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

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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 ($\lambda > .68\ \mu$). Some gaps occur in the (duplicate) records, due to troubles with the heliostat control (which happened all for $\lambda < 1\ \mu$). 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

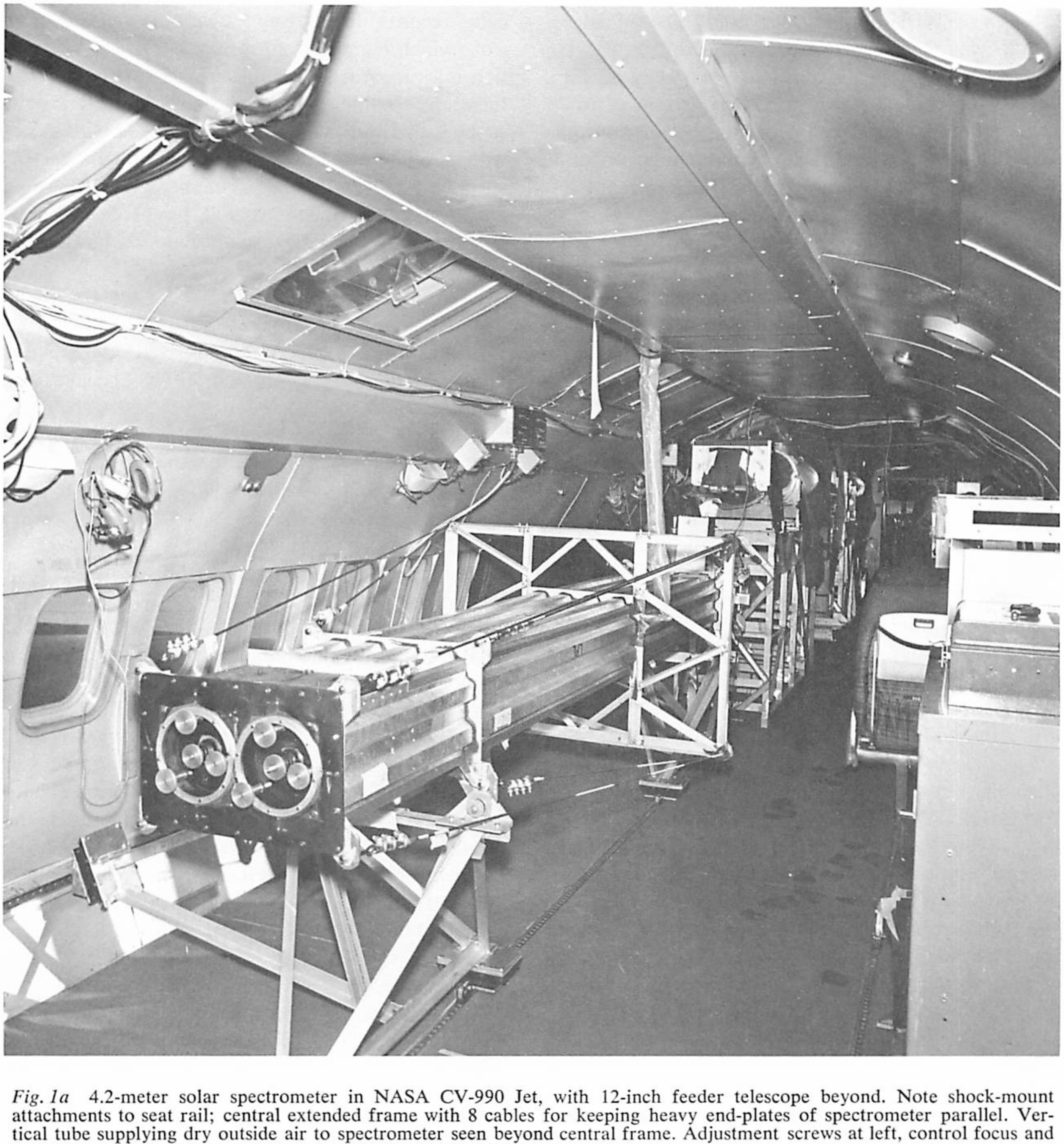

Fig. 1a 4.2-meter solar spectrometer in NASA CV-990 Jet, with 12-inch feeder telescope beyond. Note shock-mount attachments to seat rail; central extended frame with 8 cables for keeping heavy end-plates of spectrometer parallel. Vertical tube supplying dry outside air to spectrometer seen beyond central 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)

