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THE ORBITAL ELEMENTS OF γ_2 VELORUM

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ABSTRACT

A new orbital solution has been derived for the γ_2 Velorum system from 49 moderate- and seven high-dispersion spectrograms. The new orbit yields larger eccentricity ($e = 0.40$) and considerably higher semiamplitude for the absorption-line component than the previous study by Ganesh and Bappu (1967). The resulting minimum masses are 17 and 32 $\mathfrak{M}_\odot$ for the WC8 and the O9 I components, respectively. The excitation potential versus barycenter velocity correlations present in the WC8 component spectrum are interpreted as indicating an outward accelerated velocity field; and the phase-dependent variations of the violetshifted He I λ3888 absorption, as indicative of an asymmetric shape of the envelope where the line is formed. Such an asymmetric envelope may actually result from the merging of the He I line–forming layer of the W-R envelope and an expanding, asymmetric, diluted envelope associated with the system and seen predominantly around the conjunction where the O component is in front.

Subject headings: stars: binaries — stars: individual — stars: Wolf-Rayet

I. INTRODUCTION

The γ_2 Velorum system (HD 68273) is the brightest binary system with a Wolf-Rayet component. The system, classified as WC8 + O9 I (Conti and Smith 1972), has been the subject of a number of past and recent studies. Sahade (1955) announced it to be spectroscopic binary, and Ganesh and Bappu (1967) were the first to determine its orbital period as being of 78.5 days, and to derive orbital elements. This derivation was based on radial velocities of the C III–IV λ4652 blend for the WC star, and on the radial velocities of the Hγ absorption for the O component, from grating spectrograms with a dispersion of 125 Å mm^{-1}. Narrowband photoelectric photometry combined with Ganesh and Bappu's (1967) results led Moffat (1977) to conclude that the lower limit of the mass of the WR component is about 15 $\mathfrak{M}_\odot$. Since "the mass" of a Wolf-Rayet star is usually considered to be 10 $\mathfrak{M}_\odot$, a generalization of the results derived for the WN + O system V444 Cygni, it is of the utmost importance to undertake a new determination of the masses in γ_2 Vel, not only to ascertain Moffat's conclusion but also principally because of its bearing on the question of the evolutionary status of the WC stars and on the question whether or not they form a uniform group of objects, two issues that are still unsettled.

In this paper we report on a new investigation of the system of γ_2 Vel, based on a large number of spectrograms with moderate dispersion, where an orbital solution is derived from the measurement of several absorption lines of the O star. We also discuss the correlations of excitation potential versus barycenter velocity and the spectral-line phase-dependent variations related to the velocity field and to the structure of the line-emitting region of the WC component.

One of the main problems for detailed studies of γ_2 Vel is its rather long period. We have been able to improve its value by making use of the old objective prism material taken by Perrine in 1919 at the Córdoba Observatory, together with the material secured by one of us (J. S.) between 1948 and 1962. A preliminary discussion of our results has been given in Niemela and Sahade (1979).

II. THE OBSERVATIONS

Most of the spectrograms used for this study have been secured by one of us (J. S.) at the Bosque Alegre Astrophysical Station of the Córdoba Observatory, Argentina, with the Cassegrain spectrograph attached to the 1.5 m reflector. These spectra were taken in the interval 1948–1962 and have a dispersion of about 42 Å mm^{-1} in the first order; they cover the wavelength region that goes from 3200 to 7000 Å.

A few additional coudé and Cassegrain spectra were obtained by V. S. N. at the Cerro Tololo Inter-American Observatory, Chile, in the years between 1971 and 1977. All spectrograms have been measured by V. S. N. with the Grant oscilloscope-type comparator at the CTIO.

In addition, we had at our disposal 76 old objective prism spectra, with a dispersion of 33 Å mm^{-1} at Hγ, obtained by C. D. Perrine at the Córdoba Observatory between 1919 January and July.

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III. THE SPECTRUM

The spectrum of γ_2 Vel is rather flat, and hence it must be exposed on high-contrast emulsion, like Kodak IV-O, to bring out the spectral details.

The O-type supergiant component has very broad lines. If this broadening is interpreted as being due to rotation, we are then dealing with the fastest rotating O9 I star known, its $v \sin i$ being 200 km s^{-1} (Baschek and Scholz 1971), as compared to the rotational velocities of other O9 supergiant stars, which do not seem to exceed 150 km s^{-1} (cf. Conti and Ebbets 1977). This fact poses the question of whether the O star has gained angular momentum along with accreting mass from the mass-losing WC component.

