SECTION VII

CHAIRMAN: J. SAHADE

WOLF-RAYET BINARIES AND ATMOSPHERIC STRATIFICATION

LEONARD V. KUHI
Astronomy Dept., Univ. of California, Berkeley., Calif., U.S.A.

1. Introduction

Considerable effort has been expanded on both of these topics ever since the binary nature of most bright WR stars was revealed by radial velocity and eclipse observations and the basic correlation of line-width with ionization potential was discovered. I would like to describe briefly the methods of detection of binaries, to review the percentage of known binaries and to summarize the mass determinations that result from the study of WR binaries.

CV Serpentis, a former eclipsing binary will also be discussed prior to reviewing the history of the atmospheric stratification problem. I would then like to present what I think is the solution of that problem based on the behaviour of C III 5696 with increasing temperature (i.e. earlier spectral sub-class) in the WC stars interpreted in terms of a radially expanding envelope.

2. Binaries

2.1. Are all WR stars binaries?

This question has been asked at every conference on WR stars and no doubt will continue to be asked at all future meetings because there can be no final answer. The question is of such importance in understanding the evolutionary history of WR stars that it seems worthwhile to summarize the methods of detection of WR binaries before discussing the results.

At present these methods involve the following:

(a) visual detection, i.e. presence of two stars,
(b) variations in radial velocity,
(c) eclipses,
(d) presence of another spectrum,
(e) small ratio of emission-line to continuum intensities.

Because of the great distances of most WR stars the first method is virtually useless. The second will detect only those systems for which the variations in radial velocity are large enough to be readily measured and hence will leave undiscovered those systems for which the companion has a considerably lower mass or the orbital inclination is close to zero. The third requires orbital inclinations of 80° to 90° and subsequently is a very selective method which would miss a large number of possible binaries. The fourth requires a favourable luminosity ratio, i.e. the companion should be no more than ~1.5–2.0 mag. fainter than the WR star or it simply will not contrib-

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ute anything to the composite spectrum. Thus again low luminosity (which usually equals low mass) companions will be missed. The fifth method is really the same as the fourth but makes use of the continuum contribution of the companion rather than its absorption spectrum. This is especially useful when the companion is of very early spectral type and does not have any strong absorption features. However, it does contribute to the continuum of the composite spectrum and hence the emission lines will appear to have smaller intensities relative to the continuum than a single WR star.

This is a powerful method which has worked extremely well in detecting binaries but relies on two assumptions: (a) the ratio of line to continuum intensities does not vary with time nor from star to star of the same spectral type and (b) that a truly single star exists. Scanner evidence suggests that the ratios do vary in close binaries (which are readily detected by one of the other methods anyway) but probably not in the so-called single stars. In actual practice therefore any ratio that is more than ~10% (typical fluctuation in a close binary) lower than a single star can be considered as indicating a binary. Nothing can be done about the second assumption other than to say that the star with the highest ratio is taken to be single (it will usually have defied all other methods as well) and the other stars are compared to it. Again the method will fail to detect low luminosity low mass companions. If the minimum change detectable is taken as ~10% implying a luminosity ratio of ~10:1 the undetected mass can still be quite large. For example let us assume the standard mass luminosity law, take the typical mass of a detected O-type companion as 20 $M_\odot$ and its luminosity as 4 times that of the WR star. Then our luminosity limit is 1/40th that of the O star and corresponds to a mass of ~5 $M_\odot$. Since the mass of the WR star is ~5 $M_\odot$ such a large undetected companion would have a considerable effect on the radial velocity curve if the orbital inclination and separation were favourable. However, if it were not then once again no companion would be detected.

Bearing these difficulties in mind we can then attempt to answer the question posed by the title of this section. Approximately 105 WR stars are known in our galaxy and Smith's 1968 paper lists 40 of these as binaries. However all of these stars have not been studied to the same extent because of the difficulty of getting good radial velocity measurements of faint stars. We also note that a number of stars not listed as binaries by Smith were suggested as such by Kuhi (1968b) on the basis of low line-continuum ratios, e.g. HD 9974, 65865, 197406 and MR 119. Consequently her list represents a very non-uniform sample and it would be more realistic to take all stars brighter than some limiting magnitude, say $v = 10.0$ on Smith's system. There are then 33 stars of which she lists 19 as binaries. If we also allow for the fact that southern hemisphere stars have not been studied as fully as those in the north by eliminating all those with declinations south of −25° then there remain 15 stars of which 11 are listed as binaries. That is to say when we have a uniformly studied sample the percentage of binaries is ~73%. This is a very high percentage compared to field stars and if one allows for the non-detection of low-luminosity low-mass objects for the reasons cited above it may very well be that all WR stars are binaries. Arguing against this would be the fact that no star with a ring nebula appears to be a binary. Unfortunately this is as close as one can get to a definitive answer from the observations. Nothing further need be said.

2.2. MASSES

Binaries provide us with the only estimates of the masses of WR stars and consequently are of great importance in understanding the evolutionary history of WR stars. However, we stress again that unlike normal binaries the WR binaries are not well behaved in that different emission lines give velocity curves of different amplitude with different K-values. In fact the emission lines consistently give more positive K-values than the absorption lines of the companion: this is the so-called 'red-shift' and has had no satisfactory explanation. Clearly the presence of absorption on the violet side of the line could account for some of the shift as could the contribution from gas streams in the system. However, a less *ad hoc* explanation might be the following: the eclipse observations of V444 Cygni (Munch, 1950) as well as the work of Castor *et al.* (1970) suggest that the optical depth in electron scattering is ~ 0.5. The data presented below indicate that the velocity increases with radius; hence an electron in the outer parts of the envelope scattering a photon from the inner part always has a larger velocity outwards than the emitting atom. Consequently the scattered photon will be shifted to the red in wavelength and the resultant emission profile should also be shifted to the red. The amount of the shift would depend on the exact location of the line-emitting region and the optical depth in electron scattering which probably varies from line to line. In close binaries the distribution of emitting atoms is not spherically symmetric; material exists in gas streams as well so that a detailed calculation becomes very difficult.

Such radial velocity difficulties should be borne in mind when discussing the masses of WR stars; *they are not at all well determined.* Table I summarizes the present data available on the masses of WR stars. It lists not only the most recent estimates of different authors but also the different values derived by the same author from different emission lines. References to earlier work can be found in Smith's article in the Boulder Symposium volume. HD 228766 was originally left out of the table given by Smith (1968b) because she had classified it as an Of star. However, the WN 7 (Hiltner, 1951) classification is definitely confirmed by the Kuhi and Smith Atlas. In addition Bracher (1967) suggests that the inclination may be quite large because of the large mass function. Kuhi and Smith also note a weakening of absorption lines at time of conjunction which may indicate the presence of a weak eclipse.