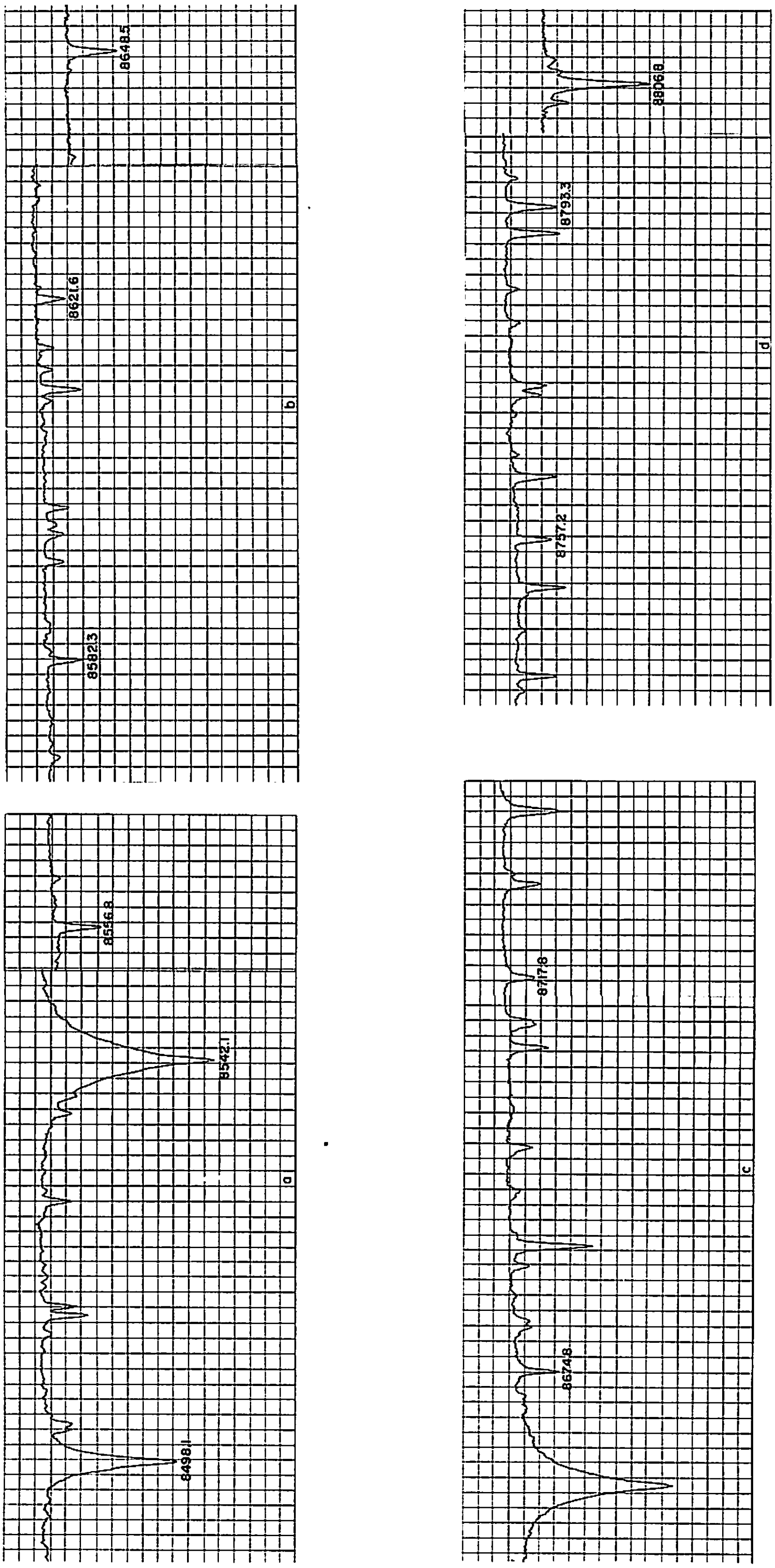

Fig. 2M Part of Michigan Atlas that matches Fig. 2. (2M–7M reproduced with permission)

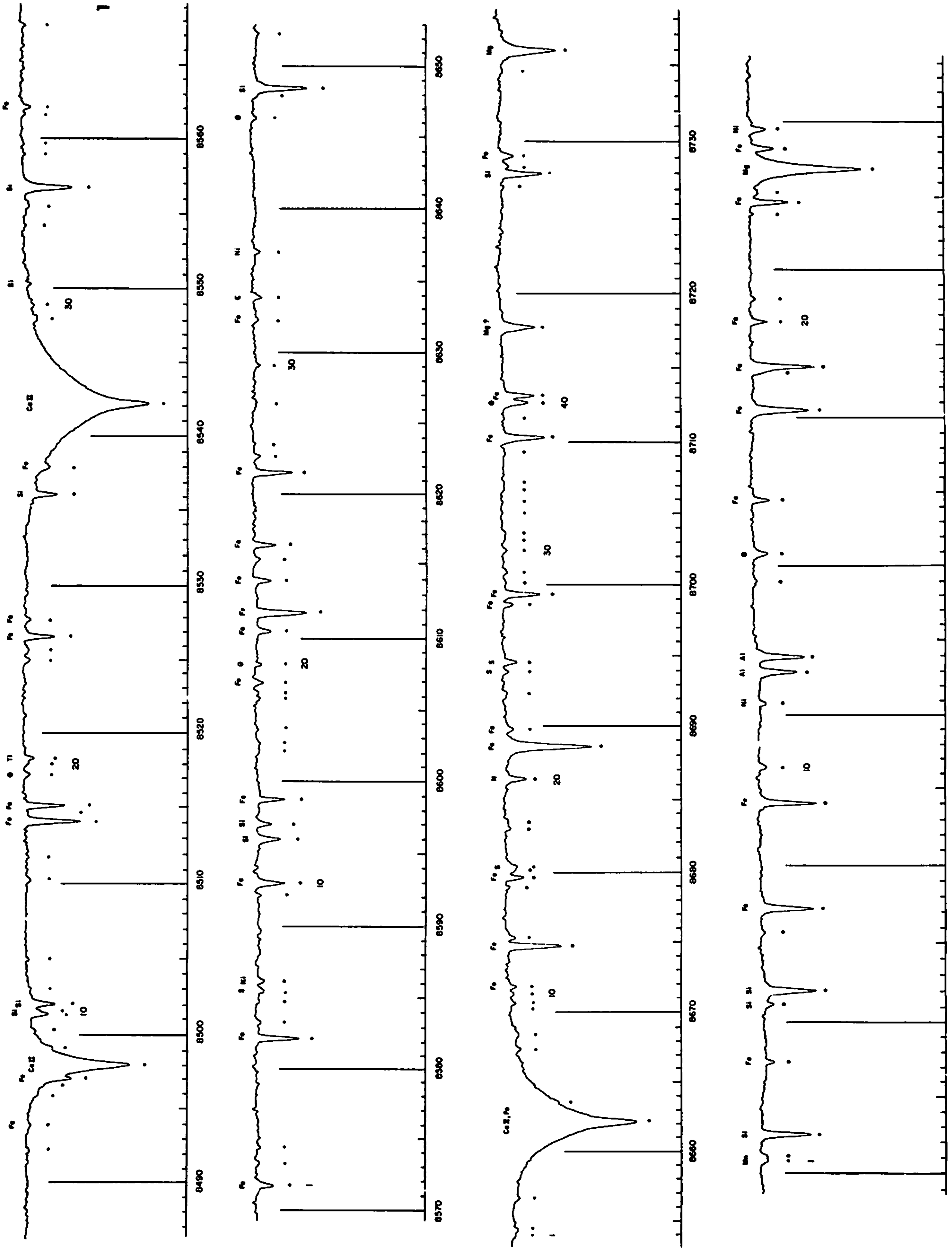

Fig. 2 Solar spectrum λλ8487–8815, in four strips (cf. Table 1).

