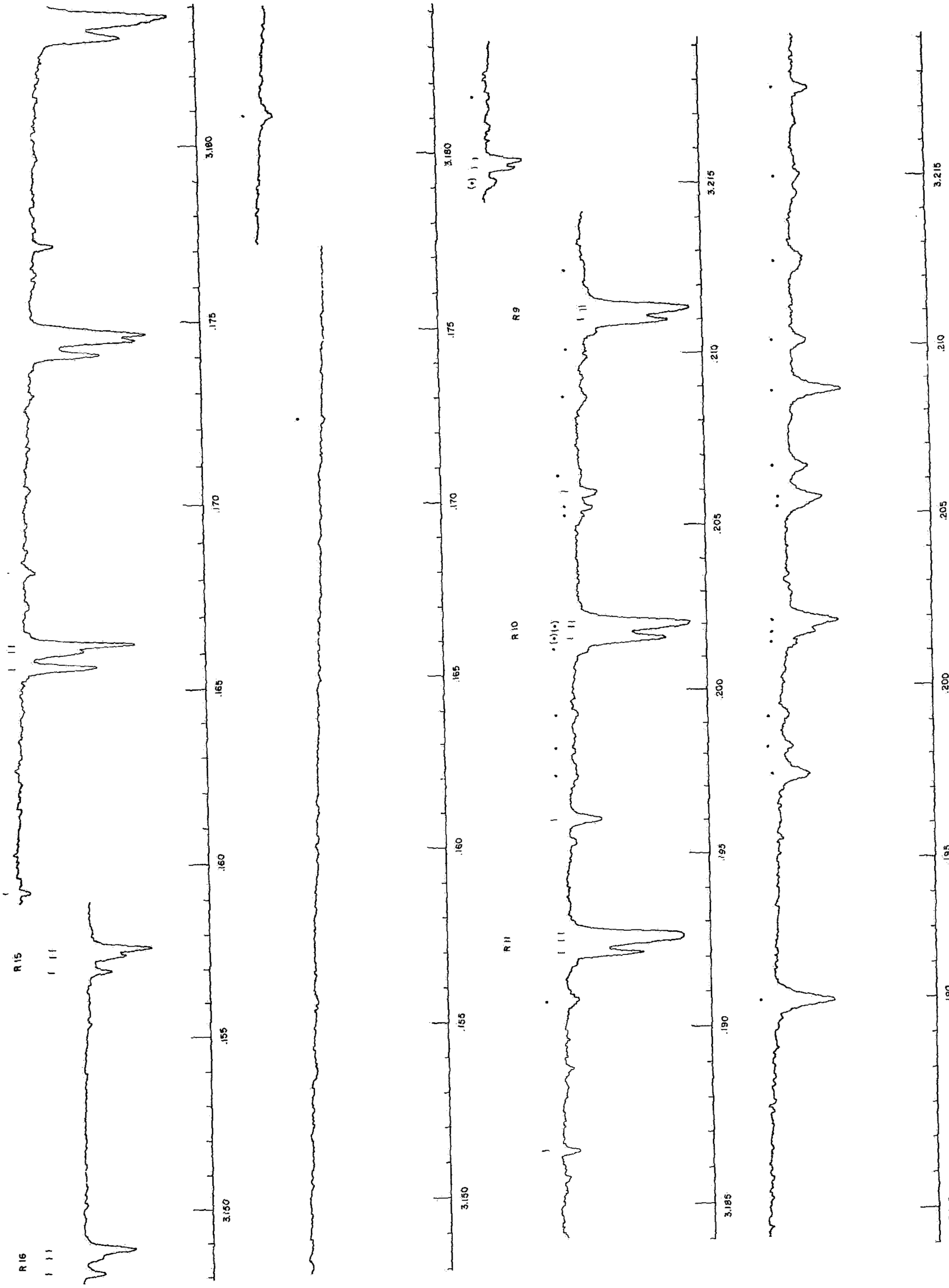

Fig. 3A Laboratory spectrum of methane, 10.5 mm atm, p = 8 cm, 3.148–3.219 μ, with water-vapor comparisons added.

