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Three Wolf-Rayet binaries

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Abstract

Radial velocities and line profiles are studied of the three Wolf-Rayet binaries HD 193928 HD 186943 and HD 211853.

HD 193928: A new orbit has been determined from radial velocity measures of HeII 4686. The orbital elements are as follows: γ axis = + 60 km/sec, K = 147 km/sec, e = 0.12, ω = 51°, f(m) = 4.62 solar masses. The NIV 4058 velocities can be represented by the HeII 4686 velocity curve displaced in phase by 0.1P. A displacement of 185 km/sec in the gamma-axis suffices to fit the 4686 Å curve onto the NV 4603 velocities. Line profile variations with phase of the emission lines are described. This system is likely to have an orbital inclination that will enables the detection of eclipses.

HD 186943: A revised period of 9.5594 days is derived for this system. Orbital elements are derived using velocity curves HeII 4686, NV 4603 and NIV 4058. The orbital elements derived from HeII 4686 are as follows:

γ axis = + 107 km/sec, K = 212 km/sec, e = 0.04,
ω = 151°, γ (NIV 4058) = + 70 km/sec, γ (NV 4603) = + 30 km/sec.

HD 211853: Preliminary elements are derived from velocity curves of HeII 4686, NV 4603 and NIV 4058. These are as follows: γ (HeII 4686) = + 15 km/sec, γ (NV 4603) = + 35.0 km/sec, γ (NIV 4058) = —120 km/sec, e (HeII 4686) = 0.12, K (HeII 4686) = 220 km/sec, f(m) (HeII 4686) = 7.25.

The observation are discussed in terms of some of the current ideas on the nature of the Wolf-Rayet phenomenon.

HD 193928

This faint Wolf-Rayet star has a spectral type on the Beals classification between WN5 and WN6. It is categorized by Hiltner (1966) as WN6-B on his new classification scheme. The emission lines are broad and quite intense and hence are easier to measure than in any other Wolf-Rayet binary of the WN sequence. The only existing orbit of the star is that derived by Hiltner (1945) in which he has used radial velocity measures of HeII 4686 and NV 4603. Hiltner has pointed out that NIV 4058 experiences severe changes in line profile and on numerous occasions displaced absorptions of HeI 3888 and HeI 4471 can be seen.

Our determination of the orbit of the star rests on eighteen spectrograms obtained at Mount Wilson with the single prism spectrograph on the 60 inch reflector. The spectra have a dispersion of Å/mm in the region of 4300Å. We have measured the emission lines 4686Å, 4603Å and 4058Å for a study of the radial velocity changes. Because of the faintness of the star, the spectra could not be over-exposed to show up the absorption lines conspicuously. The spectra were primarily obtained for the purpose of spectrophotometry of the emission lines. In Table 1 we present our radial velocity measures for this star. Phases have been calculated with phase zero as JD 2434179.77 and Hiltner's value of the period of 21.64 days. The orbital elements derived from the 4686Å velocity curve using Sterne's method are,

TABLE 1

The velocity measures of HD 193928

Plate	J.D. of observation	Phase	Velocities in km/sec. 4058e	4603e	4696e
32598 . .	2434144.97	0.60	−138.5	+62.5	+221.4
32601a . .	145.95	0.56	−173.1	−53.5	+ 98.1
32601b . .	145.98	0.56	−186.2	−92.4	+132.2
32605 . .	146.90	0.51	−147.1	−98.7	+-91.3
32632 . .	170.92	0.40	−270.0	−195.3	− 4.6
32635 . .	171.88	0.36	−265.8	−288.0	− 97.0
32643 . .	173.95	0.26	−261.0	..	− 61.2
32655 . .	175.97	0.17	−265.5	−228.7	− 53.0
32660 . .	176.83	0.13	−205.7	−307.6	− 80.0
32668 . .	177.93	0.08	−132.5	−172.4	− 19.2
32684 . .	194.94	0.29	−265.7	−266.1	− 90.5
32688 . .	195.91	0.25	..	−276.0	− 47.0
32724 . .	200.98	0.00	− 80.0	− 264.1	+ 37.2
32728 . .	201.91	0.97	− 29.0	−222.5	+ 23.6
32732 . .	202.96	0.92	− 29.4	−119.4	+ 70.8
32747 . .	224.73	0.92	..	− 83.9	+ 27.2
32754 . .	225.85	0.87	− 39.7	− 67.5	+ 76.5
32762 . .	227.93	0.77	− 28.2	+61.6	+187.4

γ = +60 ± 8 km/sec

K = 147 ± 9 km/sec

e = 0.12 ± 0.05

ω = 51° ± 21°

f(m) = 4.62 solar masses.

The γ-axis of the 4686Å velocity curve has a value of 60 km/sec, in exact agreement with the value derived by Hiltner. However, the value of K differs by about 17 km/sec. No orbit analysis has been carried out with the velocity measures off 4058 Å. We show in Figure 1, the velocity curve of 4686 Å in the upper half of the diagram. In the lower half of the diagram the solid curve is the theoretical curve of 4686 Å, the filled circles are the observed velocities of 4058 Å, and the dashed curve is the 4686 Å curve displaced by 0.1P to have a good fit with the 4058 Å velocities.