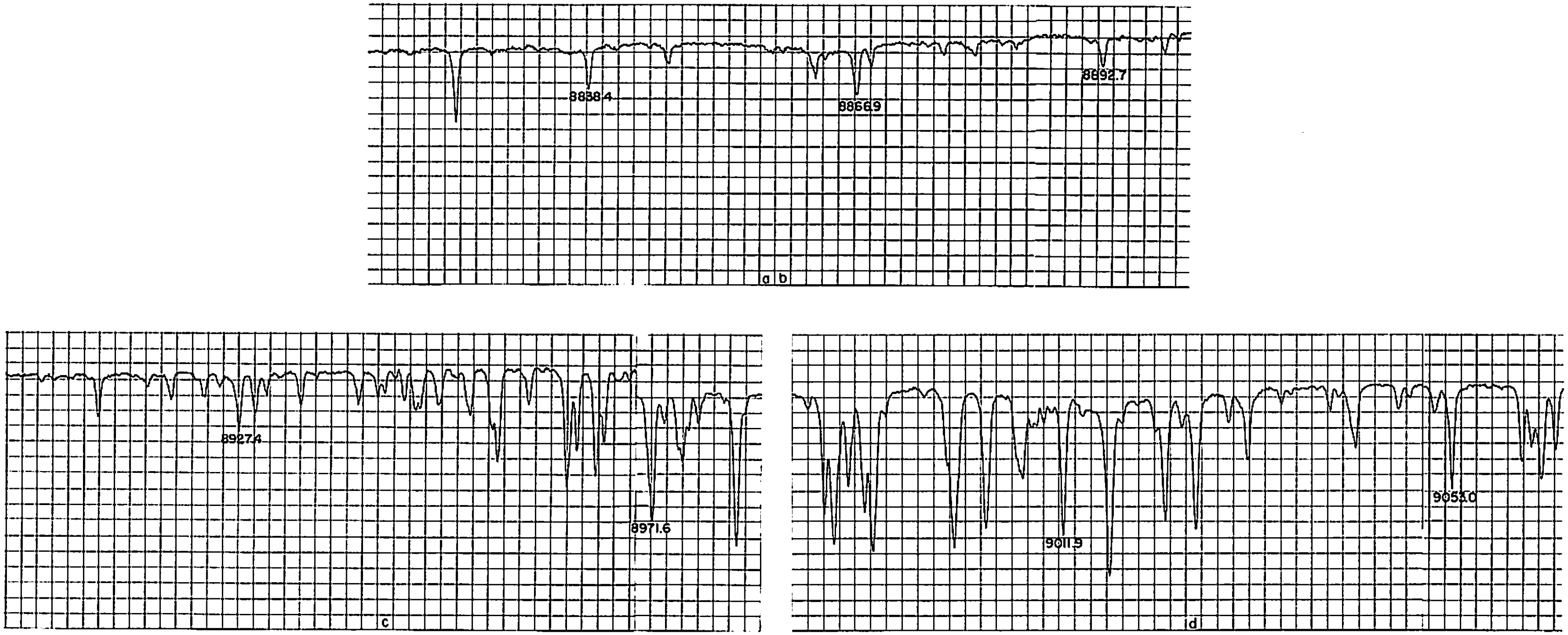

Fig. 3M Part of Michigan Atlas that matches Fig. 3.

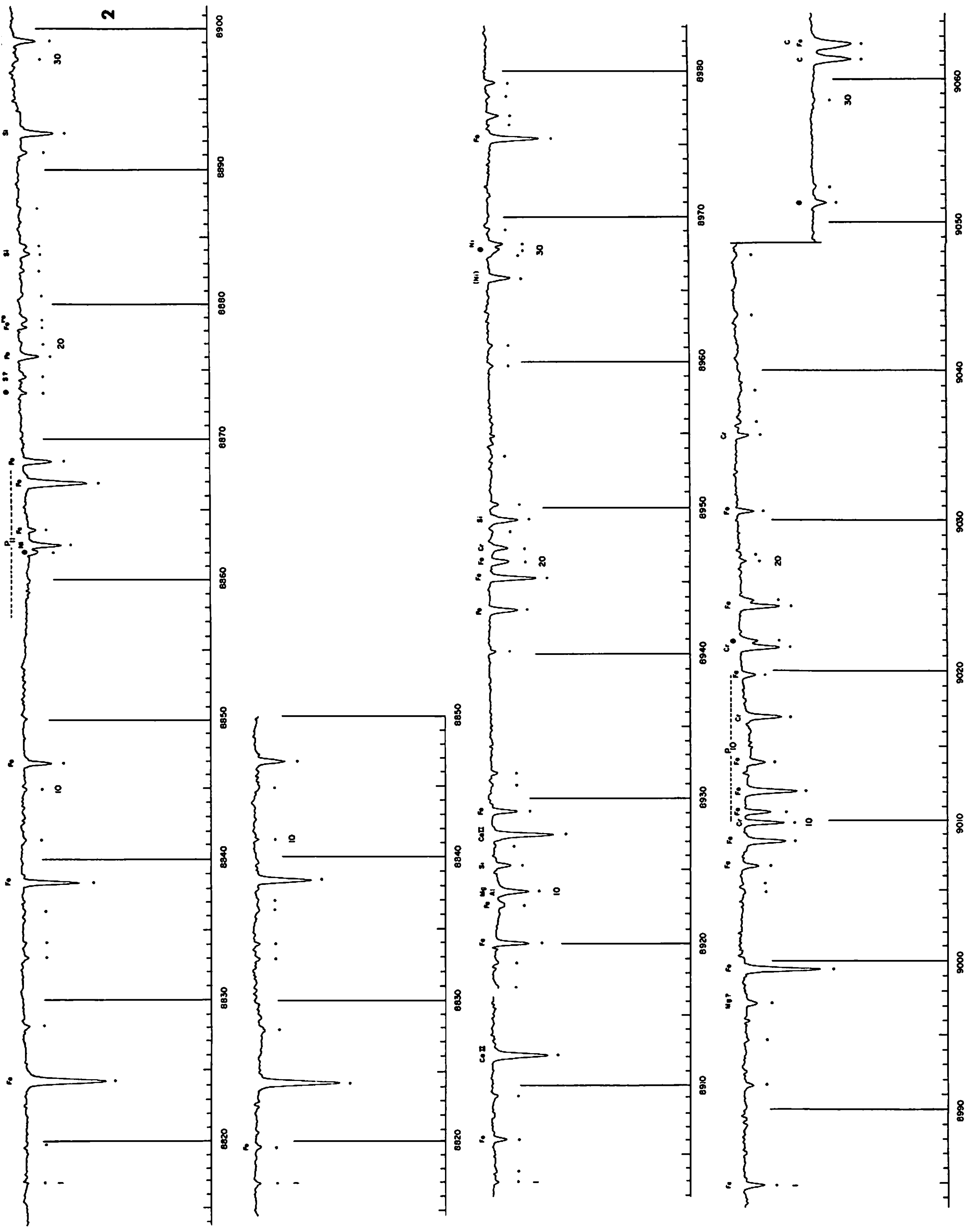

Fig. 3 Solar spectrum λλ8814–9064, in four strips (cf. Table 1).