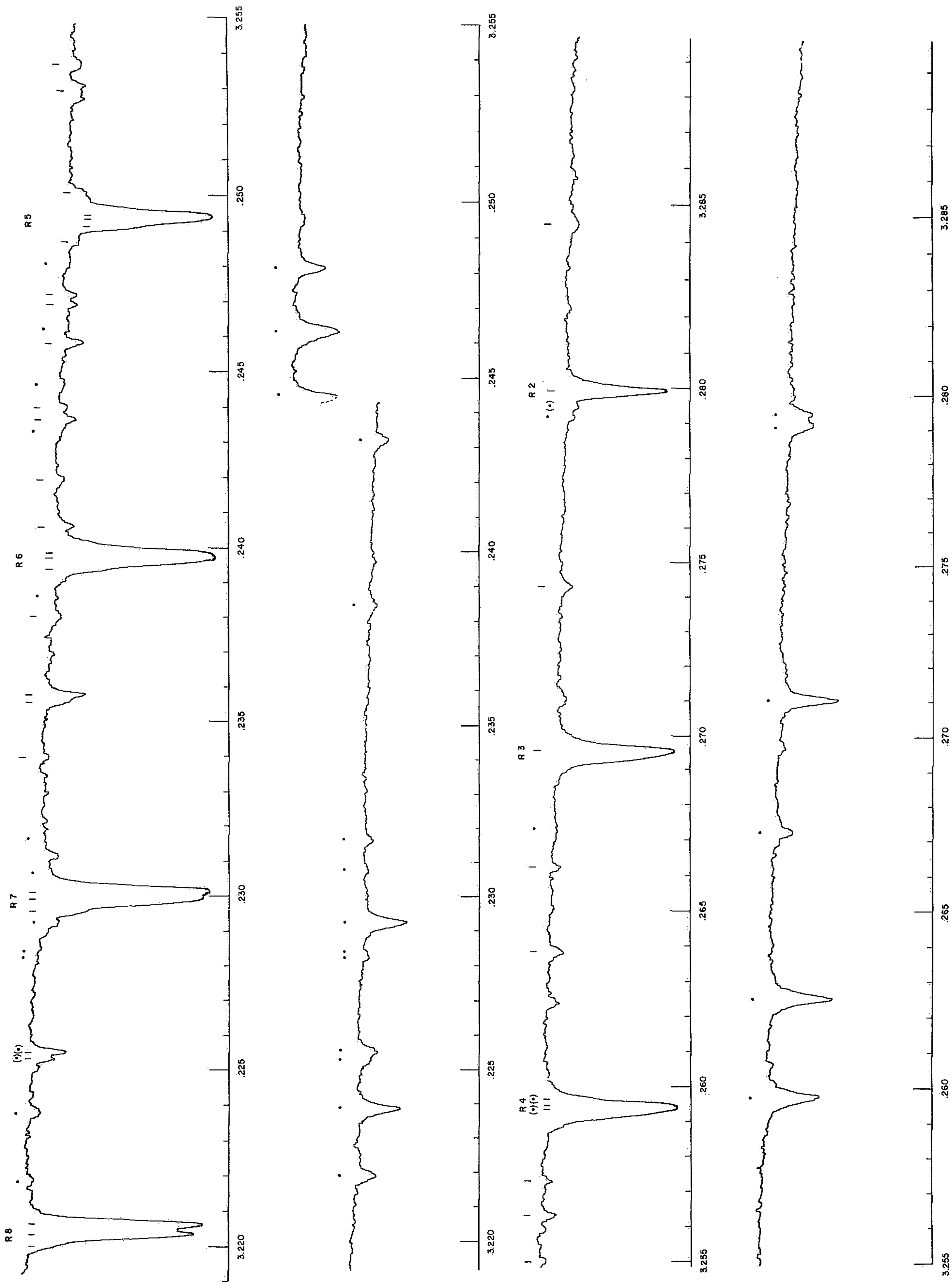

Fig. 4A Laboratory spectrum of methane, 10.5 mm atm, p = 8 cm, 3.219–3.290 μ, with water-vapor comparisons added.

