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WOLF-RAYET AND OTHER SPECTRA OF EARLY TYPE IN THE 1μ REGION

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ABSTRACT

Objective-prism and slit spectrograms have been obtained in the wave-length range 9000–11000 A for a variety of spectra of early type. The nitrogen and carbon sequences of Wolf-Rayet stars are sharply differentiated in this wave-length range: the principal emission features are to be attributed to *He* I, *He* II, and *C* III. λ 10830 of *He* I is found in the spectra of P Cygni, γ Cassiopeiae, and β Lyrae. At the dispersions employed, only the Paschen series in absorption is seen in spectra of α Lyrae and α Aquilae.

INTRODUCTION

The characteristics of N and late M spectra photographed with the combined 4° and 6° objective prisms of the Curtis Schmidt on I-Z(2) plates have been described in an earlier note (Miller 1953*a*). Spectra of stars of early type form the subject of this communication.

Our experience in warm-weather work with the hypersensitized I-Z(2) emulsion may be of interest. The plates of N and M stars were taken at air temperatures below 0° C; those of the present program at temperatures above +15° C. The first of the latter were badly fogged, although a plate kept in a box at the telescope and developed unexposed was fog-free. This hinted at a solution of the difficulty: by exposing through a filter, warm-weather fogging was eliminated. In our plateholders, the addition of a filter incloses the plate in an airtight box with a volume of 140 cc. By preventing circulation of warm air over the emulsion, plate fog is minimized.

On a number of the Schmidt plates, spectra of α Lyrae were superposed. Paschen 6 and 7, together with telluric bands, served to establish a wave-length scale for the program stars. The zero point for each of the latter is necessarily somewhat uncertain, since the telluric features on which it depends are diffuse and sometimes in underexposed spectral regions.

Through the kindness of Dr. Keller, director of the Perkins Observatory, the writer had full use of the 69-inch reflector equipped with the two-prism spectrograph, for a week in August, 1953. The neon comparison spectrum and dispersion of 512 A/mm at Paschen 6, as compared with 1450 A/mm for the Schmidt plates, made this material of the greatest value in interpreting the objective-prism spectra. The observing program included a number of stars of late spectral type which are not referred to in the present discussion.

Table 1 lists the spectrograms available for each star; those of the first seven were generally unwidened. Exposures for the Schmidt plates range from 5 to 90 minutes, and for the slit spectrograms from 15 minutes to 4 hours. The plate taken with the 4° objective prism was useful only in estimating relative intensities of emission lines. The numerous plates for α Lyrae are due to its use as wave-length standard on objective-prism plates and as test star in focusing the slit spectrograph.

Typical objective-prism spectrograms are illustrated in Figure 1. On plates made with the combined objective prisms, the distance between P6 and P7 is 0.65 mm. The striking difference between the WN and WC spectra will be noted. The resolution obtained with the objective prisms may be judged by comparing the microdensitometer tracings of

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1954ApJ...120..265M

spectra of α Lyrae shown in Figure 2, *b* and *c* The first is from a Perkins spectrogram, the second from a typical objective-prism plate.

WN SPECTRA

The spectrum of HD 192163 (Fig. 1, *b*) is typical of the four stars of the nitrogen sequence. The two strong emissions are designated A and B for convenient reference. The wave-length difference between these features can be measured with fair precision on the objective-prism plates, the mean value being

$$\delta\lambda_{AB} = 703\text{A} \pm 9 \text{ (m.e.)} .$$

On the 4-hour, weakly exposed slit spectrogram, the wave lengths of both features were measured. The images are diffuse and faint; the uncertainty in the wave lengths may be estimated as of the order of $\pm$ 15 A.

In Table 2 are the wave lengths and line widths measured on the slit spectrogram and, in the third line, the wave length of B derived by adding the wave-length difference measured on Schmidt plates to the wave length of A in the first line.

The inaccuracy inherent in the study of these spectra at low dispersion is indicated by comparison of wave lengths in Table 2 with those derived provisionally by the writer

TABLE 1

OBSERVATIONAL MATERIAL

Star	Spectrum	Curtis 4°+6°	Schmidt 4°	Perkins 2-Prism
HD 192163	WN6	3	1	1
HD 193077	WN6	1	1	......
HD 193576	WN6	1	......	......
HD 193928	WN6	......	1	......
HD 192641	WC7	1	......	......
HD 193793	WC6	1	......	2
P Cyg	B1ep	3	......	......
γ Cas	B0 IVp	1	......	2
β Lyr	Bep	4	......	......
α Lyr	A0V	6	......	6
α Aql	A7V	......	......	2

from objective-prism plates alone (Miller 1953*b*). The two sets of wave lengths differ systematically by 67 A, consistent with the estimated uncertainty of ± 40 A for the provisional results, due to near invisibility of telluric bands which provided the zero point.