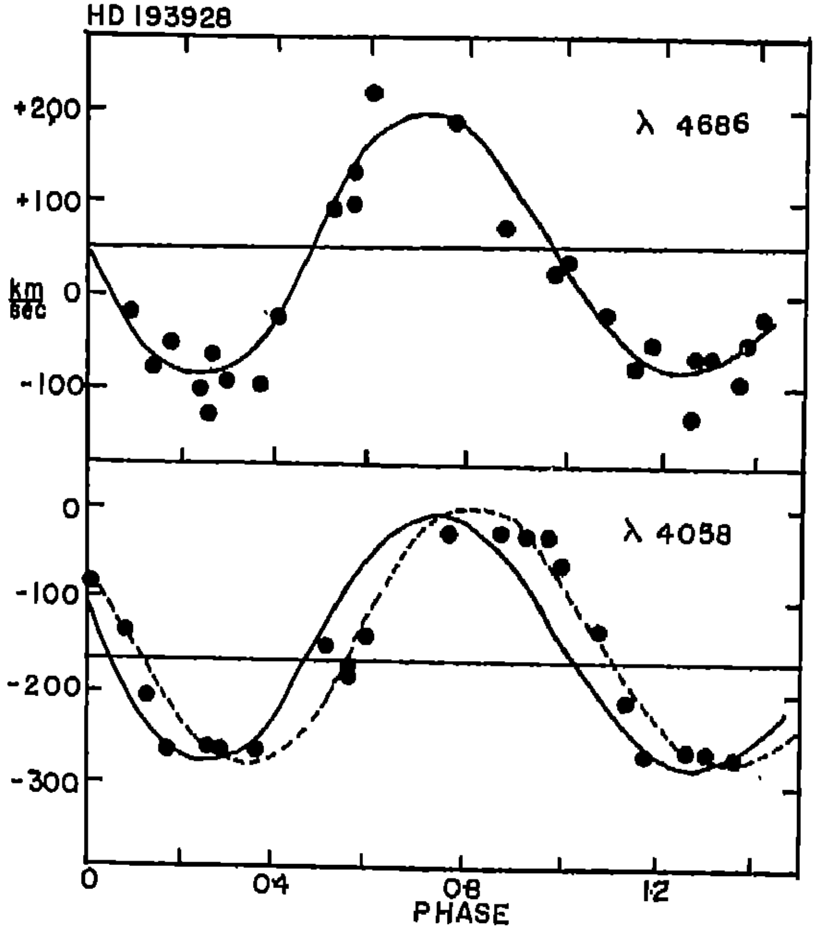

Figure 1.—Velocity curve of HD 193928. The top half of the diagram gives the HeII 4686 curve. In the lower half the solid circles are the observed velocities of NIV 4058, the solid curve is the theoretical curve of HeII 4686 and the dashed curve is the HeII 4686 curve displaced by 0.1P so as to fit the NIV 4058 velocity values.

It is difficult to explain the nature of this phase shift as seen in 4058 Å. It is likely that over the duration of the observations there has been activity on the star seen in NIV 4058 causing such a displacement.

Figure 2 is a plot of the emission line NV 4603 with the solid curve representing the variation of 4686 Å. It is seen that the curve fits the points well out for a displacement in the γ -axis by 185 km/sec.

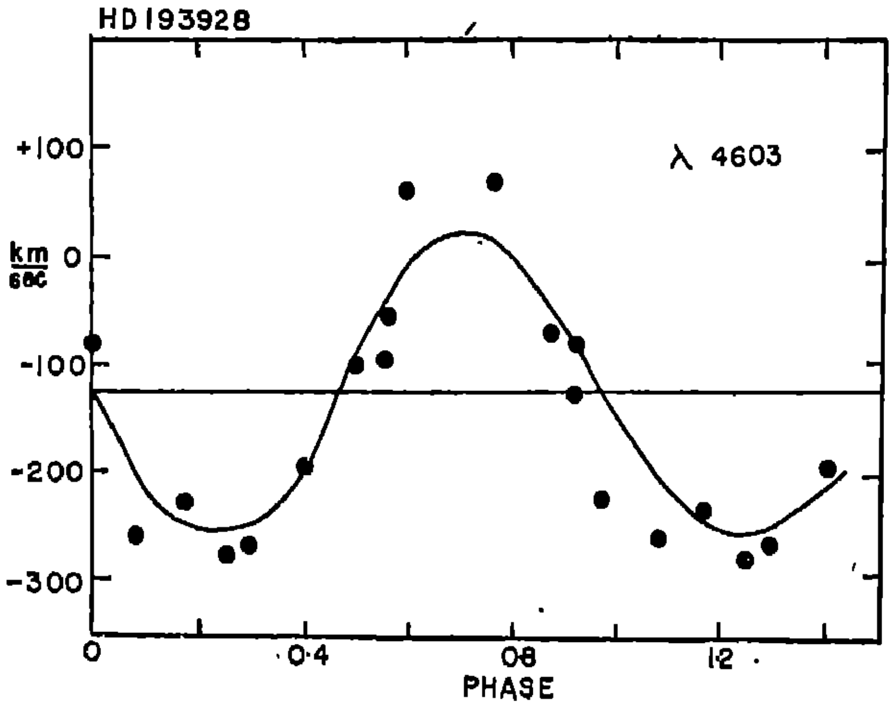

Figure 2.—Velocity observations of HD 193928. The points are the measured velocities of NV4603 while the solid curve is the velocity curve of HeII 4686.

The study of the profiles in a system of this kind is obviously of considerable interest. Figure 3 shows the variations experienced by HeII 4686 at four different phases. At phase zero, the Wolf-Rayet star is farthest from the observer. At this phase, the profile of 4686Å is narrow with a slight hump on the longward side. At a phase when the Wolf-Rayet star is closest to the observer, which happens to be at phase 0.5, the profile is almost symmetrical and narrow. The profile is broad at phases 0.77 and 0.60 and the hump seen near phase zero continues to prevail. Figure 4 depicts the variations experienced by HeII 4200. Here again, the lines are narrow at phase zero. The profiles at elongations are wider than at phase zero and on some occasions, as seen in 4200 Å, there are suggestions of displaced humps in the structure. At phase 0.51 a hump on the shorter wavelength side is seen. However, the reliability of the presence of this hump cannot be affirmed with any degree of certainty because there has been no additional plate taken on the same day to confirm it.

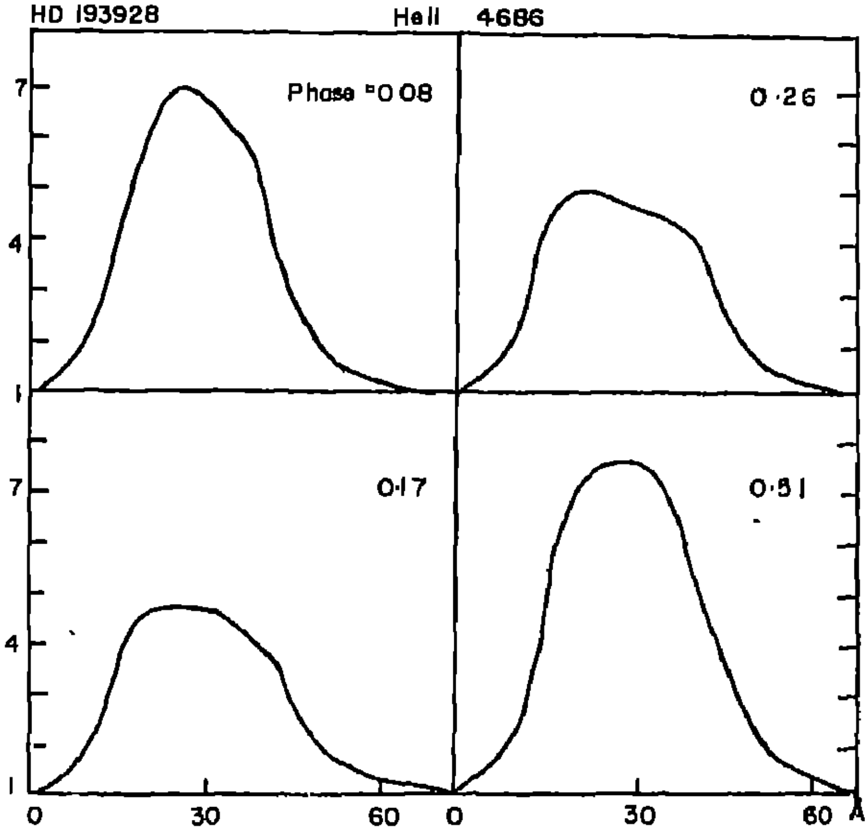

Figure 3.—HD 193928. Line profiles of HeII 4686 at four different phases.