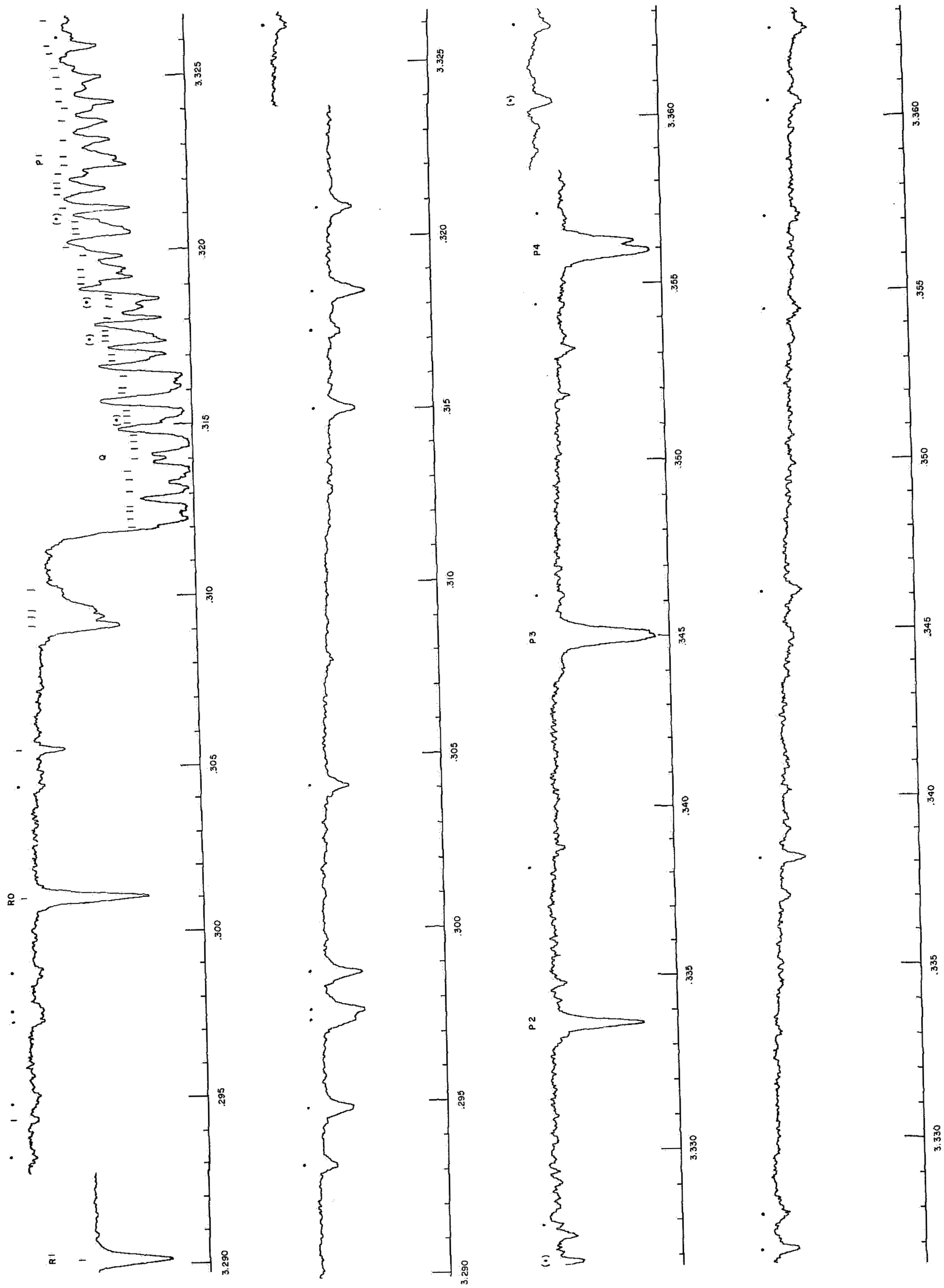

Fig. 5A Laboratory spectrum of methane, 10.5 mm atm, p = 8 cm, 3.290–3.363 μ, with water-vapor comparisons added.