Detailed description of the composite spectrum and lists of the spectral lines in the photographic region have been reported by Smith (1955) and by Baschek and Scholz (1971). The spectral behavior of γ_2 Vel on our spectrograms has already been described by Sahade (1955, 1958; cf. Struve 1956), by N. de Monteagudo and Sahade (1968, 1970), and by Niemela (1973); therefore, we refer the reader to these earlier reports that are primarily concerned with two of the variable features of the spectrum, namely, the He II emission at 4686 Å and He I absorptions at 3888 Å. The latter feature was described and correctly identified for the first time by Perrine (1920).

IV. THE IMPROVED ORBITAL PERIOD

The availability of material as old as Perrine's has made it possible for us to improve the published period of γ_2 Vel. We did this by deriving the velocity curves from the He I absorption at 3888 Å, both on Perrine's spectra and on the material taken at Córdoba in 1948–1962. We considered the stronger component only.

Since the 1919 material (see reproductions in Niemela 1973), as a result of the lack of comparison spectra, could not be used but for relative determination of velocities, the line at 3888 Å was chosen because it was good and close to an absorption line such as H8. Therefore, the two sets of radial velocities from He I were determined by measuring, on microphotometric tracings, the position of that line relative to H8. The derived velocities are plotted in Figure 1, where the phases were computed by means of Ganesh and Bappu's period. The two sets of velocities suggest a phase shift of about 3 ($\pm nP$) days between the data of the two epochs.

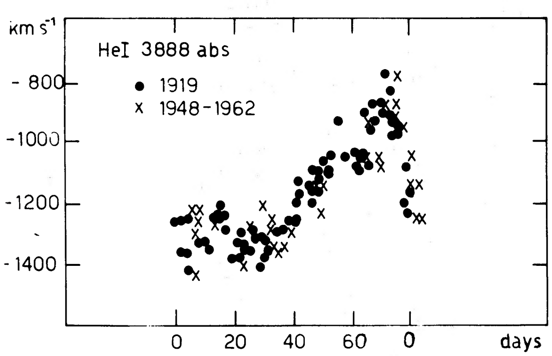

FIG. 1.—Radial velocities of the strongest violet-displaced He I absorption at 3888 Å, relative to the H8 absorption of the O9 I star: *dots*, from the objective prism spectra taken by C. D. Perrine in 1919; *crosses*, from the Cassegrain spectra taken by J. Sahade in 1948–1962. The phases were computed with Ganesh and Bappu's (1967) period.

Now, the best orbital fit for the absorption lines of the O star, measured on the 1948–1962 and the 1971–1977 materials, is obtained for the period 78.500 days. Therefore, it seems reasonable to conclude that $n = 0$, and, as a consequence, we considered the phase shift to be of 3 days; this in turn leads to an improved value for the orbital period of 78.5002 ± 0.0001 days. We should, however, remark that although the best orbit corresponds to $P = 78.500$ days, orbital solutions for periods ranging between 78.490 and 78.530 days are compatible with our data, and neither one of them is completely ruled out.

The Lafler and Kinman (1965) period search program routine was applied to our data. The routine could decide only that the true period is within the range 78.490–78.550 days. This must result because of the large scatter that characterizes the radial velocity distribution from the He I λ3888 absorption. We cannot decide at present whether this scatter is due to real radial velocity variations, i.e., perhaps secondary oscillations within the longer period (cf. Moffat 1977), or merely to errors of measurement. Periods shorter than 78.490 days and longer than 78.550 days are ruled out by our data.

V. THE RADIAL VELOCITIES

All suitable absorption and emission lines were measured for radial velocity on all of our spectrograms. The results are listed in Table 1, where we give (*a*) in column (3), the average radial velocities from the measured absorption lines, namely, H: from H10 through H4; He I: $\lambda\lambda$3820, 4026, 4471, 5876; He II: $\lambda\lambda$4200, 4541, 4686, 5411; and Si IV: $\lambda\lambda$4088, 4116; (*b*) in column (4), the average radial velocities from the emission lines that correspond to the C III and C IV ions, namely, C III: λ5696, C III–IV: λ4652, and C IV: $\lambda\lambda$3689, 4441, 5018, 5801–11; (*c*) in column (5), the radial velocities of the He II λ4686 emission line; (*d*) in column (6), the radial velocities of the strongest He I λ3888 violetshifted absorption; and (*e*) in column (7), the average radial velocities from the violetshifted absorption edges of C IV $\lambda\lambda$5801–11.

