

THE WOLF-RAYET SPECTROSCOPIC BINARIES HD 186943, HD 193928, AND HD 211853*

W. A. HILTNER

McDonald and Yerkes Observatories

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ABSTRACT

These three Wolf-Rayet stars have been investigated as spectroscopic binaries.

For HD 186943, spectral type WN5, hydrogen absorption lines were measured, as well as the emission bands $He\ II\ 4686$, $N\ V\ 4603$, and $N\ V\ 4619$. The absorption lines belong to the early B-type companion. The following elements have been derived: $P = 9.550$ days, $e = 0.0$ (assumed), $K_{WR} (He\ II\ 4686) = 235$ km/sec, $K_B = 65$ km/sec, $M_{WR} \sin^3 i = 5.8 \odot$, and $M_B \sin^3 i = 21.0 \odot$. There are pronounced differences in the gamma-velocities of the three emission bands, none agreeing with the gamma-velocity for the hydrogen absorption. The amplitude of the velocity-curve for $N\ V\ 4603$ and $N\ V\ 4619$ is smaller than that for $He\ II\ 4686$. Also, the $N\ V$ velocity-curve shows a phase shift of 0.8 day with respect to $He\ II\ 4686$.

The spectral type of HD 193928 is about WN6. Only the Wolf-Rayet component of the system is observable. The following elements have been derived from 30 McDonald spectrograms: $P = 21.64$ days, $e = 0.0$ (assumed), $K = 130$ km/sec, $\gamma (He\ II\ 4686) = +59$ km/sec, $\gamma (N\ V\ 4603) = -119$ km/sec, and $f(m) = 4.94$. Absorption lines near $\lambda\ 3873$ and $\lambda\ 4453$ have been measured and identified as $He\ I$ displaced to the violet by approximately 1200 km/sec. These lines were abnormally strong on July 14, 1944, and from observed displacements and changes in dilution we conclude that the $He\ I$ atoms recede from the star with approximately uniform velocity. A similar conclusion was suggested from earlier observations of HD 214419.

The spectrum of HD 211853, spectral class WN6, has well-defined absorption lines as well as emission bands. For the emission bands alone, the following elements are obtained: $P = 6.6864$ days, $e = 0.0$ (assumed), $K = 245$ km/sec. The gamma-velocities of $He\ II\ 4686$ and $N\ V\ 4603$ are in good agreement, both bands being displaced to the red, with respect to $N\ IV\ 4058$, by 200 km/sec. None of the emission gamma-velocities agrees with that of the absorption lines. The measurements of the absorption lines give a strange velocity-curve. If one interprets the velocity-curve as that of the early B companion with $K = 95$ km/sec, we have the following minimum masses for the two components: $M_{WR} \sin^3 i = 7.6 \odot$ and $M_B \sin^3 i = 19.6 \odot$. The line $He\ II\ 4686$ undergoes variations in structure.

The available data on discrepant gamma-velocities are collected and briefly discussed.

In 1941 O. C. Wilson¹ announced the discovery of three spectroscopic binaries in which one component of each system was a Wolf-Rayet star. Up to that time only one other known spectroscopic binary possessed a Wolf-Rayet component, HD 193576,² and one visual double, HD 219460.³ Since this announcement by Wilson, only two other Wolf-Rayet binaries have been discovered.⁴ In 1940 Wilson⁵ called attention to a number of Wolf-Rayet stars that have undisplaced absorption lines, which he suggested might belong to a second component. Stars HD 186943 and HD 211853 were in this list. To this list the author wishes to add HD 193077, which is probably a spectroscopic binary. The star HD 168206, on Wilson's list of Wolf-Rayet stars with absorption lines, has been found to be a spectroscopic binary from spectrograms taken on July 25, 1941, 6^h02^m U.T., and on June 16, 1944, 4^h56^m U.T. The relative displacement of carbon blend near $\lambda\ 4635$ on the two spectrograms is about 250 km/sec.

* Contributions from the McDonald Observatory, University of Texas, No. 108.

¹ *Pub. A.S.P.*, **53**, 295, 1941.

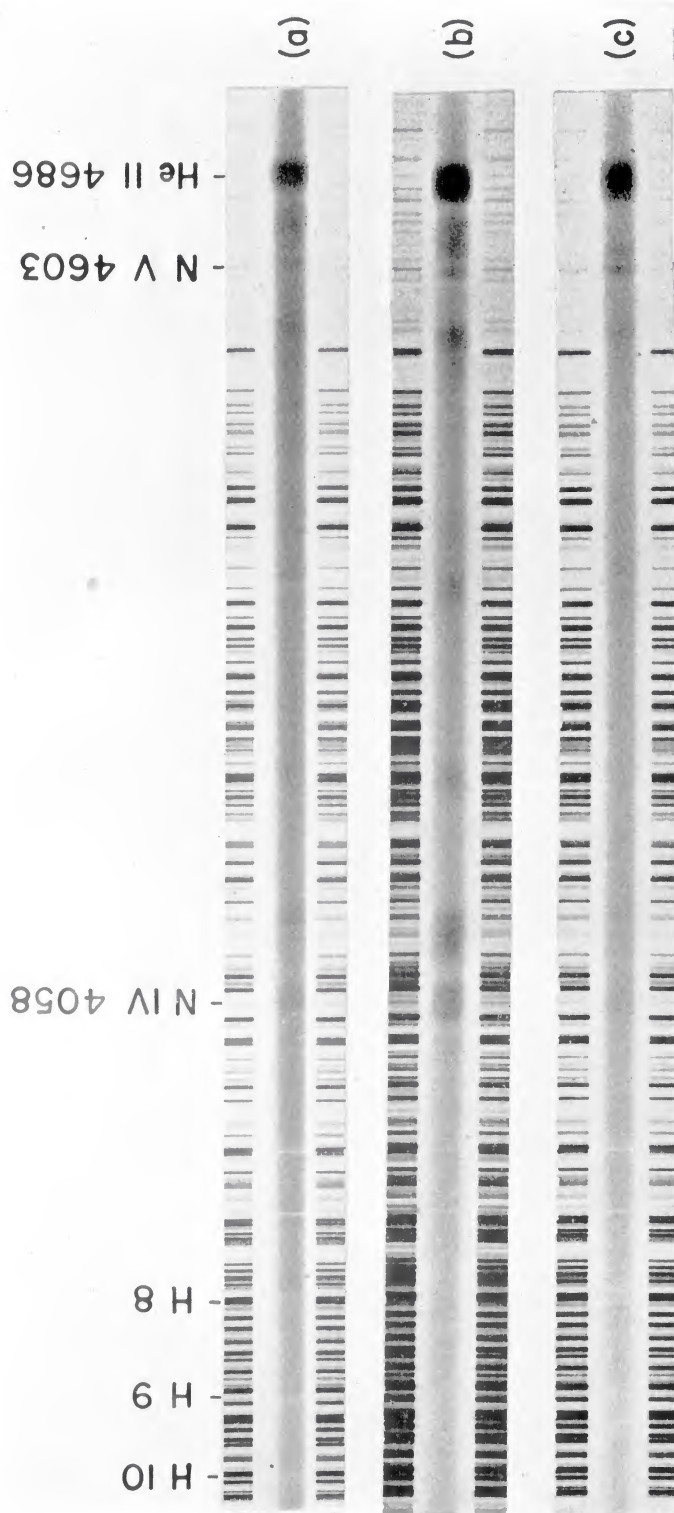
² Wilson, *Pub. A.S.P.*, **51**, 55, 1939.

