NO. 25. INFRARED SPECTRA OF STARS AND PLANETS, III: RECONNAISSANCE OF A0-B8 STARS, 1-2.5 MICRONS

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ABSTRACT

With this paper a systematic discussion of infrared spectra of stars between 1-2.5μ is begun, starting with the stars of types A0-B8.

1. Introduction

Because of the high temperatures of the B and A stars, their infrared continua are comparatively weak (cf. Figures 4 and 8, *Comm. No. 23*) and the attainable spectral resolutions low, even for the brighter objects. However, the expected absence of molecular bands and the expected presence of the several series of atomic hydrogen suggest that these types be discussed first.

The spectra were obtained with the 82-inch telescope of the McDonald Observatory, with the spectrometer attached described in *Communications No. 16*. To provide overlap with the photographic region, the photographic infrared (0.7-1.1μ) was recorded also, using a Dumont S1-type photomultiplier which fitted the space normally occupied by the PbS cells. The same modulation (60 cps) and the same amplifying system were used as for the PbS records. Only the power supply had to be replaced; we used the High-Voltage DC Supply, model 412A, of the John Fluke Manufacturing Company, which allowed continuous adjustment of the cell voltage for optimizing the signal/noise. Normally about 900 v was used. This power supply is stable to one part in 10^4, which is required because of the steep dependence of the gain on the voltage (10th power). Supplementary records, down to $\lambda = 0.3\mu$, are given in *Communications No. 26*.

The spectra reproduced here (and in successive papers for the other spectral types) do not represent a "maximum effort," but rather what could be done under average good conditions with a one-channel spectrometer during runs of about 20-60 minutes. With increased scanning times and a multichannel spectrometer, considerable improvements are still possible.

2. Description of the Spectra

In the "photographic" region, 0.3-1.1μ, the most prominent spectral features in the A and late-B stars are the Balmer and Paschen series of hydrogen and their continua. It may be expected that the next two series of hydrogen, of which 2 and 3 members have been observed in the laboratory, by Brackett (1922) and Pfund (1924), respectively, will be prominent also. Several members of the Brackett series were in fact marginally observed in the spectrum of Sirius before (Kuiper *et al.*, 1947), with a resolution of only 80.

The wavelengths of the three infrared series of hydrogen recorded here are found from the Rydberg formula,

$$\nu = R_H \left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right), \text{with } n_2 > n_1, \qquad (1)$$

where R_H is the Rydberg constant for hydrogen, 109678.7, and n_1 is 3, 4, and 5, respectively, for the Paschen, Brackett, and Pfund series. The computed frequencies and wavelengths are listed in Table 1.

TABLE 1

WAVELENGTHS OF INFRARED HYDROGEN LINES AND SERIES LIMITS

Line	ν	$\lambda(\mu)$	Symbol Used
Paschen α	5331.5	1.8757	P4
β	7799.3	1.2822	P5
γ	9139.9	1.0941	P6
δ	9948.2	1.0052	P7
ϵ	10472.8	0.9549	P8
ζ	10832.5	0.9232	P9
η	11089.7	0.9017	P10
θ	11280.1	0.8865	P11
ι	11424.9	0.8753	P12
κ	11537.5	0.8667	P13
λ	11626.9	0.8601	P14
μ	11699.1	0.8548	P15
ν	11758.1	0.8505	P16
ξ	11807.0	0.8470	P17
o	11848.0	0.8440	P18
π	11882.7	0.8416	P19
∞	12186.5	0.8206	P ∞
Brackett α	2467.8	4.0522	B5
β	3808.3	2.6259	B6
γ	4616.6	2.1661	B7
δ	5141.2	1.9451	B8
ϵ	5500.8	1.8179	B9
ζ	5758.1	1.7367	B10
η	5948.5	1.6811	B11
θ	6093.2	1.6412	B12
ι	6203.0	1.6114	B13
κ	6295.3	1.5885	B14
λ	6367.5	1.5705	B15
μ	6426.5	1.5561	B16
ν	6475.4	1.5443	B17
ξ	6516.4	1.5346	B18
o	6551.1	1.5265	B19
∞	6854.9	1.4588	B ∞
Pfund α	1340.49	7.4600	Pf6
β	2148.83	4.6537	Pf7
γ	2673.42	3.7405	Pf8
δ	3033.05	3.2970	Pf9
ϵ	3290.36	3.0392	Pf10
ζ	3480.76	2.8729	Pf11
η	3625.54	2.7582	Pf12
θ	3738.18	2.6751	Pf13
ι	3827.57	2.6126	Pf14
κ	3899.69	2.5643	Pf15
λ	3958.72	2.5261	Pf16
μ	4007.64	2.4952	Pf17
ν	4048.63	2.4700	Pf18
ξ	4083.34	2.4490	Pf19
∞	4387.15	2.2794	Pf ∞

The series limits for the next two series of hydrogen ($n_1 = 6$ and 7, respectively) are located at 3.2823μ and 4.4676μ, respectively, i.e., outside the region considered here, but within the region accessible to observation from a ground-based observatory.

Of the A-type stars, Sirius is the best suited for detailed study, being 4 times brighter than the next accessible A star, Vega. The stars β Orionis (Rigel) and α Leonis (Regulus) are the brightest of type B8, and they were observed with reduced resolution. For early B stars only fragmentary data were obtained, which are not included here.

The infrared continua at the series limits are not expected to be obvious features. The most prominent part of the Balmer continuum is about 150A wide. This interval expressed in wave numbers corresponds to about 750A at the Paschen limit, 0.24μ at the Brackett limit, and 0.59μ at the Pfund limit. These widths are so large that the absorptions will be masked by other effects. Furthermore, in each case the higher members of the series will merge toward the limit so that no discontinuity will be found at the limit itself.

The hydrogen *lines*, however, will be prominent, particularly in the main-sequence star Sirius: the Stark broadening in frequency units will for the infrared series be even somewhat larger than for the Balmer series, but the populations of the higher levels will be less, depending on the stellar temperature, in accordance with the Boltzmann equation (cf. Merrill and Wilson, 1934).

The spectra shown in Figures 1-12 bear out these expectations. On the spectra of Sirius, the Paschen series can be seen from Paschen β or P5, to P18 or P19; the Brackett series, from Brackett γ or B7, to B17 or B18. The small difference in the upper state (if real) may be due to the somewhat larger noise level near 1.5μ as compared to 0.8μ. The Pfund series does not reach well into the region examined, given the complexities in the telluric water vapor spectrum near 2.4μ, and its continuum is apparently too broad and shallow to be recognized.

After the near infrared ($\lambda \leq 0.9\mu$) had become accessible photographically, Merrill and Wilson (1934), in a comparative study of the Paschen and the Balmer series in several stars, recorded for Sirius the Paschen lines P11 to P17 or P18, and the Balmer lines to H18. It is seen that our direct recordings and the photographic results are fully consistent and that all three series of hydrogen become distinct with the upper level $n_2 \cong 18$. The interpretation of

TABLE 2

EQUIVALENT WIDTHS FOR α CMA AND α LYRAE
(Unit 1A)

n_2	Balmer Series	Paschen Series	Brackett Series
3	11.6 (1)	absent	absent
4	*15.4 (14)*	(in H_2O)	absent
5	*17.9 (13)*	15.2 (9) *	not observed
6	*19.4 (13)*	21.8 (9), 17.7: (8)	(in H_2O)
7	*16.1 (13)*	17.7: (6), 14.4 (7)	20.4 (12)
8	*15.1 (6), 15.4 (8)*	(in H_2O)	(in H_2O, CO_2)
9	*12.2 (6), 12.4 (9)*	9.3 (5), 7.6 (6), 8.4 (7)	(in H_2O)
10	*9.5 (6), 9.4 (9)*	(in H_2O)	14 (11, 20)
11	....	11.0 (4), 10.5 (5) **	13 (11), 11 (20)
12	....	7.4 (4), 7.3 (5)	8 (11), 8: (20)
13	....	5.2 (4), 4.3 (5)	7.2 (11)

* Profile of P5 restored by means of solar comparison spectrum.
** Some H_2O contamination.

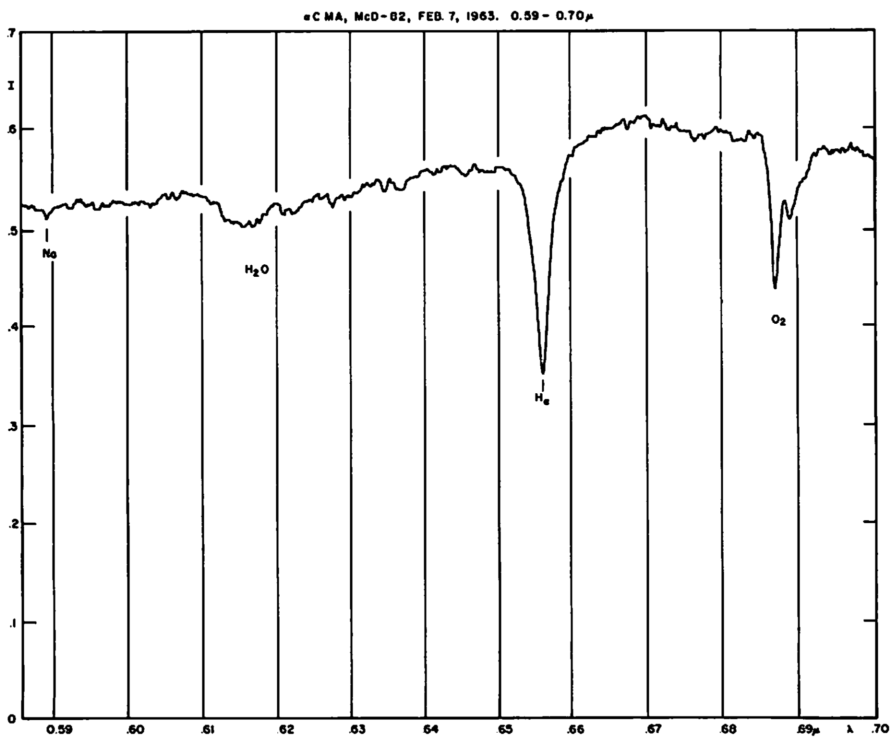

Fig. 1.—α Canis Majoris, McDonald Observatory, February 7, 1963, 0.59-0.70μ. Grating 1.6μ, second order; yellow filter; S1 cell with slit 0.25 mm; τ = 2 seconds. H.A. (*right* to *left*) 0:45-0:56W. T = 51°F, H = 0.40.