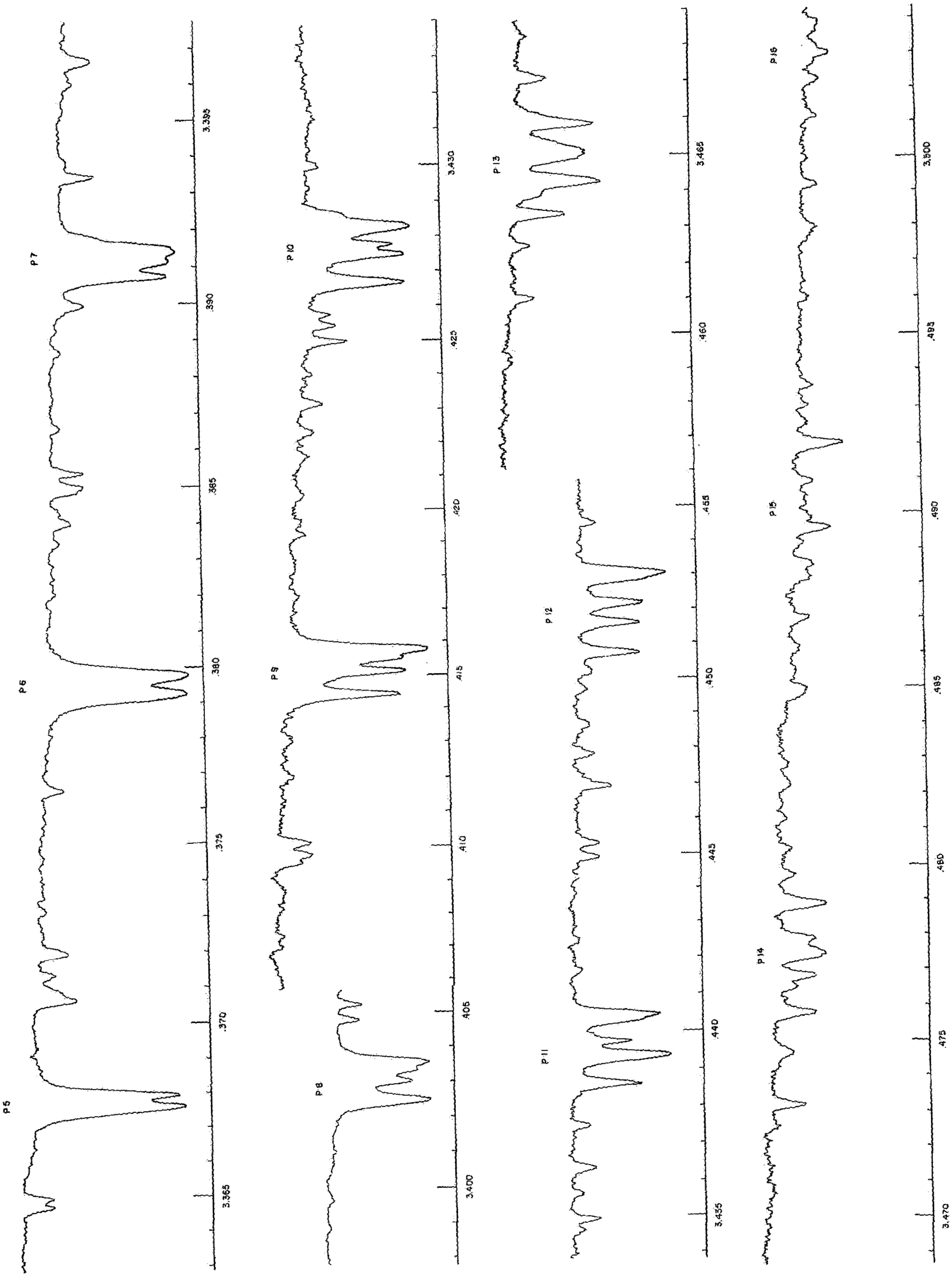

Fig. 6A Laboratory spectrum of methane, 10.5 mm atm, p = 8 cm, 3.363–3.504 μ. No observable water absorptions.

No. 126 A HIGH-RESOLUTION SOLAR SPECTROMETER FOR AIR-BORNE INFRARED OBSERVATIONS

by D. P. CRUIKSHANK, F. A. DE WIESS, AND G. P. KUIPER

November 22, 1968

ABSTRACT

The construction and operation of a 4-meter Czerny-Turner scanning spectrometer in the NASA Convair 990 Jet aircraft are described. The design of the spectrometer and its mounting support permit high resolution in spite of aircraft vibrations. Maximum resolution achieved was about 60,000, close to the theoretical limit of the optics.

1. *Objectives*

This paper describes the construction and operation of a 4-meter Czerny-Turner spectrometer for observations of the solar spectrum in the region 0.8–5.0 μ from the NASA Convair 990 aircraft at altitudes of 39,000 to 42,000 ft (12–13 km).

Ground-based astronomical spectroscopy in the infrared is severely hampered by strong telluric absorptions, with H_2O the most prominent absorber. In a discussion of the importance of infrared studies at conventional aircraft altitudes, Kuiper, *et al* (1968) pointed out that the scale height of water vapor in the atmosphere is about 1.6 km while that of the remainder of the air is about 8.0 km. Thus, at altitude 12 km the water vapor concentration is reduced by a factor of about 10^3 while the ambient air pressure is reduced only by a factor of 5.

Because of the strength and complexity of the absorption bands between 0.8 and 5.0 μ, a drastic reduction of the H_2O concentration alone is insufficient for a survey of solar lines in these regions. Resolutions up to 0.1 cm^{-1} are desirable to reach the fainter solar lines, given the various broadening effects present and the need to resolve blends as much as possible.

2. *Instrumental Requirements*

The restrictions placed on airborne spectral observations are severe. Aircraft dimensions restrict the size and weight of the spectrometer. On a given flight the observing time is limited by fuel load and flight path, demanding rapid operations. A compromise in resolution and recording speed must be reached on the basis of feasible spectrometer dimensions.

Sunlight must be introduced into the spectrometer with a telescope limited in aperture by available windows and the strength of window materials. Effective infrared transmitters are generally thin crystaline substances obtainable with clear apertures of 6 inches or less. Because of limb darkening, the guiding accuracy of the aircraft-telescope combination must be sufficient to keep the sun's image nearly centered on the spectrometer entrance slit during the observing period.

Aircraft vibrations require the spectrometer components to be rigid. The amplitude and frequency of vibrations in the aircraft depend on spectrometer location and orientation, which must be considered in the spectrometer design. For example, vibrations of frequencies perceptible to the touch are often of 50 times greater amplitude in the aft sections of an airplane than those in forward positions.

Finally, the equipment and its mounting to the aircraft must be capable to withstand emergency landing conditions with accelerations up to 9 G. This requirement constrains the spectrometer design and the shock and vibration mountings permitted.

3. *The 4-Meter Spectrometer*

Scanning spectrometers of the Ebert and Czerny-Turner types have been used successfully at the Lunar and Planetary Laboratory for several years (see Kuiper, *et al,* 1964), both in the laboratory and at the telescope. Several medium-large high-quality diffraction gratings have been used interchangeably between spectrographs and spectrometers. These gratings are plane, 128 x 154 mm in size, and are readily adaptable to different instruments.

In experiments with the Laboratory's 0.9-m spectrometer ("B"), the maximum resolution $\lambda/\Delta\lambda$ achieved was 7000 at 2.1 μ (corresponding to 3 Å). In order to obtain resolutions better than 1 Å with existing gratings and detectors, an instrument of 4 meters focal length was designed, near the maximum length that could be carried through the doors of the NASA CV-990. With the maximum beam diameter of 5 inches, governed by the dimensions of the gratings, the optical system operates at F/31, sufficient for sun and laboratory sources at $\lambda < 10\ \mu$.