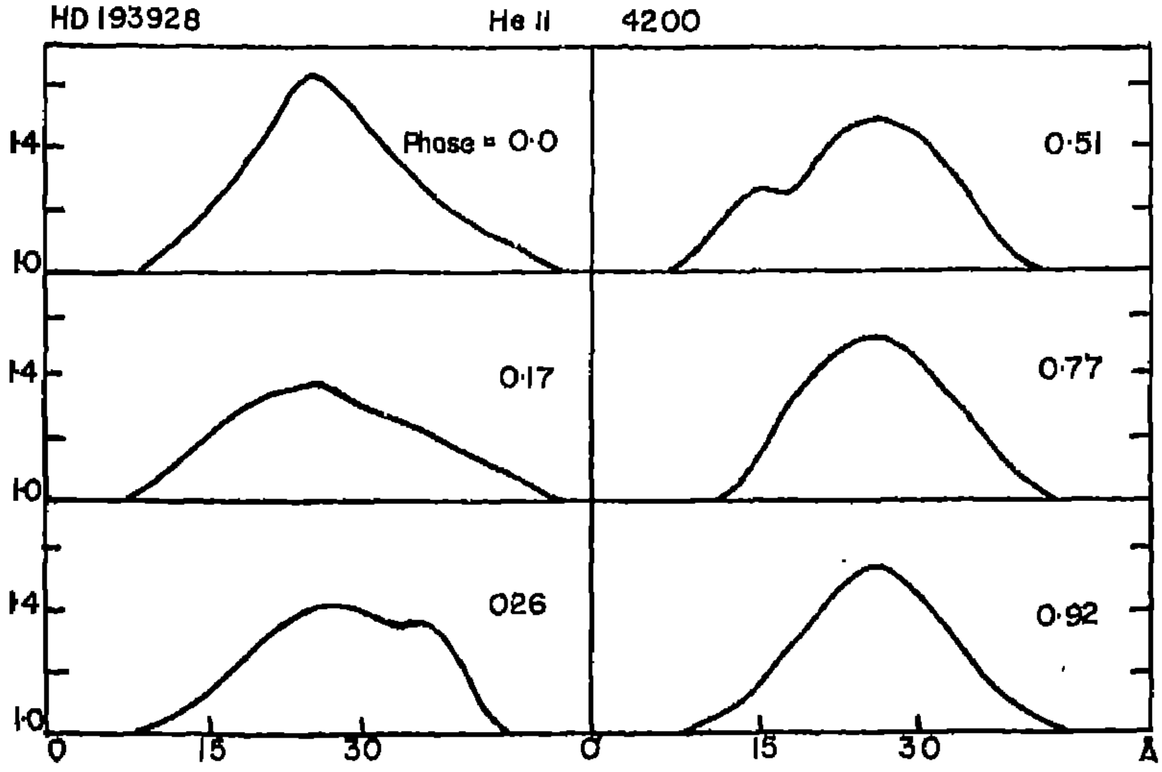

Figure 4.—HD 193928. Line profile variations of HeII 4200.

The variations experienced by 4058 Å have been striking during the period of observation by Hiltner. Our observations shown in Figure 5 indicate that there are changes in the profile of this emission line. The line is more narrow near phase zero, similar to the pattern set by the others. However, at phase 0.51 it is quite wide and indicates a rather intense hump on the longward side. This perhaps, is the kind of variation noted by Hiltner and it is the presence of this distortion in the profile that prevented us from the calculation of orbital elements from the velocity measures of this line.

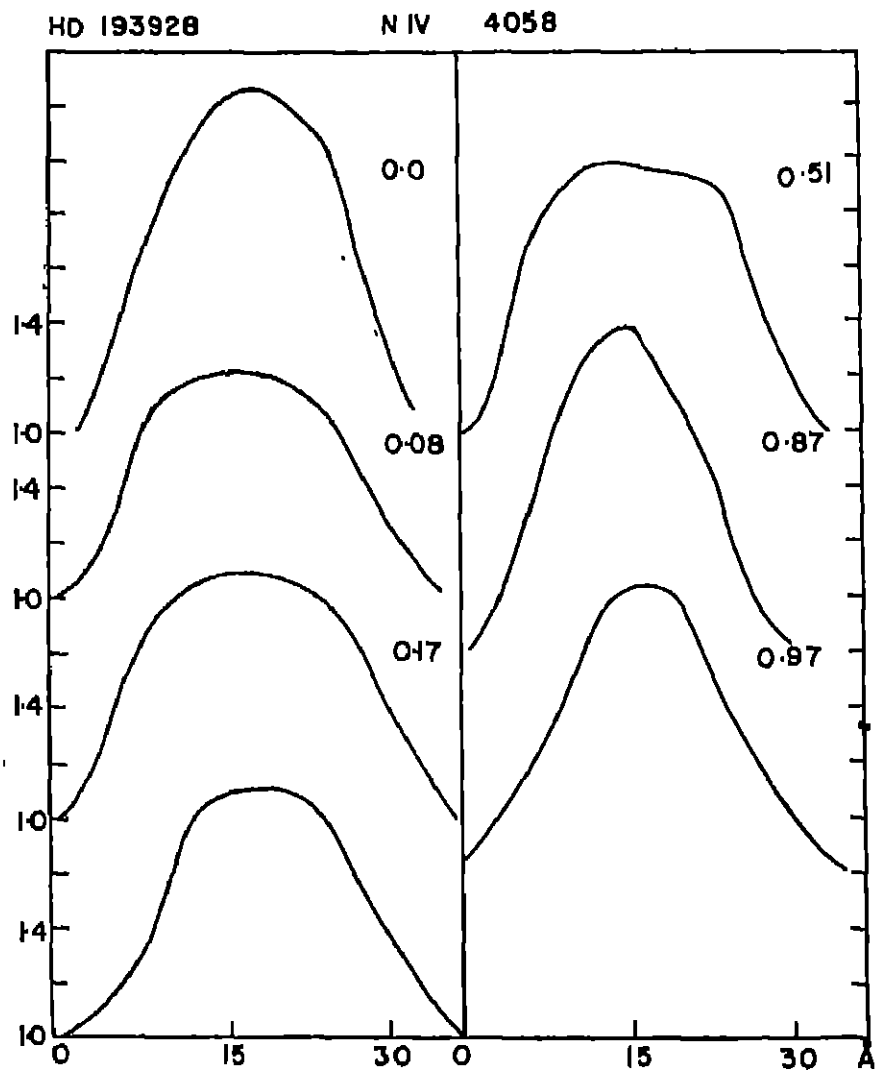

Figure 5.—HD 193928. Line profiles of NIV 4058.