The masses found range from $\geqslant 4$ to $\geqslant 20\ M_{\odot}$ with the best determined value (for V444 Cygni) being $\sim 10\ M_{\odot}$. The mass ratios $M_{\mathrm{WR}}/M_{\mathrm{OB}}$ range from ~ 0.2 to 0.4 suggesting a much smaller luminosity ratio $L_{\mathrm{WR}}/L_{\mathrm{OB}}$ then observed. The resulting conclusion is that the WR stars are overluminous for their mass. Lindsey Smith has compiled the orbital separations of WR binaries using the value of sin i determined from eclipsing systems or estimating it by assuming a mass for the WR star of $11\ M_{\odot}$. Table II lists the relevant data. She also draws attention to the fact that the WC binaries seem to have a significantly larger separation than the WN's (if one excludes

TABLE I

Masses of Wolf-Rayet stars

HD	Name	Sp. Type	$\frac{\mathcal{M}_{\rm WR}}{\mathcal{M}_{\rm OB}}$	$\mathcal{M}_{\rm WR}\sin^3 i$	$\frac{\mathcal{M}_{\rm WR}}{\mathcal{M}}$	Reference
68273	γ_2 Vel	WC8 + O9I[b]	0.22	19.7	$\geqslant 19.7$	(1)
			0.26	14.5	$\geqslant 14.5$	
			0.28	13.0	$\geqslant 13.0$	
152270		WC7 + O5–8	0.24	1.6		(2)
168206	CV Ser	WC8 + O	0.24	8.0	$\geqslant 8.0$	(2)
			0.31	5.2	$\geqslant 5.2$	
			0.23	8.1	$\geqslant 8.1$	(3)
186943		WN4 + B	0.28	6.0		(2)
			0.42	3.4		
190918		WN4 + O9I[a]	0.16	0.5		(2)
228766		WN7 + O6[a]	0.19	5.4	$\geqslant 5.4$	(2)
			0.22	4.2	$\geqslant 4.2$	
			0.21	4.6	$\geqslant 4.6$	(4)
193576	V444 Cyg	WN5 + O6	0.40	9.3	10.0	
			0.43	8.4	9.0	(5)
			0.39	9.5	10.2	(6)
211853		WN6 + O6I[a]	0.35	10.1	11.5	(7)

Notes to Table I.

[a] Classification from Kuhi and Smith Atlas.

[b] Classification from Conti and Smith (1972).

References to Table I:

(1) Ganesh, K. S. and Bappu, M. K. V.: 1967, *Kodaikanal Obs. Bull.*, No. 183.
(2) Bracher, K.: 1967, Thesis, Univ. of Indiana.
(3) Cowley, A. P., Hiltner, W. A., and Berry, C.: 1971, *Astron. Astrophys.* **11**, 407.
(4) Hiltner, W. A.: 1951, *Astrophys. J.* **113**, 317.
(5) Ganesh, K. S., Bappu, M. K. V., and Natarajan, V.: 1967, *Kodaikanal Obs. Bull.*, No. 184.
(6) Münch, G.: 1950, *Astrophys. J.* **112**, 266.
(7) Stepien, K.: 1970, *Acta Astron.* **20**, 117.

HD 190918). This feature will provide the basis for further speculation by Lindsey Smith and I will comment no further on it here.

2.3. LUMINOSITIES

The luminosities of WR stars were discussed thoroughly by Smith in 1968 and have been reviewed again by her at this symposium. As far as binaries are concerned the major new contribution comes from γ_2 Vel which has received considerable attention from various workers recently. At the Boulder conference Smith assumed that the WC 8 star was the more luminous and derived an absolute visual magnitude of $M_V = -6.2$. This was ~ 1.5 mag. brighter than the other WC stars which all had about the same value of M_V. Baschek (1970), however, in a reanalysis of γ_1 Vel, suggested that $M_V = -5.6 \pm 0.4$ for the combined system of γ_2 Vel and hence that the visual continuum of γ_2 Vel must come largely from the O-type companion. In order to verify this Baschek and Scholz (1971) compared the absorption-line spectrum of γ_2 Vel to that of standard O stars and classified the companion as O8 on the basis of

TABLE II

Separations of Wolf-Rayet binaries

HD	Name	Sp. Type	$a_w \sin i$ ($R_\odot$)	$a_w \sin i$ ($R_\odot$)	$\sin i$	Base of $\sin i$	$a/R_\odot$
186943		WN4 + B	29.7 44.3	12.6	0.77	Assume $M_{\mathrm{WR}} = 11$	64:
190918		WN4 + O9I	108	17.6	0.36	Assume $M_{\mathrm{WR}} = 11$	350
MR 114	CX Cep	WN5	12.1		>0.94	Eclipsing	$< 26^a$
193576	V444 Cyg	WN5 + O6	25.6	10.0	0.98	Eclipsing	36
211853		WN6 + O6I	27.5	13.1	0.96	Eclipsing	53
228766		WN7 + O6V	50	10.6:	≈1	Lge. mass function	61
214419	CQ Cep	WN7	9.6		≈1	Eclipsing	$< 20^a$:
193793		WN8 + O5	5.0				
			Period 3 years (Conti-private comm.) large!				
152270		WC8 + O5–8	28.2	7.6	0.52	Assume $M_{\mathrm{WR}} = 11$	69
68273	γ_2 Vel	WC8 + O9I	234	65.7	1	Lge. minimum masses	300
168206	CV Ser	WC + B0	86.5	26.4	1	Was an eclipser in the past	113

[a] Assuming $M_{\mathrm{WR}}/M_{\mathrm{OB}} <$

line ratios. They then also compared the equivalent widths in γ_2 Vel to those of a standard O8 star and deduced a ΔM_V of -2.3 ± 1.3 mag. with the O-star being the brighter. Combining their magnitude difference with that of Brown *et al.* (1970) (i.e. $\Delta M_V = 1.2 \pm 0.6$ mag.) they obtain $\Delta M_V = 1.8$ to 1.0 mag. This gives $M_V = (-3.6$ to $-4.2) \pm 0.4$ mag. for the WC 8 star. Conti and Smith (1971) also redetermined the luminosity ratio but by considering the emission-line to continuum ratios instead since this should lead to a much more accurate estimate if the WR star is the fainter star. Conti reclassified the spectrum of the companion as O9I on the basis of He I 4471/He II 4541 for spectral type and Si IV 4089/He I 4143 for luminosity class. For the emission lines between λ3850 and λ4700 they found a range of 0.59 to 0.85 in the log of the ratio of equivalent widths in HD 192103 (WC 8) to those in γ_2 Vel. Since some lines were clearly more sensitive to slight differences in excitation than others they eliminated them by looking at HD 164270 (WC 9) to see which lines changed the most. Their final result was 0.68 ± 0.05 for the log of the ratio or a $\Delta M_V = 1.4 \pm 0.1$. The same ratio from the absorption line spectrum is considerably less certain i.e. $\Delta M_V = 0.6 \pm 0.6$, and consequently the value of -1.4 ± 0.1 was adopted. This is in good agreement with the previous redeterminations as well as that mentioned by Bappu at this symposium. However, Conti and Smith prefer to use a distance modulus of 8.3 mag. as derived by Graham (1965) and confirmed by the *Hβ* work of Brandt *et al.* (1971) on the association to derive $M_V = -4.8 \pm 0.3$ for the WC 8 star. Since these estimates are all within the range of values for the other WC stars it seems safe to conclude that all WC stars in our galaxy have the same absolute visual magnitude. Conti and Smith's method assumes that the emission-line strengths of binary stars are the same as those of single stars and that those strengths do not vary appreciably. The observed variations in binaries are all less than 20% and mostly less than 10% so that the latter assumption seems all right. There is also no evidence to the contrary of the former assumption.

Other complications involving the interpretation of WR binaries such as γ_2 Vel will be discussed by Virpi Niemela who will comment on the observational changes with phase in this system as well as in others. These complications confuse the interpretation and do not help our understanding of the WR stars. Consequently I have chosen not to dwell on such details but to discuss instead only one such system, namely CV Ser, because of its role in the solution of the atmospheric stratification problem.