The spectrometer installation in the CV-990 has been illustrated in *LPL Comm.* No. 123, Figs. 1a and 1b, which includes the 12-inch feeder telescope and heliostat, units that were available from the planetary IR program (smaller units would of course have sufficed for the sun). The grating is supported on a table provided with a six-speed motor drive. At the focus of the 6-inch camera (shown with the collimator in Fig. 1; focal length 392 cm), the detector serves as the analyzing slit. Lead-sulfide and lead-selenide detectors are available in a variety of dimensions. The focal plane end of the spectrometer (mounted in the laboratory) is shown in Figs. 2 and 3. Highest spectral resolution is obtained with detectors of 0.10 or 0.05 mm width and 1.5 and 2.0 mm length, acquired from Eastman Kodak (PbS Ektron) and Santa Barbara Research Corp. (PbS and PbSe). They are factory-mounted in small bakelite Amphenol plugs to which Microdot low-noise coaxial cables are soldered. The detectors are operated in dry-ice temperature (−78°C). The preamplifier and amplifier are external to the spectrometer.

The amplifier and preamplifier were designed by Dr. H. L. Johnson and constructed under his supervision. The design is similar to that published by Kuiper, *et al* (1962), except that the new preamplifier uses solid-state components. A Sanborn recorder (Hewlet-Packard Model 7700) with response time of 10^{-2} sec. is used for rapid data acquisition.

Because of the great cost of aircraft operations, high reliability of the spectrometer was essential. For this reason, a *modular design* was adopted. The least reliable elements in the system are the chopper motor and the grating drive motor. A slit-chopper module was constructed in duplicate, each unit having alignment screws permitting optical adjustment before flight. A 900 rpm Gaylord-Rives (No. B-3274) synchronous motor and a four-blade chopper give a chopping frequency of 60 Hz. The assembly permits synchronization of lamp and photocell to the amplifier system at other chopping frequencies, but normally they were used at the 60 Hz line-frequency available in the aircraft, which is suitable to a cooled detector.

The grating drive module is seen in Figs. 3 and 4. An Insco multi-speed motor drives a single thread worm and a 360-tooth gear upon which the grating rests. Adjustment screws are provided for the optical alignment of the module. A double conical bearing carries the rotation axis of the worm gear and grating, and it was found that this is the component most susceptible to vibration in flight. The optical lever from grating to camera mirror to detector being 8 meters, small rotations of the grating surface cause considerable displacements at the detector. This module could probably be improved for flight operations by the use of *two* well-separated bearings. The grating drive will need some improvement for future laboratory use. As noted in *LPL Comm.* 124, a periodic error in the dispersion, while not seriously interfering with operations, required more detailed wavelength calibration subsequently than would have

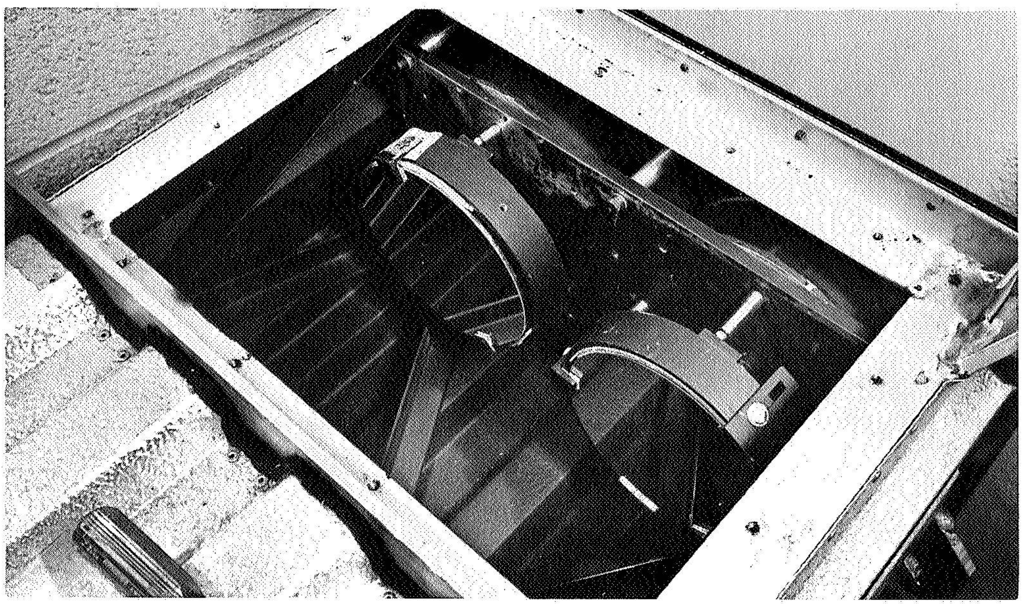

Fig. 1 Top view of camera and collimator mirrors, with cover plate removed. Note mounting of mirror cells, controlled by adjustment screws shown in *LPL Comm.* 123, Fig. 1a.

