

A SPECTROGRAPHIC STUDY OF HD 193576*

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ABSTRACT

A series of 93 spectrograms of the eclipsing system HD 193576, obtained during the summer of 1949, has been used to study the variations in radial velocity and intensity of various spectral features. The velocity-curve of the O component was determined from measures of $H8$, $H9$, and $H10$, which give $\gamma = +10$ km/sec and $K = 120$ km/sec. The radial-velocity-curves for the WR spectrum have an amplitude $K = 305$ km/sec, but the γ -axis of the $N\ v$ lines is shifted 60 km/sec to the red with respect to the systematic velocity of the H lines, while the γ -axis for $N\ iv\ \lambda\ 4058$ is shifted to the blue by 50 km/sec. The observations provide new evidence confirming the plausibility of explaining the shifts of emission lines as a result of self-absorption processes in the WR envelope.

The absorption lines of the O star, during primary minimum, have been observed to become shallower and broader than at other phases. This variation has been accounted for in terms of the noncoherent scattering of the O-star radiation by free electrons in the WR envelope and in the outer layers of the O star itself. The problem of the illumination of the envelope by radiation of the O star is briefly considered. It is shown that, at conjunctions, the light of the O star, scattered in the line of sight by the envelope, amounts to at least 10 per cent of the continuous radiation attributed to the WR component.

In the last section of the paper an attempt is made to analyze the general characteristics of the WR spectrum. It is shown how some of the observed features can be interpreted in terms of an envelope with radially decelerated motions. In this model the kinetic energy of mass motion at the lower base of the envelope, supplied by a hypothetical impulsive mechanism from the parent-nucleus, is partly used to support the matter against gravity of the core and partly dissipated into heat of atomic motion, as matter moves outward. It is also suggested that the radiation of the O star in the far ultraviolet is an important factor in determining the physical and dynamical state of the matter in the outer parts of the observed envelope. There seems to be some observational evidence indicating that the state of ionization of the envelope is higher in the hemisphere facing the O star, but no conclusive test of the hypothesis is provided by the available observations.

I. INTRODUCTION

Since O. C. Wilson¹ discovered the binary nature of HD 193576 = V 444 Cyg,² this system has been the subject of a number of investigations. Spectroscopic studies have been carried out by O. C. Wilson,³ C. S. Beals,⁴ and E. S. Keeping.⁵ Following the recognition of the object as a spectroscopic double with large amplitude, S. Gaposchkin⁶ announced its eclipsing nature from previous photographic observations, and G. E. Kron and K. C. Gordon⁷ obtained photoelectrically a light-curve of the system. For an account of the extensive work carried out by several authors on the interpretation of the light-curve, we refer to the recently published paper by Kron and Gordon.⁸ Here we only recall that the unconventional features of the light-curve have revealed the existence of a large, semitransparent envelope, surrounding the fainter and smaller component, with which the WR spectrum is associated. From the analysis of the primary minimum observed at $\lambda\ 4500$, Z. Kopal and M. B. Shapley⁹ derived the conclusion that the opacity in the

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¹ *Pub. A.S.P.*, **51**, 55, 1939.

² HV 11111 = BD+38°4010, $\alpha = 20^h15^m8$, $\delta = +38^\circ25'$ (1900).

³ *Ap. J.*, **91**, 379, 1940, and **95**, 402, 1942.

⁴ *M.N.*, **104**, 205, 1944.

⁵ *Pub. Dom. Ap. Obs., Victoria*, **7**, 349, 1947.

⁶ *Pub. A.A.S.*, **10**, 52, 1940; *Ap. J.*, **93**, 202, 1941.

⁷ *Ap. J.*, **97**, 311, 1943.

⁸ *Ibid.*, **111**, 454, 1950.

⁹ *Ap. J.*, **104**, 160, 1946.

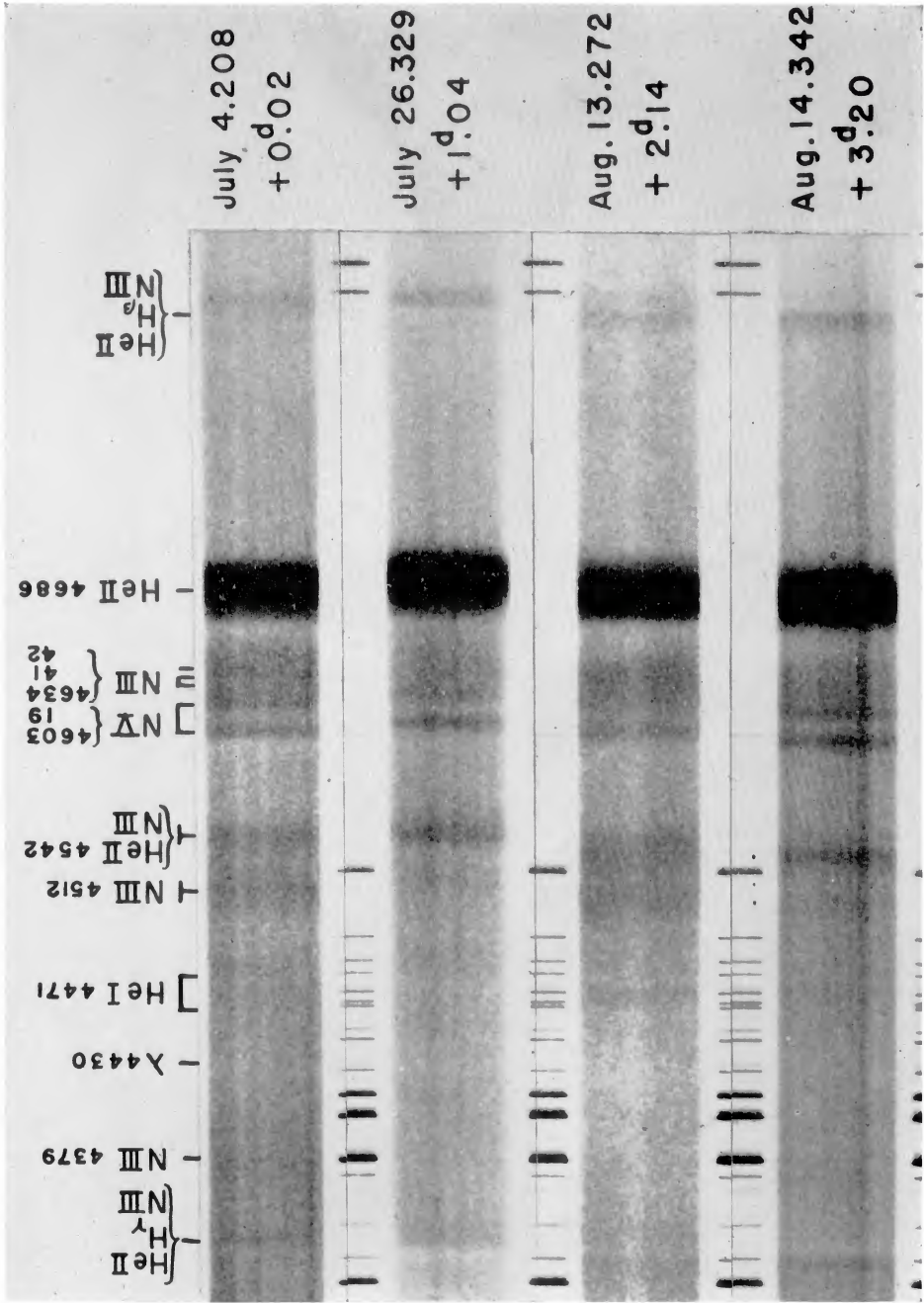


FIG. 1.—The spectrum of HD 193576 in the region $H\gamma-H\beta$

envelope was probably due to electron scattering. Later observations by W. A. Hiltner¹⁰ and Kron and Gordon⁸ have verified that the shape of the primary minimum is practically the same over the wave-length interval $\lambda\lambda$ 3300–7200, an observational fact which confirmed the hypothesis advanced by Kopal and Mrs. Shapley.

The work presented in this paper was originally planned with a view to establishing the effects of the scattering properties of the WR envelope on the observed spectral characteristics. The inspection of the first few spectrograms secured for that purpose revealed the exceedingly complex nature of the phenomena involved. Following the advice of Dr. O. Struve, it was decided to extend the observing program in order to obtain additional information in regard to the radial-velocity-curves and to variations of the line intensities through the orbital period.

II. THE OBSERVATIONS

Between July 4 and August 15, 1949, 93 spectrograms were obtained by Dr. Struve and the writer with the Cassegrain quartz spectrograph of the McDonald Observatory, in a dispersion of 40 Å/mm at λ 3933. The exposures were made alternately on emulsions 103a-O and IIa-O, keeping the slit-width constant at 0.05 mm. The length of the slit was changed in order to obtain, with an exposure time of about 40 minutes, spectra 0.4 mm wide in the former plates, while in the latter the spectra are twice as wide and have an optimum density around $H\gamma$. All plates were calibrated immediately after exposure with a spot sensitometer and filters giving effective wave lengths at 4100 and 4600 Å. In order to derive the phases of the observations, we have computed the times of primary minimum, T_0 , from the elements given by Kron and Gordon,⁸ as follows:

$$T_0 = \text{JD } 2428771.379 + 4.21238n,$$

corrected by the departures from this formula found by the same authors on July 24 and September 23, 1949. Between these two dates the observed time of conjunction changed by 0.04 day, and for this reason we give the phases of our spectra only to 0.01 day.

III. THE RADIAL VELOCITIES

Our narrow plates are well suited for a redetermination of the orbit of the absorption component of the system, if the higher members of the Balmer series are selected for that purpose. These lines are relatively free of blends, in comparison with those in the blue region of the spectrum used by earlier investigators. The heliocentric radial velocities given in Table 1 for the absorption star of the binary are the straight averages of the velocities derived from $H8$, $H9$, and $H10$, using laboratory wave lengths. The fact that we did not find any systematic difference between the velocities of $H8$ and those of the other lines indicates that the blending of $H8$ with $He\text{ I } 3888.65$ does not produce an error larger than the observational uncertainty. From the internal agreement of velocities derived from plates taken in succession and from the same plate measured twice, we estimate that the accidental errors of measurement are of the order of 15 km/sec. For this reason all velocities given in Table 1 have been rounded off to the nearest multiple of 5 km/sec. For the emission spectrum, only the velocities of $N\text{ IV } 4057.80$ and the average of the velocities of the $N\text{ V}$ lines at λ 4603.2 and λ 4619.4 are given. The line λ 4619.4 becomes almost indistinguishable at phases near secondary minimum (see Fig. 1), and consequently only λ 4603.2 was measured at those phases. No systematic difference was detected between the two $N\text{ V}$ lines. In Figure 2 we have plotted the individual velocities for the two components of the binary. It is seen that the points define, without much ambiguity, the run of the velocity-curves. Assuming that they represent circular motion, we derive the set of elements given in Table 2. For comparison purposes we have repro-

¹⁰ *Ap. J.*, 110, 95, 1949.