³ *Ibid.*, **52**, 404, 1940.

⁴ HD 214419, Dean B. McLaughlin and W. A. Hiltner, *Pub. A.S.P.*, **53**, 328, 1941, and HD 152270, O. Struve, *Ap. J.*, **100**, 199, 1944.

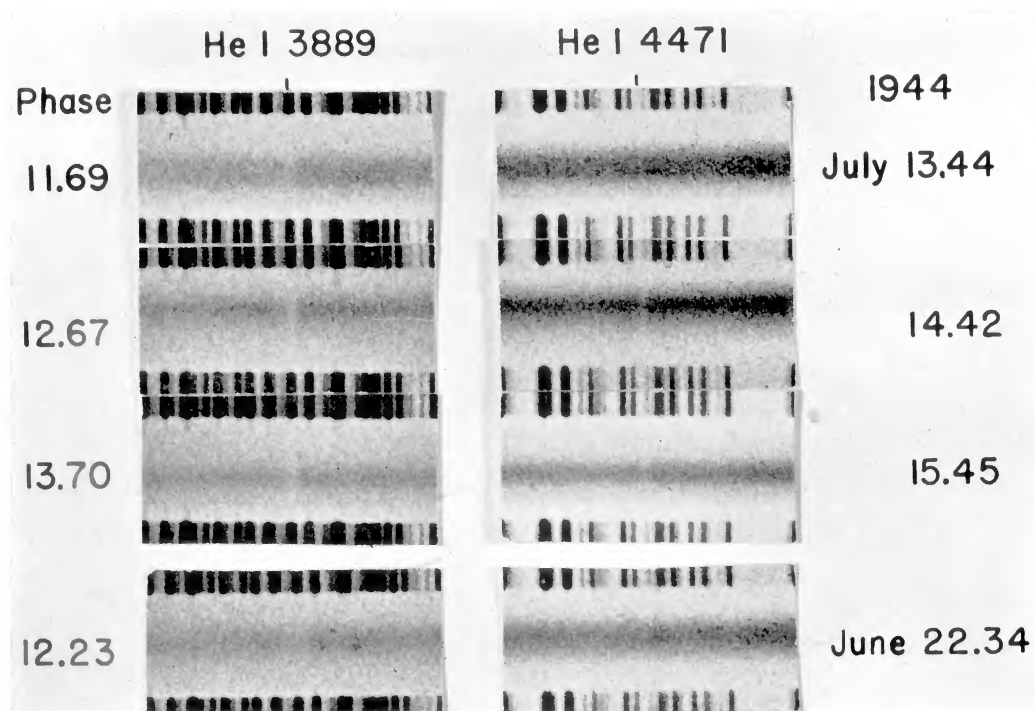
⁵ *Pub. A.S.P.*, **52**, 405, 1940.

PLATE XXXIII



SPECTRA OF WOLF-RAYET SPECTROSCOPIC BINARIES
(a) HD 211853, (b) HD 193928, (c) HD 186943

PLATE XXXIV



THE SPECTRUM OF HD 193928

Note that on July 13.44, *He* I 3889 is normal and that *He* I 4471 is present as a weak sharp line. On July 14.42, *He* I 3889 and *He* I 4471 are abnormally strong and sharp. On July 15.45, *He* I 3889 has not changed in intensity from the previous day, but *He* I 4471 is appreciably weaker. This phenomenon is apparently not periodic, as is shown by the spectrogram taken on June 22.34 at phase 12.23.

No detailed spectroscopic investigation of these three stars had been undertaken, and the binary nature of only the last one had been confirmed.⁶ Consequently, the three stars were placed on the observing program of the 82-inch reflector of the McDonald Observatory in the summer of 1944. The Cassegrain spectrograph with two quartz prisms and 500-mm camera was used. The dispersion is 42 Å/mm at λ 4000 and 70 Å/mm at λ 4700. Eastman 103a-0 emulsion was employed throughout.

HD 186943⁷

The spectrum of this star is WN5. The predominating feature in the photographic region of the spectrum is *He* II 4686. Its width is approximately 56 Å. The only other measurable emission features are *N* v 4603 and *N* v 4618. These bands are relatively narrow—only 17 Å in width. There are weak diffuse emission features of *N* IV 4058 and *He* II of the Pickering series, but all are too indefinite to measure for radial velocity. The absorption features of the spectrum are extremely weak, characterized primarily by hydrogen. The line *He* I 4471 is observed only infrequently. Wilson suspected absorption features in this star and attributed them to the companion star.

The line *He* II 4686 was measured for radial velocity on 32 spectrograms. Settings were made only on the center of the band, and no attempt was made to measure the position of the edges in order to obtain an improved value of the displacement of this band. There is some indication that the band undergoes periodic variations in shape, but the evidence is not conclusive. This point merits careful photometric observations.

The period of 9.550 days was determined with the help of Wilson's published relative velocities. Spectrograms taken 0.2 day apart do not suggest a period of about 1 day.

Radial velocities as determined by *He* II 4686 are recorded in Table 1 and are plotted in Figure 1. The wave lengths employed in computing radial velocities for this star and the subsequent stars studied in this paper are recorded in Table 2. Phases were computed in days with the formula

$$\text{Phase zero} = \text{JD } 2431262.20 + 9.550 E.$$

The measurements are well distributed in phase, and a solution with the eccentricity near zero is suggested. The following elements were obtained graphically, assuming that the eccentricity is zero:

$$\begin{array}{ll} P = 9.550 \text{ days} & K = 235 \text{ km/sec} \\ e = 0.0 \text{ (assumed)} & \gamma = +115 \text{ km/sec} \end{array}$$

The only other emission features measured in HD 186943 are *N* v 4603 and *N* v 4619. When plotted separately, they give very similar velocity-curves except for a difference in the gamma-velocity. The means for the two lines are recorded in Table 1 and are plotted in Figure 2. For 31 spectrograms we find that

$$Nv\ 4603 - Nv\ 4619 = -150 \text{ km/sec.}$$

The velocity-curve for the Wolf-Rayet component of HD 186943 as determined by *N* v again suggests an eccentricity near zero but an amplitude smaller than that obtained for *He* II 4686. The difference is large (160 and 235 km/sec) and is certainly real. Another striking difference is brought out when the velocity-curves of *He* II and *N* v are shown together (see Fig. 2). A phase difference of about 0.8 day is strongly suggested. A phase difference of *N* IV and *He* II of the Pickering series was suggested by the radial-velocity measurements of HD 214419⁸ but was not so striking as in HD 186943.

⁶ McLaughlin and Hiltner, *op. cit.*, p. 330.