We should mention that although the upper members of the Balmer series, from H16 to H11, were also measured, they were not considered in averaging the radial velocities from the absorption lines because of their being difficult to measure and, therefore, less certain; moreover, H12 seems to be a blended line, and H11 appears to be contaminated with N III. On a few plates the He II λ5411 emission was also measured, but the resulting values are not included in Table 1.

A plot of the radial velocities listed in Table 1 shows

TABLE 1

RADIAL VELOCITIES OF γ_2 VELORUM

DATE (JD) 2,430,000.000+	PHASE[a] (P)	Heliocentric Radial Velocities (km s^{-1})[b] Abs.	C Em.	He II λ4686 Em.	He I λ3888 Abs.	C IV λλ5801–11 Abs.	EMULSION (Kodak)	DISPERSION (Å mm^{-1})
2872.839	0.32	+26 (10)	−45 (4)	+3	−1314	...	103a-F	42
2873.662	0.33	+53 (13)	−22 (4)	+60	−1307	−936	103a-F	42
2875.704	0.35	+48 (12)	−54 (5)	...	−1243	−867	103a-F	42
2876.628	0.36	+43 (7)	−42 (5)	+59	...	−949	103a-F	42
2956.739	0.38	+43 (16)	−67 (5)	+11	−1283	−851	103a-F	42
2957.565	0.40	+30 (16)	−21 (6)	+25	−1245	−915	103a-F	42
2970.517	0.56	−9 (4)	+38 (5)	+82	...	−874	103a-F	42
2971.551	0.57	−11 (5)	+32 (5)	+22	...	−941	103a-F	42
2972.695	0.58	−4 (5)	+56 (5)	+65	...	−835	103a-F	42
3015.507	0.13	+37 (16)	−57 (5)	+1	−1286	−938	103a-F	42
3338.758	0.26	+62 (13)	−131 (3)	−27	−1294	...	Process O	42
3340.581	0.28	+58 (10)	−143 (3)	−18	−1293	...	IV-O	42
3630.706	0.97	−21 (13)	+41 (3)	+124	−1147	...	IV-O	42
3630.776	0.97	−27 (15)	+64 (6)	+135	−1169	−780	103a-F	42
3631.672	0.98	−20 (11)	+8 (3)	+82	−1205	...	IV-O	42
3631.710	0.98	−18 (6)	+46 (5)	+109	...	−774	103a-F	42
3632.679	0.99	+3 (13)	+40 (2)	+89	−1231	...	IV-O	42
3632.751	0.99	+4 (7)	+8 (5)	+127	...	−842	103a-F	42
3636.592	0.05	+36 (14)	−67 (3)	+82	−1205	...	IV-O	42
3636.660	0.05	+32 (6)	−99 (4)	+38	...	−952	103a-F	42
3666.813	0.43	+31 (12)	−27 (3)	+18	−1219	...	IV-O	42
3666.830	0.43	+42 (3)	−64 (2)	...	...	−872	103a-F	42
3666.845	0.43	+36 (13)	−72 (3)	+5	−1263	...	IV-O	42
3667.507	0.44	+32 (13)	−89 (3)	−17	−1244	...	IV-O	42
3667.801	0.44	+38 (12)	−49 (3)	+46	−1220	...	IV-O	42
4026.817	0.02	+37 (13)	−43 (5)	+129	−1176	...	IV-F	42
4027.803	0.03	+58 (4)	−38 (3)	+126	...	−864	IV-F	42
4027.841	0.03	+38 (13)	−15 (3)	+59	−1213	...	IV-O	42
4028.776	0.04	+48 (12)	−46 (3)	+117	−1273	...	IV-F	42
4029.657	0.05	+53 (6)	−76 (5)	+74	...	−886	IV-F	42
6556.668	0.25	+75 (6)	−104 (2)	...	−1261:	...	IV-O	42
6557.750	0.26	+65 (12)	−125 (3)	−90	−1315	...	IV-O	42
6557.814	0.26	+69 (12)	−122 (3)	−50	−1302	...	IV-O	42
6557.829	0.26	+73 (8)	−166 (3)	−130	−1310	...	IV-O	42
6558.699	0.27	+65 (11)	−187 (3)	−39	−1291	...	IV-O	42
7303.656	0.76	−18 (8)	+135 (3)	+146:	−1053	...	IV-O	42
7305.610	0.79	−49 (11)	+153 (5)	+159	−1097	−680	103a-F	42
7305.699	0.79	−38 (9)	+111 (3)	+139	−1033	...	IV-O	42
7306.761	0.80	−52 (12)	+93 (3)	+147	−1116	...	IV-O	42
7306.796	0.80	−61 (15)	+140 (4)	+190	−1026	−676	103a-F	42
7307.749	0.81	−40 (9)	+75 (3)	+176	−1073	...	IV-O	42
7308.813	0.83	−45 (12)	+100 (3)	+176	−1050	...	IV-O	42
7310.746	0.85	−70 (11)	+111 (3)	+193	−1039	...	IV-O	42
7312.673	0.88	−49 (10)	+116 (3)	+215	−1041	...	IV-O	42
7314.547	0.90	−66 (5)	+87 (2)	+88	−868:	...	IV-O	42
7319.814	0.97	−24 (10)	+91 (3)	+125	−1149	...	IV-O	42
10997.525	0.82	−40 (9)	+96 (1)	...	−1039	...	IIa-O	9
10999.807	0.84	−96 (1)	+85 (2)	...	...	−812	IIa-F	18
11289.785	0.54	−1 (13)	+10 (3)	+60	−1146	...	IIa-O	9
11488.499	0.07	+57 (13)	−82 (3)	+16	−1357	...	IIa-O	9
11490.530	0.10	+69 (8)	−89 (5)	+33	...	−909	098-02	18
12890.482	0.93	−64 (7)	+124 (4)	+194	...	−865	098-04	36
12890.490	0.93	−46 (9)	+92 (3)	+181	−1078	...	IIIa-J	18
13203.663	0.92	−73 (8)	+142 (2)	...	...	...	IIIa-J	38
13203.759	0.92	−60 (1)	+161 (2)	...	...	−710	127-04	76
13239.479	0.37	+47 (11)	−41 (3)	+45	−1241	...	IIIa-J	18