3. CV Serpentis

CV Serpentis was originally discovered to be an eclipsing system by Gaposchkin (1949) from a study of Harvard patrol plates. The photographic eclipses were quite shallow: 0.2 mag. at primary and 0.10 mag. at secondary. Hjellming and Hiltner (1963) obtained a photoelectric light-curve covering the deeper eclipse as well as a revised period of 29.640 days. They recorded a primary eclipse of ~0.6 mag. but had no observations at secondary eclipse presumably because of poor weather conditions. However, the increased depth of primary minimum was striking. Because of the long period this system was observed by Kuhi and Schweizer (1970) in order to investigate the atmospheric stratification (see below). Various emission lines and continuum points longward of λ5500 were measured with a photoelectric spectrum scanner and no eclipses larger than the observational errors were detected. Figure 1 gives typica

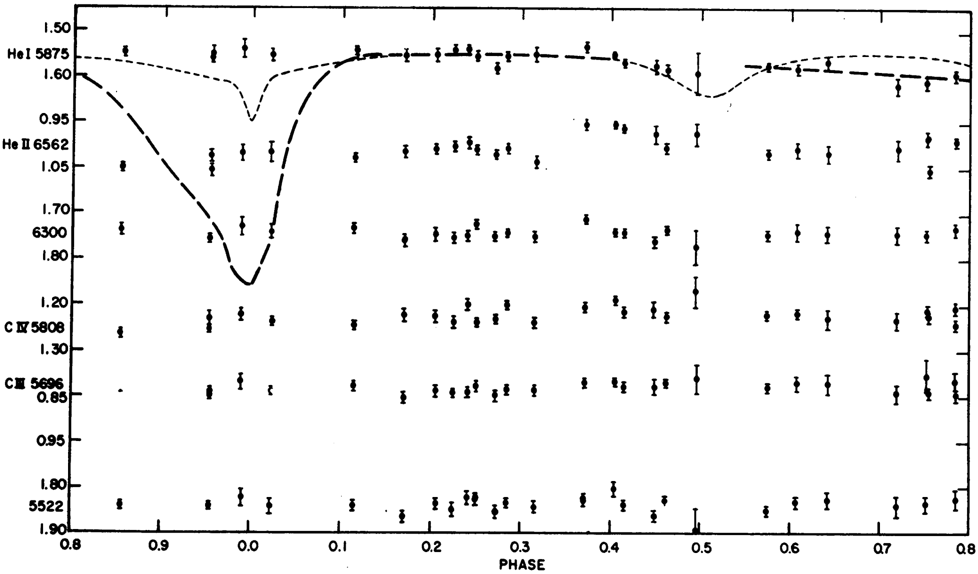

Fig. 1. Photoelectric spectrum scanner observations of CV Ser as a function of phase. The fine dashed curve is due to Gasposchkin; the thick dashed curve is due to Hjellming and Hiltner. Both have been normalized to the scanner data for 5875. No eclipses are evident.

lightcurves in He II, C IV as well as those obtained earlier by Gaposchkin and Hjellming and Hiltner. The earlier curves are normalized to the data for λ5875 to indicate the depths of eclipse expected. Clearly none is visible. Stepien (1970) also observed the star in UBV and again failed to detect any significant eclipse at either time of minimum. The system had stopped eclipsing!

Since that time a number of developments have taken place. The most important is the complete redetermination of the orbital elements by Cowley *et al.* (1971) from spectroscopic data obtained in 1970. This work has led to two major changes: (1) a new period of 29.706 days and (2) the interpretation of the deep minimum (primary) as the B-star being in front of the WR star instead of the opposite which had been assumed by all previous investigators. The new period implies that the expected time of secondary eclipse used by Kuhi and Schweizer as well as by Stepien occurred four days too soon. However, using the revised period Cowley *et al.* showed that there was still no evidence of eclipses in the photoelectric data. On the other hand Tcherepaschuk (1969) observing with a 90 Å bandwidth filter at λ4652 and the adjacent continuum still managed to see eclipses of ~0.15 mag. in the C III–C IV emission line and ~0.07 mag. in the continuum. In contrast observations longward of λ5500 by Kuhi and Schweizer still failed to show any eclipse in 1971. A closer examination of the spectroscopic behaviour of the C III–IV 4650 blend by Kuhi and Schweizer reveals the appearance of a strong absorption feature to the violet during the time of secondary minimum. This absorption component is strong for 5 to 6 days and actually occurs when the WR star is in front of the B star. If one makes a crude determination of the expected blue profile of the emission line by reflecting its red profile about the zero-velocity point one can then estimate the strength of this absorption component and hence compute the change its presence would produce on the total intensity measured in the bandwidth of the filter. The result is an 8.6% decrease in the line and no change in the continuum. This compares favourably with the value of 60% of the eclipse observed by Tcherepaschuk computed by Cowley (private communication) considering the uncertainty in the determination to the profile. It is very likely that the above estimate is a lower limit since any occultation effects would tend to decrease the redward emission profile and hence lead to an underestimate of the equivalent width of the absorption component. Hence, it seems possible that one can account for a large fraction of Tcherepaschuk's emission-line 'eclipse' entirely by the appearance and disappearance of the absorption feature. However, there is no way of explaining the continuum observations in a similar way and one is left with a real puzzle: i.e.

> *what happened to make the large eclipses disappear and why is there still a small eclipse in the blue continuum and not in the red?*

Kuhi and Schweizer suggested that the eclipses had been caused primarily by the inner dense parts of the envelope and that for some unknown reason the envelope had increased considerably in size so that the optical depth was no longer large enough to cause an eclipse. However, this explanation cannot be correct since an optically thin envelope would be expected to produce flat-topped emission profiles and no gross changes in the profiles have been observed. Alternatively one might suggest a shrinking of the envelope which would produce no major change in the emission line profiles and hence would be consistent with the observations. We can offer no argument against such a hypothesis although it does not seem particularly attractive on theoretical grounds. Specifically it seems very difficult to get such an envelope to suddenly collapse upon the star without causing a noticeable brightening of the star itself. No such changes were observed.

However, bearing in mind the gas streams and common envelopes occurring in V444 Cygni (Kuhi, 1968a) it is quite likely that material between the two stars contributes significantly to the emission lines. In fact Cowley *et al.* have suggested that variations in the amount of this material could cause the changes observed and that the 'eclipses' were initially produced by occultation of this material by the two stars. They also mention that whereas this would be consistent with the present observations it would be somewhat difficult to reconcile the large eclipse observed by Hjellming and Hiltner. The suggested variations would also account for the shallow eclipses observed by Gaposchkin as being due to the averaging of deep and shallow eclipses with an incorrect period. Unfortunately Liller (private communication) has had the Harvard patrol plates reexamined for such changes and apparently has not found any. This seems to make the variable material hypothesis somewhat untenable since it now requires the amount of material to remain constant for ~70 yrs and then suddenly decrease by a large amount. Such constancy seems very unlikely if V444 Cygni is a representative example.

Yet another possibility, namely a change in the orbit, was also ruled out by Cowley *et al.*, since there is no spectroscopic evidence for changes in the radial velocity curves. Figure 2 illustrates the agreement between old and new observations for the C III–IV 4650 blend.

Consequently we are left with no viable hypothesis that is consistent with the present observations. There remains, of course, the possibility that Hjellming and Hiltner observed some other star or committed some other error but this seems quite unlikely considering the large number of observations involved. It is to be regretted that their observations did not cover a longer time period. Clearly CV Serpentis deserves close attention during the next observing season to unravel its mysterious behaviour.