⁷ $\alpha = 19^{\text{h}}42^{\text{m}}2^{\text{s}}$; $\delta = +28^{\circ}01'$ (1900); sp., Oa; mag., ptm., 9.98.

⁸ W. A. Hiltner, *Ap. J.*, 99, 278, 1944.

Hydrogen absorption lines were measured on 28 spectrograms. At best, the lines were difficult to measure. A magnification of only seven times was employed during measurement. The lines $H\gamma$, $H\delta$, $H 8$, $H 9$, $H 10$, and $H 11$ were measured when possible, but the number of absorption lines measured per plate varied from one to six. The mean velocity for each plate is recorded in Table 2 and is plotted in Figure 3. The scatter of the measure-

TABLE 1
RADIAL VELOCITIES OF HD 186943

PLATE	DATE, U. T.	PHASE	VELOCITY (KM/SEC)		
			He II 4686	N v	H_{abs}
CQ 3263.....	1944 June 15.314	3.764	+180	+228	- 44
3272.....	16.260	4.710	+ 32	+229	.....
3295.....	18.285	6.735	-152	+ 9	+ 1
3304.....	19.241	7.691	- 49	- 4	.....
3315.....	20.256	8.706	- 18	- 69	+ 2
3327.....	21.241	0.141	+152	- 26	+133
3328.....	21.297	0.197	+ 76	+ 43	+ 13
3339.....	22.218	1.118	+273	+121	.....
3340.....	22.272	1.172	+304	+168	- 22
3349.....	27.246	6.146	- 69	+ 55	- 49
3350.....	27.303	6.203	- 78	+ 37	+ 37
3363.....	July 1.290	0.640	+221	+ 90	+ 19
3378.....	2.313	1.663	+355	+ 85	- 75
3399.....	4.327	3.677	+296	+230	-144
3412.....	5.371	4.721	+ 90	+217	+ 64
3421.....	6.311	5.661	- 14	+ 82	+ 36
3430.....	7.220	6.570	-122	+ 75	+ 70
3443.....	8.366	7.716	- 55	.....	+ 74
3446.....	11.244	1.044	+280	+111	- 11
3455.....	12.226	2.026	+307	+217	- 23
3457.....	12.350	2.150	+343	+217	- 6
3465.....	13.274	3.074	+356	+277	- 93
3466.....	13.329	3.129	+352	+246	- 32
3480.....	15.203	5.003	+118	+153	+ 19
3481.....	15.246	5.046	+ 42	+120	- 30
3490.....	16.184	5.984	- 26	+ 68	+ 4
3494.....	16.378	6.178	-191	+ 68	.....
3501.....	17.203	7.003	-151	- 38	+ 87
3503.....	17.357	7.157	-103	- 90	+ 90
3510.....	18.179	7.979	- 98	- 99	+123
3517.....	20.285	0.535	+174	+ 76	+ 7
4049.....	Dec. 7.117	6.667	-108	- 6	+ 18

ments is large. However, a variation in velocity in a phase opposite to the emission is strongly suggested. An approximate solution follows:

$$\begin{aligned}
 e &= 0.0 \text{ (assumed)} \\
 K &= 65 \text{ km/sec} \\
 \gamma &= 10 \text{ km/sec}
 \end{aligned}$$

Assuming that the absorption lines result from the companion star, which we classify only as an early B-type star, and accepting the He II 4686 velocity-curve as representative of the Wolf-Rayet star, the following minimum masses are derived:

$$\begin{aligned}
 M_W \sin^3 i &= 5.8 \odot \\
 M_B \sin^3 i &= 21.0 \odot .
 \end{aligned}$$

HD 193928⁹

The spectrum of this star has a type between WN5 and WN6. Its emission features, especially *He* II 4686, are stronger than in any of the five known Wolf-Rayet spectroscopic binaries of the nitrogen sequence. In the photographic region, in addition to *He* II 4686, there are emission bands of *He* II of the Pickering series, *N* III, *N* IV, and *N* V. Hy-

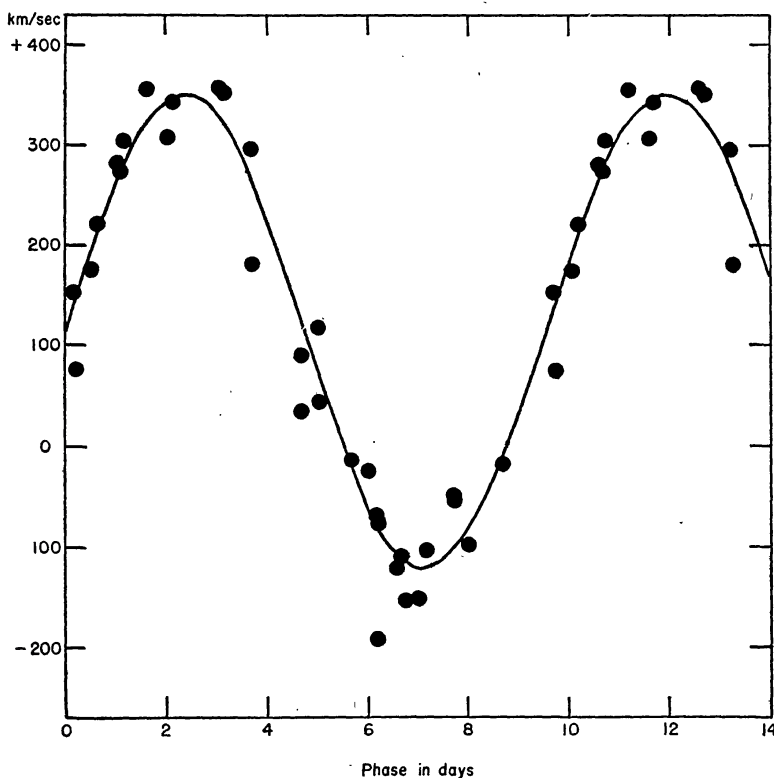


FIG. 1.—The velocity-curve of HD 186943 from *He* II 4686

TABLE 2
STELLAR WAVE LENGTHS FOR THE DETERMINATION
OF RADIAL VELOCITIES

Line	Wave Length	Line	Wave Length
<i>H</i> 11.....	3770.63	<i>H</i> δ	4101.74
<i>H</i> 10.....	3797.90	<i>H</i> γ	4340.48
<i>H</i> 9.....	3835.39	<i>He</i> I.....	4471.48
<i>He</i> I.....	3888.65	<i>N</i> V.....	4603.2
<i>H</i> 8.....	3889.05	<i>N</i> V.....	4619.4
<i>N</i> IV.....	4057.80	<i>He</i> II.....	4685.81

drogen emission must be weak. Only one absorption feature is normally present: a diffuse line at approximately λ 3873. Details of the absorption in this star will be given in a later paragraph.

In addition to the strong band *He* II 4686, *N* V 4603 and *N* IV 4058 were measured for radial velocity. Other emission bands were not measured, since they are fainter and are

⁹ $\alpha = 20^{\text{h}}17^{\text{m}}8$; $\delta = +36^{\circ}36'$ (1900); sp., Oa; mag. ptm., 9.43.