The line widths in Table 2 may be compared with those for the same star at shorter wave lengths. Beals (1930) finds widths of the order of 30–40 A for lines near λ 4000. If the widths are assumed proportional to wave length, the proportionality constant is close to 0.008, which predicts widths of about 80 A in the 1 μ region. The widths listed in Table 2 are thus consistent with those at shorter wave length. The relative intensities of A and B differ from one star to another as shown in Table 3.

The continuum between A and B on the objective-prism plates has been compared visually with spectra of stars of early type on the same plates. There is no indication that in this wave-length range the WN stars are abnormally bright, and it seems that there are no moderately strong emission lines contributing to this part of the spectrum. The continuum is invisible on the slit spectrogram.

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1954ApJ...120..265M

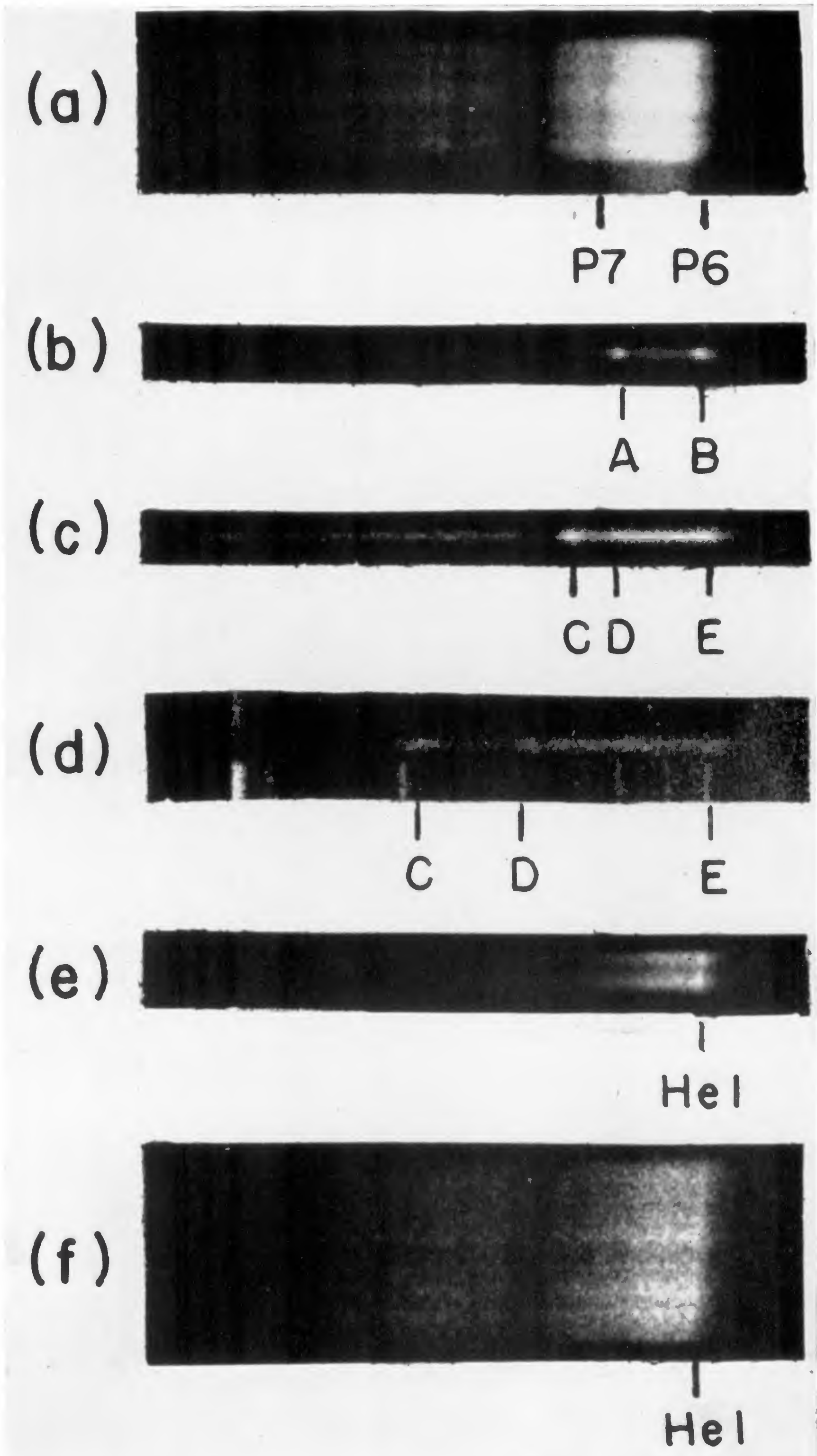

FIG. 1.—*a*, α Lyr; *b*, HD 192163 WN6; *c*, *d*, HD 193793 WC6; *e*, P Cyg; *f*, β Lyr. *d* with Perkins reflector, 2-prism spectrograph; remaining spectra with combined prisms, Curtis Schmidt.