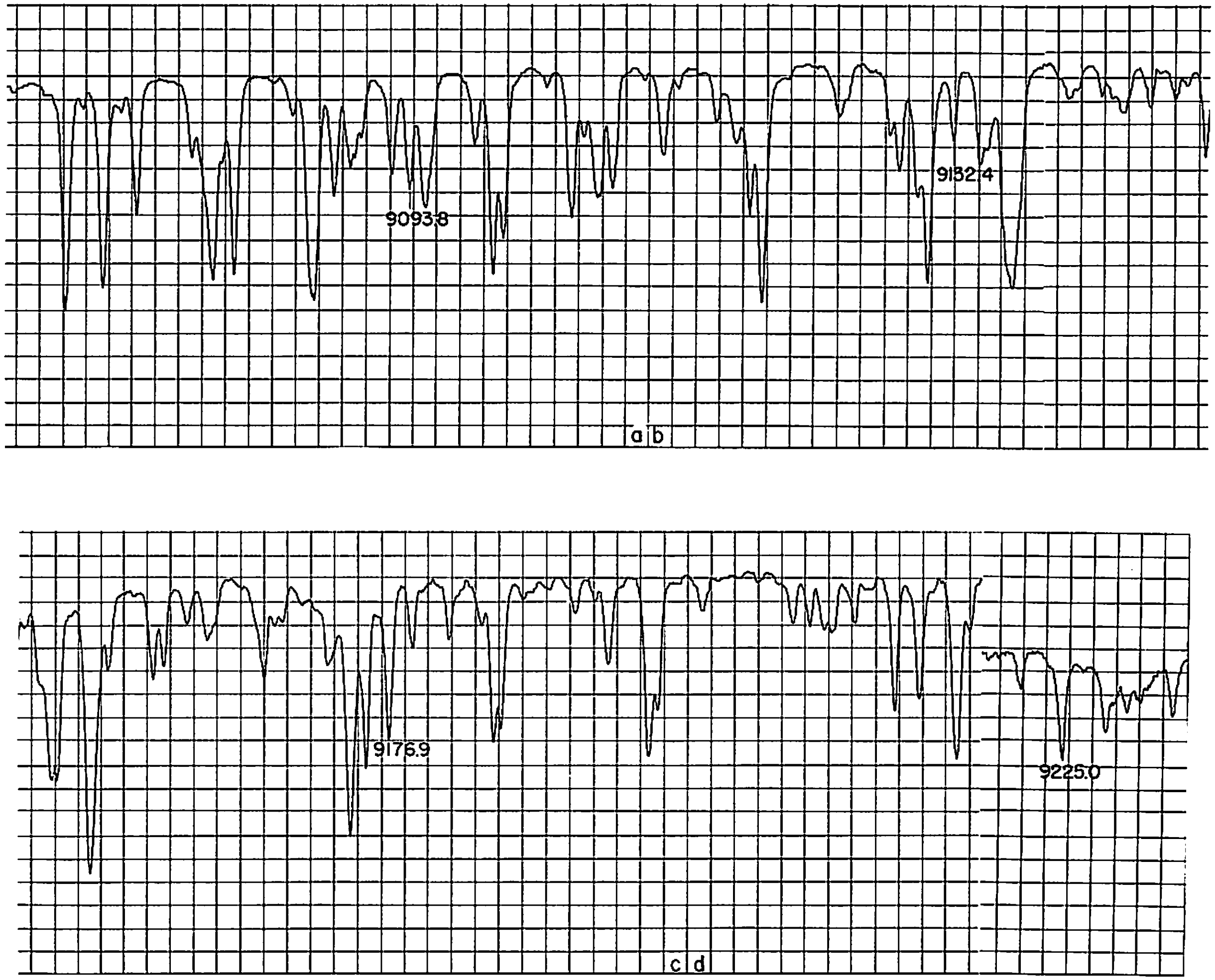

Fig. 4M Part of Michigan Atlas that matches Fig. 4.