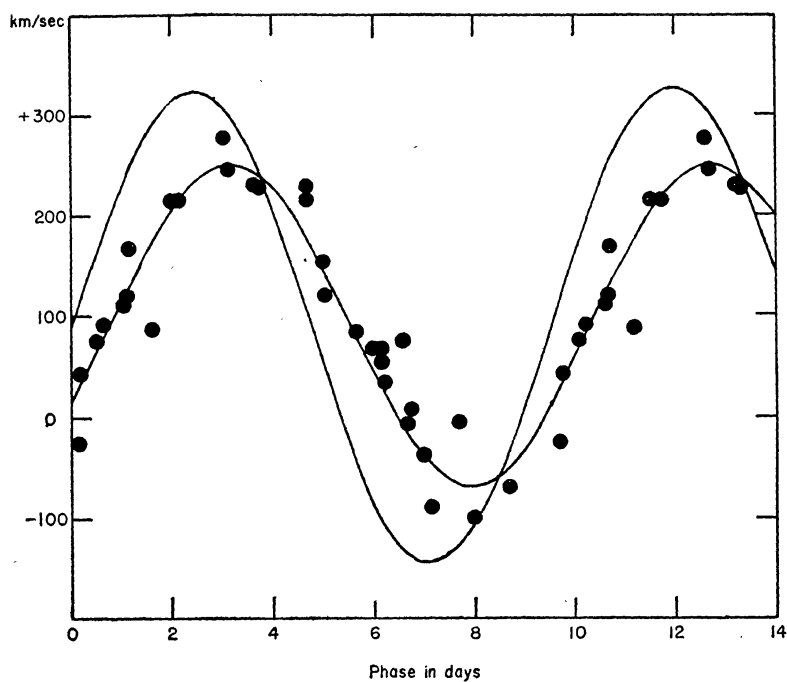


FIG. 2.—The velocity-curve of HD 186943 from $N\text{ v } 4603$ and $N\text{ v } 4619$. The curve for $\text{He II } 4686$ is drawn in to show the differences in amplitude and phase.

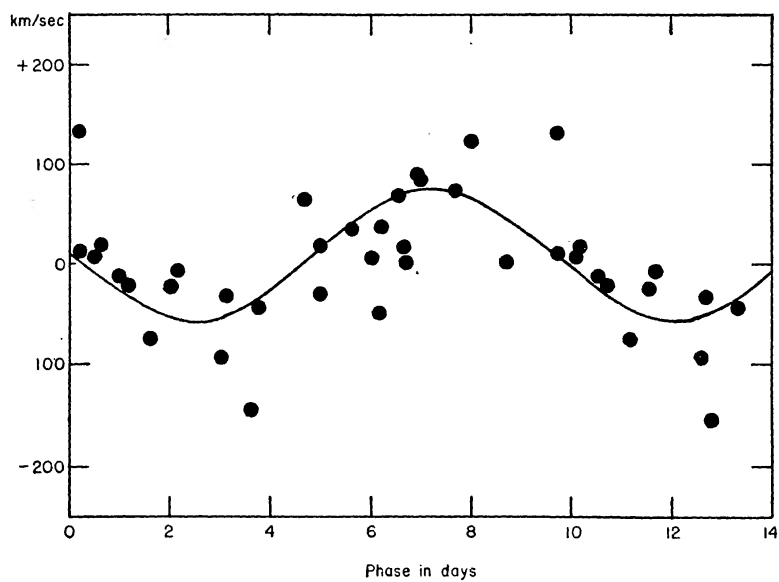


FIG. 3.—The velocity-curve of HD 186943 from hydrogen absorption

relatively difficult to measure on narrow spectrograms. Widened spectrograms were difficult to obtain, for the magnitude is 10.5 and the period was thought to be about 1 day after the first few spectrograms were obtained. The line $N\text{ IV } 4058$ appears to vary appreciably in structure. Very frequently the band possessed a narrow band superimposed on the wide band and appeared near either the violet or the red side of the broad band, or both. The narrow band seems to appear more frequently on the violet edge, but the evidence is not conclusive. The velocity-curve for this band is distorted, and this distortion

TABLE 3
RADIAL VELOCITIES OF EMISSION FEATURES IN HD 193928

PLATE	DATE, U.T.	PHASE	VELOCITY (KM/SEC)		
			$He\text{ II } 4686$	$N\text{ V } 4603$	$N\text{ IV } 4058$
CQ 3199.....	1944 May 9.456	10.626	+ 5	- 60	- 54
3264.....	June 15.369	5.259	+169	- 54	.....
3273.....	16.325	6.215	+200	+ 49	- 27
3296.....	18.367	8.257	+119	+ 44	+ 44
3329.....	21.350	11.240	+ 40	-152	-189
3341.....	22.342	12.232	+ 55	-206	-134
3351.....	27.361	17.251	- 25	-294	-187
3379.....	July 2.377	0.627	+125	-140	- 57
3422.....	6.369	4.619	+242	- 76	+ 11
3434.....	7.340	5.590	+185	+ 14	- 51
3456.....	12.285	10.535	+ 51	-124	- 46
3467.....	13.388	11.638	+ 10	-164	-171
3468.....	13.444	11.694	+ 6	-164	-220
3471.....	14.370	12.620	- 9	-103	-197
3472.....	14.423	12.673	- 16	-186	-184
3482.....	15.296	13.546	- 75	-181	-115
3483.....	15.348	13.598	- 16	-207	-132
3484.....	15.401	13.651	- 99	-155	-165
3485.....	15.452	13.702	- 60	-194	-145
3491.....	16.231	14.481	- 38	-194	-221
3492.....	16.280	14.531	- 10	-263	-237
3493.....	16.332	14.582	- 73	-237	-221
3502.....	17.256	15.506	- 80	-255	-221
3504.....	17.411	15.661	- 48	-251	-182
3505.....	17.458	15.708	- 54	-268	-201
3511.....	18.234	16.484	- 67	-256	-175
3512.....	18.292	16.542	- 69	-220	-162
3518.....	20.339	18.639	- 72	-256	-179
3521.....	20.434	18.684	- 45	-204	-179
4048.....	Dec. 7.072	6.842	+179	- 42	- 68

is probably related to the variation in structure of the band. The behavior of $N\text{ IV } 4058$, as well as of the other bands, certainly deserves careful analysis in the future. A spectrophotometric analysis can be more profitably undertaken now than when the spectrograms for this investigation were taken, since the period and, consequently, the phases are now known. Photometric spectrograms would require an exposure of, say, 3 hours, in contrast to the present exposure time of $1\frac{1}{4}$ hours.