[a] The phases were computed with the expression JD 2,433,633.0 + 78.5002E days, where the origin is at the conjunction where the O component is in front.

[b] The numbers in parentheses indicate the number of measured lines.

that all the emissions and violetshifted absorption edges follow the orbital motion of the W-R component, while the absorptions under (*a*) follow the orbital motion of the O companion. In this context we should mention that the variable structure of He II λ4686 is at least partly due to the He II λ4686 absorption of the O star cutting into the W-R emission. At some phases, the line originating in the O supergiant appears to have a P Cygni–type profile, and then the feature at 4686 Å can be described as displaying a narrow emission superposed upon the broad emission line of the W-R component, as reported by Sahade (1955, 1958; cf. Struve 1956).

VI. THE ORBITAL ELEMENTS

The orbital elements were derived by using the program developed by Bertiau and Grobben (1969). The values corresponding to the radial velocities in columns (3), (4), (5), and (6) of Table 1 are given in Table 2, which also lists, for comparison, the orbital elements that were derived by Ganesh and Bappu (1967).

The radial velocities from the absorptions that originate in the O component, and the radial velocities from the C emissions are plotted in Figure 2, where the drawn velocity curves correspond to the orbital elements listed in Table 2. Figure 3 shows a plot of the radial velocities derived from the He II emissions at 4686 and 5411 Å; although they seem to define the same orbit as the other emissions, they suggest a systemic velocity ($+69$ km s^{-1}) that is more positive than the one suggested by the C emission (-4 km s^{-1}).

In view of the very large scatter of the radial velocities from the features associated with the W-R component (see Figs. 2 and 3), it was considered advisable not to attempt the simultaneous derivation of a set of the orbital elements for the two components. It seemed preferable to use the velocities from the features that originate in the O component to define the orbital elements, and to use the semiamplitude of the velocities from the C emissions to derive the masses. Another reason that led us to this decision is the fact that an independent orbital solution for the average velocities from the C emissions yielded an eccentricity that was smaller than the one that was derived from the velocities of the lines associated with the O component; this is also true if we consider the velocities from the He II emissions, as can be seen from Figure 3. We have no ready explanation for such a result. It may be due to uncertainties in the measurement of broad and unsymmetrical features, or, more