The system of HD 193928 is, therefore, one which seems to have striking spectral variations. One is reminded of the variations seen in HD 50896 which, of course, is not an established binary system. The amplitude of velocity variation is appreciable and it is quite likely that this star is an eclipsing variable. If it is so, however, it would have only grazing eclipses. A comparison of the mass function with that of CQ Cephei (f(m)-4.4 solar masses) is of interest. It does seem possible that HD 193928 can be a good candidate in any search programme of eclipsing binaries among the Wolf-Rayet stars.

HD 186943

The spectrum of this star on the Beals classification is WN 5. Hiltner (1966) classifies it as WN5-A. The emission lines seen in the blue region of the spectrum are HeII 4686, the two NV lines at 4619 Å and 4603 Å, as well as NIV 4058. The Pickering series of HeII are also present, in emission, but are quite faint for accurate measurements. The NV lines do not seem to have violet absorption edges. There are some absorption features seen in the spectrum. The spectra available for this study were obtained with a glass prism spectrograph and hence it was not possible to observe the higher members of the Balmer series. According to Hiltner(1945), these absorption features are extremely weak.

The only orbit of the star that is available is the one derived by Hiltner (1945). This study yielded a period of 9.55 days on the basis of velocity measures of 4686 Å, the NV emission lines and NIV 4058. The elements were determined from the velocity curve of HeII 4686. Hiltner reported a phase shift between the velocity curves of 4686 Å and 4603 Å He also derived a velocity curve from the hydrogen absorption lines.

We have only ten spectra well distributed in phase of this star. We had exposed these for spectrophotometry of NIV 4058 since a variation with phase was apparent from Hiltner's work. The measures of radial velocity are given in Table 2. Preliminary orbits were obtained for 4058 Å, 4686 Å and 4603 Å. The γ-axes derived from NIV 4058 and NV 4603 are 75 km/sec and 30 km/sec respectively. On the other hand, HeII 4686 has a γ-axis value of 105 km/sec. The fact that the NV 4603 line has a systemic velocity nearly equivalent to that of NIV 4058 indicates that the NV lines have little or no violet absorption edges. The observations reported here were combined with those of Hiltner to yield a revised value of period of 9.5594 days. The phases were computed with the formula.

TABLE 2

The Velocity measures of HD 186943

Plate	J.D. of Observation	Phase	Velocities in km/sec		
			4686c	4603c	4058c
32653	2434175.75	0.78	−122.4	−116.2	−212.2
32659	176.78	0.89	− 6.8	− 32.3	−212.2
32667	177.87	0.01	+149.6	− 38.8	− 43.3
32686	195.79	0.88	+102.0	−180.8	−324.8
32720	200.74	0.39	+136.0	+103.3	−129.9
32725	201.71	0.50	− 27.2	− 58.1	−160.3
32730	202.84	0.61	−102.0	− 90.4	−316.1
32748	224.80	0.91	+ 20.4	− 6.5	−285.9
32761	227.86	0.23	+292.4	+219.6	−199.3
32766	228.90	0.33	+170.0	+ 38.8	+ 4.3

Phase zero=JD 2431253.041+9.5594E.

The Hiltner observations of 4686 Å were combined with our measures and a least squares solution obtained of the orbital elements. Table 3 lists these elements along with similar values derived from the preliminary orbits of NIV 4058 and NV 4603. The velocity curve for HeII 4686 is shown in Figure 6.

TABLE 3

The orbital elements of HD 186943

4686A		4058A	4603A
P = 9.5594 days		P = 9.5594 days	P = 9.5594 days
e = 0.0361	± 0.02	e = 0	e = 0.0162
= 150°54′	± 6°54′	= 150°	= 149°
K = 211.5	± 12.9 Km/sec	K = 165 Km/sec	K = 162.5 Km/sec
= 106.7	± 6.7 Km/sec	= +70 Km/sec	= +40 Km/sec

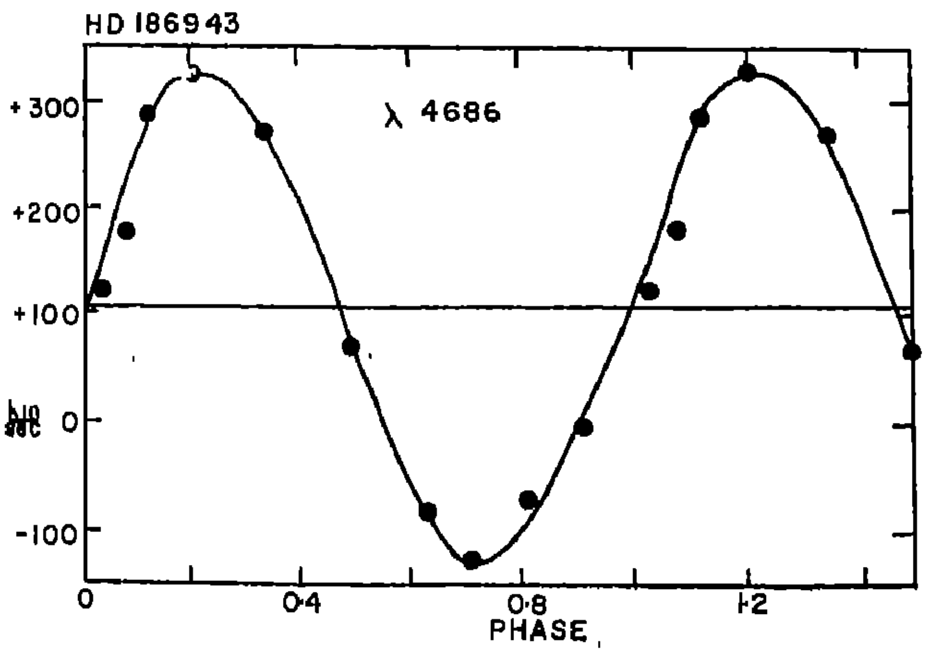

Figure 6.—HD 186943 Velocity curve of HeII 4686

The 4058 Å emission line is extremely weak in this star. In order to obtain this with the correct density, it was necessary to over-expose the 4686 Å region. As such, we have no line profiles of 4686 Å for this star. The 4058 Å line at the time of observation did not exhibit the striking changes reported on by Hiltner.