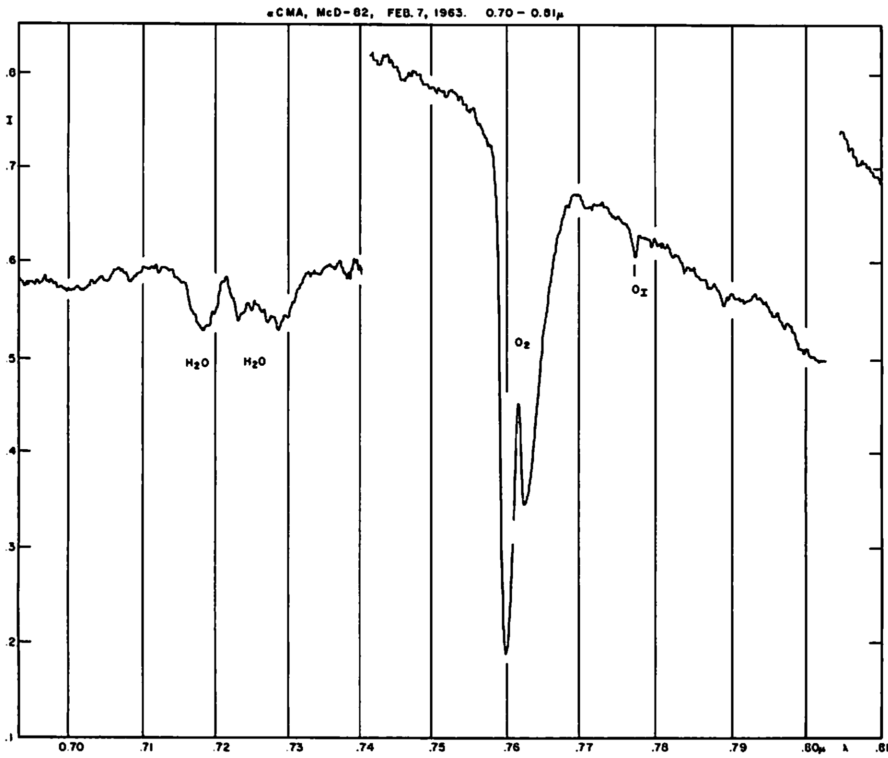

Fig. 2.—As Figure 1, 0.70-0.81μ. Filter RG8, H.A. 0:35-0:46W.

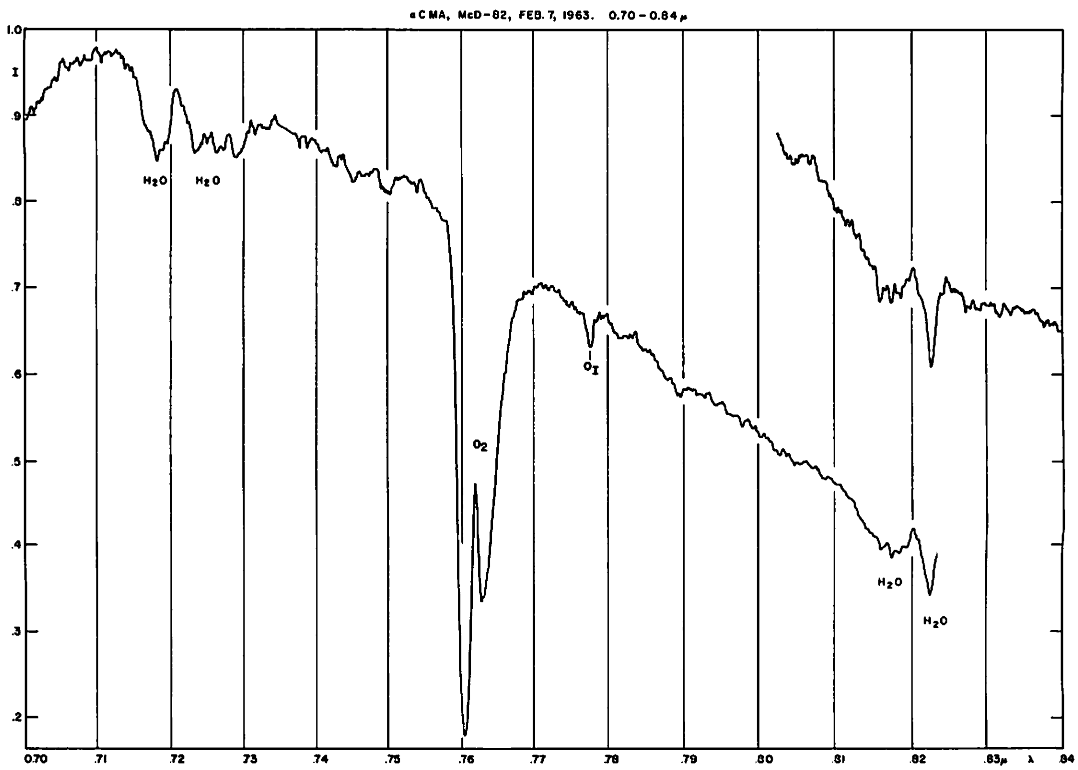

Fig. 3.—As Figure 1, 0.70-0.84μ. Filter RG8, H.A. 1:24-1:38W.

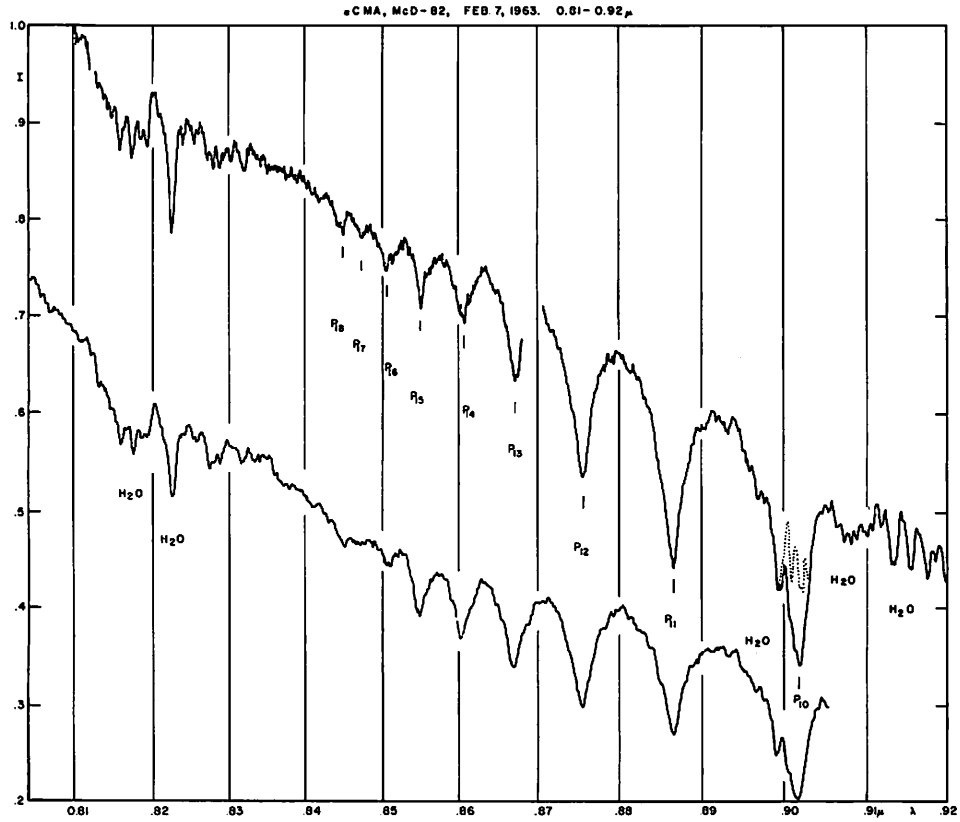

Fig. 4.—As Figure 1, 0.81-0.92μ. Dotted line at 0.90μ shows telluric profile. Filter RG8, H.A. *upper:* 0:01-0:13W, *lower:* 0:25-0:35W.