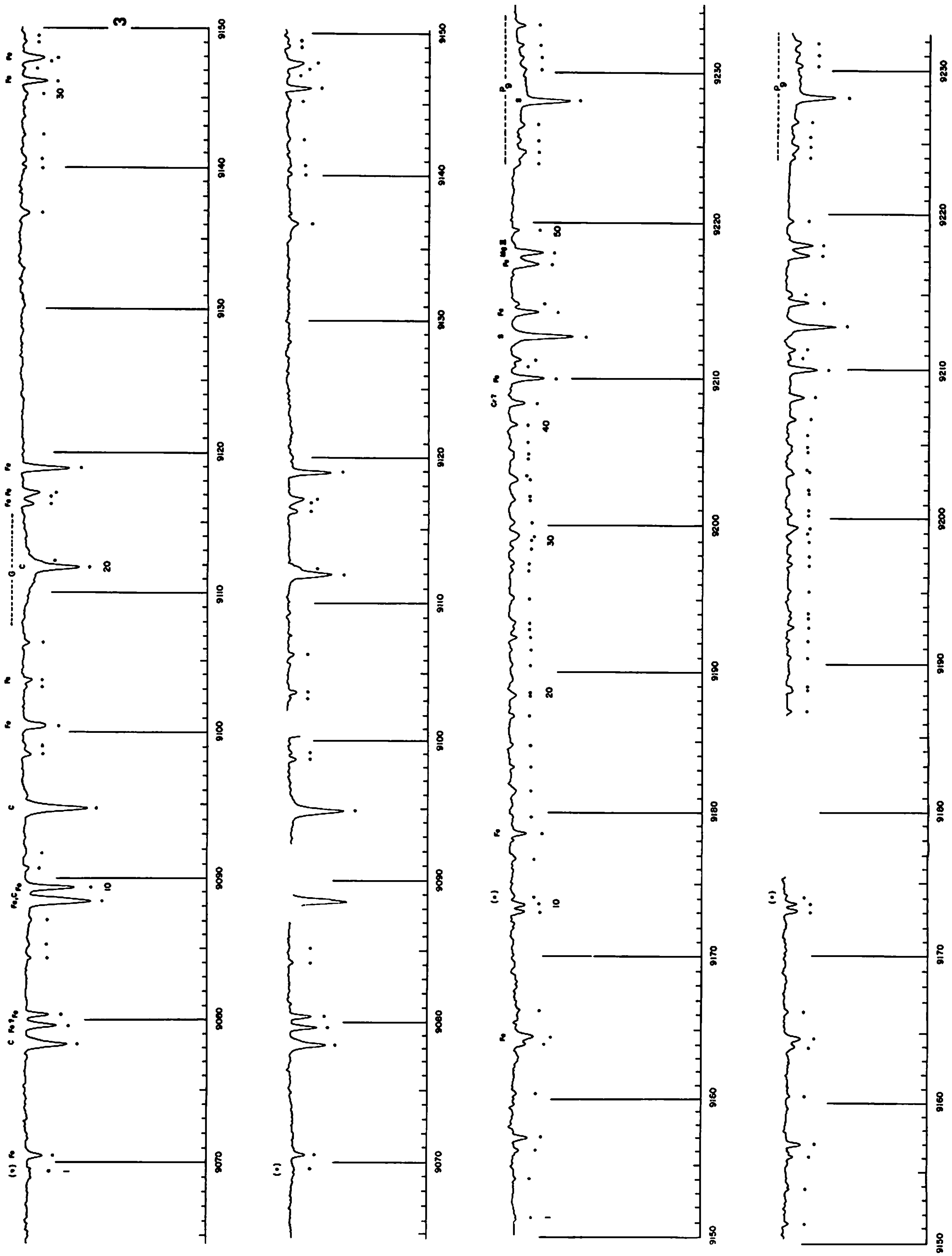

Fig. 4 Solar spectrum λλ9064–9234, in four strips (cf. Table 1).

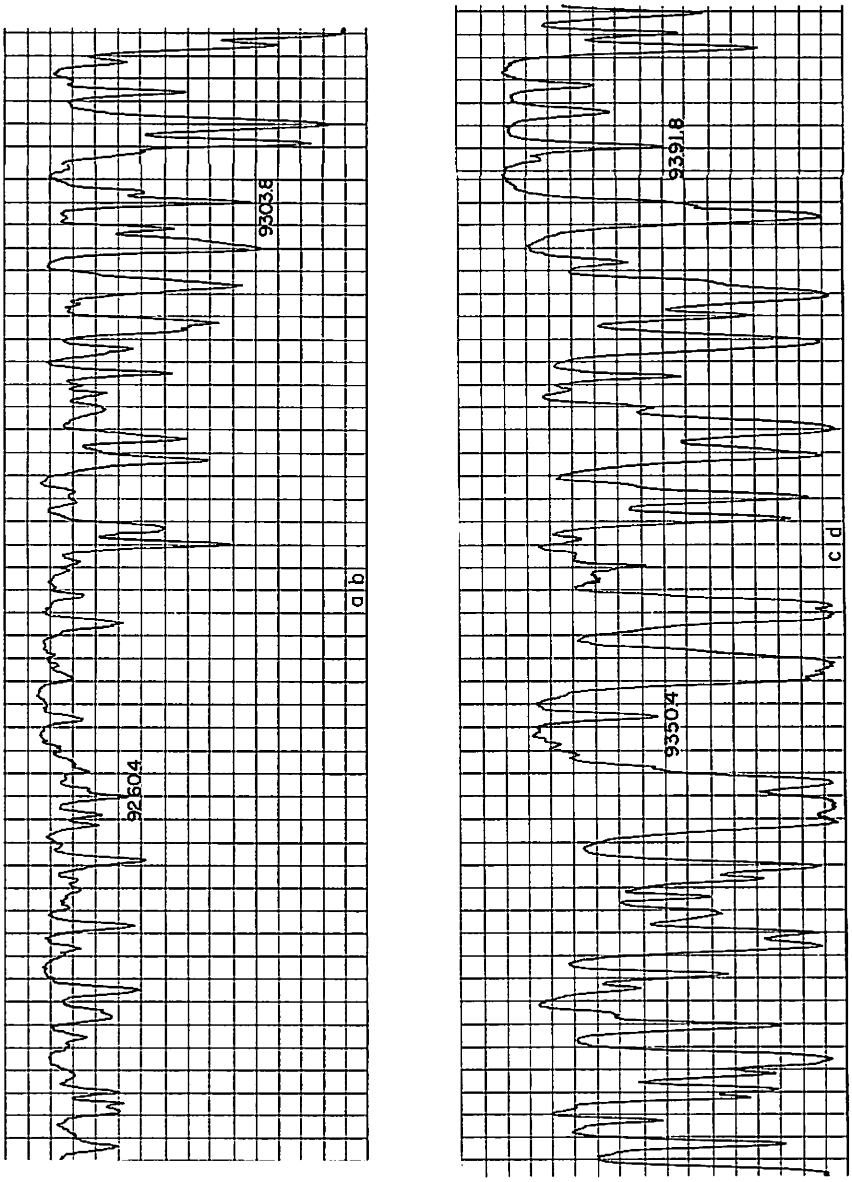

Fig. 5M Part of Michigan Atlas that matches Fig. 5.