TABLE 1
RADIAL VELOCITIES OF HD 193576

PLATE (CQ)	DATE 1949	PHASE (DAYS)	VELOCITIES (KM/SEC)					
			<i>H</i>	<i>N IV</i> 4058	<i>N V</i> 4603-19	<i>He I</i>		
						3889	3889	4471
7611.....	July 4.208	0.02	- 10	+ 65	+130	-1360	.....	.....
7612.....	4.242	0.06	- 45	- 35	+165	-1390	.....	.....
7614.....	4.413	0.23	- 30	+ 50	+150	-1365	.....	.....
7615.....	4.448	0.26	- 40	+ 95	+150	-1380	.....	.....
7621.....	5.249	1.06	- 95	+315	+415	-1385	.....	.....
7622.....	5.283	1.10	- 90	+300	+340	-1410	.....	.....
7623.....	5.425	1.24	- 80	+265	+305	-1450	.....	.....
7624.....	5.455	1.27	-125	+210	+370	-1420	.....	.....
7636.....	10.342	1.94	+ 20	- 45	+170	-1315	.....	.....
7637.....	10.405	2.01	- 5	+ 40	+190	-1345	.....	-1190
7639.....	11.202	2.80	+110	-240	-125	-1305	.....	.....
7640.....	11.325	2.84	+135	-345	-200	-1470	.....	.....
7642.....	12.155	3.76	+ 80	-310	.....	-1345	.....	.....
7645.....	13.199	0.59	- 90	+140	+260	-1450	.....	.....
7646.....	13.242	0.63	- 50	+125	+325	-1430	.....	.....
7647.....	15.460	2.85	+100	-380	-195	-1355	.....	.....
7649.....	16.174	3.56	+ 95	-335	-205	-1400	.....	.....
7650.....	16.201	3.59	+100	-370	-170	-1475	.....	.....
7651.....	16.347	3.74	+130	-300	-140	-1410	.....	.....
7652.....	16.382	3.77	+ 60	-320	-145	-1515	.....	.....
7653.....	16.414	3.80	+105	-275	-155	-1430	.....	.....
7656.....	17.154	0.33	- 65	+125	+150	-1595	.....	.....
7657.....	17.190	0.37	- 75	+160	+190	-1560	.....	.....
7658.....	17.225	0.40	- 30	+215	+280	-1520	.....	.....
7659.....	17.417	0.59	.....	.....	+300	.....	.....	.....
7660.....	17.452	0.63	.....	.....	+305	.....	.....	.....
7662.....	18.167	1.34	- 70	+215	+315	.....	.....	.....
7663.....	18.204	1.38	- 90	+225	+340	.....	.....	.....
7664.....	18.242	1.42	.....	.....	+330	.....	.....	.....
7665.....	18.259	1.44	-130	+210	+320	-1405	.....	- 845
7666.....	18.291	1.47	- 95	+150	+335	.....	.....	.....
7667.....	18.342	1.52	- 75	+130	+290	-1560	.....	- 940
7668.....	18.378	1.56	-100	+195	+310	-1535	-1100	- 905
7669.....	18.415	1.59	- 75	+180	+250	-1315	- 795	- 755
7671.....	19.117	2.29	+ 25	-145	- 15	-1160	.....	-1005
7672.....	19.147	2.32	+ 50	-205	- 30	-1175	.....	-1120
7673.....	19.171	2.35	.....	-160	- 25	.....	.....	- 920
7674.....	19.197	2.38	+ 80	-110	- 50	-1150	.....	-1015
7675.....	19.229	2.41	+ 85	-215	- 25	-1340	.....	-1165
7676.....	19.260	2.44	+ 45	-130	- 75	-1175	-1620	-1040
7677.....	19.294	2.47	.....	.....	- 75	.....	.....	.....
7678.....	19.319	2.50	+ 70	- 75	-100	.....	-1185	-1220
7681.....	19.408	2.58	+ 55	-175	-140	.....	-1260	-1015
7682.....	19.448	2.62	+ 80	-225	-160	.....	-1400	-1215
7683.....	26.239	1.04	-110	+225	+370	-1530	.....	.....
7684.....	26.377	1.09	-105	+210	+395	-1805	-1420	.....
7685.....	26.416	1.13	-155	+190	+390	-1670	-1145	.....
7702.....	30.282	0.78	-105	+235	+340	-1405	.....	.....
7703.....	30.318	0.82	-110	+220	+350	-1240	.....	.....
7704.....	30.346	0.85	-125	+290	+355	-1405	.....	.....
7707.....	30.415	0.92	-115	+225	+340	-1490	.....	.....
7708.....	30.444	0.95	-110	+305	+410	-1500	.....	.....
7709.....	30.467	0.97	.....	+360	.....	.....	.....	.....
7720.....	31.331	1.83	- 10	+ 50	+120	-1185	.....	.....

TABLE 1—*Continued*

PLATE (CQ)	DATE 1949	PHASE (DAYS)	VELOCITIES (KM/SEC)					
			<i>H</i>	<i>N</i> IV 4058	<i>N</i> V 4603-19	<i>He</i> I		
						3889	3889	4471
7721	July 31.360	1.86	— 15	+ 15	+160	—1315		
7722	31.387	1.89	— 45	— 30	+120	—1290		
7723	31.413	1.91	— 10	+ 50	+150	—1205		
7724	31.442	1.94	— 20	+ 25	+135	—1300		
7725	31.470	1.97		— 5	+155	—1305		—1155
7735	Aug. 1.417	2.92	+110	—265	—235	—1315		—1160
7736	1.441	2.94	+115	—435	—245	—1350	— 805	— 995
7737	1.474	2.98	+120	—190	—250	—1295		
7773	2.452	3.97	+ 55	—220	— 65	—1430		
7774	2.474	3.99	— 25	—170	— 30	—1430		
7775	10.137	3.21	+140	—350	—230	—1330		—1275
7777	10.219	3.29	+135	—300	—250	—1325		—1275
7779	10.353	3.43	+ 90	—350	—260	—1390		
7780	11.191	0.05	+ 15	+ 20	+ 80	—1450		
7782	11.380	0.24	— 45	— 50	+180	—1580		
7783	13.160	2.02	— 15	+ 15	+155	—1620	—1095	
7784	13.188	2.05	+ 20	— 50	+165	—1590	—1125	— 975
7785	13.217	2.08	+ 30	— 30	+115		—1060	
7787	13.272	2.14	+ 20	— 30	+120		—1050	—1055
7788	13.304	2.17	+ 30	— 75	+ 55	—1585	—1090	— 995
7789	13.338	2.20	+ 15	— 50	+ 50			—1015
7790	13.366	2.23	+ 60	— 25	+ 90		—1045	—1080
7792	14.139	3.00	+130	—390	—180	—1535	—1055	— 995
7793	14.170	3.03	+105	—400	—210	—1495	—1055	— 965
7795	14.242	3.10	+110	—385	—230	—1500	—1110	— 915
7796	14.274	3.14	+120	—370	—235	—1600	— 990	— 985
7797	14.308	3.17	+110	—415	—240	—1535	—1210	
7798	14.342	3.20	+125	—340	—230	—1590	—1255	
7799	14.378	3.24	+ 85	—345	—235	—1620		
7800	14.413	3.28	+130	—325	—235	—1420		
7801	14.449	3.31	+ 75	—320	—210	—1400		
7802	15.104	3.97	+ 5	—145	— 45	—1510		
7803	15.137	4.00	— 20	—170	— 55	—1530		
7804	15.174	4.04	+ 40	—130	— 20	—1580		
7805	15.212	4.08	+ 35	—115	+ 50	—1525		
7806	15.253	4.12	+ 50	—110	— 10	—1510		
7808	15.341	4.21	+ 30	—105	+ 65	—1520		
7809	15.390	0.04	+ 15	— 10	+110	—1495		
7810	15.432	0.08			+105			

duced in Table 2 the elements derived earlier by O. C. Wilson³ and E. S. Keeping.⁵ Disregarding for a moment our values for *N* IV 4058, we see that the only significant difference between O. C. Wilson's elements and ours is the one involved in the γ -velocities for the absorption component. With respect to this point, it should be remarked that the possibility of a systematic difference between the velocities obtained at McDonald and those at Mount Wilson is ruled out by the agreement of the measured velocities of interstellar *Ca* II for this star. We derive, from 83 spectrograms, $V = -8.8 \pm 3.3$ (p.e.) km/sec, while O. C. Wilson obtained $V = -8.6$ km/sec from 11 spectra. The discrepancy we find, therefore, is most likely to have originated in the distortion produced by the emission of *N* III and *He* II on the contour of *H* γ in absorption, on which Wilson's