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1954ApJ...120..265M

THE WC STAR HD 193793

A single underexposed objective-prism spectrogram of HD 192641 confirms the marked difference in the appearance of WC and WN spectra illustrated in Figure 1, *b* and *c*, but is not suited to measurement.

The features measured are lettered in Figure 1, *c* and *d*, which are reproductions of spectrograms of HD 193793 made with the Schmidt and Perkins reflectors, respectively. *C* is a strong emission line. *D* marks the short-wave-length limit of a region of enhanced

TABLE 2

WAVE LENGTHS IN WN SPECTRA

	A	B
λ(Perkins)	10,126	10,850
$\Delta\lambda$(Perkins)	90	100
λ(Schmidt)	......	10,829

TABLE 3

RELATIVE INTENSITIES IN WN SPECTRA

HD 192163	B clearly stronger	HD 193576	A slightly stronger
HD 193077	A slightly stronger	HD 193928	B slightly stronger

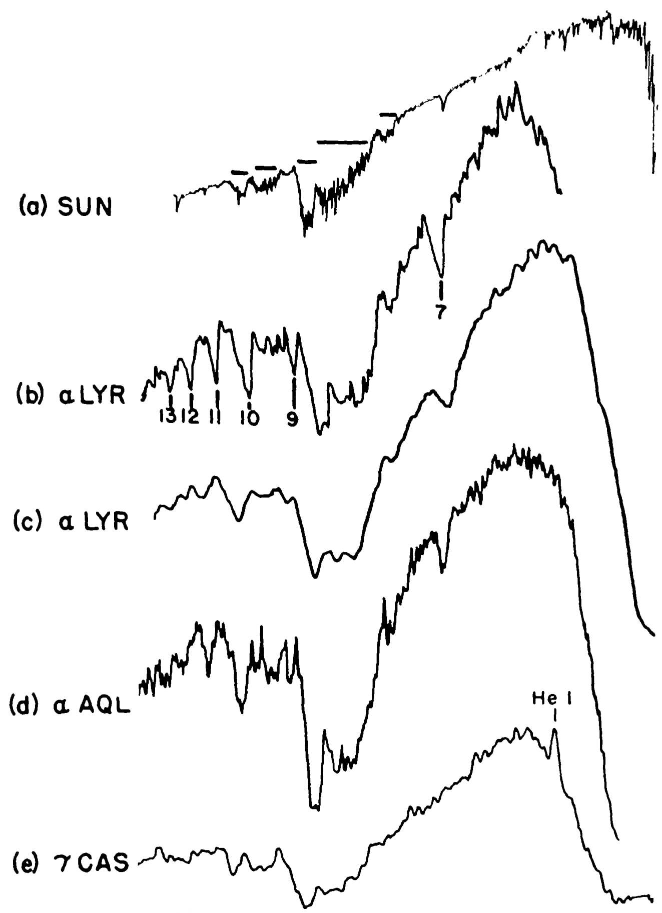

FIG. 2.—*a*, Snow telescope, infrared spectrograph; *b*, Perkins reflector, 2-prism spectrograph, Paschen lines marked; *c*, combined prisms, Curtis Schmidt; *d* and *e*, Perkins reflector, 2-prism spectrograph.