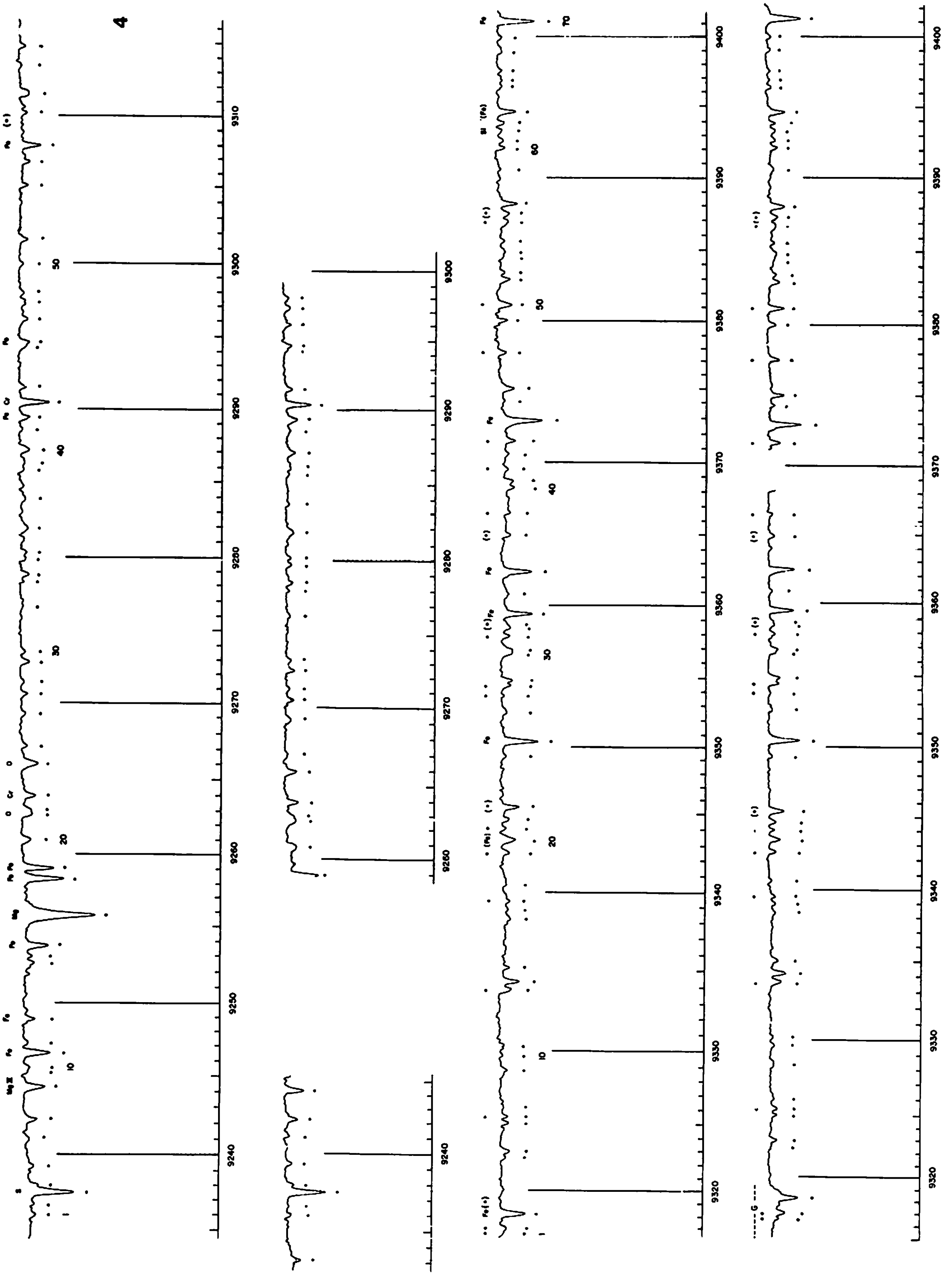

Fig. 5 Solar spectrum λλ9233–9402, in four strips (cf. Table 1).

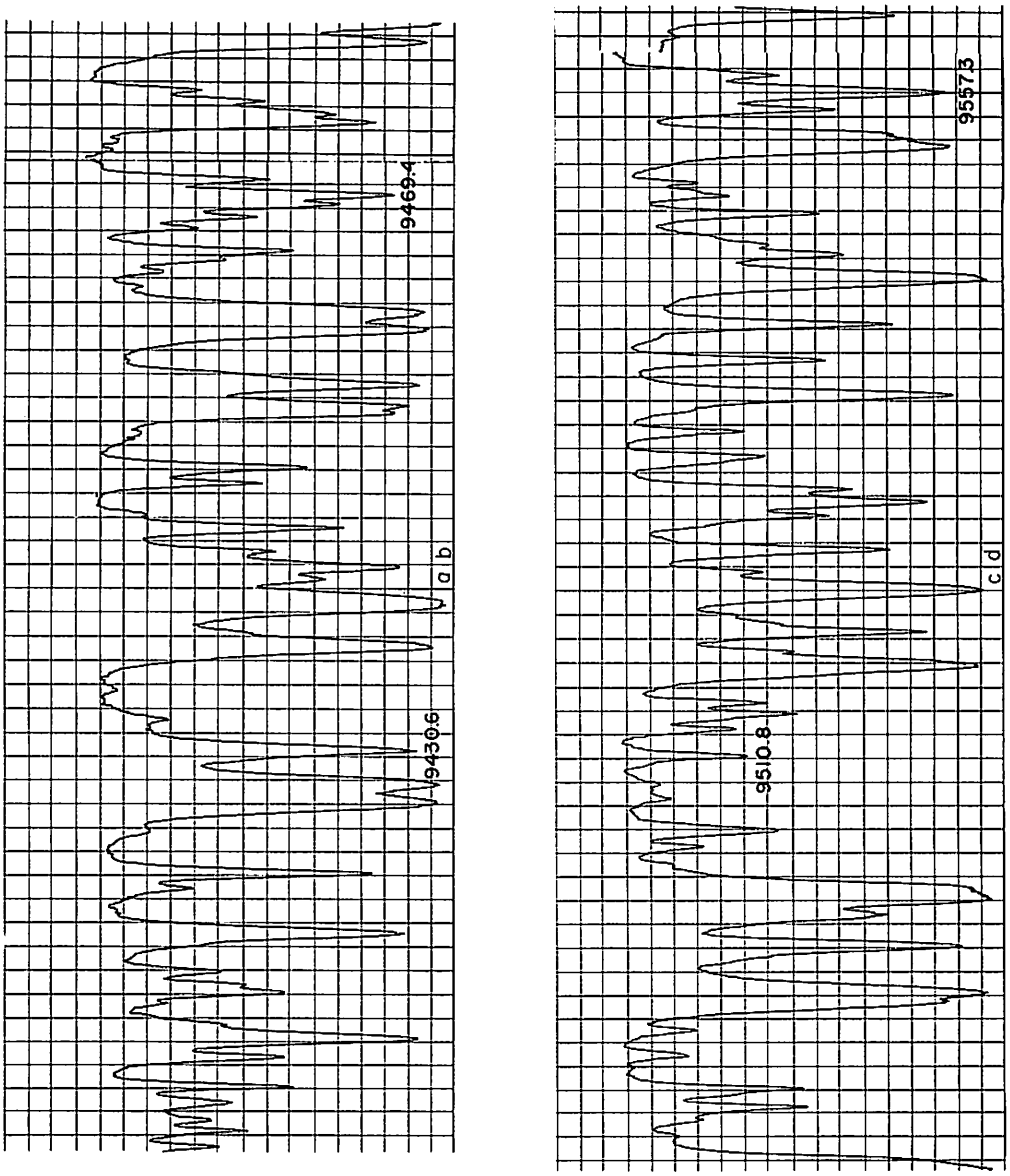

Fig. 6M Part of Michigan Atlas that matches Fig. 6.