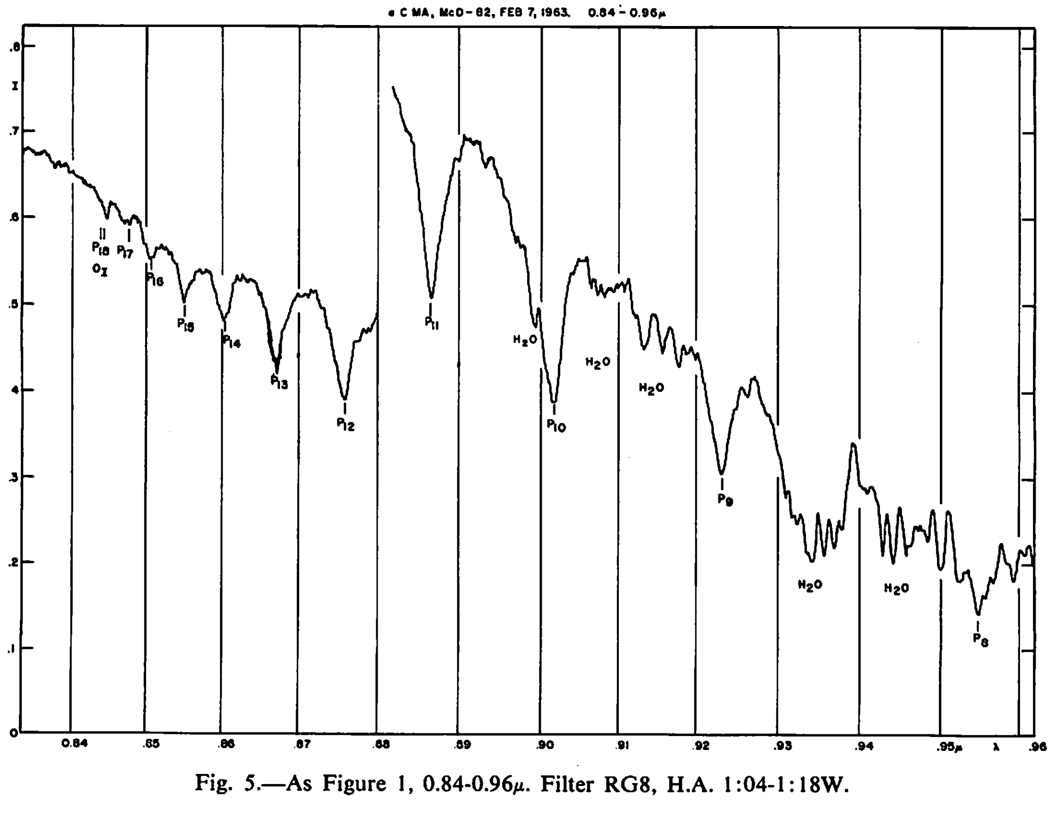

Fig. 5.—As Figure 1, 0.84-0.96μ. Filter RG8, H.A. 1:04-1:18W.

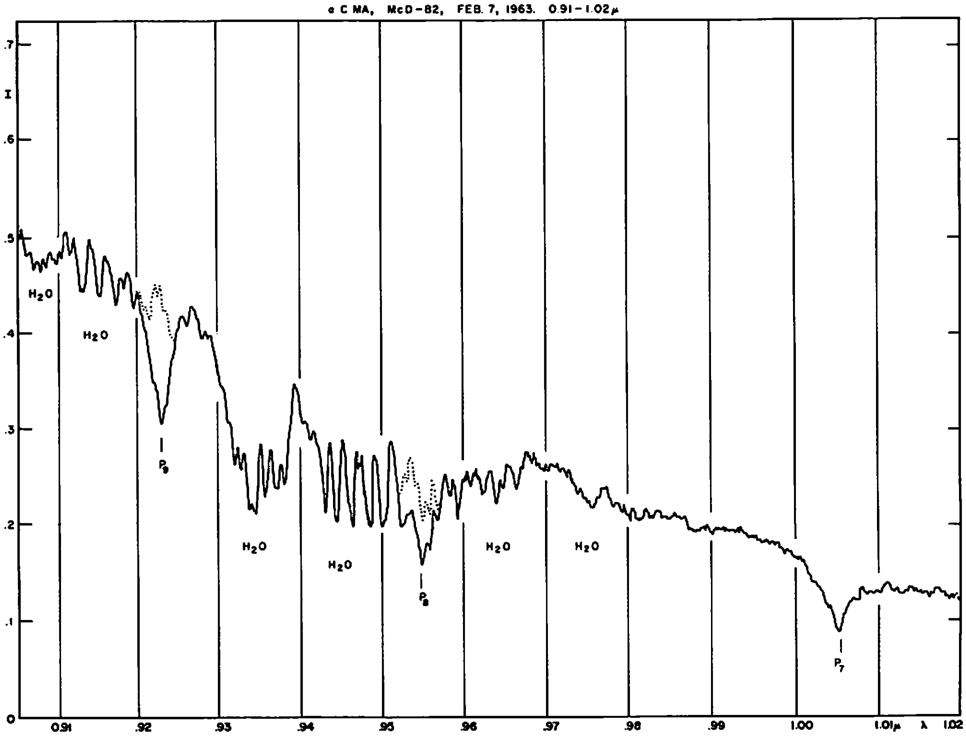

Fig. 6.—As Figure 1, 0.91-1.02μ. Filter RG8, H.A. 0:10E-0:02W.

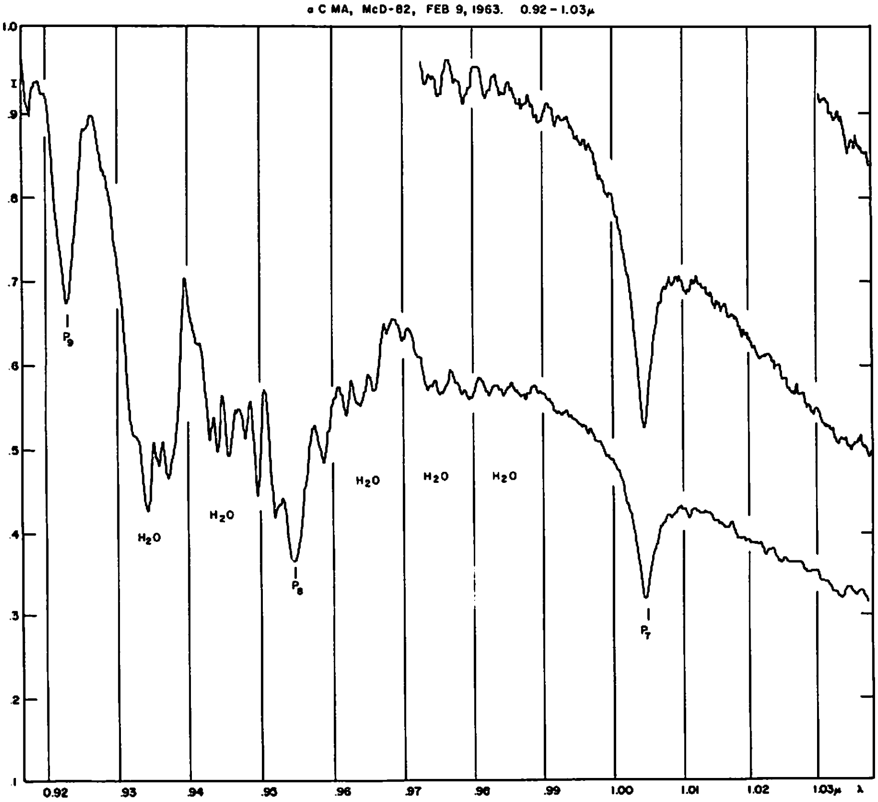

Fig. 7.—α Canis Majoris, McDonald Observatory, February 9, 1963, 0.92-1.03μ. Grating 1.0μ, first order; filter RG8; S1 cell with slit 0.25 mm; $\tau = 2$ seconds. H.A. *upper:* 0:12-0:06E, *lower:* 0:03E-0:08W. T = 56°F, H = 0.30.

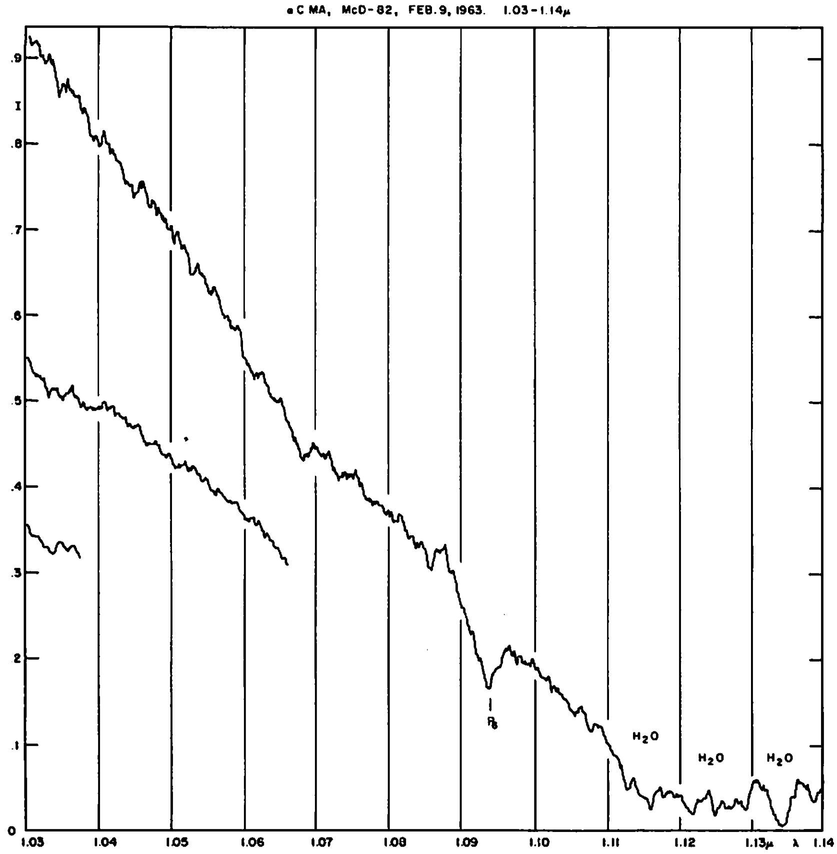

Fig. 8.—As Figure 7, 1.03-1.14μ. H.A. 0:25-0:15E.