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1954ApJ...120..265M

intensity which is terminated by what appears to be another emission feature at E. In Figure 1, d, a plate defect gives feature D the appearance of an isolated emission line.

Wave lengths measured on the slit spectrograms, mean widths, and wave lengths obtained by combining differential measures on the Schmidt plate with the wave length of C in the third line are given in Table 4.

The provisional wave lengths (Miller 1953*b*) differ systematically by 25 A from those in the third line of Table 4. The estimated zero-point uncertainty in the provisional wave-length system is as mentioned above, ± 40 A.

Beals (1930) has measured line widths in the spectrum of this star. Considering width proportional to wave length, his factors for *C* III and *He* II lead to widths of 166 and

TABLE 4

WAVE LENGTHS IN SPECTRUM OF WC STAR HD 193793

	C	*D*	*E*		*C*	*D*	*E*
λ (Perkins No. 8640)	9726	10,066	....	Δλ (mean)	127	....	....
λ (Perkins No. 8659)	9724	10,041	....	λ (Schmidt)	......	10,038	10,875
λ (mean)	9725	10,054	....				

93 A, respectively, at 9725 A. The 127 A width of feature C is thus consistent with measures at shorter wave lengths.

On both Schmidt and slit spectrograms, there is a marked discontinuity at point D, which is not characteristic of emulsion sensitivity. It appears that longward of λ 10040 there must be a series of emissions which are unresolved on the present plates.

WN AND WC SPECTRA—IDENTIFICATIONS

The wave-length and intensity data described in preceding paragraphs is necessarily of low weight compared with that which can easily be obtained for shorter wave lengths. Nevertheless, the striking dissimilarity of the spectra of stars of the nitrogen and carbon sequences suggests that it should be possible to interpret the conspicuous features in terms of the carbon-nitrogen differentiation. The identifications listed below were proposed by Dr. Leo Goldberg as probable explanations of the emission bands summarized in Tables 2 and 4.

The emission lines designated A and B in the spectra of the WN stars may be attributed to λ 10124 *He* II and λ 10830 *He* I, respectively; the wave-length agreement is excellent. Beals (1930) classifies these stars according to the intensity ratio 5875 *He* I/5411 *He* II and assigns the first two and the fourth stars in Table 3 above to OW6, intensity ratio 0.3. HD 193576 is classed as OW5, intensity ratio 0.1. The corresponding ratio in our spectra is B/A; it is, in fact, smaller for HD 193576 than for HD 192163 and HD 193928. The ratio for HD 193077 is also smaller, contrary to Beal's classification. In our spectra, the B/A ratio certainly does not appear to vary by a factor of 3, and the correlation between B/A and Beal's classifications is extremely weak.

The principal contribution to feature C in the WC spectra should be from the *C* III multiplet $2s3p\,^3P^0\text{–}2sd\,^3D$, with six lines between λ 9702 and λ 9720. On the slit spectrogram this band extends from λ 9662 to λ 9789. Other high-excitation lines of *C* III may also be present, for example, the multiplet $2p3p\,^3D-2p3d\,^3F^0$ with six lines between λ 9697 and λ 9758.

The short- and long-wave-length limits of the continuous strip of emission between points D and E are undoubtedly set by λ 10124 *He* II and λ 10830 *He* I. Leading contributors to the intervening emission should be the two strong transitions, *C* III λ 10291, $2p3s\,^1P^0-2p3s\,^1P$, and *C* II λ 10506, $2s^24f\,^2F^0-2s^25d\,^2D$.

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1954ApJ...120..265M

OCCURRENCE OF λ 10830 OF *He* I

P Cygni, γ Cassiopeiae, and β Lyrae were observed with the Schmidt, in anticipation of the occurrence of emission features in their spectra. The plate of γ Cassiopeiae was taken under unfavorable conditions at low altitude, and no emission lines appeared in its spectrum. It was, nevertheless, included in the program at the Perkins Observatory. A sharp emission line appears on the two slit spectrograms, taken on JD 2434612 and 2434616, respectively. The mean wave length of the line on these plates is λ 10831, and it is certainly to be identified with *He* λ 10830. A tracing of a slit spectrogram of the star is reproduced as Figure 2, *e*.