4. Atmospheric Stratification

One of the basic correlations discovered by Beals many years ago was the fact that lines from ions of high ionization potential had much narrower widths than those of low. This relation is most readily seen in the WN stars for which the line widths are easily measured. For example, in HD 192163 these half-widths vary from 350 km s^{-1} for N V, 700 km s^{-1} for N IV, to 1150 km s^{-1} for N III and from ~1000 km s^{-1} for He II to 1350 km s^{-1} for He I. Figure 3 shows that the correlation is extremely well defined. The relation also exists for the WC stars but because of very severe blending problems the measured line widths show a much larger scatter and hence define the relationship

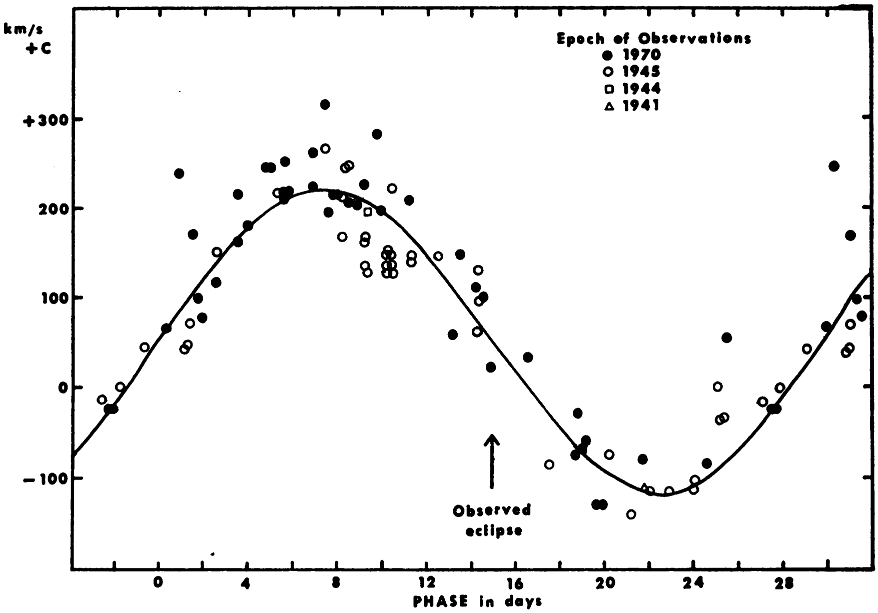

Fig. 2. Radial velocity measurements for CV Ser from Cowley *et al.*

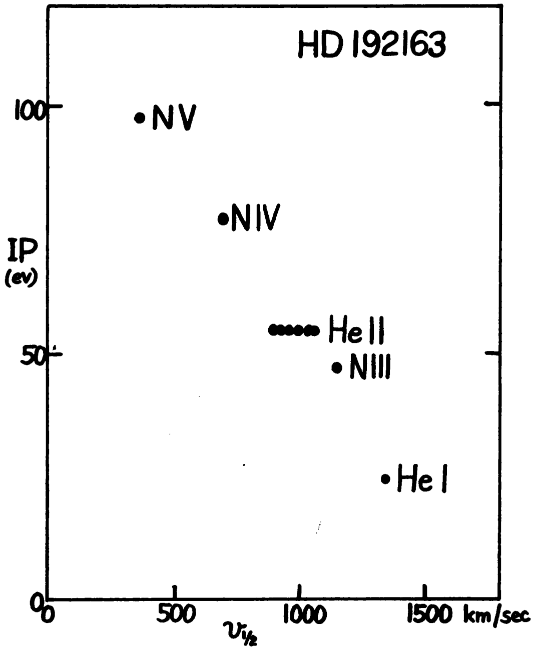

Fig. 3. Correlation of emission line-width and ionization potential for HD 192163 (WN6). $v_{1/2}$ is the half-width at half-intensity in km s^{-1}.

much more poorly. The correlation is also upheld in the velocities of the violet-displaced absorption components when such lines occur e.g. He I, C IV 4650, N IV 3483, etc. This has already been pointed out by Bappu in his talk on spectral line identification and typical values are tabulated there.

The correlation immediately implies the presence of stratification in the WR envelope since such a large number of stages of ionization cannot exist in the same physical location. It also implies that the velocity field is either an accelerating or a decelerating one depending on the temperature structure. Beals assumed that the dominant mechanism of ionization was akin to that in planetary nebulae, i.e. ionization by far UV photons and the resultant recombination followed by cascading produced the emission-line spectrum observed. Because the higher energy photons would be absorbed closest to the star this picture led to the 'ionization temperature' decreasing outwards with increasing radius. This immediately implies an accelerating velocity field. Today we are much less certain about the ionization and excitation mechanisms and would hesitate to apply Beals' scheme to all the lines formed in the WR envelope. However, it seems likely that many lines are indeed recombination lines and hence that Beals' mechanism may still play an important role although not necessarily a unique one. Consequently a model with temperature decreasing outwards is a very viable one even though the exact mechanisms of excitation, ionization and acceleration are not known. The outward increasing velocities could be provided by radiation pressure for example if there were enough flux available to do the job.

A different suggestion was made by Thomas in 1949 who interpreted the velocities in terms of random motions or large scale turbulence. However, the very large temperatures ($\geqslant 10^7$ K) required did not prove acceptable to most investigators and consequently the model died quietly although it was briefly revived during the Boulder conference on WR stars.

A model with temperatures increasing outwards was put forth by Münch in 1950 in order to interpret the spectroscopic (Münch, 1950) and photometric (Kron and Gordon, 1950) observations of V444 Cygni. The small separation of the system ($\sim 35 R_\odot$) made it very difficult for Munch to see how the temperature could decrease outwards under the very strong heating influence of the O-type companion. In particular he found it impossible to reconcile the existence of He I in the outer parts of the WR envelope which he felt would be subjected to the ionization produced by the UV radiation from the O star. Therefore, the temperature must increase outwards and consequently the velocity must decrease with increasing radius. If the material were ejected ballistically then gravity could provide the decelerating mechanism.

The rotating model proposed by Limber (1964) in which material was ejected equatorially because of rotational instability would also suggest a structure with temperature increasing outwards with radius. Presumably the material at larger distances from the star would have slower rotational velocities than the material close to the surface because of the conservation of angular momentum. Consequently the emission lines should be narrowest at large radii and hence the linewidth-ionization potential correlation implies that the temperature must increase outwards.

An attempt was made by Kuhi (1968a) to resolve the question by obtaining eclipse curves in the light of individual emission lines for V444 Cygni (Period = 4.2 days). If the temperature decreased outwards then one might expect to find a shallower broader eclipse for lines from ions of low ionization potential and very deep narrow eclipses for lines of high ionization. Qualitatively the observations obtained at secondary minimum (i.e. O star in front) did suggest this but the emission lines decreased by even larger amounts at primary eclipse (WR star in front) leading to the conclusion that a significant fraction of the light was produced in the region between the two stars. Other peculiarities were also observed in the behaviour of individual lines and these were attributed to the interaction effects arising between two hot stars so close together. Typical light curves were given at the Boulder Symposium as well as in the original paper and need not be repeated here. Consequently it was impossible to disentangle the stratification problem from the interaction effects.

The other known eclipsing systems (all discovered by Gaposchkin) are CQ Cep (P = 1.6 days and hence even closer than V444 Cygni), CX Cep which is too faint, and CV Ser with a period of 29.7 days. CV Ser should, therefore, have a large enough separation so that interaction effects would be minimal. It had already been observed by Hjellming and Hiltner (1963) to have a primary eclipse of 0.5 to 0.6 mag. Thus it seemed like the best candidate on which to repeat the emission-line experiment but unfortunately it stopped eclipsing (Stepien, 1970; Kuhi and Schweizer, 1970) as discussed above. Consequently this simple method of attack was totally doomed to failure.

In 1970, Brown, Davis, Herbison-Evans and Allen used the intensity interferometer to study the multiple star γ_2 Vel. They made measurements of γ_2 Vel (WC8 + O9I) both in the continuum at 4430 and in the light of C III–IV 4650 to determine the angular size of the star and of the C III–IV emitting region. The star would have a radius of $17 \pm 3R_\odot$ and the envelope $76 \pm 10R_\odot$ or $(0.24 \pm 04)a$ where a = semi-major axis if the distance were 350 ± 50 pc. This result was obtained by assuming a uniform brightness distribution across the disk of the C III–IV emitting region. Interestingly enough the mean radius of the critical Roche lobe for stars in the mass ratio 0.28 is $(0.26 \pm 0.01)a$. This suggests that the C III–IV producing region fills the critical Roche lobe around the WR star. The measurements also provided the first incontrovertible evidence that the line emitting region was indeed much larger than that responsible for the continuum, in this case ~4.5 times larger. Unfortunately no other lines were measured so that no information was obtained that could settle the stratification problem.