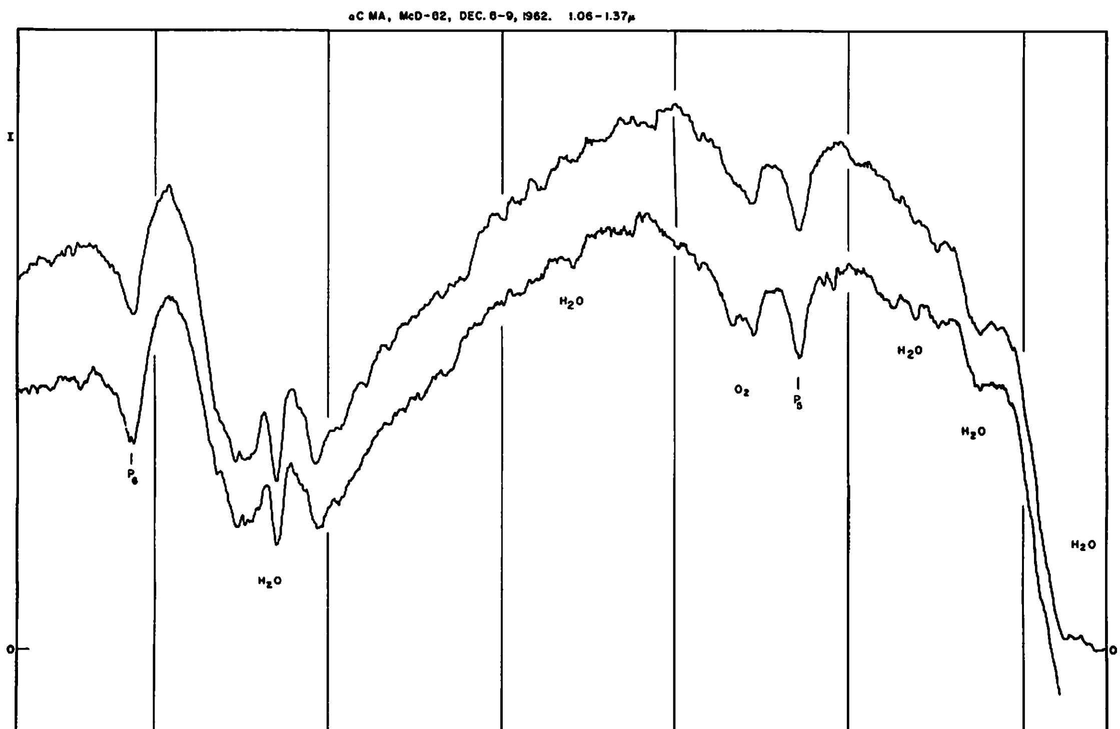

Fig. 9.—α Canis Majoris, McDonald Observatory, 1.06-1.37μ. *Upper:* December 9, 1962. Grating 1.6μ, first order; filter Corning 2540 (> 1μ); PbS ¼ x ¼ mm cell with sapphire Fabry lens; slit 1.0 mm; τ = 11 seconds. H.A. 0:56-1:25W. T = 42°F, H = 0.55. *Lower:* December 8, 1962. As above except H.A. 0:44-1:13W.

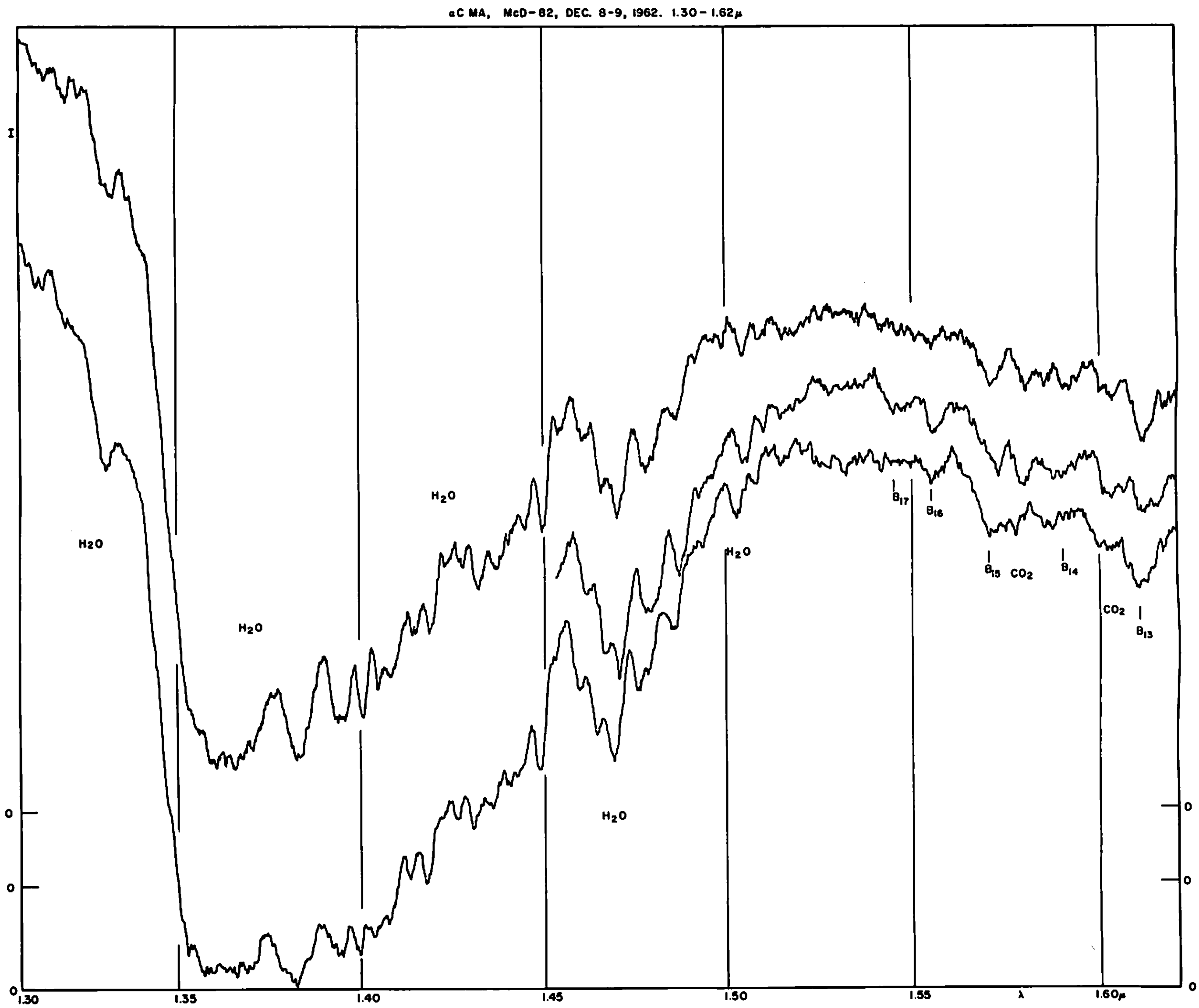

Fig. 10.—α Canis Majoris, McDonald Observatory; *upper two,* December 9; *lower,* December 8, 1962; 1.30-1.62μ. Grating 1.6μ, filter 2540, PbS ¼ x ¼ mm cell, Fabry lens with slit 1.0 mm, τ = 11 seconds. H.A. *upper:* 0:13-0:43W, *middle:* 1:46-2:02W, *lower:* 0:01-0:31W. T = 42°F (Dec. 9), 44°F (Dec. 8); H = 0.55.