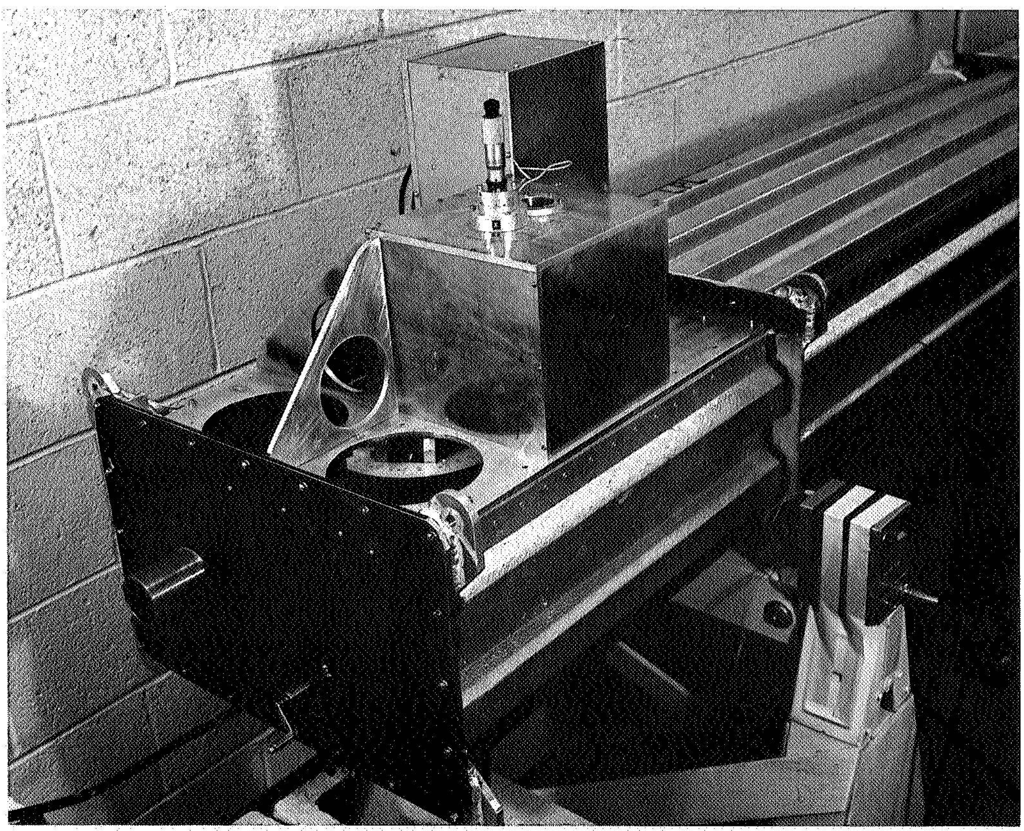

Fig. 2 Focal plane end of 4-meter spectrometer containing entrance slit (with chopper in front), grating and drive, and detector mounted in cold box. Micrometer screw seen on top for focusing detector; small crank at bottom, for hand setting of grating position.