At a phase close to zero in Figure 7, the line is sharper and more intense than at other phases. It is quite possible that our spectra were exposed during a quiescent spell of the system. Hiltner reported on a phase shift between the velocity curves of 4686 Å and 4603 NV. Based on our observations alone, we fail to find such a phase shift. This is also an added confirmation of the fact that the spectra available for this study were obtained at a particularly quiescent phase.

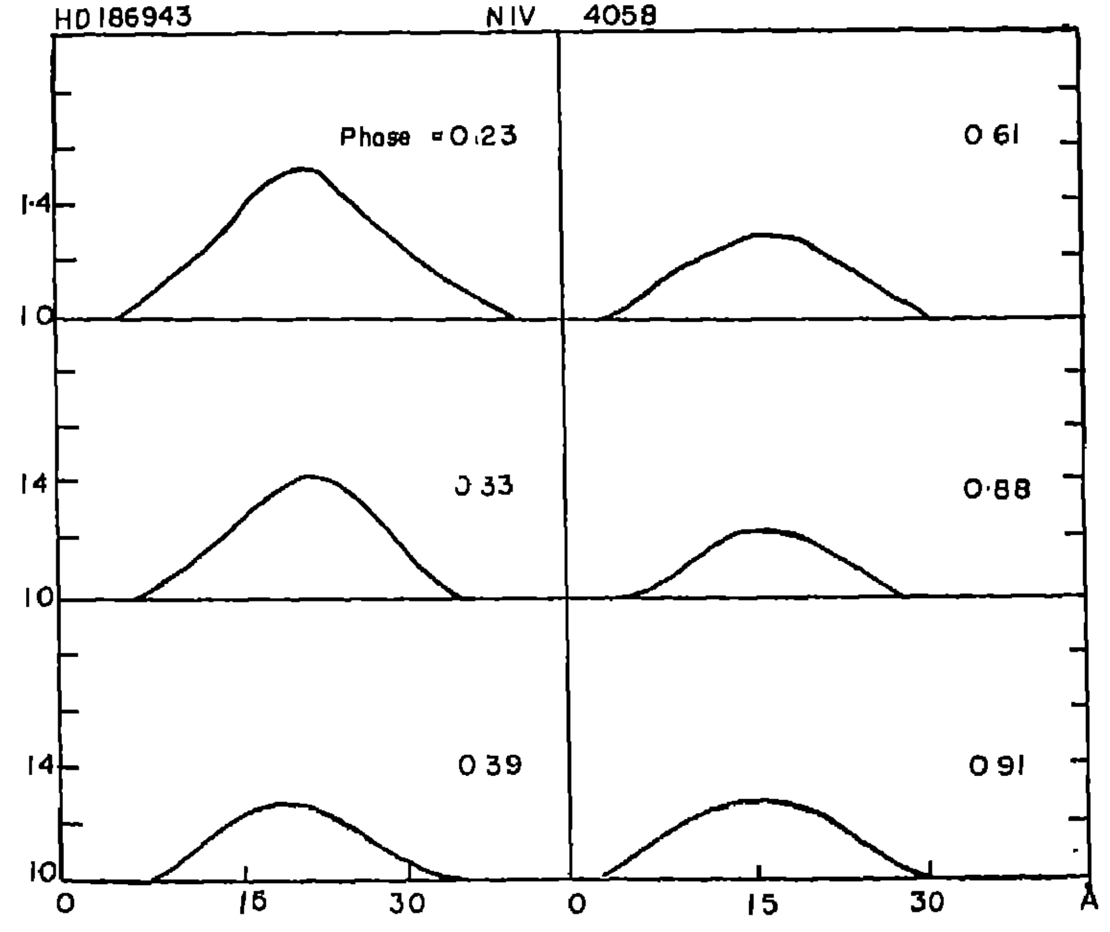

Figure 7.--NIV 4058 Profile changes in HD 186943

HD 211853

The spectral type of this star is WN6. Hiltner (1966) classifies it as WN6.5-A. The predominant line is HeII 4686. The rest of the emission lines are fairly weak. Absorption lines at Hβ, Hγ and Hδ are present. The velocity changes of these lines indicate that they originate from the companion. Occasionally a violet shifted 4471 Å is seen. Hiltner (1945) has given an orbit for the star utilizing the velocity measures of 4686 Å, 4058 Å and 4603 Å. His measures of the H-lines were not such as to give a confident measure of the velocity curve of the companion. Recently Hjellming and Hiltner (1963) have reported on the light variation of this star. The obvious characteristic of the light curve is the intrinsic variability of the system shown by a lack of repeatability from cycle to cycle. An improved period of the binary has also been derived by Hiltner. This is one of the stars in which Hiltner (1950) has measured the emission line intensities photoelectrically and found that when the Wolf-Rayet star was eclipsed by the companion, the emission intensity was the greatest. The observations of light variations by Hiltner through UBV filters indicate that an eclipse of the system does take place, but the intrinsic variation in the Wolf-Rayot star is such as to prevent easy study of this light curve by conventional methods.

We have only 10 spectra, primarily obtained for spectrophotometry, available for velocity measures. However, these have been utilized for measuring the velocities of 4686 Å, NIV 4058, NV 4603 and the hydrogen lines of Hγ and Hδ of the companion. These measures are given in Table 4. Only preliminary elements have been derived on the basis of the three emission lines. These indicate that the system is one of small eccentricity. The preliminary elements and the mass function values derived are given in Table 5. There is close agreement between the mass functions derived from HeII 4686 and NV 4603 while that derived from 4058 Å, deviates considerably from the other two emission lines. This is in agreement with the findings of Hiltner that NIV 4058 lacks repeatability.