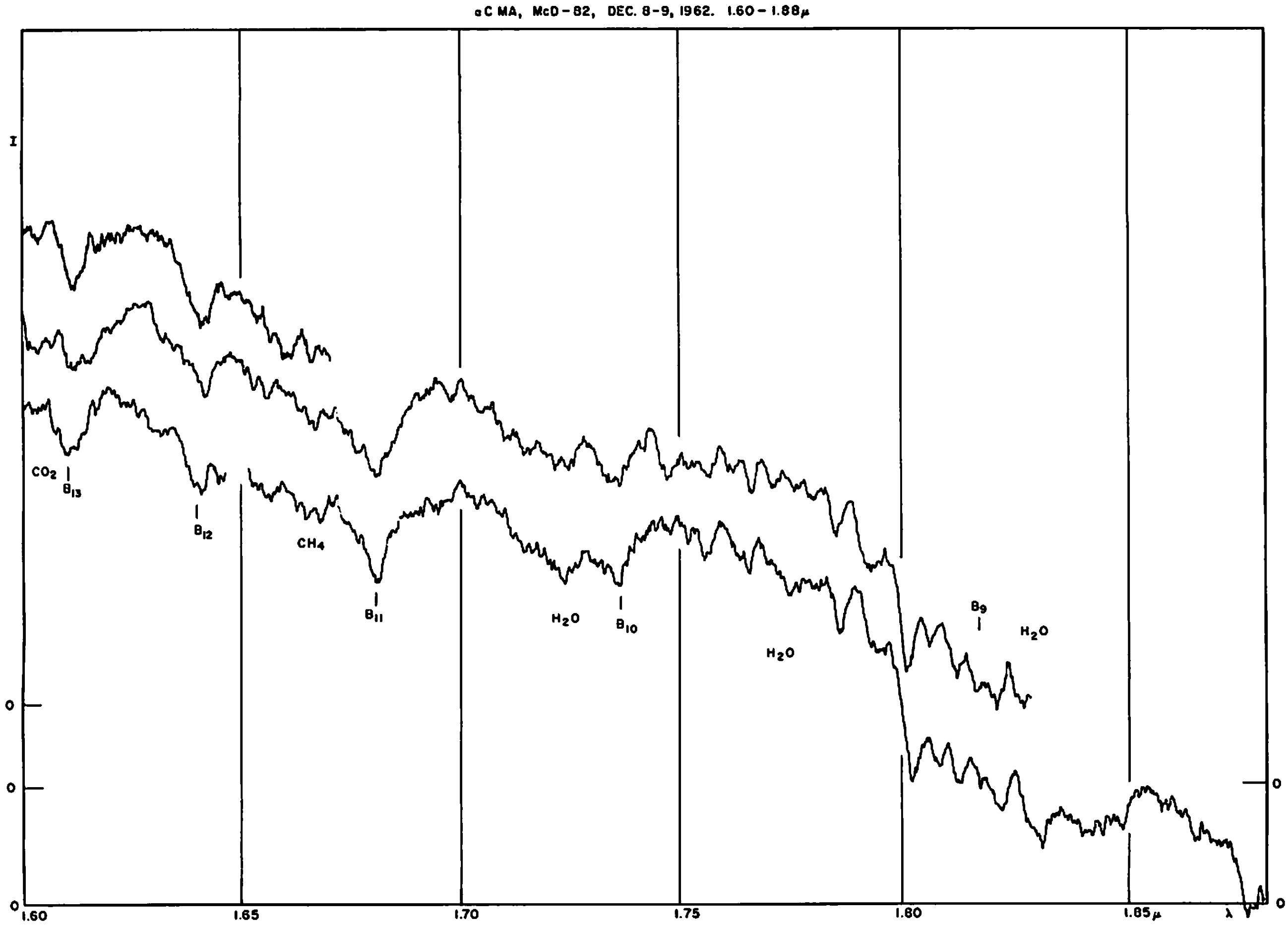

Fig. 11.—As Figure 10, 1.60-1.88μ. H.A. *upper:* 0:08-0:15W, *middle:* 1:25-1:48W, *lower:* 0:25E-0:03W.

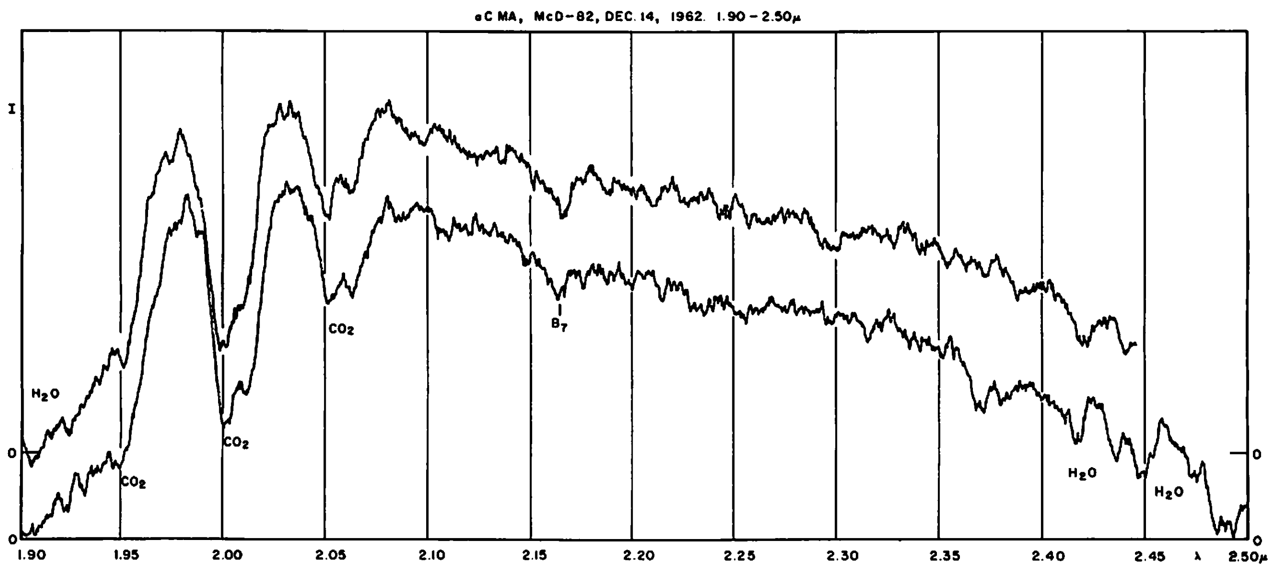

Fig. 12.—α Canis Majoris, McDonald Observatory, December 14, 1962, 1.90-2.50μ. Grating 2μ, filter 2μ, PbS ¼ x ¼ mm cell (Fabry lens) with slit 1 mm, $\tau = 11$ seconds. H.A. *upper:* 0:29-0:54W, *lower:* 0:04E-0:24W. T = 42°F, H = 0.82.

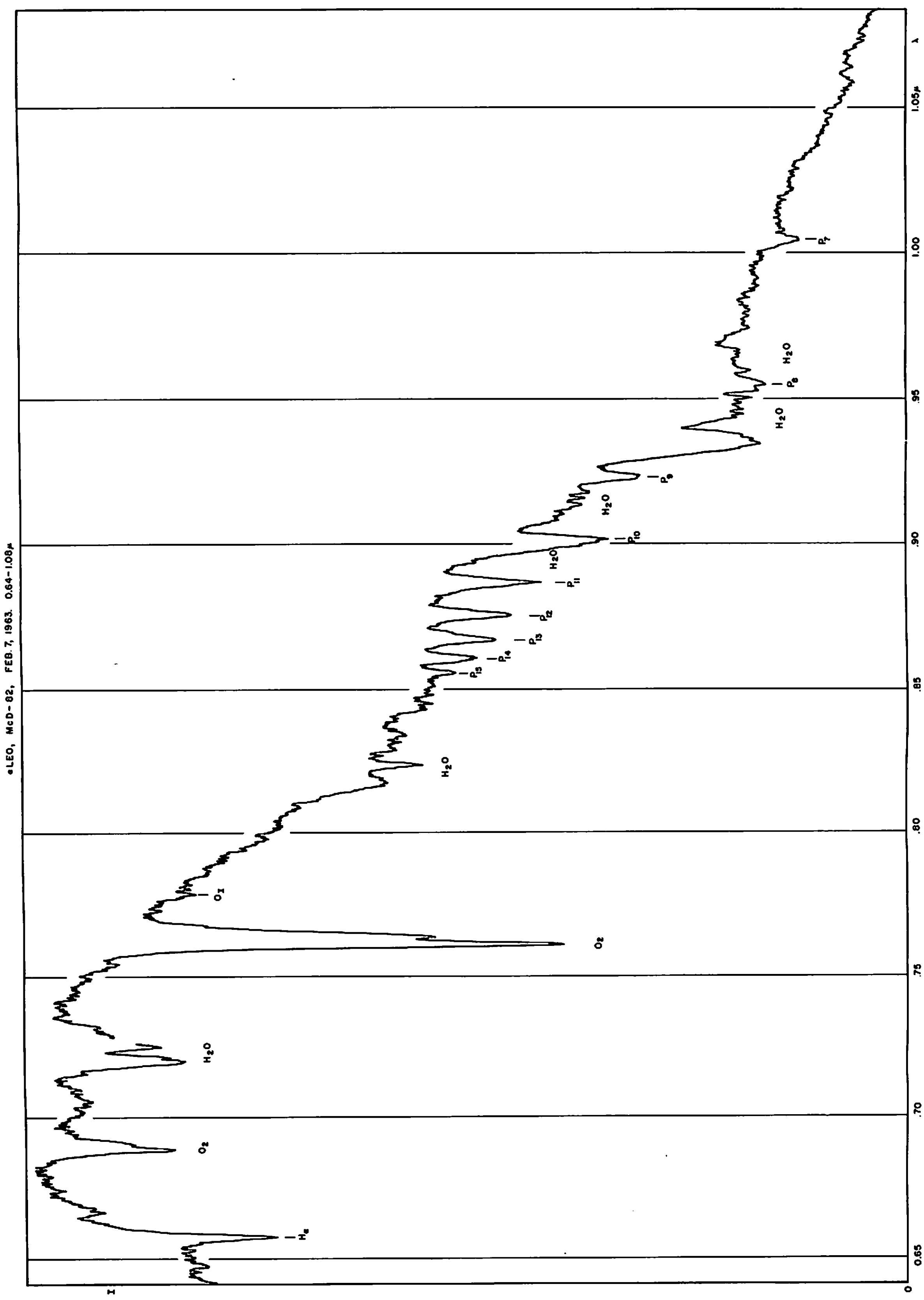

Fig. 13.—α Leonis, McDonald Observatory, February 7, 1963, 0.64-1.08μ. Grating 1.0μ, first order; filter RG8 (λ > 0.73μ), yellow (λ < 0.73μ); S1 cell with slit 0.25 mm; τ = 5 seconds. H.A. 0:18-0:58W. T = 50°F, H = 0.49.