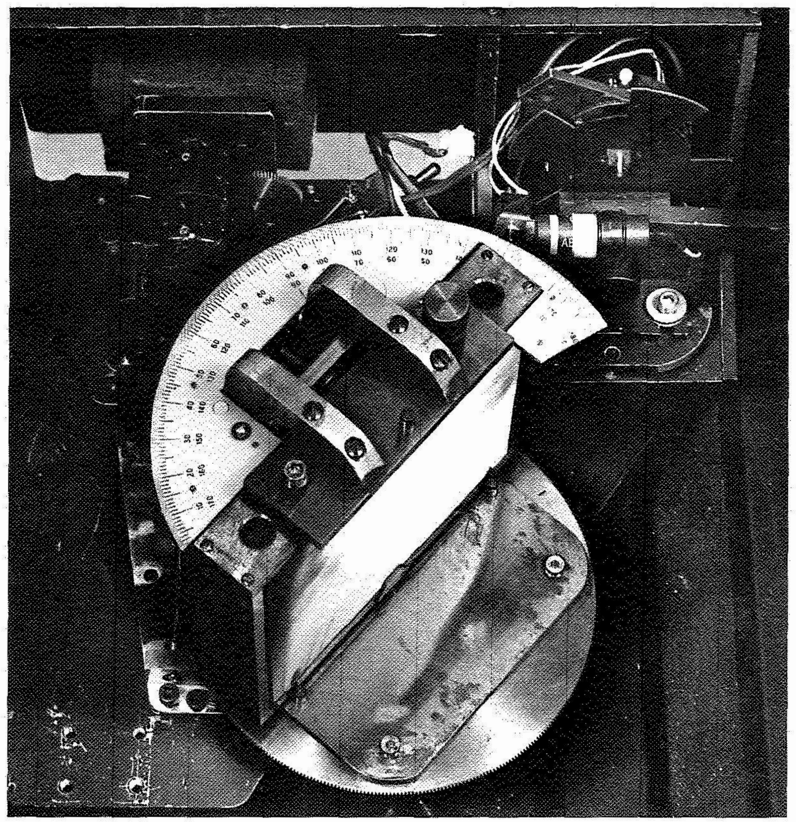

Fig. 3 Top view of grating drive assembly in spectrometer, with cover removed. Grating angles read to 0°.1 (for setting purpose) from large protractor shown (index mounted on top cover, removed). Grating surface is light-colored rectangle below center; worm gear engaged to worm, at left, driven by motor assembly seen at upper left (6 speeds). Chopper at upper right, with bar beyond used for phasing, and slit assembly just below it; channel to right contains micrometer screw for setting slit width.

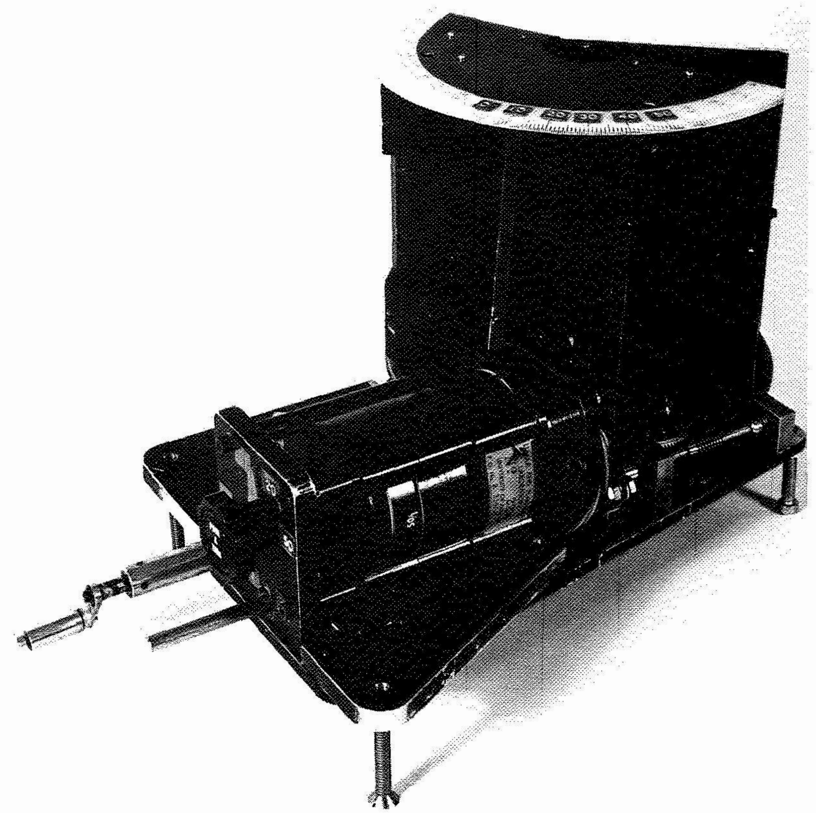

Fig. 4 Separate view of second grating-drive module, blackened (details differ from first unit, shown in Fig. 3).

TABLE 1

RUNNING TIME (SECONDS/100 Å) AND DISPERSION (CM/100Å) FOR AVAILABLE MOTOR AND CHART SPEEDS AND 1200 LINES/MM GRATING AT λ 1.2 μ

PAPER SPEED (MM/SEC)		0.5	2.5	10.	50.
REDUCTION OF MOTOR SPEED	TIME NEEDED FOR 100 Å INTERVAL (SEC)	DISPERSION (LENGTH 100 Å INTERVAL IN CM)			
1	30	1.5	7.5	30	150
2	60	3.0	15.0	60	300
5	150	7.5	37.5	150	750
10	300	15.	75.	300	1500
20	600	30.	150.	600	3000
50	1500	75.	375.	1500	7500

Multiply all Table entries by 0.86 for 1200 l/mm grating at λ 1.0 μ; by 0.43 for 600 l/mm grating at $\lambda = 2.0\ \mu$; and by 0.215 for 300 l/mm grating at $\lambda = 4.0\ \mu$. (These cases refer to grating angles at 37°; for other angles α, multiply with the further factor sec α/sec 37° or cos 37°/cos α.

been necessary otherwise. However, the versatility of the drive motor, with its six gear shifts, was an asset in a program where observing time was at a premium. Table 1, prepared by Mr. L. A. Bijl, lists the available options of motor and chart speeds for a particular grating and grating angle. As indicated in the footnote of Table 1, the numbers are readily converted to other wavelength settings with the same grating or other gratings.

The cold box is shown in Fig. 2. The detector in its Bakelite mount is held in a brass cylinder that for focusing can be moved axially against a spring, using a metric micrometer screw with 1.5 cm travel. Focusing is accomplished in two stages: (a) the spectrum of an emission line source (fluorescent lamp) is formed on a translucent screen in a dummy detector assembly. Visual inspection gives the approximate focus; (b) repeated scans with various micrometer screw settings through the spectrum of a nearby H_2O vapor band refine the focus. The adjustment appears fairly insensitive to changes of $\pm$ 1 mm around the optimum focus, as expected at F/30. Usually step (a) is adequate.