TABLE 4

The radial velocity measures of HD 211853

Phase	Velocities (km/sec)		
	4686A	4603A	4058A
0.06	+ 15	− 145	− 105
0.09	0	..	− 160
0.20	+ 95	− 80	0
0.34	+ 180	+ 125	+ 20
0.48	+ 250	+ 280	+ 65
0.58	+ 40	+ 125	− 160
0.64	+ 30	+ 120	− 145
0.92	− 225	− 200	− 290
0.93	− 140	− 200	− 225

TABLE 5

The orbital elements of HD 211853

4686A	4058A	4603A
K = 220.00 km/sec	155.00 km/sec	235.00 km/sec
= +15.00 km/sec	−120 km/sec	+35.0 km/sec
e = 0.12	0.20	0.24
= 79°	64°	315°
a sin i = 2.01 x 10⁷	1.39 x 10⁷	2.10 x 10⁷
f(m) = 7.2460	2.4010	8.239

The velocity measures of the hydrogen lines plotted are seen in Figure 8. One sees a general scatter of the points but the trend of velocity is similar to what has been noticed by Hiltner, many years ago. It is rather difficult to fit a velocity curve of the companion, through the points that are available and therefore, we have made no attempt to estimate the mass of the companion.

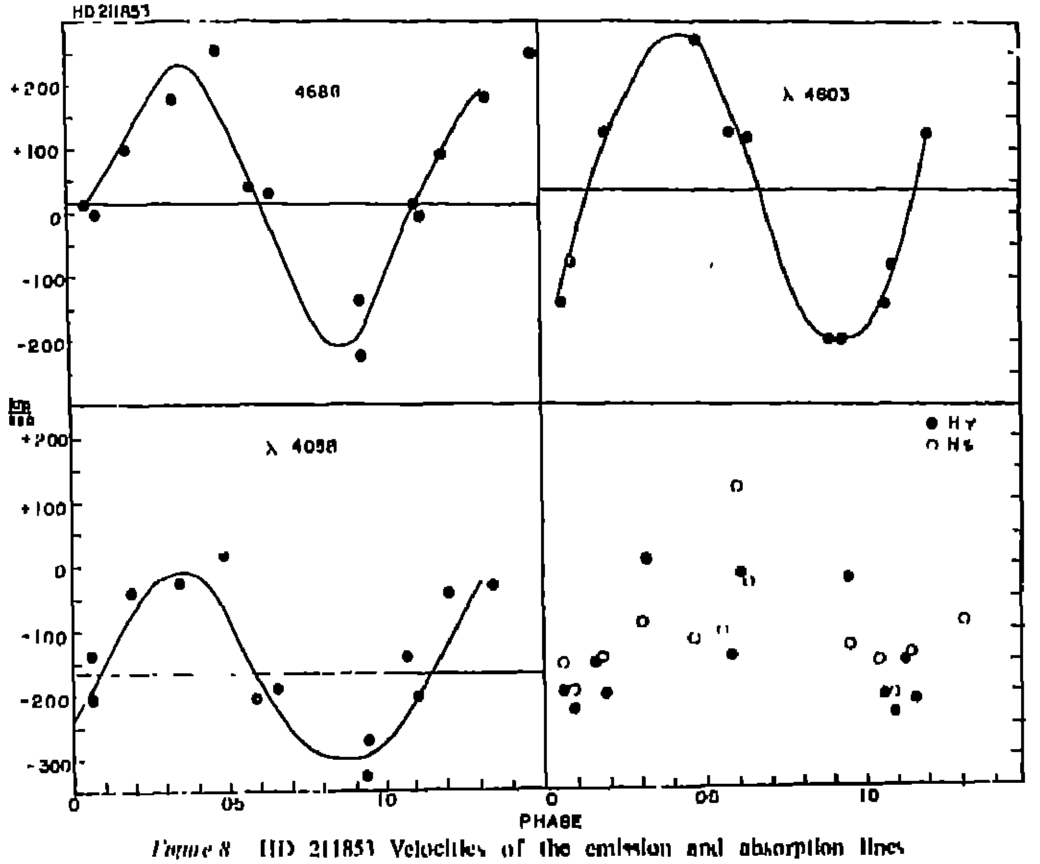

Figure 8 HD 211853 Velocities of the emission and absorption lines

We have derived line profiles for this system for 4686 Å, 4058 Å and 4861 Å (Figures 9a, b, c). The variations seen in HeII 4686 are reminiscent of those seen in V444 Cygni. At a phase close to zero corresponding to the position when the Wolf-Rayet sar is closest to the observer, the profile is narrower than when the Wolf-Rayet star is farthest from the observer. At phase 0.47, there is a double hump structure in 4686 Å. This double hump is seen even at phases 0.60 and 0.61 and one can speculate on its existence even at phase 0.09. However, the fact that at phase 0.31 the profile is symmetrical indicates that this change of profile is more due to the intrinsic variations in the system than one caused by the variation of phase. The 4058Å profiles show in general that in the vicinity of phase zero, the profile is narrower than it is elsewhere. The intensity of 4058Å is extremely weak in this star and hence it is not easy to derive a reliable profile of this emission line. The profile of the emission line at 4680 Å is affected considerably by the presence of the Hβ line of the companion. In general, the emission intensity of ionized helium in the vicinity of phase zero seems to be much less than what it is in the vicinity of phase 0.50 to 0.60. The double hump structure at 0.6 is typical of what one would expect of a receding O star and an approaching Wolf-Rayet star, with the absorption line of Hβ of the O star multilating the smooth structure of the emission line originating from the Wolf Rayet star.