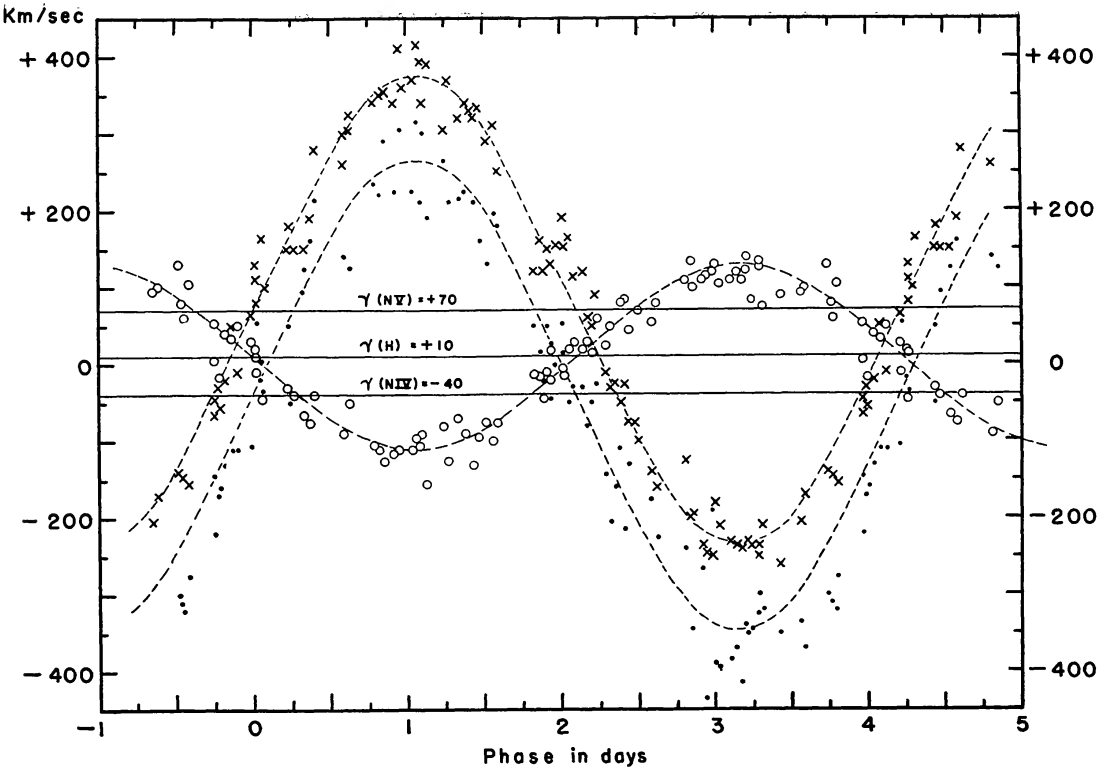


FIG. 2.—The radial-velocity-curves of HD 193576. The circles represent the average of the velocities derived from *H*8, *H*9, and *H*10. The crosses and dots represent the velocities given by the *N* v lines at λ 4603 and λ 4619 and by the *N* iv line at λ 4058, respectively.

TABLE 2
ELEMENTS OF THE SPECTROSCOPIC ORBITS

	O. C. Wilson	E. S. Keeping	Present Work
(Km/Sec)			
Emission { γ	+ 56.4 $\pm$ 4.4	{ <i>N</i> v: +55	<i>N</i> v: +70
{ <i>K</i>	308.6 $\pm$ 6	{ <i>N</i> iv: + 8	<i>N</i> iv: -40
Absorption { γ	- 33.6 $\pm$ 4.4	+ 32.8 $\pm$ 1.5	+ 10
{ <i>K</i>	120.7 $\pm$ 5.8	177.2 $\pm$ 3.9	120
$m_0 \sin^3 i$ ($M_\odot$).....	24.8	30.8	24.1
$m_w \sin^3 i$ ($M_\odot$).....	9.74	17.3	9.5
$a_0 \sin i$ ($R_\odot$).....	10.1	14.4	10.0
$a_w \sin i$ ($R_\odot$).....	25.7	25.5	25.4
$(a_0 + a_w) \sin i$	35.8	39.9	35.4

orbit is based. This distortion is undoubtedly more serious than the blending with the line of $He\ II$ in absorption, a blend which E. S. Keeping thought could be accounted for by adopting the average of the laboratory positions of $H\gamma$ and $He\ II\ 4388.71$ as standard wave length. Such a procedure does not seem to be justified. When comparing the various elements for the emission lines, we should keep in mind that the procedure followed by Keeping of averaging the velocities of all emission lines to find the "motion" of the WR star is incorrect. Recent measures by O. Struve¹¹ and W. A. Hiltner¹² in the spectra of WR systems have established beyond any doubt that different emission lines are shifted by different amounts with respect to the velocity of their center of mass. If we assume that the γ -axis of our velocity-curve for the hydrogen lines represents the motion of the center of mass of the system, we see that, in our measures, the $N\ V$ lines are shifted 60 km/sec to the red, while the $N\ IV$ line is shifted 50 km/sec to the blue. With respect to the apparent blue shift of $N\ IV\ \lambda\ 4057.80$, it should be said that the line at the elonga-

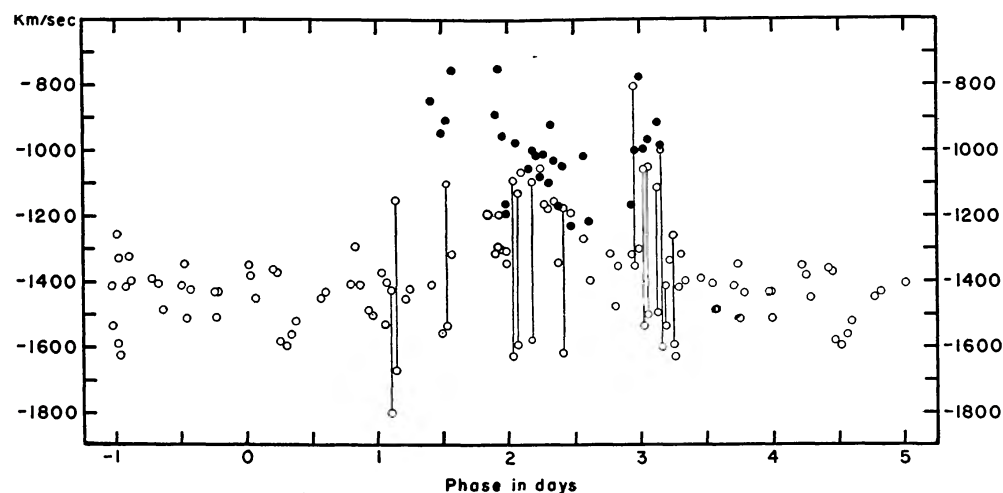


FIG. 3.—The radial velocities of the violet absorption edges of the emission lines of $He\ I$ at $\lambda\ 3888.65$ (empty circles) and $\lambda\ 4471.48$ (filled circles). The circles joined by a line represent the velocities of the two apparent components at times when the line is double.

tions is often distorted on the red side, in the manner described in the next paragraph. This distortion explains the greater scatter of the representative velocities around the elongations. For the same reason, the center of the emission feature, as estimated visually on the plate, does not necessarily coincide with the center estimated in a microphotometer tracing. Hence the difference between our γ -velocity and the one derived by Keeping is probably not physically significant.

The violet absorption edges of the emission lines of $He\ I$ at $\lambda\ 3888.65$ and $\lambda\ 4471.48$ have also been measured whenever possible. The $\lambda\ 4471$ edge, as Beals¹³ first pointed out, is visible only in the neighborhood of secondary minimum. Around this conjunction the $\lambda\ 3889$ edge can often be seen clearly as double, and the velocities derived for the two apparent components are given in Table 1. The plot of the radial velocities of the two lines, given in Figure 3, does not show any definite tendency to follow the general run of the curve found previously for the velocities of the emission lines. In regard to the absorption edge of $\lambda\ 3889$, it should be said that it becomes very shallow and difficult to

¹¹ *Ap. J.*, **100**, 188, 1944.

¹² *Ap. J.*, **101**, 356, 1945.

¹³ *Op. cit.*, Fig. 5. The displacement measured by Beals for the edge of $\lambda\ 4471$ was -400 km/sec, a value which is less than half the average velocity which we derived. This discrepancy raises the question of a possible intrinsic change in the spectrum from the time that the star was observed at Victoria.

measure around the first quadrature, when the associated emission is strongest and extends farther to the violet. We have noticed also that there is a rough correlation between the intensity of the emission line and the measured displacements of its absorption edge. For these reasons it is believed that the measured wave-length displacements do not reflect the mass motion of the absorbing atoms in a straightforward fashion.

IV. DESCRIPTION OF THE WOLF-RAYET SPECTRUM

The WR spectrum of HD 193576 displays conspicuous changes not only throughout the orbital period but also from cycle to cycle. On account of the general relevance of such changes for a proper understanding of the physical state of the matter producing the spectral lines, in this section we describe in detail the variations observed in their intensities and shapes.

He II

The asymmetry of the λ 4686 line of *He II* at phases near conjunctions³ is easily detected in a casual inspection of the plates. The measurement of its total strength, however, is a difficult problem, on account of the overexposure of the central parts of the line and the uncertainty involved in drawing the "continuum" between two regions "free" of emission which are over 100 Å apart and where the sensitivity of the emulsion is falling off rapidly. The average equivalent widths derived from the measurement of eight plates with the proper level of density are 88, 83, and 74 Å at the times of primary minimum, secondary minimum, and outside eclipse, respectively. These results are in essential agreement with the values obtained by Wilson. Taking into consideration the effect of the eclipse on the continuum to which the measures are referred, we obtain an intrinsic decrease of about 12 per cent at primary minimum. The information derived from photographic measures is certainly not accurate enough to establish any eclipse effect on the intensity of the line when the Wolf-Rayet nucleus is eclipsed. The only proper method of obtaining information about such an effect would be observing it photoelectrically, as W. A. Hiltner¹⁴ has recently done in the system CQ Cep. The appearance of the *He II* 4542 emission line in Figures 1 and 4 gives the impression that the line is narrower and slightly stronger near the elongations than at conjunctions. This effect, however, is certainly not real but is caused by the distortion produced by the same line in absorption in the spectrum of the companion star. It is believed that at the present time it is impossible to say whether or not the line is effectively stronger at the conjunctions, because of the blending with some lines of *N III*, which are stronger at these phases. Similar situations are encountered when attempting to ascertain the behavior of other emission lines of the Pickering series.