An objective-prism spectrogram of P Cygni is reproduced as Figure 1, *e*. The strong emission line has a measured wave length, referred to the telluric bands, of 10843 A. Within the zero-point uncertainty, this agrees with *He* I λ 10830. The line is conspicuous on all plates, two of which were taken on JD 2434555 and the third 28 days later.

Spectra were obtained of β Lyrae with the Schmidt on dates corresponding to values of cycle and phase 2790.630, 2790.786, 2790.941, and 2791. 320 (Rossiter 1934). Figure 1, *f*, shows the appearance of the spectrum on the first date. On each plate an emission line of moderate strength is seen, whose wave length referred to the telluric A band is 10847 A. As in the case of P Cygni, this agrees, within the observational uncertainty, with the wave length of λ 10830 of *He* I. The plates at phases 0.320 and 0.630 are of comparable density and quality; the intensity of the emission line appears to be about the same as these two phases. The intensity of λ 10830 on our plates is in agreement with its appearance on the microphotometer tracing lately published by Barocas and Righini (1954). On two slit spectrograms made with the 122-cm reflector of the Asiago Observatory at a dispersion of 570 A/mm, they find that, 2.1 and 4.1 days after primary minimum, the density of the photographic image of λ 10830 exceeds that at any other point in the infrared spectrum of the star. The phase of their second plate coincides closely with the fourth in our series, but was taken about a month earlier.

ABSORPTION SPECTRA, CLASS A

Unwidened spectra of α Lyrae and α Aquilae in the wave-length range covered by the present material were obtained some years ago by Morgan and Wooten (1934) at a dispersion similar to that of our objective-prism plates. Their program was an investigation of the energy distribution in the continuous spectrum. More recently, Kuiper, Wilson, and Cashman (1947) have published a tracing of α Canis Majoris (made with a lead sulfide cell as receiver and the McDonald reflector) which shows the conspicuous absorption lines of Paschen 6 and 7 in the 1μ region, as well as Paschen 5 at longer wave length.

Figure 1, *a*, is a typical 5-minute exposure of α Lyrae with the combined objective prisms: the Paschen series and a number of telluric features are well visible. Paschen 6 is easily seen on the original plates but is difficult to reproduce; it falls at a point where the combined atmospheric transmission and plate sensitivity is decreasing rapidly, as may be seen from the position of λ 10830 of *He* I in the tracing of γ Cassiopeiae (Fig. 2, *e*).

A number of slit spectrograms of α Lyrae and α Aquilae were obtained in the course of the work at Perkins Observatory. Tracings are reproduced in Figure 2, *b* and *d*. Telluric bands are conspicuous in the spectra to longward of 9000 A. To assist in sorting out these features, Dr. Mohler, of the McMath-Hulbert Solar Observatory, arranged for the recording of a number of relatively low-dispersion tracings of the solar spectrum with the Mount Wilson Snow telescope and infrared spectrometer. For this purpose, the grating was rotated rapidly by hand. The resulting dispersion is somewhat variable with wave length, but the tracings are entirely adequate for comparison with the stellar spectrograms. One such tracing is included as Figure 2, *a*, reduced in scale to agree roughly with the prismatic dispersion from 0.9 to 1.0 μ. Telluric bands which also appear in the stellar spectrograms are marked by horizontal lines.

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1954ApJ...120..265M

With the telluric bands eliminated, only the Paschen series remains in the spectra of the two stars of class A. Paschen 6, as stated above, is located on the steep slope of the observed intensity-curve and appears as an inflection (e.g., Fig. 2 *c*, *d*) in the tracings. Paschen 8 is lost in the complex structure of the telluric bands; Paschen 10 overlies, and in these stars, dominates, the telluric band, which falls at the same wave length.

The writer is indebted to the director and staff of the Perkins Observatory for their interest and co-operation in the observing program at that institution; to Dr. Mohler and Mr. Mitchell, the observer, for the solar tracings; to Dr. Leo Goldberg for discussion of identifications; and to Dr. D. B. McLaughlin for a variety of helpful comments and suggestions.

REFERENCES

Barocas, V., and Righini, G. 1954, *Observatory*, **74**, 73.
Beals, C. S. 1930, *Pub. Dom. Ap. Obs. Victoria*, **4**, 271.
Kuiper, G. P.; Wilson, W.; and Cashman, R. J. 1947, *Ap. J.*, **106**, 243.
Miller, F. D. 1953*a*, *Ap. J.*, **118**, 572.
———. 1953*b*, *A.J.*, **58**, 222.
Morgan, W. W., and Wooten, B. A. 1934, *Ap. J.*, **80**, 229.
Rossiter, R. A. 1934, *Pub. Obs. U. Michigan*, **5**, 67.