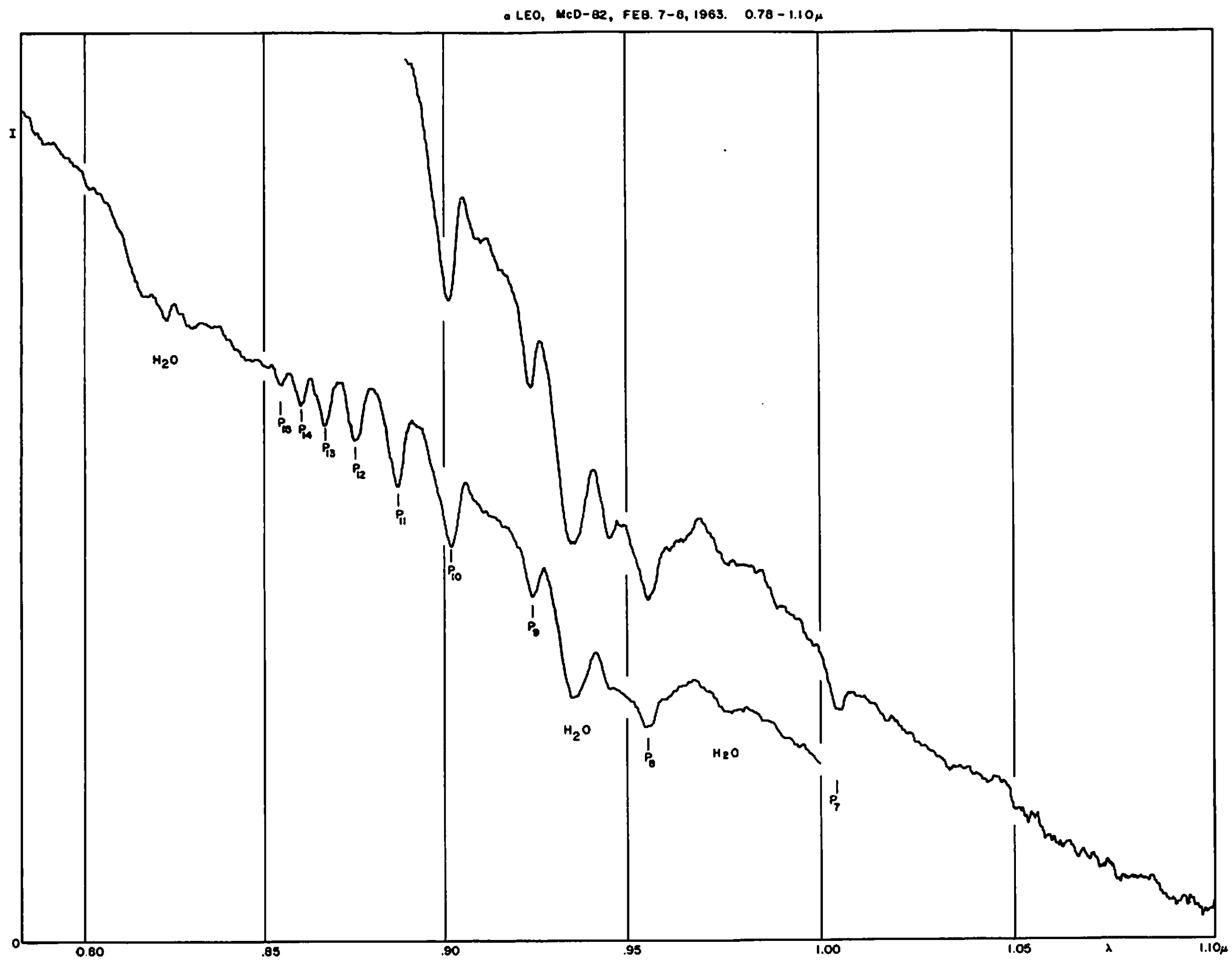

Fig. 14.—As Figure 13, 0.78-1.10μ. *Upper* (Feb. 7): Grating 1μ, first order; filter RG8; S1 cell with slit 1 mm; τ = 5 seconds. H.A. 1:04-1:14W. T = 50°F, H = 0.49. *Lower* (Feb. 8): As above except τ = 2 seconds, H.A. 1:17-1:27W. T = 52°F, H = 0.34.

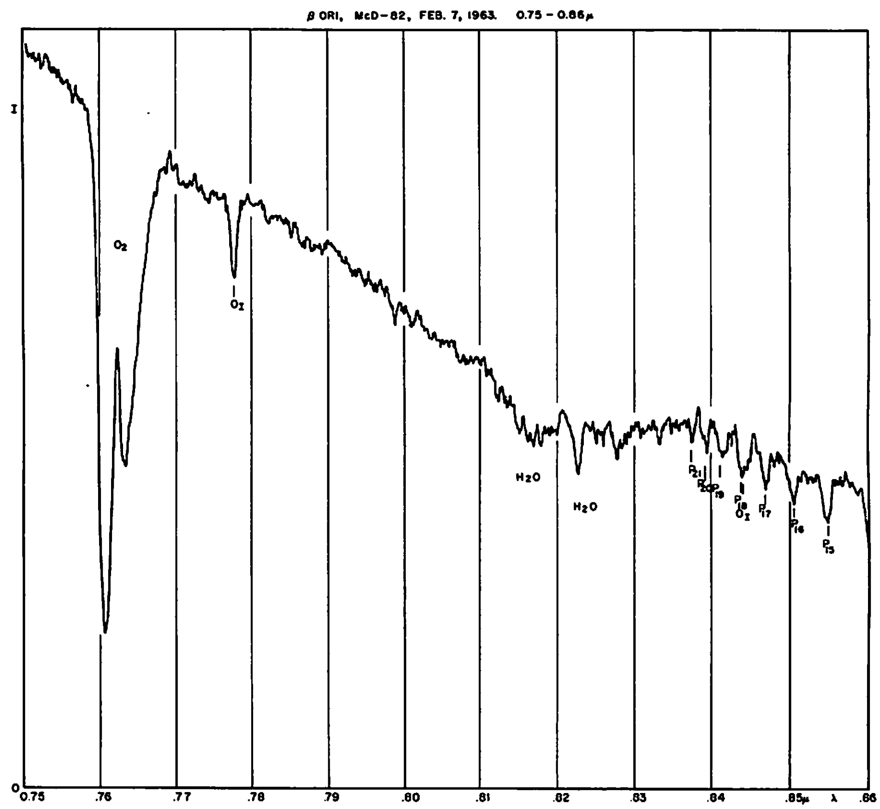

Fig. 15.—β Orionis, McDonald Observatory, February 7, 1963, 0.75-0.86μ. Grating 1.6μ, second order; filter RG8; S1 cell with slit 0.25 mm; τ = 2 seconds. H.A. 0:33-0:44W. T = 51°F, H = 0.40.

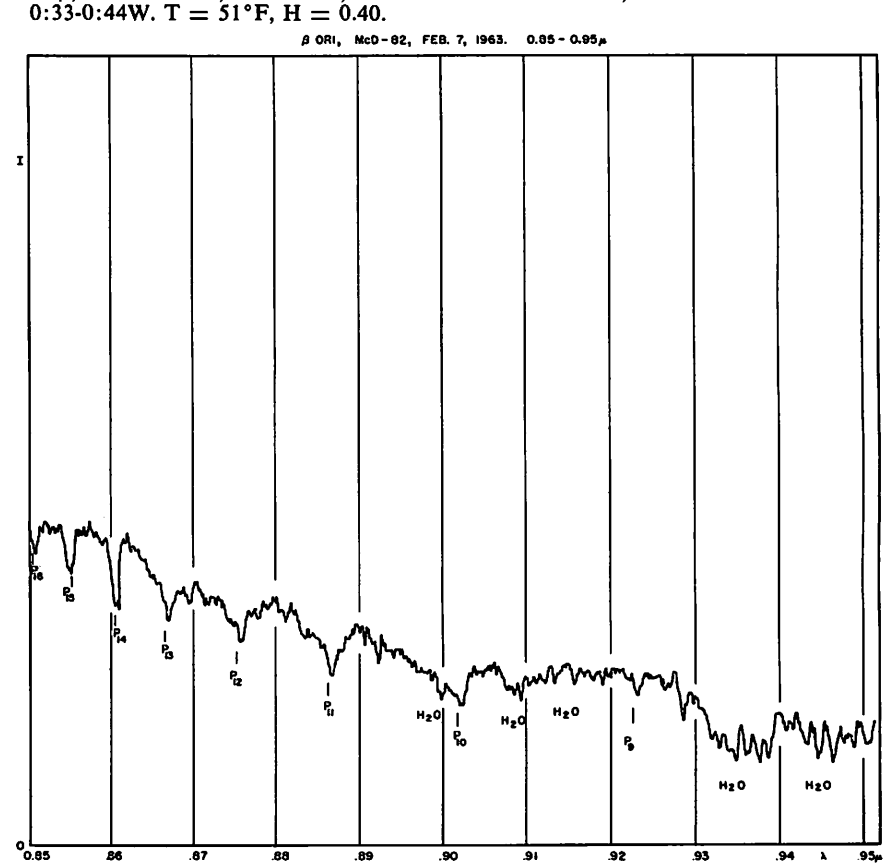

Fig. 16.—As Figure 15, 0.85-0.95μ. H.A. 0:24-0:34W.