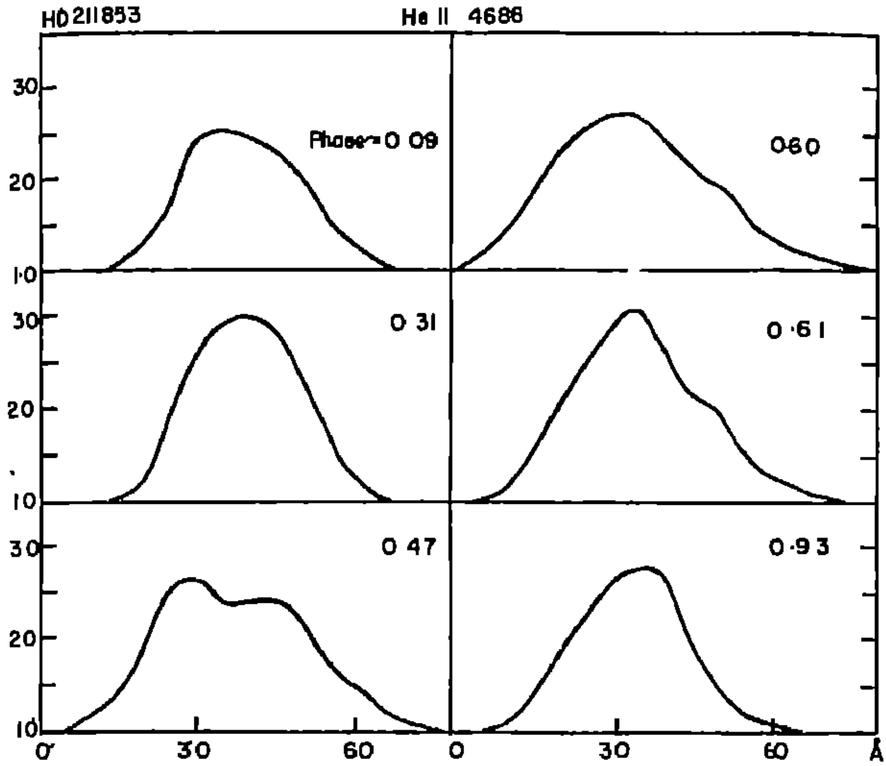

Figure 9 (a).—HD 211853 Line profiles of emission lines in HeII 4686

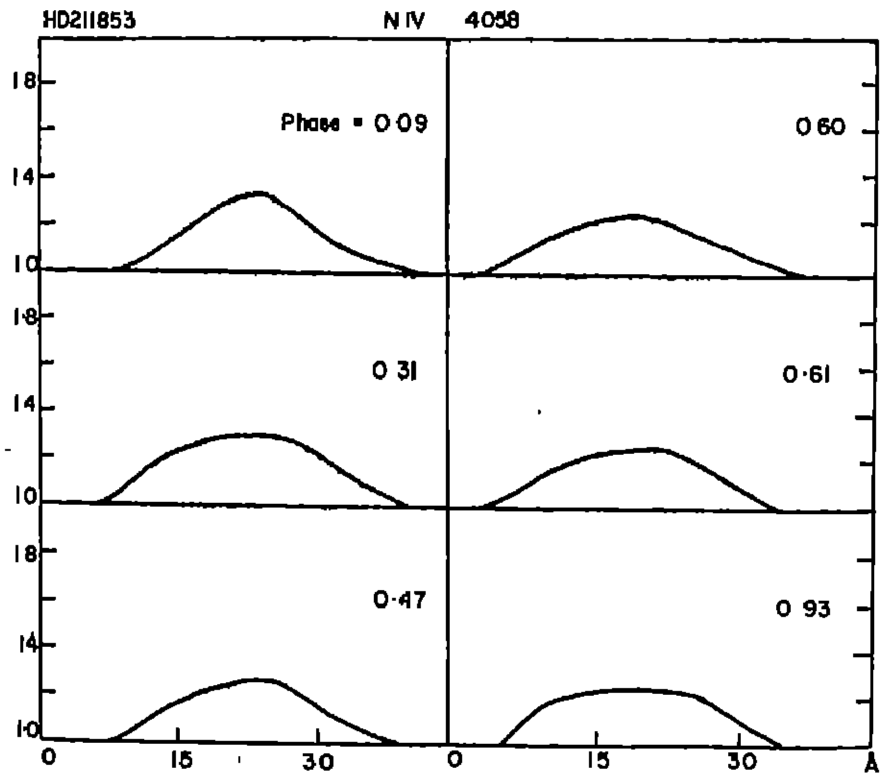

Figure 9 (b).—HD 211853 Line profiles of emission lines in NIV 4058

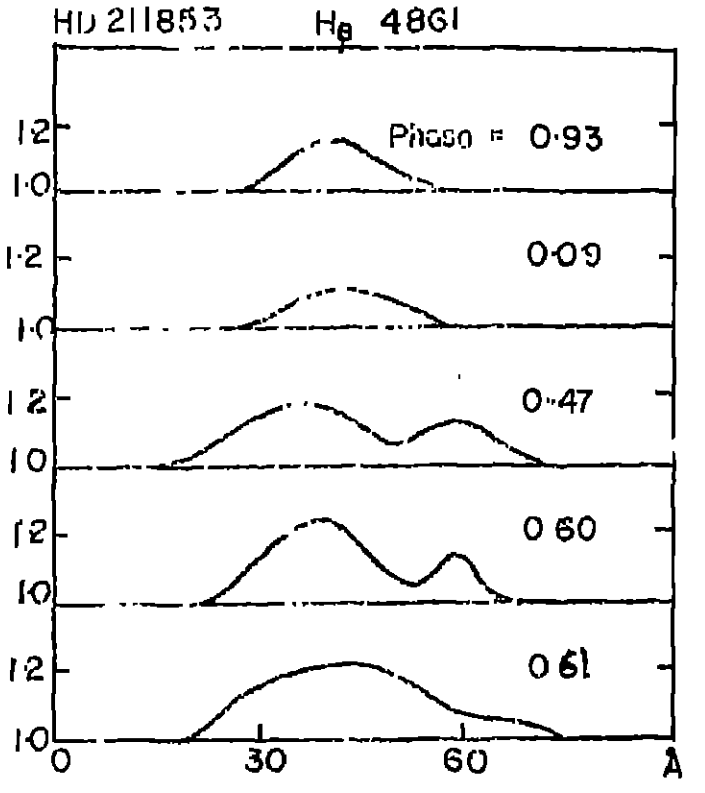

Figure 9 (c). HD 211853 Line profiles of emission lines in HeII 4861

Discussion

The observations of five binary systems that we have studied (Ganesh and Bappu, 1967a, Ganesh, Bappu, Natarajan 1967b) provide us with a set of information which can be usefully examined to obtain a picture of the Wolf-Rayet atmosphere. We have attempted to derive orbital elements for the different systems using different lines. While these orbital elements are liable to be affected by mass motions in the binary system, the availability of line profile data simultaneously, enables a judicious selection of the orbital elements to be made. Four of the systems have orbital elements with a least squares fitting of the observations. The system of V444 Cygni is the only one that has a well established light curve. It, therefore, provides the best mass estimate for the Wolf-Rayet star as well as the companion O star. The values obtained for HD 68273 satisfactorily agree with the present day concepts of masses of the Wolf-Rayet stars. It remains to be seen whether HD 68273 is also an eclipsing binary.

A striking feature observed in most of the binary systems examined is that there are large-scale changes in the line profiles caused either by intrinsic variability in the atmosphere of the Wolf-Rayet star or a phase-dependent variation depending on the geometry of the situation. Many of these systems have a structure in HeII 4686, at phases of conjunction, that are typical of material flow through the inner Lagrangian point. It is present even in such a well separated system like HD 68273. Hence, we may conclude that in almost all cases of Wolf-Rayet binary systems, gas flow through the inner Lagrangian point is likely to be present. Many of the systems examined show large-scale changes in intensity of emission. These are apparent in the HeII lines of the Pickering series in V444 Cygni, in HD 193928 and also in HD 211853. This is suggestive of the fact that it is likely that in a Wolf-Rayet atmosphere, specially of a Wolf-Rayet star that is a member of a binary system with an early type component, the longitudinal distribution of emission is by no means uniform. We have ample justification for this presumption, not only from the data given here but also from the study of CQ Cephei. In general, there seems to be more emission present near the conjunctions than at elongations. The question of course, is whether such a peculiar longitude distribution of emission intensity is stimulated by the presence of the companion. It is difficult to answer this question with any degree of certainty with the present state of observation.