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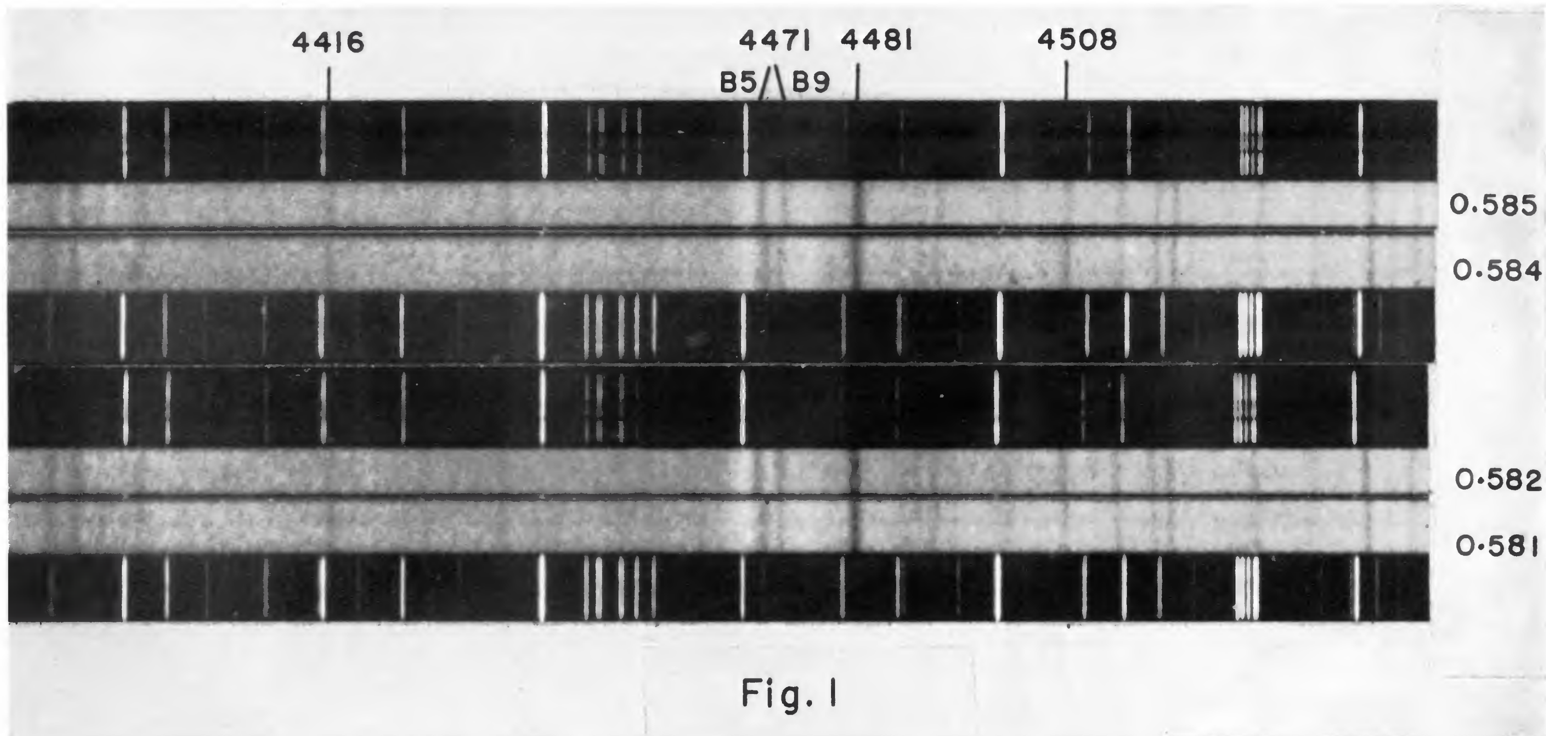

FIG. 1.—Spectrum of β Lyrae at phases 0.585 and 0.582 on November 2, 1952, and at phases 0.584 and 0.581 on October 20, 1952. The B5 absorption line *He* I 4471 shows different velocity shifts on these two days, despite the fact that the phases are very nearly the same.

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