N III

The emission spectrum shows a number of broad features identified with groups of *N III* lines, which cannot be easily measured; nevertheless, they undergo rather remarkable changes. Thus, in Figures 1 and 4 the difference of the feature centered around λ 4542 at conjunctions and at the elongations is conspicuous. It appears stronger in the plates at primary minimum than at the secondary, being weakest at elongations. The same behavior probably is shown by the line at λ 4379 and the group of lines which appears blended with *He II* λ 4542. Unlike the lines just mentioned, the members of the multiplet $3p^2P-3d^2D$ around λ 4640 are stronger at secondary minimum than at the primary. The increase in the intensity of the lines at phases near secondary minimum takes place very rapidly and is accompanied by a marked change in the intensity distribution within the emission feature, as the tracings reproduced in the right half of Figure 4 illustrate. The appearance of the feature as a whole in the plates of best quality suggests evidence for an inner structure. It is also believed that the feature extends too

¹⁴ *A. J.*, in press.

far into the red at primary minimum to be due only to the three N III lines and that possibly there is a further contributor around λ 4650.¹⁵

N IV

The members of the $3s^3S-3p^3P$ multiplet of N IV at $\lambda\lambda$ 3479, 3483, and 3485 are blended together, forming the strongest feature in the ultraviolet emission spectrum. It appears only in our narrow spectra, overexposed in the blue region. The most remarkable change shown by this feature is the appearance, at primary minimum, of a strong absorption component, displaced to the violet by 4 Å ($= -340$ km/sec) with respect to the apparent center of the emission ($\lambda = 3482.8$ Å). This violet absorption edge is not present at all when the absorption star is out of eclipse, as can be seen in the tracings

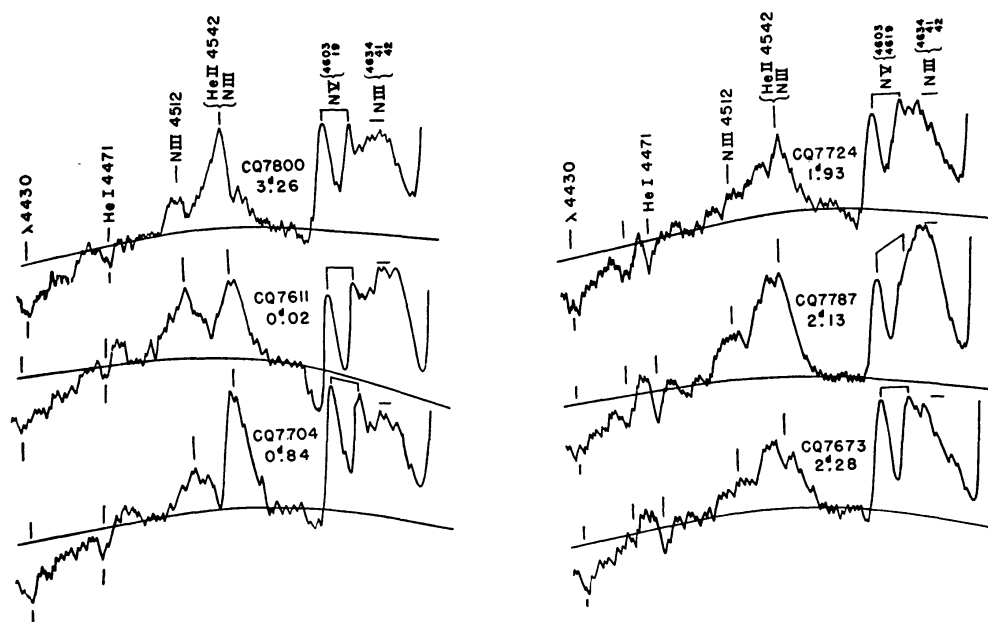


FIG. 4.—Microphotometer tracings of the spectrum of HD 193576 over the wave-length region $\lambda\lambda$ 4430–4660.

reproduced in Figure 5. The measures of the intensity at the center of the emission, marked in the figure, were made on the characteristic curve for λ 4100 and are given only to show the considerable decrease of the apparent strength of the feature at primary minimum. The other strong line of N IV at λ 4057.8 does not show a displaced absorption component at primary minimum, and, on the contrary, it looks strongest at these phases. In Figure 6 we give representative contours of the line at times when it appears to the eye nearly symmetrical. In some plates, however, it appears more or less distorted in a manner which suggests the presence of a superimposed narrow absorption line on the red wing of the emission. In extreme cases it is possible to see clearly a narrow absorption line overlying the emission, as is illustrated in Figure 7, where the tracings of two plates at the same phase, but at different epochs, are reproduced. The reality of the absorption feature in the plate CQ 7684 is unquestionable, as it runs clearly across the whole spectrum and appears nearly in the same position ($\lambda = 4061.9$ Å) in four plates taken in

¹⁵ P. Swings (*Ap. J.*, **95**, 112, 1942) has suggested that the broad emission feature observed around λ 4638 in the spectrum of HD 192163 extends too far to the red to be attributed to N III only and that there may be some blending effect by C III and C IV around λ 4652 Å.

succession. Only on another occasion did four successive plates, CQ 7720–23, covering the phases 1.83–1.91, show the same absorption line nearly as strong as it appears in CQ 7684. The appearance of this absorption line is not periodical, and we have not been able to find out whether it is correlated to some other varying feature of the WR spectrum.¹⁶ On the basis of the material now available, it appears that the emission line under consideration is more often distorted when the WR star is farther away from, than when it is nearer to, the observer and that the presence of the absorption feature does not persist longer than about 6 hours. It is certain that the large scattering shown

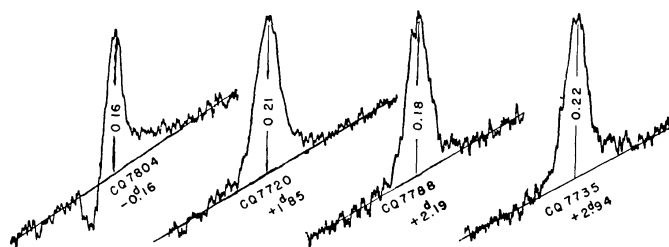


FIG. 5.—Tracings of the line $N\text{ IV } \lambda 3483$ in HD 193576 at different phases. Notice the appearance of the absorption component at primary minimum.

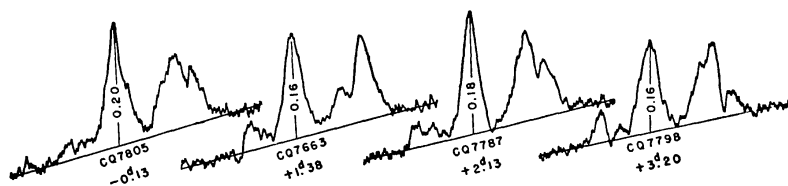


FIG. 6.—Tracings illustrating the average behavior of the line $N\text{ IV } \lambda 4058$ at various phases. The number marking the maximum ordinate in the profile of the line considered is the logarithm of the intensity at that point in units of the apparent continuum.



FIG. 7.—Comparison of the profiles of the $N\text{ IV } \lambda 4058$ line at the same phase and different epochs.

by the radial velocities of $\lambda 4057.80$ is due to the distortion of its profile. To study the variations in intensity of the line through the orbital period, we have selected for measurement the wide plates which appear free of noticeable distortion. As an indicator of the strength of the line, we have taken the height of the emission line in units of the continuum. The results of the measurements are given graphically in Figure 8, where we have plotted the logarithm of the ratio of the maximum intensity in the profile to the intensity in the continuum as a function of phase. The increase of the values of this ratio at the times of conjunction is well marked. If all the measures are referred to the continuum outside eclipse, the figure shows that the apparent increase in the intensity of the emission at primary minimum is due to the decrease in the continuum. It may be intrinsically stronger at secondary minimum than at other phases.

¹⁶ C. S. Beals (*op. cit.*, Fig. 4) has observed a narrow absorption core on the contour of $H\alpha$, which possibly might have the same nature as the one we have observed in $N\text{ IV } \lambda 4058$.

N v

The weakening of the *N* v lines at λ 4603.2 and λ 4619.4 at the times of conjunctions is noticeable in Figure 1. This visual impression is confirmed by the measurements, as can be seen in Figure 9, where we have plotted the logarithm of the ratio of the maximum intensity in the λ 4603.2 line to the intensity in the continuum as a function of phase. The representative points show considerable scatter, but it is apparent that the general run of the points is opposite to that shown by the measures of *N* iv λ 4057.8 in Figure 8.

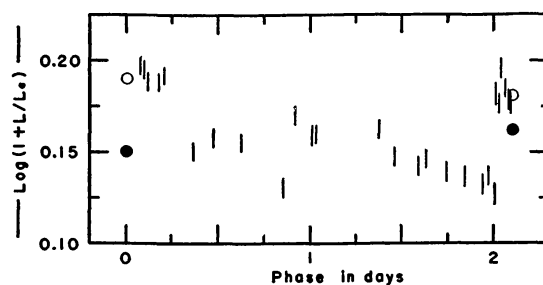


FIG. 8.—The dependence on phase of the height of the emission line *N* iv λ 4058, measured in units of the apparent continuum. The vertical bars represent individual measures, reflected about each minimum. The empty circles denote the values adopted at central eclipses, and the filled circles represent the values obtained when the height at the time of eclipse is measured in units of the continuum outside eclipse.

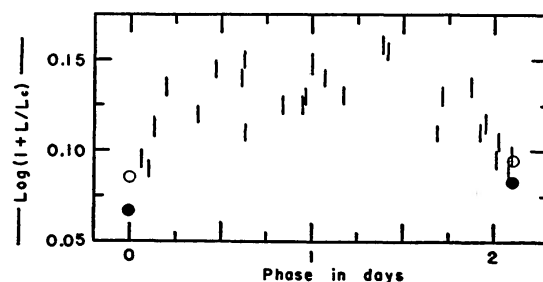


FIG. 9.—The dependence on phase of the height of the emission line *N* v λ 4603 measured in units of the apparent continuum. The vertical bars represent individual measures reflected about each minimum. The empty circles denote the values adopted at central eclipses, and the filled circles represent the values obtained when the height at the time of eclipse is measured in units of the continuum outside eclipse.

When the effect of the eclipses on the continuum is taken into account, we obtain a further decrease of the intensities at conjunctions. The absorption edges which border the emission lines in the violet also undergo conspicuous changes through the period. In Figure 4 they appear considerably deeper at primary minimum than near the elongations, while they become weaker in the neighborhood of secondary minimum, disappearing completely at central conjunction. The approximate values of the apparent central residual intensities, in units of the continuum, at primary minimum and at the elongations are, respectively, 0.88 and 0.96.

He I

The emission lines of *He* I are very broad and have low contrast with the continuum. For this reason it is difficult to estimate variations in their intensity. The violet absorption edges associated with the emission, however, vary in intensity and shape in a spectacular fashion. The violet edge of λ 3888.65 is narrowest and looks strongest around pri-

mary minimum, but it does not have the same intensity at different epochs. Thus, in the four plates obtained near the conjunction which took place on July 4.18, 1949, the line appears much stronger than in plates of corresponding phases at three other epochs observed (see upper part of Fig. 10). On plates taken the following night, however, the line in question has nearly the same strength as in corresponding phases of other cycles. Around secondary minimum the line appears to be considerably broader and sometimes even gives the impression of being double or, at least, of having a central reversal (see lower part of Figs. 10 and 11), but again in a manner which is not strictly periodical. In general, the line as a whole can be seen more clearly when the Wolf-Rayet nucleus is approaching the observer (phases 2.1–3.2) than when it is receding (phases 1.0–2.1). We have not found indications that the aperiodical changes of $He\ I\ \lambda\ 3889$ are accompanied by similar variations in other absorption or emission features of the WR spectrum. Since the variability of the absorption edges of the lines of $He\ I$ has been observed by W. A. Hiltner in HD 214419¹⁷ and HD 193928,¹⁸ it is reasonable to consider it as a common characteristic of all WR systems.