It now seems, however, that the question can be answered quite definitely from the behaviour of the emission line profiles as a function of spectral subclass (e.i. temperature) at least for the WC stars. Numerous authors have pointed out the strikingly flat-topped appearance of C III 5696 in the hotter WC stars but no one has interpreted the change in its profile with temperature. Because the line is normally very strong and hence quite difficult to analyze photographically I have obtained profiles for each spectral subclass from WC9 to WC5 with the Wampler photoelectric spectrum scanner at Lick Observatory using an exit slit of ~4 Å. This provides adequate resolution to map out the entire profile with an error of only a few per cent. Figures 4 to 8 illustrate

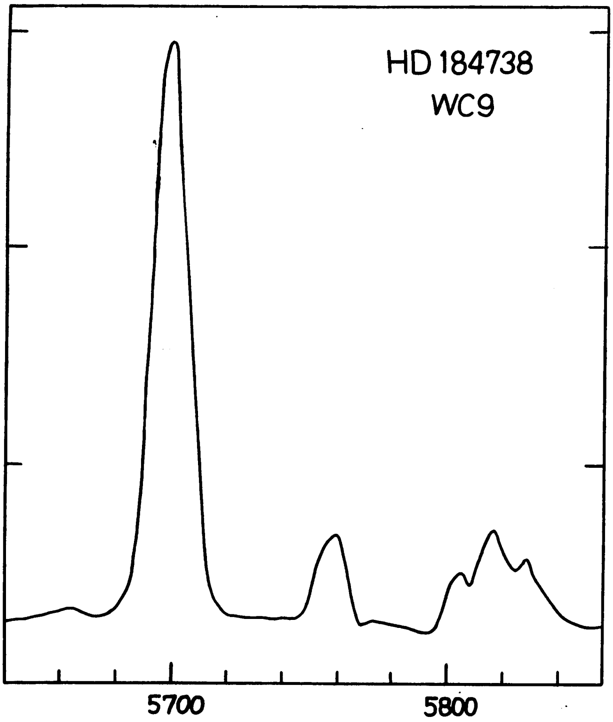

Fig. 4. Photoelectric spectrum scanner profiles of C III 5696 and C IV 5808 in HD 184738 (WC9). The vertical scale (arbitrary) is linear.

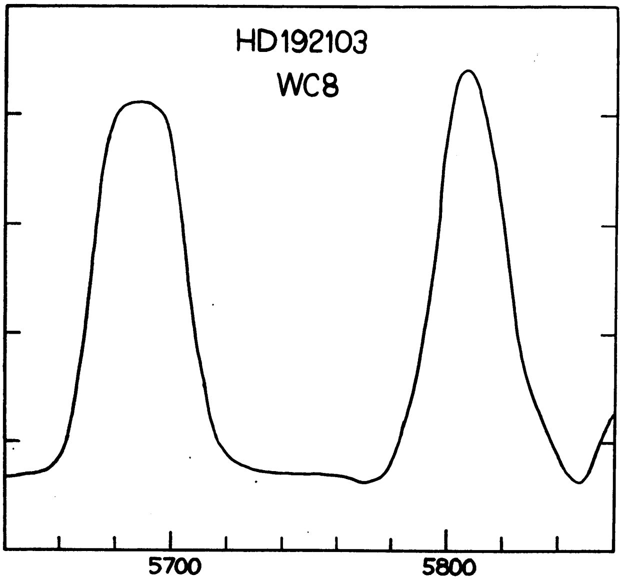

Fig. 5. Scanner profiles of C III 5696 and C IV 5808 in HD 192103 (WC8).

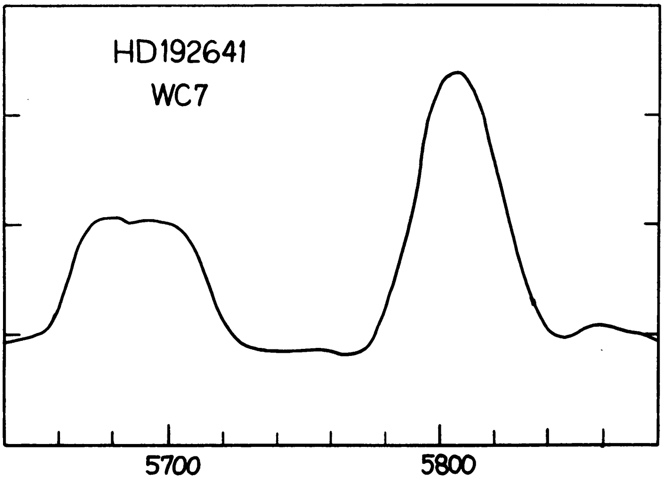

Fig. 6. Scanner profiles of C III 5696 and C IV 5808 in HD 192641 (WC7 + Be).

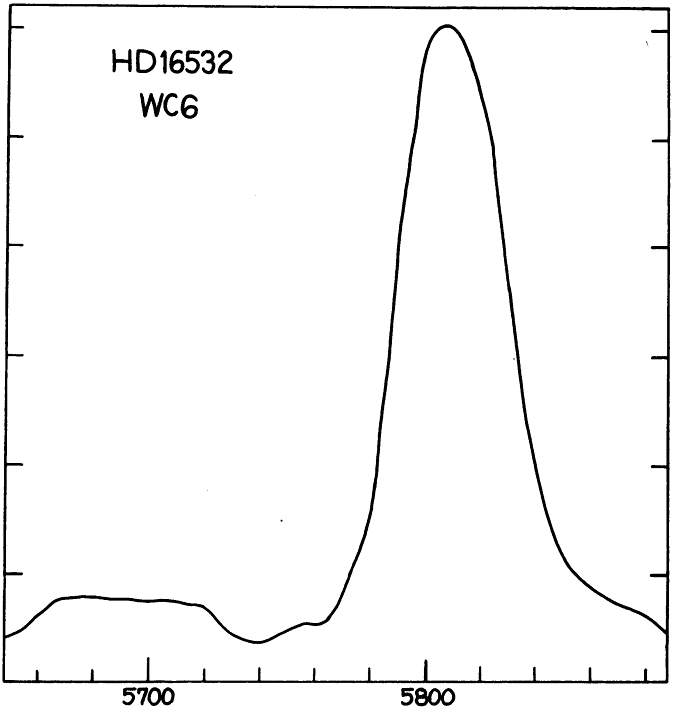

Fig. 7. Scanner profiles of C III 5696 and C IV 5808 in HD 16532 (WC6).

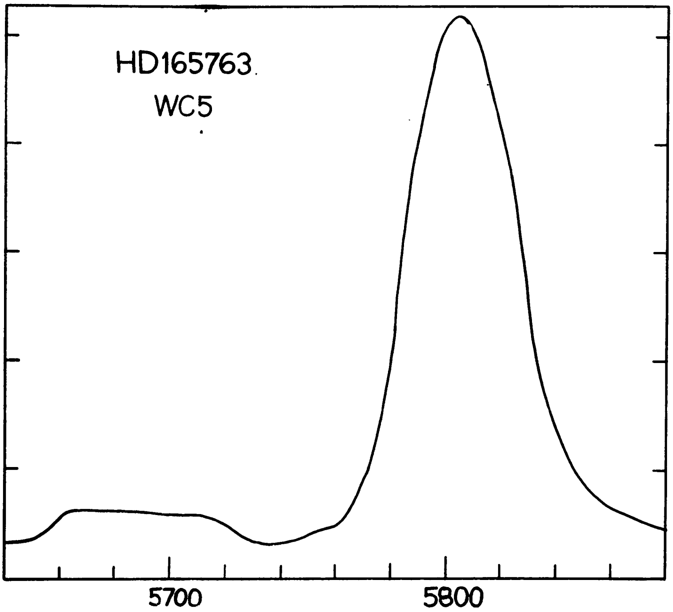

Fig. 8. Scanner profiles of C III 5696 and C IV 5808 in HD 165763 (WC5). Note the dramatic flattening that has taken place in C III 5696.

the dramatic change from a distinctly round-topped profile in WC9 through progressively flatter profiles in the hotter types to a very flat-topped profiles in WC5. The increase in line width used to set up the the WC subclasses is also readily apparent.