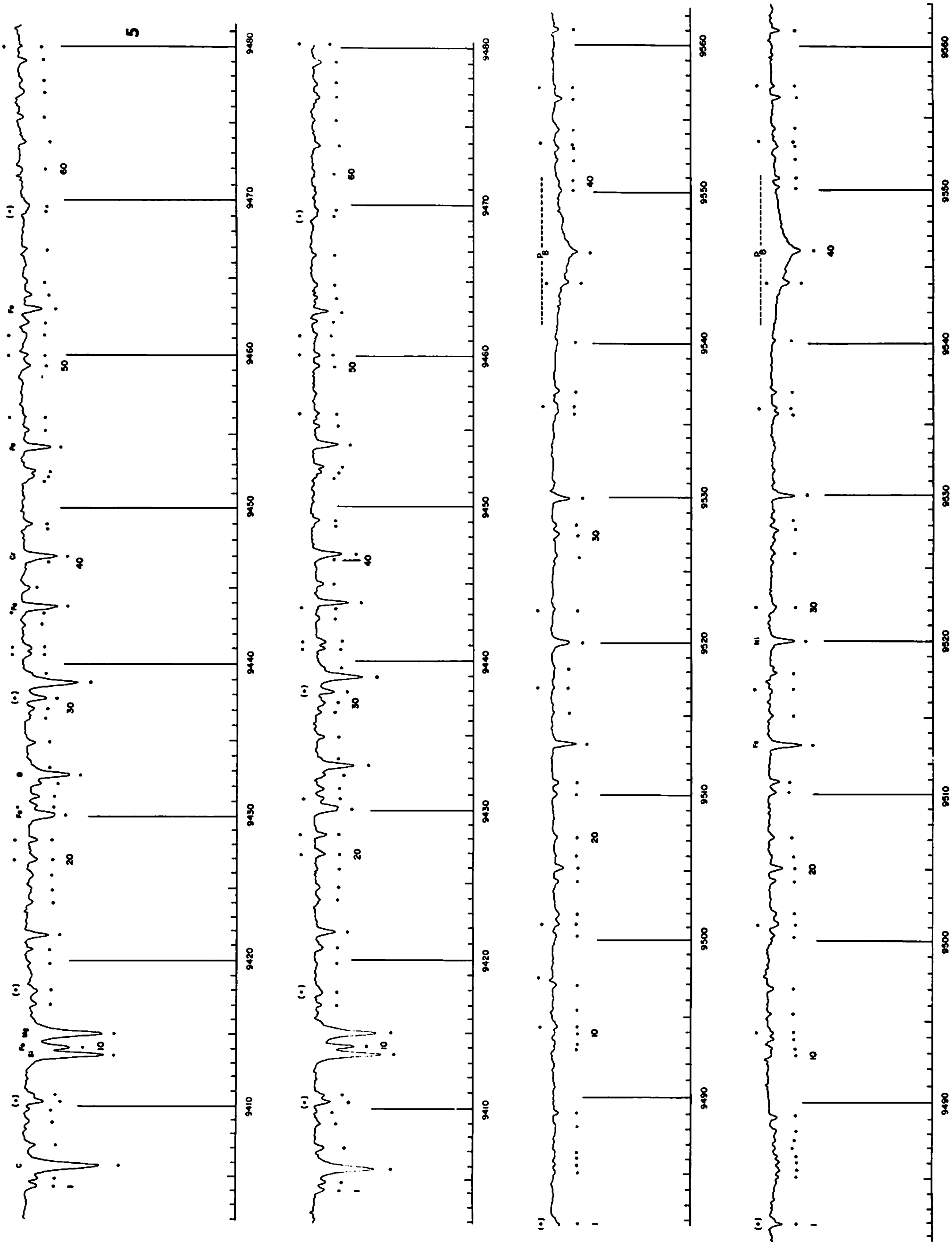

Fig. 6 Solar spectrum λλ9402–9563, in four strips (cf. Table 1).