V. ANALYSIS OF THE SPECTRUM OF THE ABSORPTION STAR

The standard intensity ratios of the absorption lines of $He\ I$ and $He\ II$ in HD 193576, according to C. S. Beals,⁴ give for the absorption component of the system a type near O6. The same author, on the basis of the relative intensities of the absorption lines in HD 193576 and in standard stars of type O6, also estimated that the O component provides five-sixths of the continuous light observed in the whole system, out of eclipse, over the wave-length region $\lambda\lambda\ 4000$ – 6000 . The correct order of magnitude of this estimate was confirmed by Beals, who compared the emission-line intensities in the system and in other “typical” WN 5–6 stars. Our observations are not entirely consistent with all the conclusions derived by Beals. While there is no question that the emission-line intensities correspond to a ratio of the luminosities near 5, the appearance of the O spectrum in the near ultraviolet is not exactly that of a star of type O6. In Figure 11 we have reproduced tracings of the spectra of the system and of $\lambda\ Cep$, a standard star of type O6f. It is noticed that in $\lambda\ Cep$ the ratio $He\ II\ \lambda\ 3813/He\ I\ \lambda\ 3820$ is about unity, while in HD 193576 it is appreciably smaller than unity and corresponds to a star of type O8 ($\xi\ Per$). It also can be seen that the line $H10$ is stronger and has more extended wings in the binary than in the standard star. The manner in which $H10$ and $H11$ overlap suggests that the Stark effect may be the cause of stronger lines in the O star of the system. A further indication of this possibility is provided by the sudden termination of the Balmer series at $H14$, while in $\lambda\ Cep$ and in other O stars ($\theta'\ Ori\ C$, $\lambda\ Ori$) it ends with $H16$. This difference can hardly be explained by the presence of the $\lambda\ 3750$ group of emission lines, for neither is strong enough or extends sufficiently to the violet in “typical” WN 5–6 stars. It is therefore tempting to conclude that the end of the Balmer series at $H14$ is due to the higher Stark effect in the O component of the system.

On an earlier occasion¹⁹ the writer called attention to the change suffered by the absorption lines of the O star when it is eclipsed. To the eye this change is striking, as can be seen in Figure 10 by comparing the appearance of $H9$ and $H10$ during primary minimum and out of eclipse. Figure 11 also shows that the contours of the same lines at minimum light are more shallow and have a different shape than when the O star is not eclipsed. In the note just mentioned there was suggested a tentative explanation of this phenomenon, based on the redistribution in frequency suffered by radiation of the O star when scattered by thermal free electrons in the WR envelope. It would be a difficult problem to attempt a critical test of this hypothesis, taking into proper consideration the actual circumstances of the eclipse. We should have to discuss the geometry of the WR envelope, the darkening toward the limb of the O spectrum, and the possible effects of

¹⁷ *Ap. J.*, **99**, 273, 1944.

¹⁸ *Ap. J.*, **101**, 356, 1945.

¹⁹ *Ap. J.*, **108**, 540, 1948.

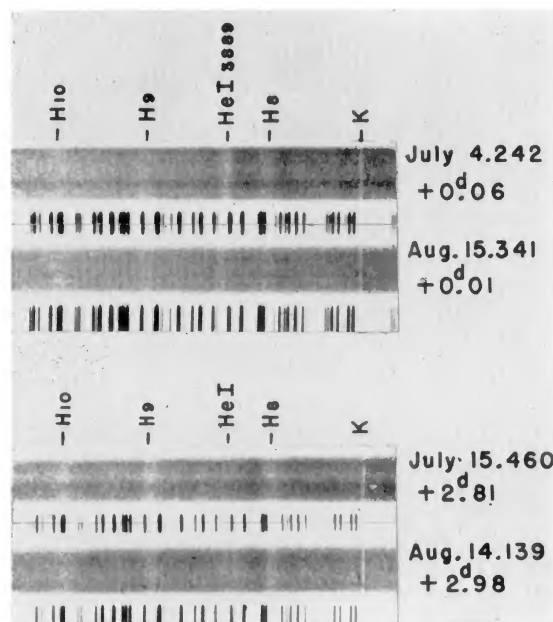


FIG. 10.—The spectrum of HD 193576 in the near ultraviolet. Notice the different intensity of the violet absorption edge of *He I* λ 3889 at the primary minima occurred on July 4.18 and August 15.34, 1949. Compare also the different appearance of *H9* and *H10* at primary minimum and at other phases.

rotation on the absorption lines of the partially eclipsed star. We restrict our considerations, therefore, to a simple situation which illustrates only the essential characteristics of the radiation scattered in the WR envelope. Imagine a plane surface, S , radiating in all directions the spectrum of the O star. We idealize the conditions of eclipse by superposing on S a plane-parallel layer of electrons of optical thickness τ and with a kinetic temperature T . This layer is also supposed to radiate a continuous spectrum equal to that of the WR component. We shall now show that the spectrum of the surface S , when observed through the electron layer, has some of the characteristic features of the O-star spectrum at minimum light.

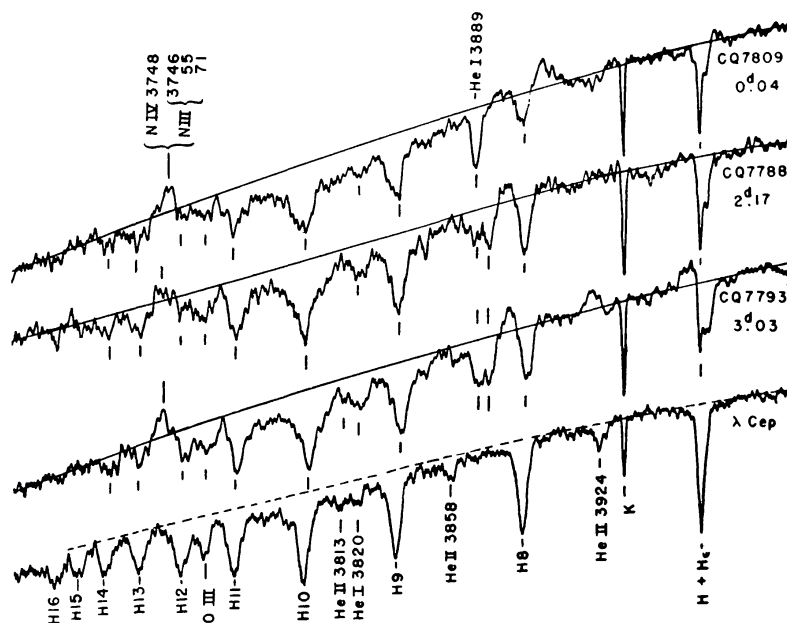


FIG. 11.—Tracings of the spectrum of HD 193576 in the near ultraviolet. Notice the different appearance of the $H10$ line and of the region between $H10$ and $H9$ at primary minimum and at other phases. The tracing of λ Cephei is included for comparison purposes.

Let $F_0(\lambda)$ and $F_1(\Delta\lambda)$ be the emergent fluxes from the surface S , respectively, at a wave length λ in the continuous spectrum and at a distance $\Delta\lambda$ from the center λ of an absorption line. We denote by $F'_0(\lambda)$ and $F'_1(\Delta\lambda)$ the corresponding quantities at minimum light. Then, if $F_W(\lambda)$ is the monochromatic flux of the WR spectrum radiated by the layer, the depths $D(\lambda)$ and $D'(\Delta\lambda)$ of the absorption line considered, respectively, when S is uneclipsed and eclipsed, are

$$D(\Delta\lambda) = F_0 - F_1(\Delta\lambda) \quad \text{and} \quad D'(\Delta\lambda) = \frac{F'_0 - F'_1(\Delta\lambda)}{F'_0 + F_W}, \quad (1)$$

where we express all fluxes in units of $F_0 + F_W$ and measure the depths from, and in units of, the continuum. In order to express $D'(\Delta\lambda)$ in terms of $D(\Delta\lambda)$ and the parameters τ and T of the electron layer, we use the approximate solution of the relevant Schuster problem given by the author.²⁰ Writing

$$a = \left(\frac{mc^2}{4kT} \right)^{1/2} \frac{\Delta\lambda}{\lambda} = 3.850 \times 10^4 \frac{\Delta\lambda}{\lambda \sqrt{T}}, \quad (2)$$

²⁰ *Ap. J.*, **108**, 116, eqs. (11) and (55), 1948. This paper will be referred to as "Paper I"; cf. also S. Chandrasekhar, *Radiative Transfer* (Oxford: Clarendon Press, 1950), eqs. (119) and (141), pp. 337 and 341.

we have

$$F'_1(a) = e^{-\tau\sqrt{3}}F_1(a) + \int_{-\infty}^{\infty} F_1(\beta) \Phi(\tau, a - \beta) d\beta, \quad (3)^{21}$$

where $\Phi(\tau, a)$ is a certain function of its arguments known in numerical form and with the property

$$\int_{-\infty}^{\infty} \Phi(\tau, a) da = \frac{1}{1 + \frac{1}{2}\tau\sqrt{3}} - e^{-\tau\sqrt{3}}. \quad (4)$$

Setting $F_1(a \rightarrow \infty) = F_0$ in equation (3), we obtain

$$F'_0 = \frac{F_0}{1 + \frac{1}{2}\tau\sqrt{3}}; \quad (5)$$

and, by substituting equations (3) and (5) in equation (1), we derive the required relation:

$$D'(a) = \frac{1 + \frac{1}{2}\tau\sqrt{3}}{1 + \frac{1}{2}\tau\sqrt{3}F_w} \left\{ e^{-\tau\sqrt{3}}D(a) + \int_{-\infty}^{\infty} D(\beta) \Phi(\tau, a - \beta) d\beta \right\}. \quad (6)$$