It is my contention that this behaviour allows only one interpretation regarding the temperature stratification under reasonable assumptions concerning conditions in the envelope. We can apply Sobolev's theory for expanding envelopes as modified by Castor (1970) and Castor and Van Blerkom (1970) since their basic condition is definitely satisfied i.e. the velocity of expansion and hence the velocity gradient in the line of sight is very large, compared to the thermal motions. Hence the problem is dominated by the expansion of the envelope and emission and absorption can be assumed to take place only over the distance corresponding to two Doppler half-widths. I will not discuss the details of such calculations here since they are fully covered in the article by Van Blerkom in his discussion of the 'On-the-Spot-Approximation'.

However, the basic conclusion reached is that a flat-topped profile is produced in an optically thin region which is expanding with constant velocity. Applying this to C III 5696 means that in the hottest WC stars the line must be produced in some part of the envelope which meets these conditions. (Please note that optically thick or thin as used here refers to the optical depth in the distance in the envelope corresponding to two Doppler thermal half-widths according to the Sobolev approximation. Once outside this region the envelope is completely transparent). The most likely location is at some distance from the star so that the density and hence the optical depth has become sufficiently low. However, this also means that the C III in the interior regions must not be producing any λ 5696. Otherwise, since the density is high and consequently the optical depth large a round-topped profile would be produced instead. This can be accomplished (1) by increasing the degree of ionization so that C IV is the dominant ion (if T decreasing with radius) or (2) by cutting off the special mechanism that may be responsible for λ 5696. The constant velocity requirement must be met by the acceleration (or deceleration) mechanism which is still unknown.

Now if one accepts a decreasing temperature and an accelerating velocity field, then the above indicates that as one increases the stellar temperature as indicated by the spectral sub-class C IV becomes the dominant ion and produces a round-topped profile at all times which simply gets stronger as the type gets earlier. The temperatures reached are not high enough to produce sufficient C V so that it never becomes the dominant carbon ion. This C IV emission occurs throughout the envelope in high density regions as well as low and consequently in no case could it have a flat-top. The behaviour of C IV is not specified in the second case where the special excitation mechanism is destroyed. On the other hand with an increasing temperature and a decreasing velocity field then C IV must occur in a region exterior to C III 5696 i.e. in a region of even lower density and hence of even lower optical depth. Consequently the C IV lines must exhibit flat-topped profiles which would most likely become less flat-topped as one went to earlier spectral type because one would expect the C IV region to encompass more material at higher density with increasing temperature. This would apply in both cases since the region of higher temperature is always exterior to the C III region.

The observed behaviour of the C IV 5808 multiplet is also shown in Figures 4 to 8 and it is clearly seen that it is always round-topped and hence the increasing temperature alternative must be ruled out i.e. *the temperature must decrease radially outwards from the star*. This behaviour can also be demonstrated theoretically by computing the line profile expected from a radially expanding spherically symmetric envelope with some assumed velocity and temperature distributions using the 'On the-Spot Approximation'. We assume a temperature decreasing with increasing radius and a velocity law of the form

$$v^2 = v_0^2 + (v_\infty^2 v_0^2)\left(1 - \frac{R_0}{r}\right)$$

as might be expected if radiation pressure is responsible for the acceleration. v_∞ is the velocity at infinity, v_0 the initial velocity, r the radial coordinate and R_0 the stellar radius. This law guarantees the accelerating envelope where the density is large and the approximately constant velocity in the outer envelope where the density is low. We can then impose an arbitrary cut off to the C III 5696 emission without requiring a detailed knowledge of its excitation mechanism. That is to say, we can compute a series of profiles produced by the envelope with differing values of some critical inner radius inside of which no C III 5696 emission occurs. If the temperature profile were even crudely correct then we should be able to mimic the qualitative behaviour discussed above. Figure 9 indicates the results: as the cut off radius increases the profile becomes more and more flat-topped exactly in the manner observed. Similar calculations could be made for the temperature increasing with radius case but these were not performed since the observations already rule out the qualitative predictions. Therefore, we can safely conclude that over most of the radius the temperature must decrease outwards. This of course immediately rules out Limber's rotational model.

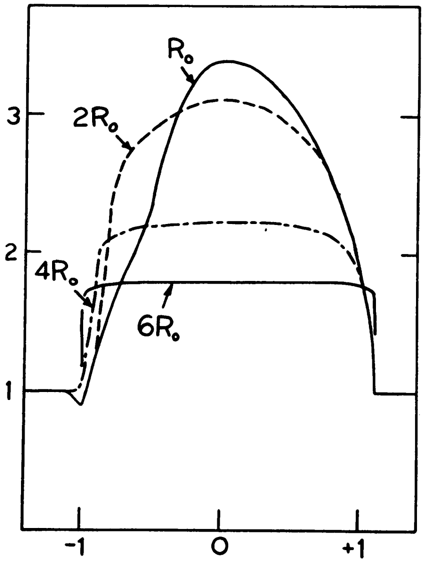

Fig. 9. Theoretical profiles computed for a spherically symmetric radially expanding envelope. R_0 is the stellar radius, the continuum is normalized to 1.0, and the velocity scale to 1.0 for the maximum velocity. The profiles show the expected change as the inner cutoff radius becomes progressively larger.

The distinction between a simple increase in ionization or the destruction of a special excitation mechanism is not so easily made. The difficulty is the severe blending that is present in most emission lines in WC spectra and which makes precise profile determinations very hazardous. However, it does appear that other C III lines do exhibit the same type of behaviour as λ5696 (e.g. λ3608, λ6720) but not so well defined because of blends. Also the flattening does not always start at the same spectral subclass: λ3608 behaves similarly to λ5696 but λ9710 does not really look flat-topped until WC6 or WC5. Consequently it seems likely that both possibilities for the inner cutoff occur but that the special excitation mechanism starts getting destroyed before the conversion of the C III region into predominantly C IV by increased ionization takes place. The C II lines in stars hotter than WC9 are so weak and badly blended as to render them useless in profile determination. They should of course become flat-topped even more rapidly than the C III lines and remain so until there is virtually no C II left.

In principle it also seems possible to set definite dimensions to the C III emitting region if one had a satisfactory velocity and temperature distribution. Further work along the lines of Castor and Van Blerkom's theoretical studies is clearly in order before such estimates can be made.

The final picture for the temperature profile requires one additional detail, namely reconciliation of the very high electron or kinetic temperatures required by the presence of lines from O VI and other highly ionized atoms and the considerably lower photospheric temperatures implied by the continuum (Kuhi, 1966) and other temperature determinations (Morton, 1970). Since the observations rule out any increase in temperature occurring over a large fraction of the radius the only acceptable solution is to have a very rapid temperature increase near the surface occurring over a very small (and hence unobservable) range in radius, probably less than 1% of the total radius. This would then correspond to the region in which the energy required to maintain the envelope is dumped by some mysterious as yet totally unknown mechanism. The final temperature profile then would have a very rapid initial rise to a few 100000 K followed by a gradual decrease with increasing radius.

Therefore, one might conclude that the temperature stratification problem is definitely solved for the WC stars. Unfortunately no such firm statement (except by analogy or by faith) can be made for the WN stars since no flat-topped lines are observed other than He I. Comparing He I profiles which are flat to He II profiles which are round-topped in all types would strongly suggest, however, that the same conclusion applies to the WN stars as well. Ionization equilibrium calculations would help considerably here since the conclusion implies that N III persists longer in large enough quantities in the WN stars than C III does in the WC stars. Otherwise the N III lines should be more flat-topped than they are observed to be in the hotter WN stars. Alternatively the temperature structure may remain the same among different subclasses while the extent of the envelope changes.