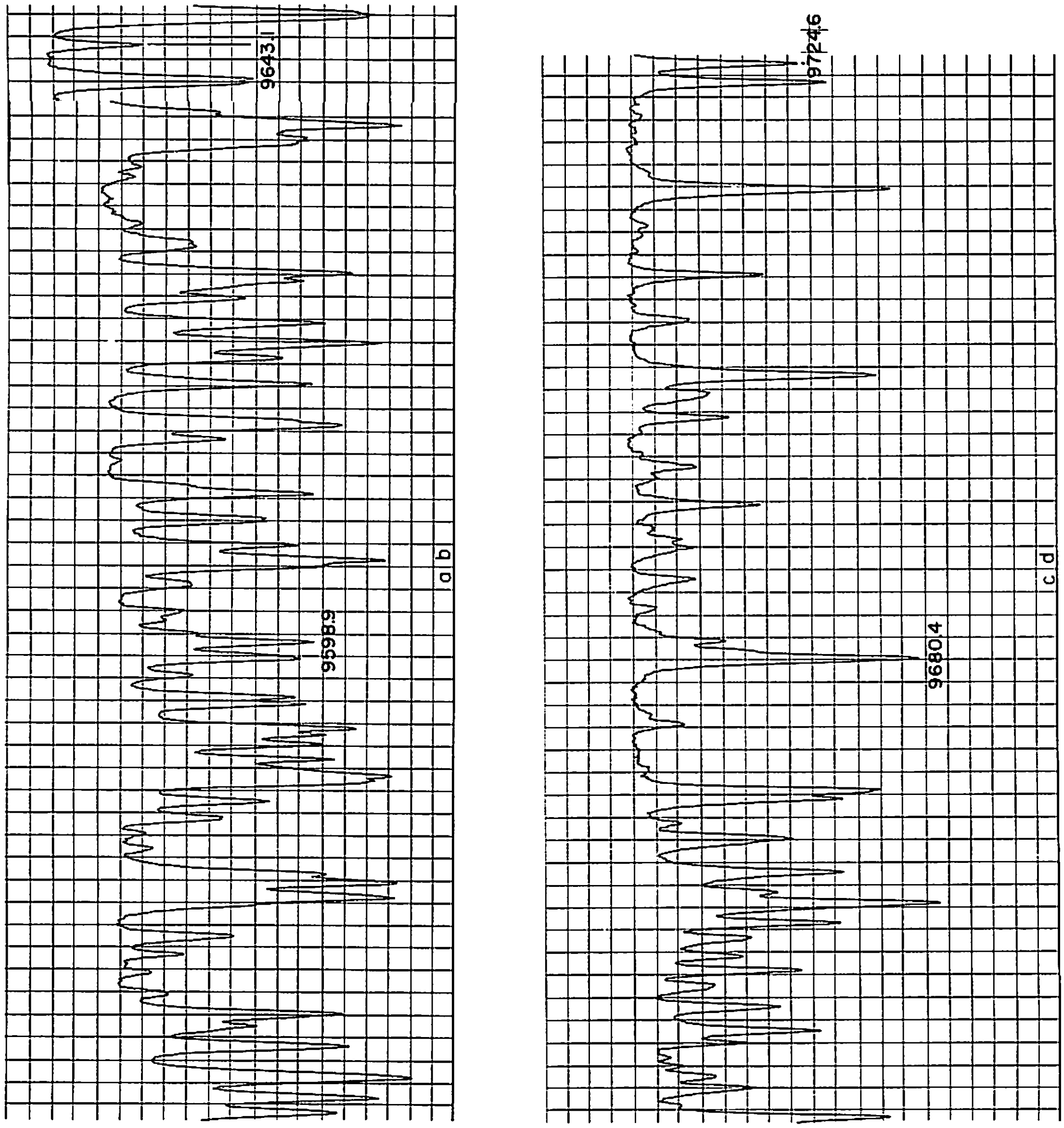

Fig. 7M Part of Michigan Atlas that matches Fig. 7.

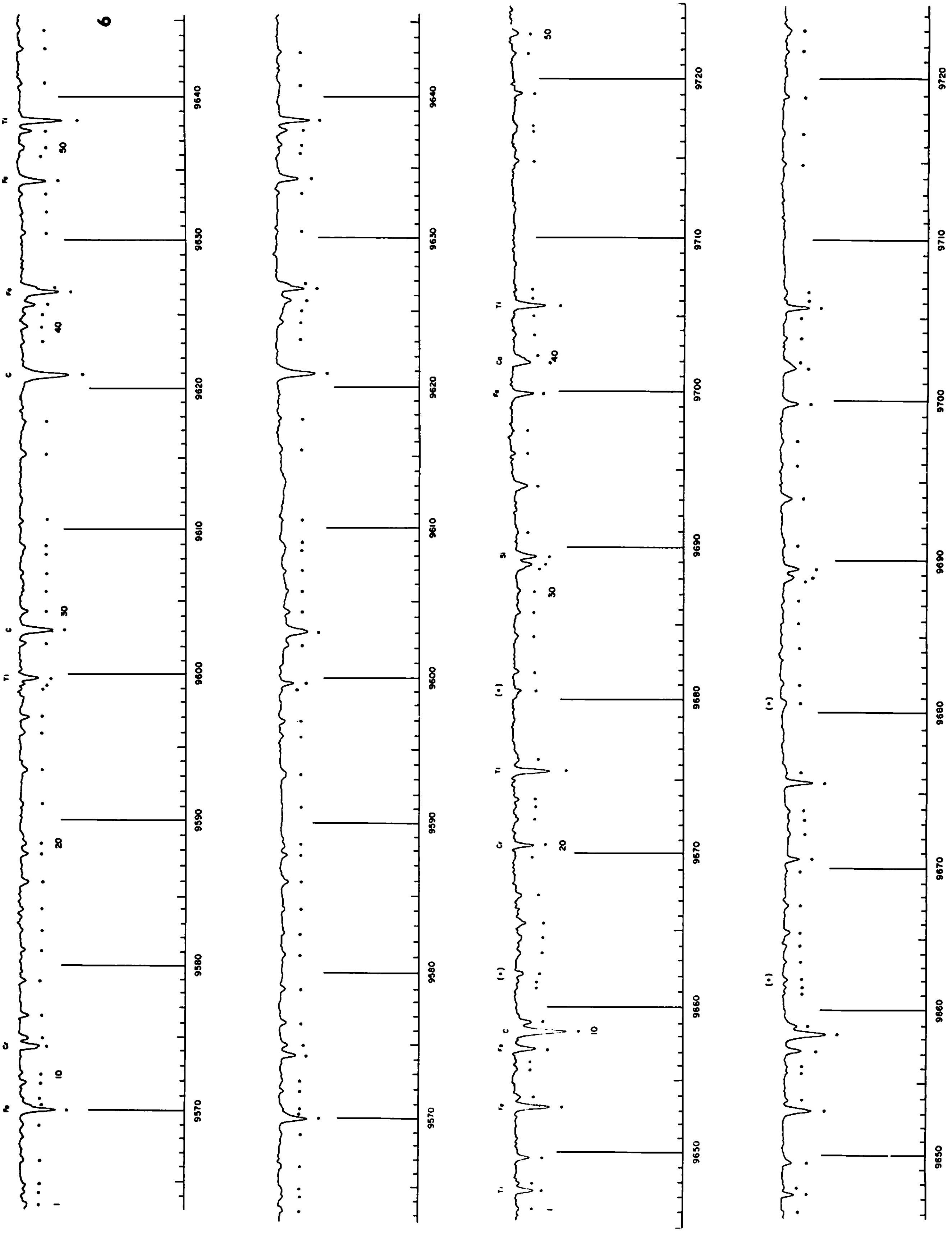

Fig. 7 Solar spectrum λλ9563–9725, in four strips (cf. Table 1).

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°.

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TABLE I

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