For comparison, if there were no redistribution in frequency in the scattering process, we should have

$$\Phi(\tau, a - \beta) = \left(\frac{1}{1 + \frac{1}{2}\tau\sqrt{3}} - e^{-\tau\sqrt{3}} \right) \delta(a - \beta) \quad (7)$$

and

$$D'(a) = \frac{D(a)}{1 + \frac{1}{2}\tau\sqrt{3}F_w}. \quad (8)$$

We now consider the specific example when $D(\Delta\lambda)$ has the simple analytical form

$$D(\Delta\lambda) = \frac{0.25}{1 + (0.286\Delta\lambda)^2}, \quad (9)$$

which roughly represents the observed contour of $H10$ in HD 193576 out of eclipse. Using equation (6) and the numerical values of $\Phi(\tau, a)$,²² we have computed the resulting contours $D'(\Delta\lambda)$ for $\tau = 0.4$ and $\tau = 0.8$. The result of the calculations is given graphically in Figure 12, where we have plotted two contours of the form (9), with centers 38 Å apart, and the broadened contours $D'(\Delta\lambda)$. We can then compare the appearance of the profiles of $H9$ and $H10$ in the tracings of Figure 11 with the theoretical contours of Figure 12. In a general way, we see that the main features of the change suffered by the lines during eclipse are present in the contours broadened by electron scattering in a layer of optical thickness around $\tau = 0.5$. In order to estimate an upper limit for the value of τ compatible with the observed light-curve, we may substitute the values $F_0 = 0.83$ and $F'_0 = 0.61$ in equation (5). In this manner we obtain $\tau \cong 0.3$, a value which

²¹ In connection with the use of eq. (3) it is useful to give an approximate form for the function $\Phi(\tau, a)$,

$$\Phi_1(\tau, a) = \left(\frac{1}{1 + \frac{1}{2}\tau\sqrt{3}} - e^{-\tau\sqrt{3}} \right) \left(\frac{3}{\pi} \right)^{1/2} e^{-3a^2}, \quad (3')$$

which represents the spectral distribution of monochromatic light after being scattered once at an angle of $\cos^{-1}(\frac{2}{3})$. This function has been normalized in order to satisfy the flux condition of the Schuster problem in the first approximation. Numerically, it has been verified that, for contours narrow compared with $\lambda(4kT/mc^2)^{1/2}$, the use of $\Phi_1(\tau, a)$, as defined above, gives values for the scattered light which do not differ by more than 10 per cent from the values obtained from the more approximate function $\Phi(\tau, a)$ for $\tau \leq 0.5$.

²² Paper I, Table 1 and eq. (62).

would seem not sufficiently large to explain the observed broadening of the lines. We should keep in mind, however, that in the actual eclipse the central parts of the disk of the O star are more occulted than are the regions near its limb. Under these conditions the effects of electron scattering in the outer layers of the atmosphere of the O star itself should be considered,²³ in accordance with a suggestion made earlier by the author.²⁴ It is also relevant to mention, in this context, that Kron and Gordon²⁵ in their analysis of the light-curve have considered the possibility of the existence of a "tenuous atmosphere surrounding the O component." Such an envelope would be so highly ionized as to be detectable only by means of its scattering properties. From these considerations we may conclude with confidence that the observed appearance of the absorption lines of the eclipsed O star can be explained in terms of the scattering of its radiation by free electrons in the WR envelope and in the outer layers of the O star itself.

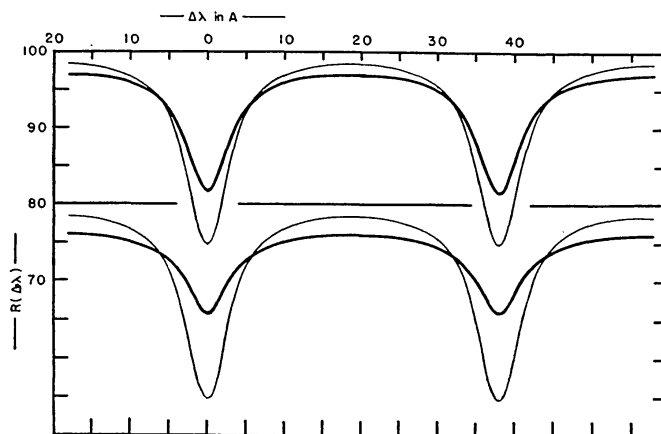


FIG. 12.—Comparison of the contours of two absorption lines (*thin lines*), nearly as strong as *H10* in HD 193576 outside primary minimum, with the same profiles as modified by electron scattering (*thick lines*) in a layer of optical thickness τ and temperature $T = 80,000^\circ \text{K}$. The upper figure is obtained for $\tau = 0.4$ and the lower for $\tau = 0.8$.

VI. ILLUMINATION OF THE WOLF-RAYET ENVELOPE BY THE O STAR

The light of the O star scattered in the line of sight by the WR envelope plays a very important role in the analysis of the light-curve, for it may amount to an appreciable fraction of the continuous radiation observed in the WR component.²⁶ It is not our intention now to study the intricacies of the problem, as it would carry us into a complete analysis of the light-curve. Instead, we shall consider a model based on the simple geometry of the system, derived in previous analysis of the photometric orbit. Specifically, we shall evaluate the illumination of a spherical distribution of free electrons, with known density and dimensions, by parallel radiation of a net flux πF coming from a point *O*. We assume that a quantum of radiation is scattered isotropically by the electrons only once, the cross-section for scattering, σ , having the classical Thomson value. Let us take a system of co-ordinates (see Fig. 13) with origin at *W*, its *z*-axis in the direc-

²³ Recent calculations of model atmospheres of stars of early B types, by Miss A. B. Underhill (*Ap. J.*, 111, 203, 1950), have shown that the effective depth of the layers at which the wings of the strong absorption lines are formed may be as high as $\tau = 1.5$, the opacity in the outer layers being largely due to electron scattering.

²⁴ Paper I, § 7.

²⁵ *Ap. J.*, 111, 454, 1950.

²⁶ See the remarks made by Kopal and Mrs. Shapley, *op. cit.*, pp. 169–170.

It is noticed that, as they should be, these values are identical with the reflected and transmitted diffuse intensities in a plane-parallel atmosphere of thickness τ_T , when the directions of illumination and observation coincide with the normal.²⁷

To obtain the total diffuse radiation of the envelope, as observed from the earth at full phases, we integrate equations (15) and (16) over the visible hemisphere. The values r and t , of the radiations diffusely reflected and transmitted in the WR envelope, in units of the observed light of the WR component, L_W , are, therefore,

$$r = \frac{R_W^2}{L_W} \int_0^{2\pi} d\phi \int_0^{\pi/2} \frac{1}{8} F (1 - e^{-2\tau_T}) \cos \vartheta_0 \sin \vartheta_0 d\vartheta_0 \quad (17)$$

and

$$t = \frac{R_W^2}{L_W} \int_0^{2\pi} d\phi \int_0^{\pi/2} \frac{1}{4} F \tau_T e^{-\tau_T} \cos \vartheta_0 \sin \vartheta_0 d\vartheta_0. \quad (18)$$

In terms of the radius a of the relative orbit of the O star, the flux incident on the envelope is approximately given by

$$\pi F = \frac{L_0}{a^2}; \quad (19)$$

and equations (17) and (18) become, after writing $x = \sin \vartheta_0$,

$$r = \frac{L_0}{L_W} \left(\frac{R_W}{a} \right)^2 \frac{1}{8} \left\{ 1 - 2 \int_0^1 e^{-2\tau(x)} x dx \right\} \quad (20)$$

and

$$t = \frac{L_0}{L_W} \left(\frac{R_W}{a} \right)^2 \frac{1}{2} \int_0^1 \tau(x) e^{-\tau(x)} x dx. \quad (21)$$

Now in Figure 13 it is readily seen that

$$\tau_T = \tau_T(\vartheta_0) = 2 \sigma R_W \sin \vartheta_0 \int_{\vartheta_0}^{\pi/2} N_e \left(R_W \frac{\sin \vartheta_0}{\sin \vartheta} \right) \frac{d\vartheta}{\sin^2 \vartheta}. \quad (22)$$

This equation, in terms of the variable x and by the definition of R_W , can be written with sufficient accuracy in the form

$$\tau(x) = 2 \sigma R_W x \int_1^\infty N_e(R_W x t) d(t^2 - 1)^{1/2}. \quad (23)$$

The electron densities derived by Kopal and Mrs. Shapley²⁸ can be represented with any desired accuracy by an interpolation formula of the type

$$N_e(r) = e^{-kr} \sum_{j=0}^n c_j r^j, \quad (24)$$

for which the integration in equation (23) can be carried out explicitly. For our purposes, it is sufficient to take a first-order expansion, with $k = 2.68 \times 10^{-12} \text{ cm}^{-1}$ and $c_0 = 2.32 \times 10^{12} \text{ cm}^{-3}$. With $R_W = 1.85 \times 10^{12} \text{ cm}$ ($= 0.75a$),²⁹ equation (24) takes the numerical form

$$\tau(x) = 5.73 \times K_1(4.96x), \quad (25)$$

²⁷ Cf. Chandrasekhar, *op. cit.*, chap. viii, eqs. (108), (109), and (113), pp. 201–202.

²⁸ *Op. cit.*, Table 9.

²⁹ This value of R_W , taken from Kopal and Mrs. Shapley's work, is considerably larger than the value derived by Kron and Gordon. The final numerical values of r and t , however, are quite independent of the value of R_W adopted.

where $K_1(x)$ is the Bessel function of the second kind for an imaginary argument.³⁰ If the integrals of the functions of $\tau(x)$ indicated in equations (20) and (21) are then numerically carried out, we obtain

$$r = 0.031 \frac{L_0}{L_W} \left(\frac{R_W}{a} \right)^2 \quad \text{and} \quad t = 0.030 \frac{L_0}{L_W} \left(\frac{R_W}{a} \right)^2. \quad (26)$$

If the adopted values of L_0/L_W and R_W/a are inserted into equations (26), we obtain the result that the diffusely reflected and transmitted light at full phase, in our model, amounts to nearly 10 per cent³¹ of the observed radiation in the WR component. This value represents only a rough lower limit for r and t , and the true values for the reflected and transmitted lights are probably much larger for the following reasons: In the first place, the contributions of higher-order scattering are certainly large in an atmosphere of diametral thickness of the order of unity. In the second place, the values of $N_e(r)$ derived by Kopal and Mrs. Shapley are minimum values. And, finally, if the illuminating radiation is considered conical instead of parallel, quite large additive corrections may be expected.³²

We should keep in mind that the preceding estimate of the illumination of the WR envelope refers only to radiation of the O star scattered by free electrons. The intensity distribution of the diffuse continuous spectrum has nearly the same form as the incident radiation. There is, however, another process which may induce a true continuum in the envelope. As a consequence of the large cross-section of the material in the envelope for short wave-length radiation, it is reasonable to expect that a significant fraction of the light of the O star absorbed in the far ultraviolet will be re-emitted at longer wave lengths. The physical conditions in the envelope are, however, so far removed from thermodynamic equilibrium as to make invalid the use of the Kirchhoff-Planck equation for describing the induced radiation field. Consequently, a strict evaluation of the energy density in the outer envelope would be a very difficult problem. At the present time we cannot develop these considerations in a quantitative manner; we merely recognize the possibility that the continuous spectrum observed by Kron and Gordon in the inner parts of the WR envelope derives to some extent from the ultraviolet light of the companion.