The capacity of the cold box is 2 liters, sufficient to keep the detector cold for 8 hours. Thermal insulation is provided by a mantle of finely divided silica (Santocell.) A small electrically-heated sapphire window prevents condensation of water on the detector surface.

During the CV-990 flights the plane's interior is flushed with heated, compressed outside air. The moisture content of the cabin atmosphere is thus potentially quite low. However, the total water vapor introduced by the 20–25 scientists and other personnel aboard into the 16-m spectrometer path was found to be far greater than in the entire atmospheric column from aircraft to sun. A simple solution was achieved at no cost by continuously flushing the spectrometer interior with fresh air taken from the plane's airconditioning system. We confirmed on several occasions that this continuous flushing was essential to keep the instrumental H_2O vapor concentration within tolerable limits. For example, when an incandescent source was used for calibration in flight, the lines in the H_2O band at 1.13 μ were invisible when the spectrometer was flushed, but quite strong when the ambient cabin air was admitted. During the solar observations, the entire heliostat and telescope area were enclosed with plastic sheets and also flushed with outside air. The total optical path inside the aircraft is about 22 meters, of which less than one meter is through the ambient cabin air.

4. Vibration Problems

The total length of the instrumentation, consisting of heliostat, telescope, and spectrometer, is 6.3 meters. Over this distance flight-induced vibratory deformations of the fuselage vary in amplitude by values far greater than the relative displacements permissible for the optical components of the system. An analysis indicated that the weight of a *single* structure, to be suspended floating in the fuselage and of sufficient vibratory rigidity, would be a multiple of the flyable value for the airplane.

It was therefore decided (a) to divide the system into *two* units, one heliostat plus telescope, the other the spectrometer; (b) to provide each unit with rigidity sufficient to maintain alignment of its optical components under maximum amplitude of their harmonic response to fuselage vibrations; and (c) to control this response by suspending each unit separately by vibration absorbers.

The penalty for decoupling the two units comprising the optical path, namely, a displacement of the ray bundle at the interface under different oscillatory reactions of the two units, was made acceptable by locating the plane of separation close to the slit of the spectrometer, where the light bundle is narrowest, and because of the fact that the solar image at this point is 50 times wider than the effective slit length (100 mm vs. 2 mm).

The first unit containing heliostat, telescope and some of the electronic equipment and consisting of a boxframe of crossbraced aluminum angles, was attached to several points of the fuselage by vibration absorbers. To provide this unit with the required rigidity posed no serious problem as its length-to-diameter is low (1.85) and the masses of its components could be distributed quite evenly in its volume.

More of a problem was posed by the spectrometer unit, as its length-to-diameter ratio is high (9.5) and its main masses — the optical components — are located at its extreme ends. These components and, therefore, the end faces of the unit, have to remain parallel within 1.3 seconds arc; or, stated differently, the unit has to be of sufficient rigidity to prevent it from responding to flight-induced vibration with transversal vibrations with amplitudes of more than .05 mm at distances from the node up to 2 m.

The design developed to meet these constraints provides a rectangular tube fabricated of aluminum angles, crossbraced and covered with corrugated aluminum sheeting. Both ends are formed into boxes of aluminum plate, attached to bulkheads, providing the supports for the respective optical components. Eight tensioned steel cables attached to both ends of the tube and tilted 10° away from the tube axis toward the center, where they are supported by an external frame, serve to load the tube in compression. A total cable tension of 2455 lb (1120 kg) was chosen for a calculated safe column strength of the spectrometer tube of 3890 lbs (1770 kg). The weight of the complete assembly came to 189.3 lb (86 kg), and its length to 13 ft 6½ in. (4.13 meters), not counting the projecting screws and small entrance tube.

The unit was supported with vibration absorbers in two transversal planes, each located at the respective center of gravity of the instrument end boxes. Two three-dimensional trusses providing these suspension points were in turn attached with vibration mounts to the fuselage in such manners that their main axis of absorption is at right angles to those of the mounts supporting the instrument tube.

A stress analysis of the whole system indicated a safety factor of 4.9 for its weakest structural member under crash loading of 9g as specified by flight-safety regulations.

5. *Operation of the Spectrometer*

The 4-meter spectrometer was used on the CV-990 for a series of solar observations from July 2 to August 12, 1968, as described in *LPL Comm.* 123. In flight, the highest resolution obtained with a 1200 line/mm grating blazed for 1.0 μ, and a detector 0.10 mm wide, was about 0.2 Å. Reference is made to three preceding *Communications,* especially No. 124, for sample reproductions of solar spectra.

Acknowledgments. The construction and testing of the airborne solar spectrometer was sponsored by NASA through Grant NsG 161-61 and the University of Arizona Institutional Grant NGR-03-002-091.

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