The radial-velocity measurements of the emission features are recorded in Table 3. The lines $He\text{ II } 4686$ and $N\text{ V } 4603$ gave almost identical velocity-curves except for a difference of gamma-velocity of

$$He\text{ II } 4686 - N\text{ V } 4603 = +178 \text{ km/sec.}$$

The mean velocities of these two lines are plotted in Figure 4. A period of 21.64 days was derived with the help of three relative radial velocities published by Wilson. A period of about 1 day has been eliminated by spectrograms obtained in one evening over a period of 0.2 day. The observations are not well distributed in phase, and consequently the elements are not well defined. However, the following elements are indicated:

$$\begin{array}{ll} P = 21.64 \text{ days} & \gamma(\lambda 4686) = +59 \text{ km/sec} \\ e = 0.0 \text{ (assumed)} & \gamma(\lambda 4603) = -119 \text{ km/sec} \\ K = 130 \text{ km/sec} & f(m) = 4.94 \odot \end{array}$$

This large mass function is similar to that derived for HD 214419, which in this case is $f(m) = 4.38$.

The strongest absorption feature in HD 193928 is a diffuse line with an approximate wave length of 3873 Å. This line was measured on 24 spectrograms (all that were suffi-

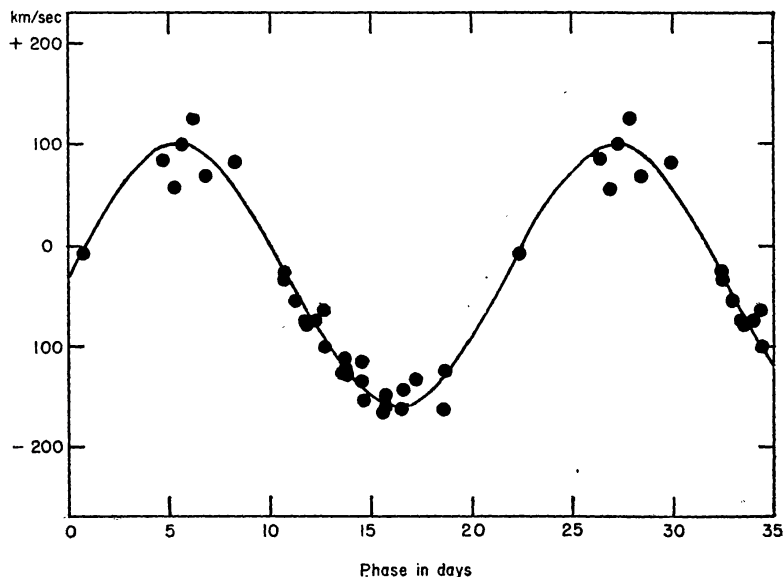


FIG. 4.—The velocity-curve of HD 193928 from $He\ II\ 4686$ and $N\ V\ 4603$

ciently well exposed in this region), and the measured wave lengths are recorded in Table 4. The measurements, when plotted (see Fig. 5), indicate that this line possesses a displacement similar to that obtained for the emission features of the spectrum. Infrequently a second line was measured at a wave length near $\lambda 4453$. The measurements are also recorded in Table 4. The behavior of this line with phase is uncertain because of scatter in the measurements. On July 13, phase 11.7 days, this line appeared unusually sharp but still faint (see Pl. XXXIV), but $\lambda 3873$ appeared normal on this date. On July 14 (phase 12.6 days) both lines were abnormally strong and sharp. On the following day, $\lambda 4453$ had weakened appreciably, but $\lambda 3873$ remained nearly as strong as during the previous night. On July 16, $\lambda 4453$ was no longer visible with certainty, and $\lambda 3873$ was only slightly stronger than normal. The behavior of these lines does not appear to be related with phase, since on June 22, phase 12.2 days, the line $\lambda 4453$ was very weak and diffuse and $\lambda 3873$ had a normal intensity. If $\lambda 4453$ is identified as $He\ I\ 4471$ and $\lambda 3873$ as $He\ 3889$, we find that the resulting radial velocities are almost identical for

$$V(3889) - V\ 4471 = 6 \text{ km/sec.}$$

Furthermore, it is observed that for the two spectrograms obtained on July 14, when the two lines were sharp and consequently could be measured with greater precision, the

TABLE 4
RADIAL VELOCITIES OF *He* I ABSORPTION IN HD 193928

Date, U.T.	Phase	λ	Velocity <i>He</i> I 3889 (Km/Sec)	λ	Velocity <i>He</i> I 4471 (Km/Sec)
1944 May 9.456.....	10.626	3873.12	-1298	4453.52	-1204
June 21.350.....	11.240	3872.58	1240	4452.93	1245
22.342.....	12.232	3872.92	1214	4451.78	1322
27.361.....	17.251	3871.74	1305	.....	.....
July 6.369.....	4.619	3875.70	999	.....	.....
7.340.....	5.590	3874.22	1113	4454.67	1128
12.285.....	10.535	3873.59	1162	4452.62	1265
13.388.....	11.638	3873.51	1168	4451.47	1342
13.444.....	11.694	3872.71	1230	4453.51	1206
14.370.....	12.620	3873.16	1195	4453.69	1194
14.423.....	12.673	3873.16	1195	4453.69	1194
15.348.....	13.598	.....	.....	4454.94	1110
15.401.....	13.651	3873.00	1207	4453.02	1238
15.452.....	13.702	3873.13	1197	4453.79	1187
16.231.....	14.481	3872.33	1259	.....	.....
16.280.....	14.531	3872.85	1219	.....	.....
16.332.....	14.582	3872.29	1262	.....	.....
17.256.....	15.506	3871.80	1300	.....	.....
17.411.....	15.661	3871.83	1298	.....	.....
17.458.....	15.708	3872.61	1237	.....	.....
18.234.....	16.484	3872.64	1235	4453.02	1238
18.292.....	16.542	3871.91	1291	.....	.....
20.339.....	18.639	3871.82	1298	.....	.....
20.434.....	18.684	3871.62	1314	4452.58	-1268
Dec. 7.072.....	6.842	3873.96	-1132	.....	.....