It is appropriate here to make some general remarks on the interpretation of the light-curve of the system. The most striking characteristic of the light-curve is the difference in the duration of the two eclipses. In their work Kopal and Mrs. Shapley³³ advocate the view that a "great difference in width of the alternate minima discloses immediately that the conditions in the W envelope must depart widely from thermodynamic equilibrium." But this view does not seem to have much physical basis: if the opacity of the envelope in the accessible region is electron scattering, it must re-emit exactly as much as it absorbs; the lack of thermodynamic equilibrium in the envelope will not disturb this situation. The narrowness of the secondary minimum must, therefore, have a different explanation. It would be interesting to analyze in detail the possibility of explaining it in terms of a large reflection effect in the system. We do not observe a decrease in the total light when the outer parts of the envelope are being occulted by the disk of the O star, because the increase in brightness of the unocculted parts compensates for the effect of

³⁰ Cf. G. N. Watson, *Treatise on the Theory of Bessel Functions* (Cambridge: At the University Press, 1944), eq. (6.15.4), p. 172.

³¹ In magnitudes, the reflected and transmitted radiations would be 0.02, a quantity which should be compared with the observed depth, 0.14 mag., of the secondary minimum.

³² Cf. Z. Kopal, *An Introduction to the Study of Eclipsing Variables* ("Harvard Observatory Monographs," No. 6 [Cambridge, Mass., 1946]), § 64, p. 155.

³³ *Op. cit.*, pp. 160–161, also n. 5.

eclipse. When the O star is behind, there is no such compensation, because in a thick atmosphere the diffusely transmitted light will be smaller than the reflected.

VII. ON THE SHIFT OF WOLF-RAYET EMISSION LINES

Recent work by O. Struve¹¹ and W. A. Hiltner¹² has established the plausibility of explaining the red shift of certain emission lines in WR spectra in terms of self-absorption processes in the envelope. Our observations of V 444 Cyg provide new information related to the question, which will now be discussed. We have seen that all violet absorption edges, with the exception of *He* I 4471, become deeper at the time of primary minimum. This phenomenon cannot be explained in terms of the decrease in the intensity of the continuous spectrum, if the ratio of the lights of the two components is 5 to 1. It is undoubtedly due to the absorption of the direct continuous radiation of the O star by atoms in the WR envelope. This observational fact provides the most convincing proof for the relevance of absorption processes in the formation of the observed emission lines.

The clearest example of a red shift being produced by an absorption edge is provided by the observed behavior of the group of *N* v lines at λ 3483 Å. At minimum light, when the absorption edge appears, the center of the emission is displaced to the red by 1.5 Å (= +130 km/sec), with respect to the apparent center of the emission feature at secondary minimum. If this line could be measured for radial velocity, we should probably find a red shift only during primary minimum.

The strengthening of the absorption edges of the lines of *N* v at λ 4603 and λ 4619 does not produce a measurable increase in their red shift. This observational fact cannot be used as an argument against the explanation of the red shift in terms of self-absorption. The emission line λ 4603 is placed just in between the two absorption edges, in such a manner that the increased absorption produces only a decrease in the intensity of the emission, without appreciable shift. The line at λ 4619, on the other hand, is difficult to measure around primary minimum and, being badly blended with the *N* III lines, does not provide conclusive evidence. It is, nevertheless, not easy to understand why the disappearance of the absorption edge of λ 4603 at secondary minimum does not produce a shift to the blue in the measured radial velocities. If it is a geometrical effect of the eclipse, one would expect such a blue shift. But the possibility of blending with an emission feature increasing in intensity at secondary minimum cannot be definitely excluded.

VIII. INTERPRETATION OF THE WOLF-RAYET SPECTRUM

The main features shown by WR spectra have been described by C. S. Beals³⁴ and other investigators in terms of a hypothesis which postulates an ejection of material from a high-temperature nucleus. The ejected atoms are supposed to form a symmetrical extended envelope, in which the characteristic emission spectrum originates. The discussion of observational data related to HD 193576, however, led O. C. Wilson³⁵ to formulate serious doubts as to whether the ejection hypothesis could at all explain the observed phenomena. The main difficulty encountered by this author in accepting the existence of a large envelope in outward motion is that it necessarily implies a difference between the times of photometric and of spectroscopic conjunctions, which is definitely ruled out by the observations. In the original form of Beals's hypothesis, the motion in the envelope is accelerated outward, to such an extent that the presence of the O star cannot modify appreciably the trajectories of atoms moving with velocities several times as large as the velocity of escape from the whole system. The absence of a transit-time effect, therefore, could hardly be explained by the asymmetry of the envelope produced by tidal forces, as Beals suggested later.³⁶ This and other difficulties encountered in Beals's original hypoth-

³⁴ *M.N.*, **90**, 202, 1929.

³⁵ *Ap. J.*, **95**, 402, 1942.

³⁶ *M.N.*, **104**, 205, 1944.

esis, however, may be avoided by postulating that the ascending mass motions in the envelope are decelerated.³⁷ Such a situation is realized if matter leaves the nucleus by the action of an impulsive force: part of the kinetic energy supplied is used for support of the matter against the gravity of the nucleus, and the rest is dissipated into heat of atomic motion by turbulence.³⁸ We shall discuss, in the following paragraphs, the consequences of this alternative hypothesis, in the light of the observational evidence available at the present time. The nature of the physical processes determining the spectral characteristics will also be briefly considered.

STRATIFICATION IN THE ENVELOPE

In Beals's model for a WR envelope the ions are arranged outward in order of decreasing ionization potentials. This stratification is an immediate consequence of the postulate of a high-temperature core producing the ionization in the envelope. The recognition of HD 193576 as a binary with an O component, however, immediately throws doubt on the possibility that the observed *He I* lines could arise in the outermost layers of the envelope. Recalling that O stars radiate sufficient energy in the far ultraviolet to produce nebular luminosity and interstellar emission, we find it difficult to imagine the conditions under which *He I* could exist in a low-density envelope close to the O star without being completely ionized. In a decelerated envelope, on the contrary, the highest ionization comes from the highest levels, in such a way that the continuous radiation of the O star beyond the ionization limit of a given ion does not reach the layers in which the lines of that ion mostly originate. This remark does not imply that the state of ionization of the envelope depends only on the ultraviolet radiation of the O star. The physical conditions in the envelope will be determined primarily by the manner in which the energy of mass motion supplied by the core is dissipated in the higher layers. It would seem reasonable to expect, nevertheless, that the ultraviolet radiation of the O star would have an appreciable effect on the state of ionization of the outer envelope. Careful comparisons of line intensities in WR systems with different orbital radii could establish the magnitude of such an effect.

STATE OF MOTION IN THE ENVELOPE

The striking behavior of the displaced lines of *He I* immediately reveals the intrinsic variability of the conditions in which they are formed. We have observed erratic changes in their intensity in such short intervals of time as a few hours. On this account alone, it is tempting to describe the state of motion in the lower envelope in terms of a random flow of gas leaving the WR nucleus in all directions, with the same velocity on the average. The statistical fluctuations of the field, observed at the lower strata, are smoothed out as matter moves outward, in such a manner that lines originating in the higher layers do not undergo erratic changes. It would also be a simple matter to ascribe certain symmetry properties to the gas flow in order to explain the observed dependence on phase of the average intensity of the *He I* lines. Thus we could imagine that a greater amount of matter leaves the core from the advancing hemisphere than from the opposite one.³⁹ But, once this hypothesis is made, we should have to explain why lines originating at the

³⁷ In *M.N.*, **94**, 522, 1934, S. Chandrasekhar considered the possibility of decelerated radial ejection of atoms in WR stars.

³⁸ This mechanism is essentially the same as that considered by W. H. McCrea (*M.N.*, **89**, 718, 1929) to explain the support of the solar chromosphere. It also should be mentioned in this context that recently R. N. Thomas (*Ap. J.*, **109**, 500, 1949) constructed a model for a WR envelope based on a similar fundamental idea.

³⁹ An anisotropic pattern of this kind has been observed by O. Struve in the streams of gas flowing between the components of a number of close binaries. In the case of the eclipsing system UX Mon, such a flow has been described by the same author (*Ap. J.*, **106**, 253, 1947) in terms of a field of prominences subject to considerable random variations.

higher levels do not show any asymmetry between the advancing and receding sides of the envelope. This question leads us to the main difficulty encountered in attempting to explain the observed spectrum of V 444 Cyg and similar systems. In a close binary of this kind one would expect the existence of an envelope common to both components, formed by a system of currents between them. The dynamics of such an envelope have been studied by G. P. Kuiper,⁴⁰ and observations of a variety of eclipsing binaries by O. Struve⁴¹ have established the properties and dimensions of the phenomena involved. In the case we are dealing with, the photometric observations can be interpreted in terms of a large envelope surrounding the fainter and smaller component. However, spectroscopically we find that the material giving origin to the observed emission lines is not subject to large-scale currents (within the observational uncertainty of the radial-velocity-curves) and has a spatial distribution nearly symmetrical around the line of centers.⁴² Although it has not been possible to determine even approximately the linear dimensions of the emitting regions, there is no doubt that they must be comparable to the diameter of the primary star, which is about half the radius of the relative orbit. Nevertheless, the measured velocities of the emission lines originating in the higher strata are apparently unaffected by the gravitational field of the heaviest component. The solution to this paradoxical situation is undoubtedly related to the strong radiation pressure of the O star and the effectiveness of the mixing processes in the WR envelope. The ions directly exposed to the ultraviolet radiation of the O star are subject to a repulsive force, which tends to keep them bound to the WR star. It is difficult to foresee, without a careful analysis, whether the combined effect of the mixing agents in the WR envelope, the radiation pressure of the O star, and the general gravitational field could localize the emitting material to a region which, as a whole, would show the observed properties. It should also be added that it is not entirely unreasonable to think of an envelope extending so far as to inclose the O star. We have mentioned before that Kron and Gordon,²⁵ from the purely formal aspects of the light-curve, have suggested such a possibility. And, from the spectroscopic point of view, it could very well happen that it is not observed because its state of ionization is very high. In any case, before attempting to formulate these considerations in a less speculative manner, we should find some observational facts revealing the effects of the radiation of the O star on the high-level emission lines of the WR spectrum. Certain features we have observed in V 444 Cyg can be tentatively interpreted in terms of these effects, but they do not offer a conclusive test, mainly because of our lack of knowledge of the basic processes forming the lines.