Acknowledgements

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DISCUSSION

Sahade: We started talking about percentage of binaries and the ways in which we can detect them. Perhaps Virpi Niemela could add a few words about this question. I am happy to see that the figure that represents the percentage of binaries among WR stars surpasses 70%; it is such a large percentage that there can be little doubt that they all must be binaries. I feel certain that the next meeting will find everybody agreeing on this.

Niemela: I should like to show some spectra of γ_2 Velorum taken by Perrine in 1919 (Figure 10), where you can see the violet-shifted, variable absorption edge of the He I 3888 line. The variations of

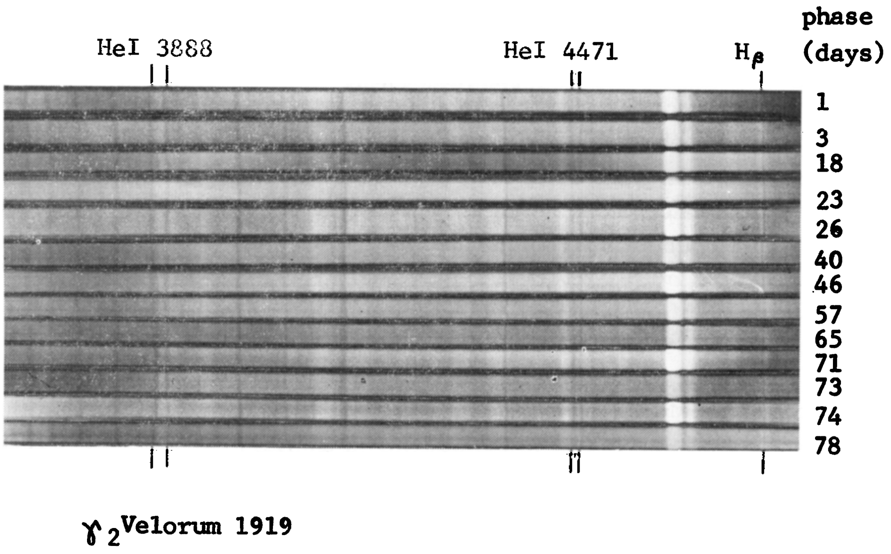
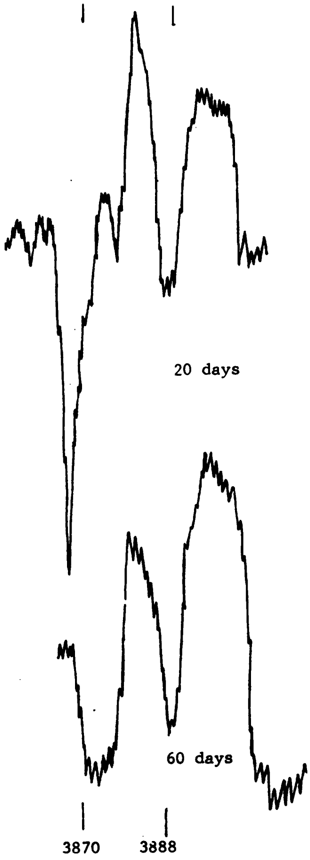


Fig. 10.

the shape of this absorption line depend on the phase of the binary, and so do the *V*/*R* variations of the Balmer and the He I emission lines. The same thing is shown by the spectra taken by Dr. Sahade in Cordoba, between 1948 and 1962. When the O star is in front, the violet absorption edge of He I 3888 becomes very strong, and the emissions have their peak intensity on the violet side. When the Wolf-Rayet star is in front, the violet-displaced absorption edge of He I 3888 is very broad and very shallow, and the emission lines have their intensity peak shifted to the red. These *V*/*R* variations in the emission lines could perhaps be explained in terms of Doppler effect as mass flows from the WC to the O star. In microphotometric tracings this kind of variations can be better observed. Figure 11 shows the He I 3888 emission; at phase 20 days (according to Ganesh and Bappu), the violet part is much stronger and the violet absorption edge very intense, while at phase 60 days, the violet displaced absorption is wide and shallow, and the emission line intensity peaks on the red side. The same kind of behavior can be observed on the spectra taken by Perrine, so it seems that no changes have occurred in 50 years time. The microphotometric tracings of Figure 12 show similar *V*/*R* variations in Hβ on Perrine's plates.

Coming back to the violet-displaced absorption of He I 3888, at phases near 20 days, and perhaps also near 64 days, there appear two components, one of which changes velocity very fast, in 24 h, or so, and then disappears. At phase of about 17 days, there is a remarkable splitting into two very strong components. He I 4471 seems to exhibit the same kind of behaviour. In Figure 13 we can see the variations in radial velocity of the violet-displaced He I 3888 absorption. The circles are velocities relative to H8, since Perrine's plates have no comparison spectra. The velocities go from



γ_2 Velorum 1960

Fig. 11.

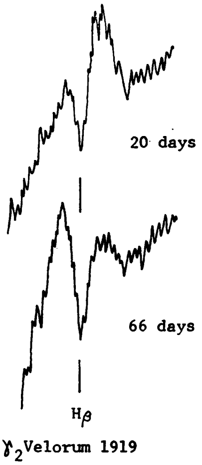


Fig. 12.

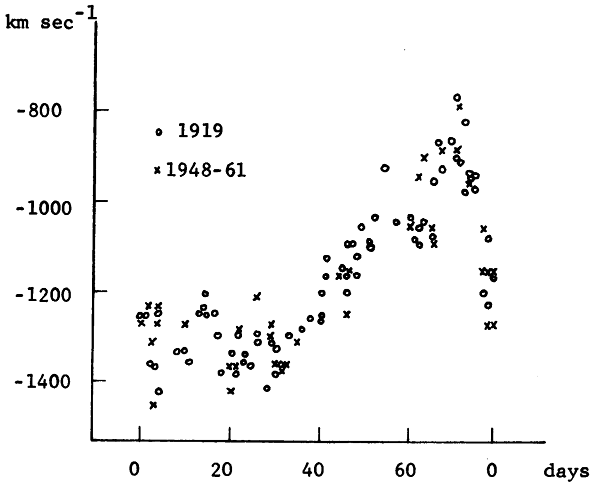


Fig. 13.

— 800 km s^{-1} to — 1400 km s^{-1}, so the amplitude is twice as large as that derived from the velocities of the emission lines.

Bappu: And this reproduces every period?

Niemela: Yes, Perrine's plates cover 2½ periods. The same curve is derived from the plates Dr. Sahade took in Cordoba between 1948 and 1962. The superposition of the two curves has permitted me to improve Ganesh and Bappu's period to 78.5004 days.

Sahade: The behaviour of the violet-displaced He I 3888 with phase is similar to what we find in stars like β Lyrae, for instance. There is a certain variation in the shape, in the structure, and in the profile of He I 3888 which changes with phase, and this must be connected, in the case of β Lyrae, with the gas stream that comes from the B8 component towards the unseen companion, and the variations must be also connected, not only with the geometry of the problem, but also with the outflow of matter. Allen Batten and I are studying new material on β Lyrae, and we hope to being able to throw more light on the problem of He I 3888.

Underhill: A part of the larger amplitude of λ3888, may be due chiefly to increased rates of ejection at those phases. Either you say, the largest amplitude is the amplitude of the stellar motion, or you say the smaller one is, and you are always getting more outflowing gas.

Sahade: I think that λ3888 is formed way out from the system, and, therefore, the amplitudes might be connected with the shape of the outer envelope, and perhaps with the way in which material is replenished to the envelope. We have to check this.

Conti: Even with such a sharp line, you think it is due to the system, rather than...?

Sahade: But sometimes it is not very sharp, and sometimes you see many components.

Underhill: The question I am trying to get at is, whether that displacement is the real amplitude, or whether it is just a false amplitude due to seeing it at moments of greater outward driving force.

Conti: I would think that that is the correct amplitude.