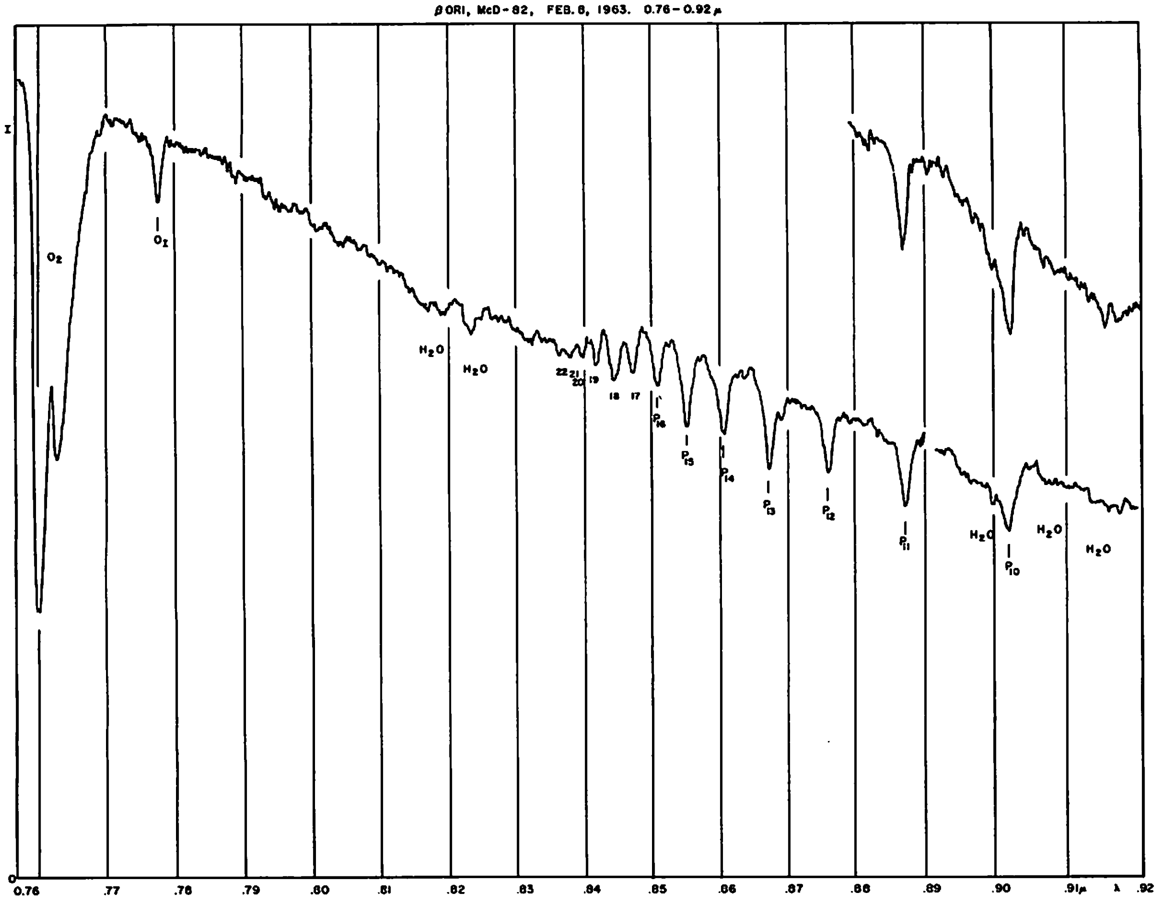

Fig. 17.—As Figure 15, February 8, 1963, 0.76-0.92μ. Grating 1.0μ, first order; H.A. *upper:* 0:47-0:51W, *lower:* 0:52-1:05W. T = 52°F, H = 0.35.

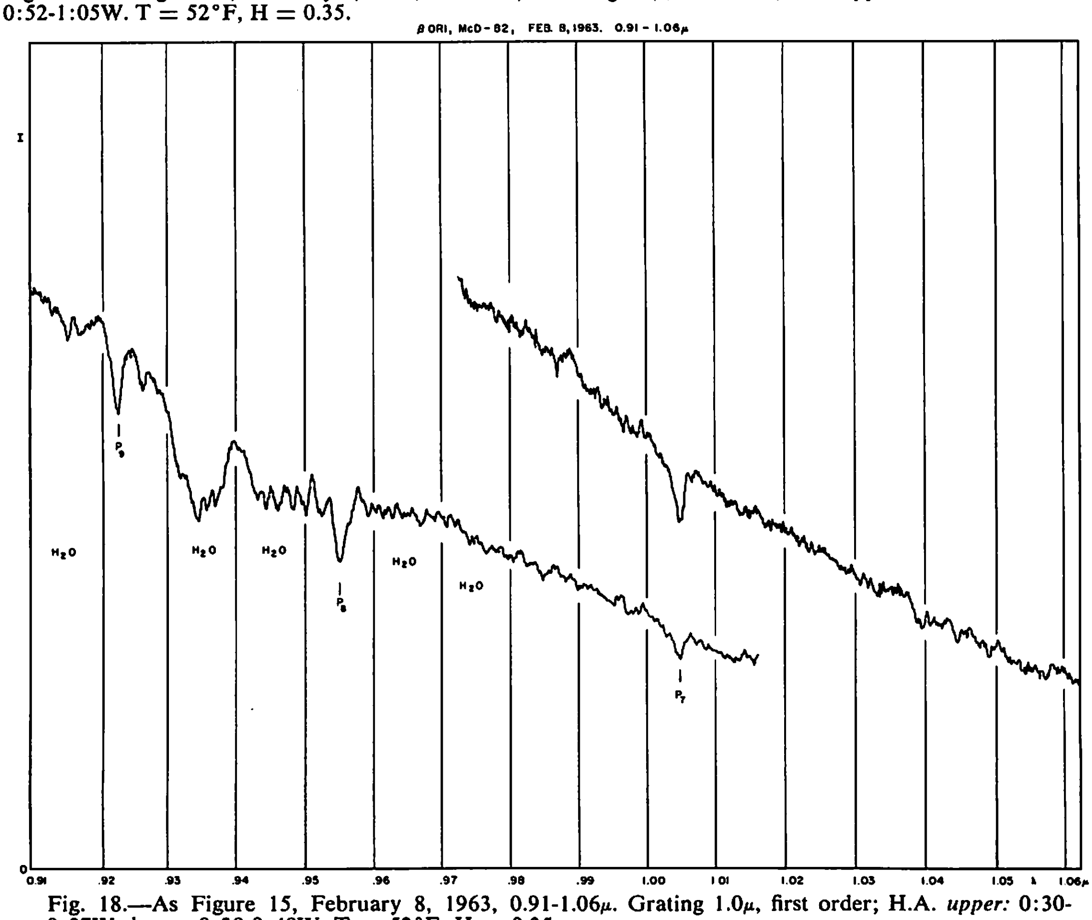

Fig. 18.—As Figure 15, February 8, 1963, 0.91-1.06μ. Grating 1.0μ, first order; H.A. *upper:* 0:30-0:37W, *lower:* 0:38-0:48W. T = 52°F, H = 0.35.