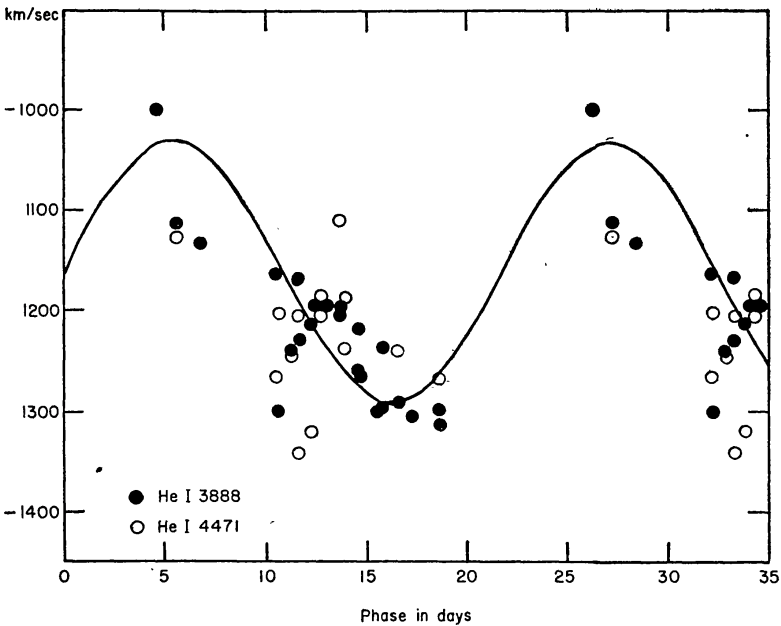


FIG. 5.—The radial velocity observations of *He* I 3888 and *He* I 4471

radial velocities agree within 1 km/sec. If the above identifications are correct, then we should expect to observe *He* I 4026. The behavior of this line is uncertain. On a widened spectrogram taken on July 14, when *He* I 4471 was at maximum intensity, there is certainly a line present at λ 4010; but a narrow spectrogram obtained the same evening gives no indication of a line at this wave length, although it shows λ 3873 and λ 4453 quite strongly. However, in spite of this peculiar behavior of *He* I 4026, it appears logical to conclude that we are observing *He* I absorption lines resulting from light from the central core of the Wolf-Rayet star passing through that part of the shell which is ejected toward the observer. This conclusion is supported by the total widths of the measurable bands. The total width of *He* II 4686 is 2400 km/sec. The average velocity of the *He* I absorption lines is 1200 km/sec. The variation in intensity must be interpreted in terms of abundance, and any variation in dilution that may have occurred while the lines were unusually strong can be interpreted by a variation in distance of the material from the central core of the Wolf-Rayet star.

The variation in intensity and the radial velocity measures of λ 3889 and λ 4471 may provide some information on the velocity variation of the ejected *He* I atoms with distance from the central core of the Wolf-Rayet star. On July 14 both *He* I 3889 and *He* I 4471 were strong. Their velocities were, respectively, 1195 and 1194 km/sec. The next night, July 15, four spectrograms were obtained, but only two were well exposed. Line *He* I 3889 was of approximately the same intensity as on the previous night; but *He* I 4471 was much weaker, indicating a change in dilution during the interval of twenty-four hours. The radial velocities of λ 3889 and λ 4471 are -1202 and -1178 km/sec. The velocity given by λ 3889 should be given greater weight. It is evident that in an interval of twenty-four hours, during which time a marked change in dilution occurred, the velocity of the ejected gas remained constant within the errors of the measurements. In this connection we should call attention to a similar phenomenon in HD 214419.⁸ This star normally shows the Wolf-Rayet component of *He* I 4471, 4026, and 3889. However, a second component of these lines was observed on November 13, 1943, with a displacement of -800 km/sec. On the following night, November 14, only the displaced component of λ 3889 was present, still with a displacement of -800 km/sec. Here, again, a large change in dilution was observed, but the velocity of the *He* I atoms remained constant as the material receded from the core of the Wolf-Rayet star.

HD 211853¹⁰

The emission features in the spectrum of this star are relatively weak. The line *He* II 4686 predominates in intensity in the photographic region. Its width is 2500 km/sec, and it shows variation in structure with phase. The most pronounced asymmetry occurs at phase 3.3 (the Wolf-Rayet star on the far side of the system), when the band is shaded toward the red. There is some suggestion that *N* IV 4058 undergoes periodic variation in structure, but the band is too weak to make the observations conclusive. The other principal emission features are *He* II of the Pickering series, *N* III, *N* V 4603, and possibly *He* I, especially λ 4471. Plate XXXIII shows the spectrum of this star in the photographic region. Its spectral type is near WN6. The lines *He* II 4686, *N* IV 4058, and *N* V 4603 have been measured for radial velocity.

Absorption features in this star are quite evident, as is shown on Plate 000. The lines *H* γ , *H* δ , *H* 8, *H* 9, and *H* 10 are always present on well-exposed spectrograms. They are usually diffuse, indicating a rotational velocity of the order of 230 km/sec.

The measurements of the radial velocities of the emission bands give very similar velocity-curves except for differences in the gamma-velocity and have been combined to give the following elements:

¹⁰ $\alpha = 22^{\text{h}}15^{\text{m}}0$; $\delta = -55^{\circ}36'$ (1900); sp., Ob; mag. ptm., 9.0.

SPECTROSCOPIC BINARIES

365

$$\begin{aligned}
 P &= 6.6864 \text{ days} & \gamma(4686) &= +50 \text{ km/sec} \\
 e &= 0.0 \text{ (assumed)} & \gamma(4603) &= +62 \text{ km/sec} \\
 K &= 245 \text{ km/sec} & \gamma(4058) &= -125 \text{ km/sec}
 \end{aligned}$$

The period was improved by referring to Wilson's published relative velocities. A period of about 1 day has been eliminated by obtaining as many as 5 spectrograms in the same evening over an interval of 0.14 day or less. The measured radial velocities are collected in Table 5, and the mean velocities for the emission features are plotted in Figure 6.

TABLE 5
RADIAL VELOCITIES OF HD 211853

PLATE	DATE, U.T.	PHASE (DAYS)	VELOCITY (KM/SEC)		
			Emission	H_{abs}	He I 4471
CQ 3175.....	1944 May 7.465	1.483	+312	-185	.....
3265.....	June 15.428	0.326	+ 76	-162	.....
3275.....	16.424	1.322	+246	- 50	.....
3284.....	17.433	2.331	+185	- 87	- 49
3297.....	18.437	3.335	+ 6	-140	-158
3305.....	19.321	4.219	-176	- 89	- 36
3306.....	19.383	4.281	-152	- 20	.....
3307.....	19.441	4.339	-166	- 56	- 81
3316.....	20.325	5.223	-208	+ 14	.....
3317.....	20.380	5.278	-213	+ 28	.....
3318.....	20.433	5.331	-202	+ 16	+ 57
3330.....	21.397	6.295	+ 13	- 42	- 61
3331.....	21.433	6.331	- 8	-107	- 61
3342.....	22.410	0.622	+187	-117	-182
3343.....	22.448	0.660	+188	-123	.....
3352.....	27.412	5.624	-179	+ 35	+ 78
3353.....	27.450	5.662	-137	+ 35	+ 24
3354.....	28.448	6.660	+ 25	-114	-121
3356.....	30.334	1.860	+296	-106	.....
3357.....	30.389	1.915	+275	- 36	.....
3358.....	30.435	1.961	+305	- 90	.....
3364.....	July 1.358	2.884	+ 92	- 32	- 44
3365.....	1.399	2.925	+130	- 66	.....
3366.....	1.435	2.961	+121	- 26	- 76
3380.....	2.433	3.959	- 28	- 54	-117
3381.....	2.462	3.988	- 56	- 98	.....
3386.....	3.322	4.848	-212	- 62	- 19
3387.....	3.358	4.884	-134	- 27	- 84
3388.....	3.392	4.918	-175	- 26	.....
3389.....	3.427	4.953	-148	- 24	+ 17
3390.....	3.458	4.984	-198	- 20	-100
3401.....	4.408	5.934	-115	+ 14	+ 50
3402.....	4.437	5.963	- 68	+ 12	+ 5
3413.....	5.428	0.268	+135	- 84	.....
3414.....	5.461	0.301	+ 85	-150	-142
3423.....	6.414	1.254	+295	-133	-117
3445.....	8.451	3.291	+ 59	- 67	.....
3451.....	11.381	6.221	- 63	+ 50	+ 5
3458.....	12.407	0.561	+212	-126	-146
3459.....	12.444	0.598	+198	-116	-190
3513.....	19.474	0.942	+292	-133	-207
4050.....	Dec. 7.157	1.219	+256	- 40	.....