Sahade: We have to observe the star in many cycles and see whether there is any correlation between the intensities of the line, the behaviour velocity-wise, and so on.

Underhill: How big is the orbit? It is a long period, 78 to 79 days, but with respect to the size of the stars (you know the nominal size of an O9 and the nominal size of a Wolf-Rayet say 20 solar radii), what is the size of the orbit? How much space is there in between? Because, if you are going to see λ3888 in absorption over all that space, the absorbing gas must have something to be projected against, which makes you wonder if there is a lot of what I call 'false' light or extra light in the system due to a lot of electron-scattering.

Smith: The separation of the system is 300 solar radii, according to Bappu's figures.

Kuhi: Could I say something about λ3888 also? In V444 Cygni for example, which is a close binary, that line, does not seem to have the motion of the binary system, although at certain phases, it doubles by quite a large amount. So, you might say that in a binary system in which the stars are close together, the He I emitting region really extends past both stars and it is very large, surrounding the entire system. In the case of γ_2 Velorum, the period is so long and the separation quite large, that it may be that the He I emitting region again probably being comparable in size to what it was in V444 Cygni is sharing the binary motion because it is still far enough away from the O-type star. However, it is still close enough so that there is enough interaction so that you actually end up with streams of material perhaps flowing around the O-type star and seen in projection against it. I do not really know, I am just suggesting the possibility.

Conti: I will throw in something else. HD 193793 is the star in which this violet-shifted absorption line at λ3888, discovered by Anne Underhill seems to be a binary of a rather long period. I have plates extending over 3 or 4 yrs and I think the period is a year or a few years. I have measures of λ3888, which is quite broad, plus the violet-shifted absorption component of the C III triplet. Both show the same large violet shift, and they show a motion which is opposite to that of the absorption lines in the O star. So in HD 193793, which is apparently a very wide binary, the λ3888 appears to follow the star.

Sahade: There is a case, HD 211853, where the opposite was true i.e., in which the velocities from the violet-displaced line of He I 3888 followed the O star, rather than the WR star.

Bappu: Almost in every case that I can think of, starting from CQ Cephei, the behaviour of λ3888 is different from the rest of the lines.

Kuhi: It is certainly always different, but is it really out of phase with the other lines?

Bappu: I have never come across a situation where it was out of phase.

Underhill: That is very reasonable for the spectroscopic characteristics. If you are ever going to see any reasonably hot, thin gas, you are going to see it by means of that line. The only better line would be λ10830, but it is too difficult to observe.

If it goes with the speed of the star, it will not go any faster than the star around the orbit. However, if you are making an apparently larger K, it must be going faster. Then you have to say that those changes that give you an idea of an apparent extra K, are actually changes in outflow velocity. And that means that in the case of γ_2 Velorum we are observing changes of outflow velocity on the order of 1200 km s^{-1}, which is a considerable amount.

Sahade: Now, as regards the location of the source, I think that we have to remember that Stecher's UV observations showed us the intercombination line, which should arise from a less dense region, and the suggested expansion velocity is the same as the one you obtained from He I 3888. I remember Stecher reported these observations at Boulder.

Morton: Stecher's resolution and wavelength scale are not adequate for estimating a velocity shift of λ1909. However, one Princeton UV spectrum shows that the C III 1175 line does show an ejection velocity of a few hundred kilometers a second, but that could be part of the overall Wolf-Rayet ejection effect. I see no reason to suspect that it is connected with the kinetic problem.

Sahade: Summarizing, I think we should accept that the envelope where the violet-displaced He I 3888 is formed, surrounds the whole system, rather than only the W star.

Niemela: Then, why does He I 3888 show a radial velocity curve of such large amplitude?

Sahade: I still think that the reason must be connected with what I said a little bit earlier.

Voice: And perhaps the large distance between the components.

Morton: The distance between the components does not particularly worry me, because the interferometer data shows that the Wolf-Rayet shell is still in the Roche lobe, and with a situation like that, you can imagine some additional complications.

Underhill: What does worry me, is the apparent changes in the ejection velocity; these are considerable changes.

Bappu: This particular plot of yours of λ3888 shows up the fact that you do find this amplitude of the velocity curve from cycle to cycle, and that the curve is well defined.

My question now is whether the apparent increases in the amplitude are confined to a very limited range of phase values around zero. It is around zero, that you get this sharp, violet-displaced feature which comes at about 1300 km s^{-1}, over and above the normal value of about 800 or so for the Wolf-Rayet star.

Now, if you get it sometimes, it is possible that at phase zero, your points go up to 1300 and then increase the overall velocity value. Could this the be reason, or is the cause something else which is systematic and smooth, right through the entire velocity curve?

Sahade: I suppose you have to evaluate the whole thing by considering the way the profile changes, before you try to draw any conclusions.

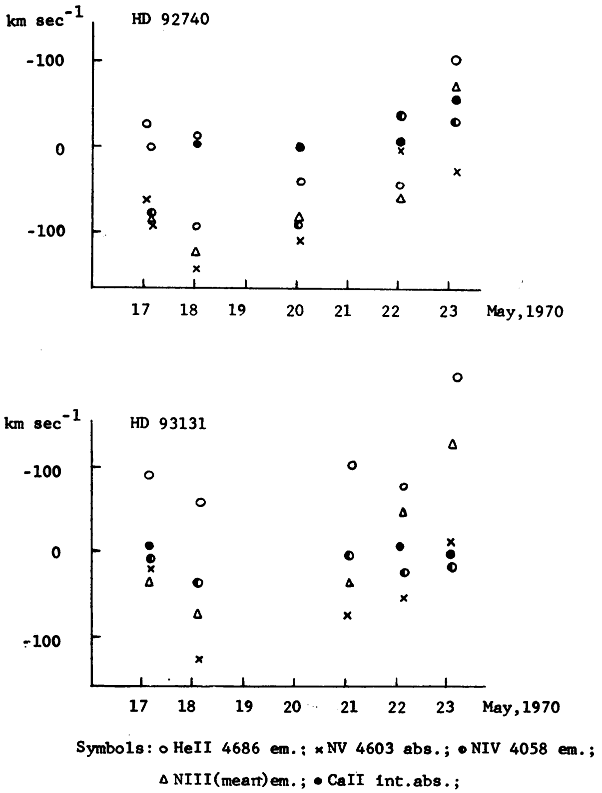


Fig. 14.

Bappu: No, I am not trying to draw any conclusions. I am only saying, that if you plot over the conventional $\lambda 3888$ absorption line velocity curve, you will find that around phase zero, where you do get some of these sharp displaced features an additional 600 km beyond, then, apparently, the whole amplitude of the velocity curve would change by another 600 km.

Niemela: I never used the two components. I always used the most intense component, and when it is double it only lasts for some 24 h. And 24 h in almost 80 days is a very small fraction that could not affect the velocity curve. If I may, I would like to show you observations of another two WR stars, HD 92740 and HD 93131, both WN7 and in Carina, that show the Balmer lines in weak absorption. The observations were made at Tololo. Figure 14 show plots of the measured radial velocities; they look like parts of velocity curves. The two stars have the same apparent magnitude, the same spectral sub-type; have they about the same period?

De Groot: How are the curves for different elements, do they cross over or are they parallel?

Niemela: They are approximately parallel. This is what usually happens in WR stars, the different elements suggest different γ-velocities. There is another thing: N V in absorption is not violet-shifted, while the N IV 3482 absorption edge is violet-shifted some 500 km s^{-1}.

Kuhi: Should you not point out that radial velocity value of the interstellar line at about phase 23 days, which indicates that there may be something wrong with the spectrograph?

Niemela: Yes, in this case there may be something wrong. In the others cases, the velocities of the interstellar line were just the same all the time. In both stars the hydrogen absorption lines are seen up to H11. The radial velocity appears also to be variable, the difference between extreme values being larger than 100 km s^{-1}.