The red-shift experienced by HeII 4686 seems more or less a certainty for the systems examined. HD 68273 with its large separation of components and a period of 78.5 days also shows the phenomenon. This puzzling aspect of the enhanced systemic velocity determined from HeII 4686 is likely to be a vital clue in any explanation of the origin of the emission of HeII 4686. Could it be due to fluorescence as a result of which selective excitation is possible only when the gases that give rise to 4686 Å emission have a certain velocity of recession with respect to the exciting source ? This is a problem that needs careful consideration. For the present, the reality of the phenomenon is established beyond doubt.

The binary systems have been an automatic choice for examination of several of the hypotheses advanced earlier concerning the nature of the Wolf-Rayet atmosphere. HD 193576 stimulated Wilson to show that a "transit time effect" would be present if the Beals hypothesis was valid. The Beals picture of a simple expanding shell suffers from various defects. Alternative models postulated have their own difficulties. Many years ago, Bappu (1951) showed that rotational instability could explain the large widths in the emission line in the stars. He also showed that this would call for an excitation gradient of the Wolf-Rayet atmosphere in such a way that the widest lines have the highest excitation. Quite independently, Limber (1964) has postulated that the wide emission in the Wolf-Rayet star can be explained in terms of forced rotational instability consequent to the continual gravitational contraction in a post main-sequence stage. Limber has examined this hypothesis quantitatively and he has shown that it is very attractive when compared to Beal's old hypothesis. A significant aspect of this theory is that the narrow lines originate farther away from the stellar surface than the lines which have enhanced widths. Limber also pointed out that there is a surprising coincidence between the volume occupied by the electron scattering envelope of HD 193576 and that formed by the inner Lagarangian lobe about this component.

While the rotational instability hypothesis has many attractive features which indicate a situation closer to reality than any achieved so far, nevertheless, several difficulties exist that need explanation. In Figure 10, we have plotted the individual velocities of 4686 Å for three binary systems. If rotation is an important feature, then for the eclipsing system V444 Cygni or even for the other systems it would be necessary to observe the Rossiter effect, caused by rotation. It will be seen that an examination of these curves shows that Rossiter effect cannot be detected. Limber, of course, postulates that the absence of a Rossiter effect is not likely to invalidate the hypothesis, since several mechanisms could mask the feature. The broadest emission lines in the system of HD 68273 are identical to those seen in V444 Cygni. The observations listed above on the broadening of the higher members of the Balmer series at the phase when the O star is eclipsed by the Wolf-Rayet star clearly indicate the definite manifestation of electron scattering. Therefore, one can postulate with sufficient degree of confidence, the fact that such an electron scattering envelope exists in every Wolf-Rayet atmosphere. Several of the binary systems studied have different values of K. It is very likely that some of them may be systems with high orbital inclinations and some with a small value of sin i. In general, it seems as though there is very little difference in the line widths of 4686 Å for the various systems. On the basis of the rotational instability hypothesis, it is necessary to find a change with the inclination. However, the lack of decrease in the emission widths is likely to be offset, by the postulate of electron scattering envelopes of differing properties in such a way that the electron scattering more than offsets the narrowness of the emission lines.

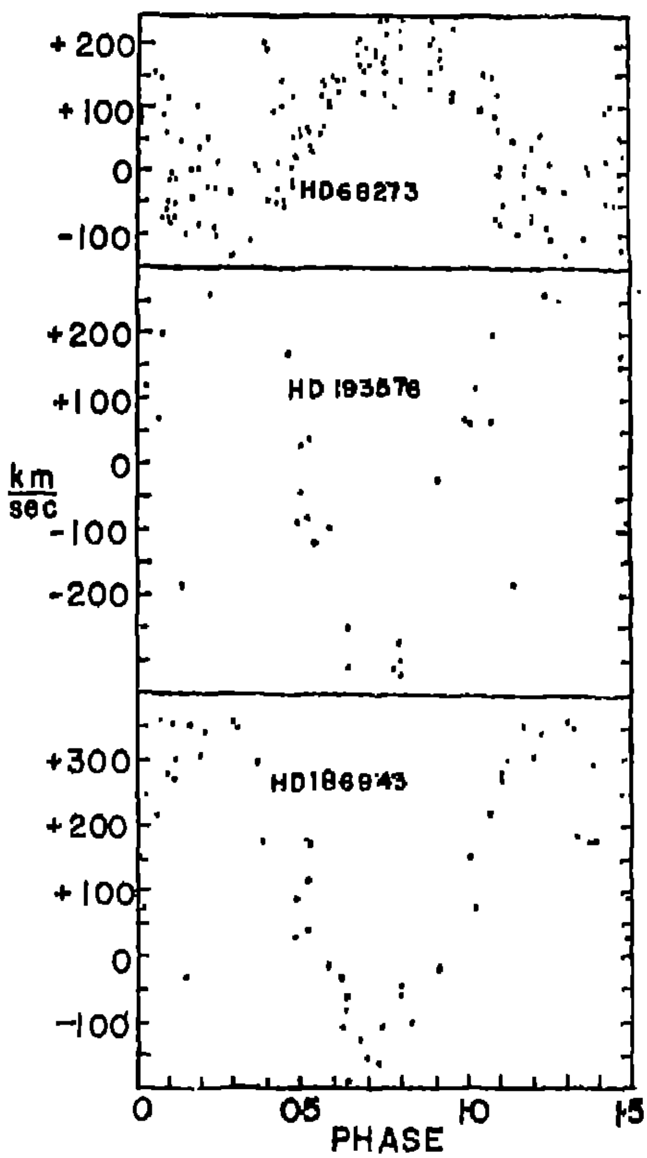

Figure 10.—Velocities of HeII 4686 in the Wolf-Rayet binaries HD 68273, HD 193576 and 186943.

It seems that a profitable avenue for study of the Wolf-Rayet phenomenon, is to study in detail the binary systems. We need to detect many more binary systems than we have so far, in order to find among them systems that have favourable inclinations for an eclipse, systems that can provide reliable information on the masses of the stars and also those that can be usefully utilized in enabling the easy conjecture of a model of the Wolf-Rayet atmosphere.

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