NATURE OF THE EMISSION SPECTRUM

One of the unsolved problems is offered by the appearance of absorption edges only in certain emission lines and not in others. There is no doubt that a long life for the lower state of the transition involved is favorable for the appearance of the edges, but it is not a necessary condition. As examples we mention the lines $He\ I\ 3889$ and $N\ IV\ 3483$, which have violet absorption edges and arise from metastable levels, but the $N\ V$ lines also have strong absorption edges and arise from short-lived states. Essentially the same problem is encountered in the selectivities shown by certain lines to appear in emission in Of stars. We recall that, in the spectrum of 9 Sge, Struve and Swings⁴³ observed the line $3p^1P^o - 3d^1D$ of $N\ IV$ in emission, while the lines $3s^3S - 3p^3P^o$ occur only in absorption. In our case the former always appears in emission, while the latter develop an absorption edge at primary minimum. Another analogy between the spectra of 9 Sge and V 444

⁴⁰ *A. J.*, **93**, 133, 1941.

⁴¹ *Stellar Evolution* (Princeton: Princeton University Press, 1950), p. 188.

⁴² This remark is based on the apparently similar characteristics of the emission lines in systems with the same WR type but with different orbital inclinations.

⁴³ *A. J.*, **91**, 546, 1940.

Cyg is found in the behavior of the multiplet $3p^2P^o - 3d^2D$ of $N\text{ III}$. In the Of star it is the only one which appears in emission, while in the WR star it increases in intensity at secondary minimum much more than other lines of the same ion. Independently of the detailed mechanisms producing such selectivities, we may draw the definite conclusion that we are not dealing with a pure recombination spectrum. This conclusion invalidates the methods followed by C. S. Beals⁴⁴ and other authors⁴⁵ in deriving the excitation temperatures of emission lines.

It would be impossible to explain the detailed variations with phase of the intensity in the emission lines only in terms of the geometrical effects of the eclipses. Undoubtedly, there are unknown physical reasons for the strengthening of some lines at certain phases. We can notice, however, that most of the lines are intrinsically weaker at primary minimum than at secondary. Considering, also, that there are no appreciable eclipse effects on the lines (disregarding the lines of $N\text{ V}$), we can conclude that the emission lines of the envelope are stronger over the hemisphere facing the O star than in the opposite one. This phenomenon could be interpreted by postulating an *ad hoc* geometrical form for the emitting regions. But it can also be explained less artificially as a phase effect of the ultraviolet radiation of the O component. At the present time, however, no critical choice can be made between these two points of view.

THE FORM OF THE EMISSION LINES

It is well known that the interpretation of the profiles of emission lines observed in WR spectra in terms of the expanding-envelope hypothesis has encountered serious difficulties.³⁵ We are not going to rediscuss every aspect of the problem, but it is appropriate to make some remarks about the absence of an "occultation effect." In the earlier work on the subject, the observed symmetry of the contours was taken as a proof that the nucleus was of negligible dimensions as compared with the envelope. The study of the eclipsing properties of the WR envelope of V 444 Cyg has revealed, however, that the envelope is far from transparent to its own radiation. The value $\tau = \frac{1}{2}$ found for the radial optical thickness of the envelope in electron scattering invalidates the afore-mentioned explanation for the absence of an occultation effect.⁴⁶ The nearly symmetrical form of the emission lines, therefore, must result from the processes of self-absorption, which tend to cancel the occultation effects, and from other broadening agents with a local character. One question of some interest in this context is to analyze the extent to which the observed broadening in an emission line can be attributed to the effect of electron scattering in the upper strata. We shall consider specific examples to illustrate this effect. Let us suppose that the whole line is formed at a certain level and that between this level and the observer there is a layer of free thermal electrons of optical thickness τ . The problem is to find the intensity distribution within an emission line, $R(\Delta\lambda)$, which, after being scattered in the electron layer, will look like the observed contour $R'(\Delta\lambda)$. Using equation (3), we have no difficulty in finding the solution by trial and error. For order-of-magnitude considerations it is sufficient to use the approximate equation (3'), and then we have simply

$$R'(\Delta\lambda) = kR(\Delta\lambda) + (1 - k) \int_{-\infty}^{\infty} R(\Delta\lambda') \psi(\Delta\lambda - \Delta\lambda') d(\Delta\lambda'), \quad (27)$$

where

$$k = k(\tau) = (1 + \frac{1}{2}\tau\sqrt{3}) e^{-\tau\sqrt{3}} \quad (28)$$

and

$$\psi(\Delta\lambda) = \frac{1}{\sigma\sqrt{\pi}} e^{-(\Delta\lambda/\sigma)^2}, \quad (29)$$

⁴⁴ *Pub. Dom. Ap. Obs., Victoria*, **4**, 271, 1930, and **6**, 95, 1934.

⁴⁵ In a recent paper (*B.A.N.*, **11**, 165, 1950), H. Zanstra and J. Weenen have investigated the problem of the abundances of the ions in a WR envelope under the hypothesis of pure recombination.

⁴⁶ R. N. Thomas (*Ap. J.*, **106**, 482, 1947) has also called attention to this circumstance.

with

$$\sigma = 1.50 \times 10^{-5} \lambda \sqrt{T} \quad (\lambda \text{ in } \text{\AA}). \quad (30)$$

Let us now consider, as an example, a contour of the form

$$R(\Delta\lambda) = \frac{E}{m\sqrt{\pi}} e^{-(\Delta\lambda/m)^2}. \quad (31)$$

Equation (28) then becomes

$$R'(\Delta\lambda) = kR(\Delta\lambda) + \frac{(1-k)E}{[\pi(\sigma^2 + m^2)]^{1/2}} e^{-(\Delta\lambda)^2/(\sigma^2 + m^2)}. \quad (32)$$

For the case of the $He\text{ II } \lambda 4686$ line, we have observed $E = 370 \text{ \AA}$, in units of the intensity of the neighboring continuum of the WR star only. With $\tau = \frac{1}{2}$, $T = 80,000^\circ \text{ K}$, and $m = 8 \text{ \AA}$, we obtain the contours $R(\Delta\lambda)$ and $R'(\Delta\lambda)$ represented in Figure 14. We plot in a log scale observed points in the contour of $\lambda 4686$ to illustrate the rough agreement of the observed contour with $R'(\Delta\lambda)$. It is seen that the original contour $R(\Delta\lambda)$ is broadened considerably by electron scattering. Interpreting as a Doppler motion a dispersion of $8 \text{ \AA}$ for the original contour, we find a spread in velocity of about 500 km/sec , a value which is less than half the range of representative velocities in the broadened contour. As another example we consider in Figure 15 the broadening of a line with about the

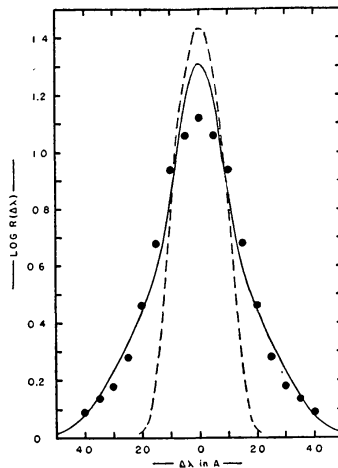


FIG. 14.—The effect of electron scattering on a strong emission line. The dashed-line contour is changed by scattering in an electron atmosphere of optical thickness $\tau = 0.5$ and temperature $T = 80,000^\circ \text{ K}$ into the full-line profile. The broadened contour was chosen so as to represent nearly the observed intensities (dots) of $He\text{ II } \lambda 4686$ in HD 193576.

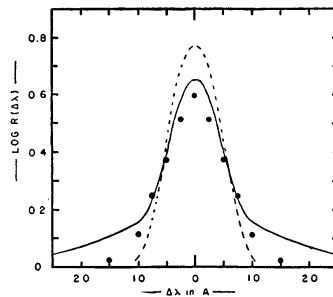


FIG. 15.—The effect of electron scattering on an emission line of moderate intensity. The dashed contour is modified by scattering in an electron atmosphere of thickness $\tau = 0.5$ and temperature $T = 80,000^\circ \text{ K}$ to the full-line profile. The broadened contour was chosen so as to represent roughly the observed intensities (dots) of $N\text{ IV } \lambda 4058$ in HD 193576.

same intensity and shape as $N\text{ IV } \lambda 4058$ ($E = 44\text{ A}$, $m = 5\text{ A}$) by a layer of electrons with the same optical thickness and kinetic temperature as before. It is seen that in this narrower line, with smaller total strength, the broadened contour has marked the extended wings more, reflecting the high Doppler velocities of the electrons. From these two examples it is seen that electron scattering produces an appreciable broadening in the emission lines formed at the deeper layers of the WR envelope. Nevertheless, the widths of the lines, after allowing for the broadening effects of electron scattering, are still very large. As further broadening agents we may invoke the large-scale turbulence of the envelope and the collisional broadening of ions and electrons. Earlier workers in the field have discarded the possibility of broadening by interatomic forces, on the grounds that the densities in a WR envelope are not sufficiently high. Since the study of V 444 Cyg has established electron densities of the order of 10^{12} cm^{-3} , it would seem that, at the high thermal velocities involved, the effects of particle perturbations on the atomic energy levels cannot be disregarded without a careful analysis. In conclusion, we may remark that local broadening agents, such as electron scattering, turbulence, and collisional broadening, necessarily require a stratification in the envelope in which the state of ionization increases outward.

It is a pleasure to express my gratitude to Professor O. Struve for his help in securing the observations studied in this paper and for many valuable discussions. I am indebted to Drs. G. E. Kron and K. C. Gordon for allowing me to read their investigation in advance of publication. My thanks are also due to Dr. S. Chandrasekhar, Dr. W. A. Hiltner, and Dr. O. C. Wilson for reading the manuscript and for their criticisms.