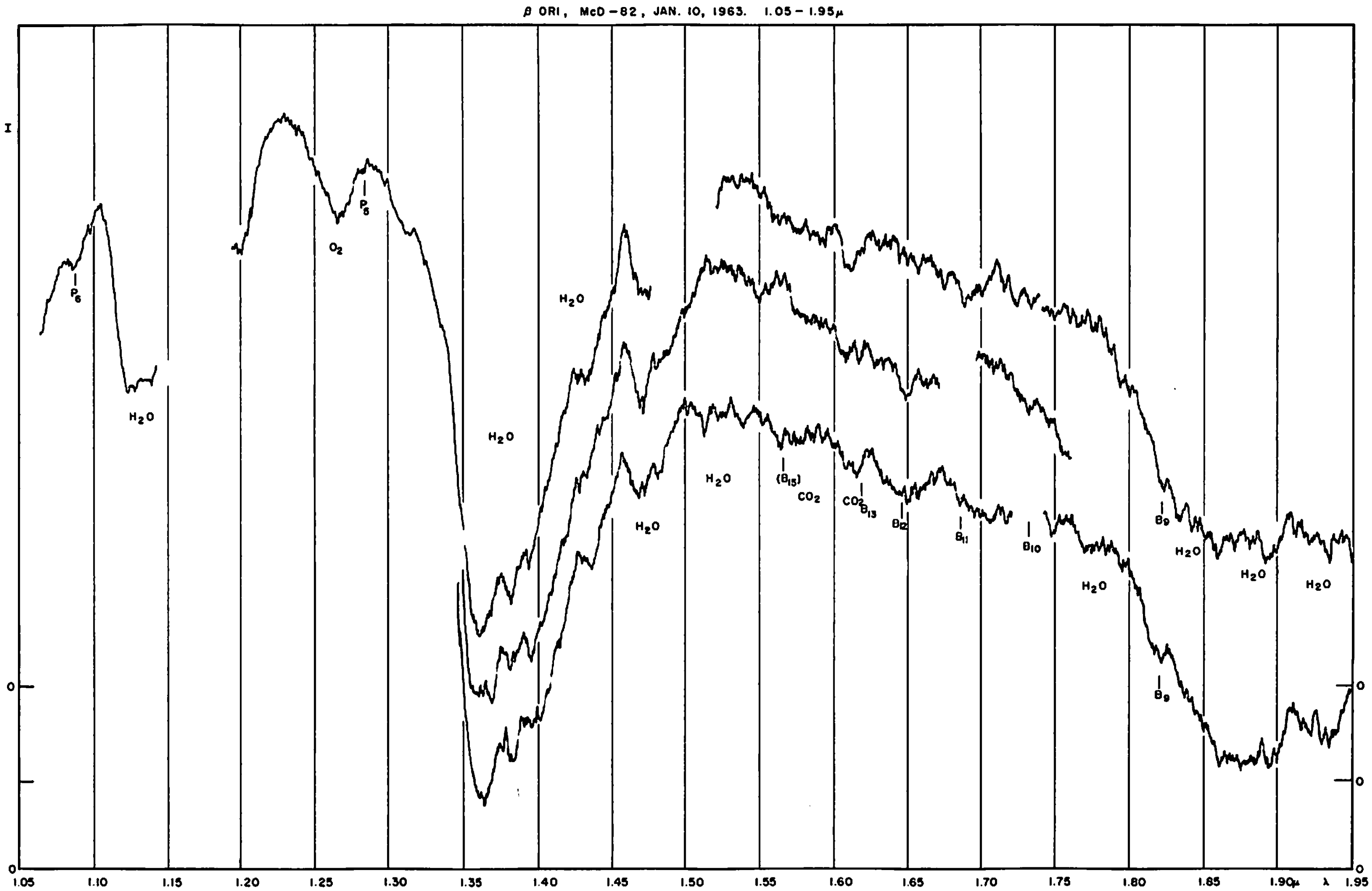

Fig. 19.—β Orionis, McDonald Observatory, January 10, 1963, 1.05-1.95μ. Grating 1.6μ, filter 2540, PbS ¼ x ¼ mm cell (Fabry lens) with slit 2 mm, τ = 40 seconds. H.A. *upper:* 1:06E-0:20W, *middle:* 0:27-1:07W, *lower:* 1:12-2:09W. T = 46°F, H = 0.56. Seeing poor, high wind. Missing sections of traces spoiled by substandard seeing.

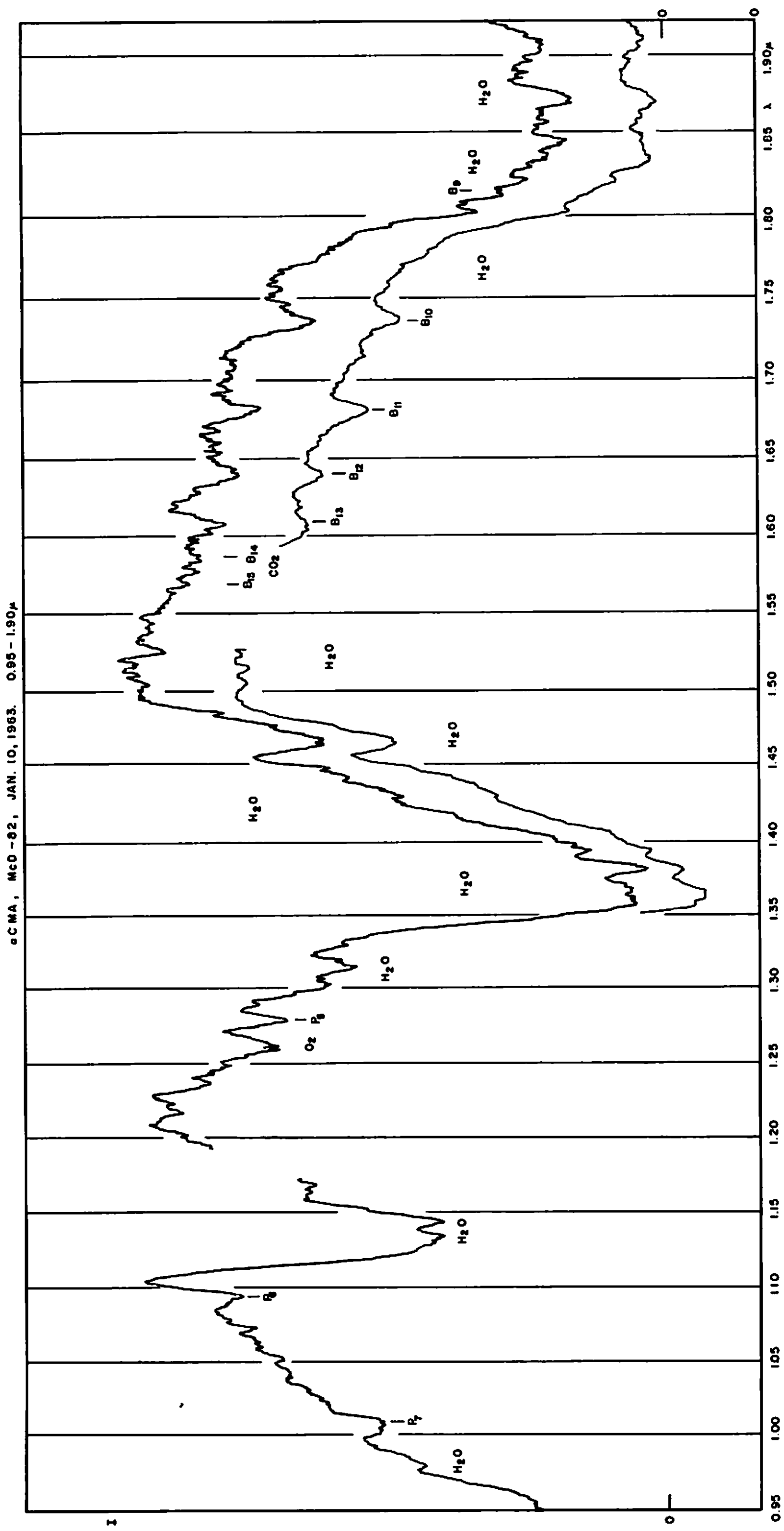

Fig. 20.—For comparison with Figure 19. α Canis Majoris, McDonald Observatory, January 10, 1963, 0.95-1.90μ. *Upper:* Grating 1.6μ, filter 2540, PbS ¼ x ¼ mm cell (Fabry lens) with slit 2 mm, τ = 5 seconds. H.A. 0:06-0:25W. T = 45°F, H = 0.59. Seeing poor, high wind. *Lower:* As above except τ = 20 seconds, H.A. 0:39-1:08W.

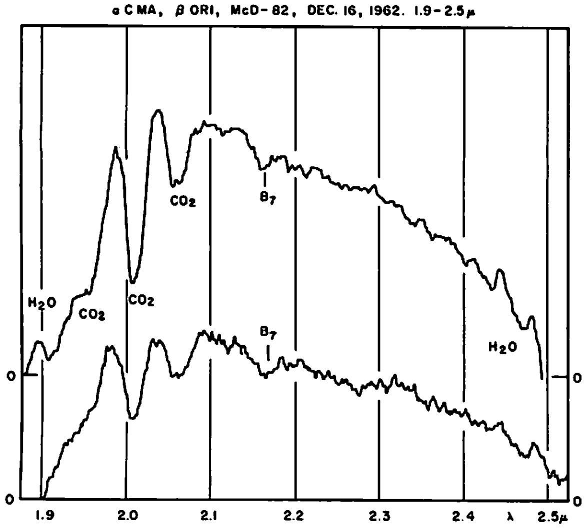

Fig. 21.—α Canis Majoris and β Orionis, McDonald Observatory, December 16, 1962, 1.9-2.5μ. *Upper:* α CMa. Grating 2μ, filter 2μ, PbS ¼ x ¼ mm cell (Fabry lens) with slit 2 mm, τ = 11 seconds. H.A. 0:16E-0:14W. T = 46°F, H = 0.44. *Lower:* β Ori. As above except τ = 30 seconds, H.A. 0:39-1:10W.

this result in terms of pressure in the stellar atmosphere is found from the well-known formula by Teller and Inglis (1939).

A few representative equivalent widths of hydrogen lines for Sirius and Vega are listed in Table 2. The numbers in parentheses refer to the figures used in the measures; *italics* refer to *Communications No. 26*. The Balmer series of Vega has its maximum at Hδ or H6. The Paschen series in the similar star Sirius has its maximum at P6 and the Brackett series has its maximum probably at B6 or B7. The intensities of the higher members of each series are reduced because of overlapping wings for which allowance is not readily made. The data as they stand show remarkably little difference between the equivalent widths of the three series. Additional observations will be made to pursue this matter.

The telluric absorptions by H_2O and CO_2 are broadly identified in the spectra. Reference is made to Figures 1, 3, 5, and 16 of *Communications No. 15* for suitable solar comparisons showing the telluric features with resolutions and strengths comparable to the spectra of Sirius.

Stellar absorptions here recorded, but not attributable to hydrogen, are the OI triplet at 7774A and the OI doublet at 8446A, both of which occur in a region previously observed photographically with somewhat greater resolution by Merrill (1934).

The spectra of two B8 stars are reproduced in Figures 13-21, with a comparable spectra of Sirius added for purposes of comparison. The Paschen series of hydrogen is well shown for α Leonis in Figures 13 and 14. The water-vapor content for the lower graph of Figure 14 was quite low so that the convergence of the lines to the series limit is well brought out. Corresponding records for β Orionis are found in Figures 14-18. This star, being a supergiant (low atmospheric densities), shows the Paschen lines up to P22, compared to P18 for Sirius. Figures 17 and 18 were obtained with low atmospheric water-vapor content.

Atmospheric conditions did not permit, within the telescope time available, the acquisition of good records in the 1.1-1.9μ region. Figure 19 shows the fragmentary records obtained, with Figure 20, of Sirius, taken as a comparison. Figure 21 shows two small tracings of the region 1.9-2.5μ, showing unmistakably the presence of B7.

For the brighter stars of later spectral type much larger infrared energies are available, and better resolutions have been obtained. Such spectra will appear in subsequent papers in this series.

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