Hydrogen absorption, consisting usually of $H\gamma$, $H8$, $H9$, $H10$, and $H11$, was measured on all spectrograms. The mean radial velocity for each spectrogram is recorded in Table 6 and plotted in Figure 7. The form of the velocity-curve is not well defined because of

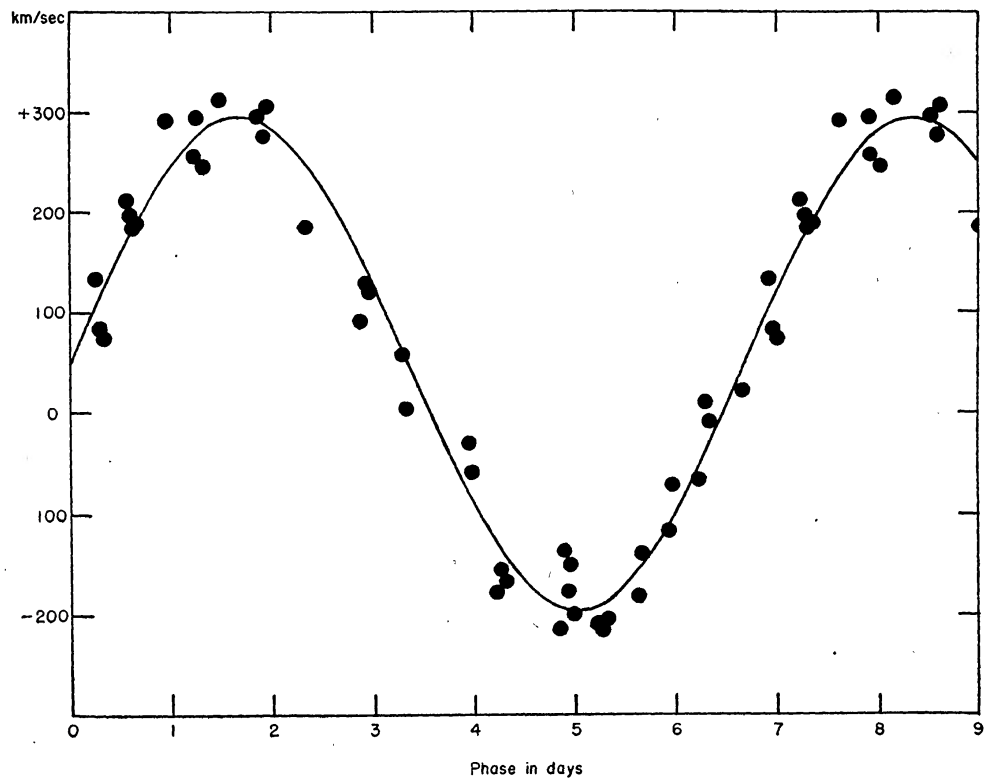


FIG. 6.—The velocity-curve of HD 211853 from $He\ II\ 4686$, $N\ V\ 4603$, and $N\ IV\ 4058$

TABLE 6
RADIAL VELOCITIES OF $He\ I\ 3889$ ABSORPTION IN HD 211853

Plate	Phase	λ	Velocity (Km/Sec)	Plate	Phase	λ	Velocity (Km/Sec)
CQ 3445.....	3.291	3873.5	−1160	CQ 3318.....	5.331	3872.9	−1210
3386.....	4.848	3872.3	1260	3352.....	5.624	3871.6	1310
3387.....	4.884	3872.9	1210	3353.....	5.662	3871.7	1300
3389.....	4.953	3872.3	1260	3451.....	6.221	3871.6	1310
3390.....	4.984	3871.8	1300	3330.....	6.295	3871.3	1330
3316.....	5.223	3872.5	1240	3331.....	6.331	3871.5	1320
3317.....	5.278	3872.7	−1230	3354.....	6.660	3870.7	−1380

the large scatter. However, the hydrogen-absorption velocity appears approximately constant at -65 km/sec from phase 1.6 days to 4.9 days, at which time there is a marked increase in velocity, reaching a maximum of $+40\text{ km/sec}$ at phase 5.6 days. The velocity then decreases rapidly to -150 km/sec at phase 0.8 day. Although $He\ I\ 4471$ was measured less frequently than the hydrogen lines, it verifies the general form of the velocity-curve, especially the rapid decrease in velocity.

The interpretation of the absorption velocity-curve is not clear, and it certainly deserves further careful examination. From phase 1.6 days to phase 4.9 days, when the velocity of the absorption lines remains approximately constant, the B-type component of the system is between the observer and the Wolf-Rayet component. From phases 4.9 to 1.6 days, when the velocity of the absorption lines is changing rapidly, the B-type component is on the far side of the system. This suggests that the observed variation in velocity may be related to a rotation effect of the B-type component. This suggestion does not appear adequate, primarily because it is necessary to assume that the two stars are nearly in contact and that the resulting mass of the B-type component would become unreasonably large. If one wishes to interpret this velocity-curve as resulting from the second component, one is faced with an eccentricity of about 0.4, in contrast to an eccentricity near zero obtained for the emission lines. This discrepancy may possibly find

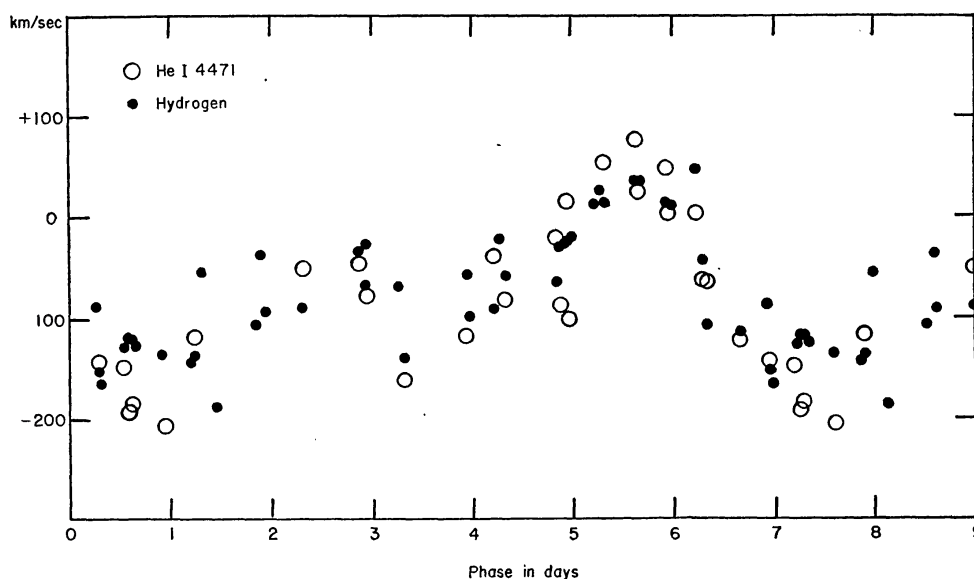


FIG. 7.—The radial velocity variations of hydrogen and *He* I 4471 absorption

its explanation in streams of gas which are known to distort velocity-curves of certain eclipsing variable stars. Pending further investigations of the form of the velocity-curve, we shall assume that we have a measure of the variation in velocity of the companion star, which we will classify only as early B, with $K = 95$ km/sec. This permits us to compute the following minimum masses:

$$M_{WR} \sin^3 i = 7.6 \odot,$$

$$M_B \sin^3 i = 19.6 \odot.$$

In HD 193928 an absorption line near $\lambda 3873$ was observed, and evidence was presented indicating that this line should be identified with *He* I 3889. In HD 211853 a similar line was measured whenever detected on the spectrograms. The results of the measurements are listed in Table 6. It is to be observed that the line was usually measured between phases 4.8 and 6.6 days (on 13 of 16 spectrograms), but only once between phase 0.0 and 4.8 days and then at phase 3.3 days. This indicates that the line may be variable with phase and is probably related to the general variations in the spectrum of the Wolf-Rayet star with phase. The average velocity of this line when identified as *He* I 3889 is -1260 km/sec.

DISCUSSION

In all the four Wolf-Rayet spectroscopic binaries thus far investigated by the author, the so-called "center of mass," or gamma-velocity, has shown considerable divergence, from one emission line to another. The data thus far available on this question are collected in Table 7. Wilson measured three emission bands (*He* II 4686, *N* V 4600, and *N* V 4619) in HD 193576 and, upon accepting Edlén's computed wave lengths for the two *N* V lines, as we have done in the present investigation, observed that

$$V(4603) = \overline{V(4603)} - \overline{V(4686)} = +8 \text{ km/sec}$$

$$V(4619) = \overline{V(4619)} - \overline{V(4686)} = -19 \text{ km/sec}.$$

TABLE 7
OBSERVED γ -VELOCITIES

Star	Line	γ (Km/Sec)	Remarks
HD 186943.....	<i>He</i> II 4686 emission	+115	No violet absorption
	<i>N</i> V 4603 emission	+ 15	No violet absorption
	<i>N</i> V 4619 emission	+165	No violet absorption
	<i>H</i> _{abs}	+ 10	
HD 193928.....	<i>He</i> II 4686 emission	+ 59	Violet absorption?
	<i>N</i> V 4603 emission	-119	Weak violet absorption
	<i>N</i> IV 4058 emission	-100	No violet absorption
HD 211853.....	<i>He</i> II 4686 emission	+ 50	No violet absorption
	<i>N</i> V 4603 emission	+ 62	No violet absorption
	<i>N</i> IV 4058 emission	-125	No violet absorption
	<i>H</i> _{abs}	- 55	
HD 214419.....	<i>He</i> II 4686 emission	+137	No violet absorption
	<i>N</i> IV 4058 emission	- 75	No violet absorption
	<i>He</i> II emission Pickering	+180	Violet absorption

He also observed that the gamma-velocity for the Wolf-Rayet star was more positive by 90 km/sec than the gamma-velocity of the absorption-line component. The conclusion was made that the emission bands were shifted to the red by 90 km/sec. Struve¹¹ concluded that in HD 151932, which is located in the cluster NGC 6231, *N* IV 4058 gave the velocity of the cluster and that *He* II 4686 possesses a red shift of 85 km/sec. The spectrum of this star is remarkably similar to HD 214419. The emission bands are of similar width, and each star shows violet absorption edges of certain bands which are variable in intensity. In HD 214419, *He* II 4686 is displaced to the red by 212 km/sec with respect to *N* IV 4058. In this connection attention should be drawn to HD 211853, in which *He* II 4686 is again displaced to the red with respect to *N* IV 4058; but neither band gives a velocity comparable to the absorption lines which probably belong to the B-type component.

The existence of different gamma-velocities for various emission bands is certainly real and cannot be explained in terms of inaccurate laboratory wave lengths. It is difficult to draw any general conclusions concerning the behavior of the various bands, other than that, thus far, *He* II 4686 is always displaced to the red with respect to *N* IV 4058.

¹¹ *Op. cit.*, p. 192.

Violet absorption edges do not, in general, appear adequate to explain all the displacements of emission bands with respect to each other. For example, in HD 186943, *He* II 4686, *N* V 4603, and *N* V 4619 do not show any visible violet absorption, although the observed gamma-velocities differ by as much as 150 km/sec. This phenomenon of discrepant gamma-velocities is probably associated with the observed variations in profiles of certain emission bands, for which a nonsymmetrical shell about the Wolf-Rayet type component offers, at present, the most plausible explanation.

In Figure 2 it is clearly shown that the velocity-curve as determined by the emission bands of *N* V differs, not only in amplitude, but also in phase from that of *He* II 4686 by approximately 0.8 day. These differences are certainly real, and an explanation must be sought. To explain the differences in phase, the "transit-time-effect," as developed by Wilson,¹² immediately suggests itself; but the assumption that the shell of the Wolf-

TABLE 8
MASSES OF WR STARS

Star	Type	WR Star	Absorption Star	Ratio
HD 152270.....	WC6+	$M \sin^3 i = 1.9 \odot$	$M \sin^3 i = 6.9 \odot$	0.28
HD 186943.....	WN5	$M \sin^3 i = 5.8 \odot$	$M \sin^3 i = 21.0 \odot$	.28
HD 193576.....	WN5	$M = 12.4 \odot$	$M = 31.8 \odot$	.39
HD 211853.....	WN6+	$M \sin^3 i = 7.6 \odot$	$M \sin^3 i = 19.6 \odot$	0.39
HD 193928.....	WN6	$f(m) = 4.94 \odot$	.....	.....
HD 214419.....	WN6-	$f(m) = 4.38 \odot$	.....	.....

Rayet star is not appreciably influenced by the more massive B-type companion does not appear to be justified.

At the present time six Wolf-Rayet stars have been investigated as spectroscopic binaries. In four of the six stars, an absorption-line component is present; and in the other two, only the Wolf-Rayet component has been observed. This gives us some information concerning the masses of these peculiar objects. All the data known at present is summarized in Table 8.¹³ The ratio of the mass of a Wolf-Rayet star to that of an early-type absorption star appears to be fairly well defined, with a value of $\frac{1}{3}$. Less can be said with certainty concerning the mass of a Wolf-Rayet star, but the evidence suggests that the mass of a Wolf-Rayet star is of the order of ten times that of the sun. With the completion by the author of a photometric investigation of the three spectroscopic binaries discussed in this paper, more information should become available concerning the mass of a Wolf-Rayet star.

The author wishes to express his thanks to Dr. O. Struve and Dr. S. Chandrasekhar for many helpful discussions.

¹² *A. J.*, **95**, 409, 1942.

¹³ HD 152270, O. Struve, *A. J.*, **100**, 387, 1944; HD 193576, O. C. Wilson, *A. J.*, **95**, 406, 1942; and HD 214419, W. A. Hiltner, *A. J.*, **99**, 274, 1944.