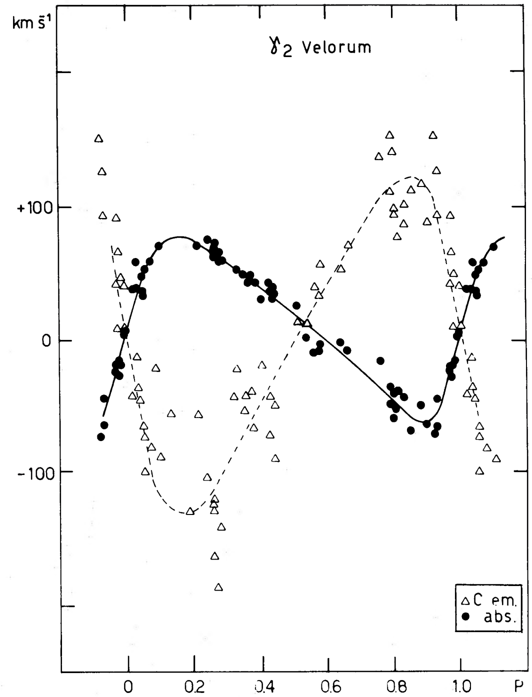

FIG. 2.—Radial velocities from absorption lines originating in the O star (*filled circles*) and from C emissions (*triangles*). The curves represent the orbital solutions labeled "O9 I component" and "C em." in Table 2. (This figure is similar to Fig. 1 in Niemelä and Sahade 1979).

TABLE 2

ORBITAL ELEMENTS[a] OF γ_2 VELORUM FROM DIFFERENT ELEMENTS

Parameter	O9 I Component	WC8 Component: C Em.	WC8 Component: He II Em.	WC8 Component: He I λ3888 Violetshifted Abs.	Ganesh and Bappu's (1967) Elements: Hγ Abs.	Ganesh and Bappu's (1967) Elements: C III–IV Em. at 4652 Å
P (days)	78.5002 ± 0.0001	...	...	...	78.5	...
γ (km s^{-1})	$+12 \pm 1$	-4 ± 3	$+69 \pm 4$	-1185 ± 5	-18.0 ± 1.8	$+59.9 \pm 3.0$
e	0.40 ± 0.01	0.31 ± 0.02	0.24 ± 0.05	0.5 ± 0.03	0.17	0.17 ± 0.03
ω (deg)	256 ± 3	94 ± 6	84 ± 14	56 ± 6	...	87
T_0	JD 2,432,846.8 $\pm$ 0.5	...	...	...	...	...
K (km s^{-1})	70 ± 2	130 ± 10	111 ± 6	166 ± 9	43.1 ± 2.6	153.5 ± 4.4
$a \sin i$ (km)	6.7×10^7	1.33×10^8	1.16×10^8	1.55×10^8	...	...
$a \sin i (R_\odot)$	96	191	167	223	...	...
$f(\mathfrak{M})$ $(\mathfrak{M}_\odot)$	2.1	15.4	10.2	24.3	...	...

[a] And probable errors.

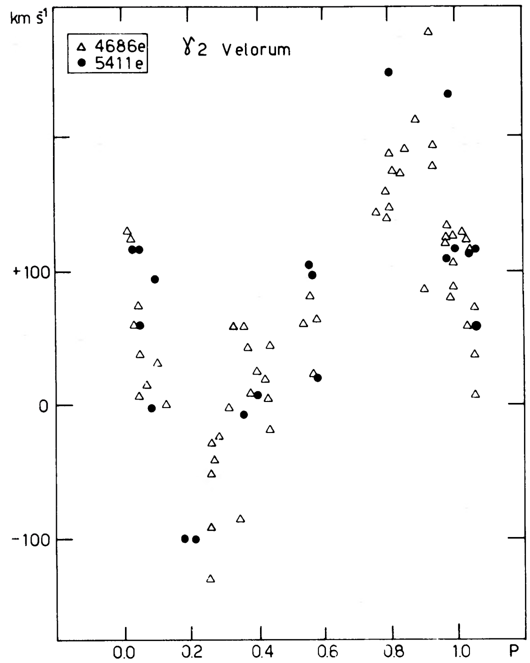

FIG. 3.—Radial velocities of He II emissions at 4686 Å (*triangles*) and at 5411 Å (*filled circles*).

probably, to a particular distribution of the C and He II ions in the emitting envelope around the W-R star.

As we have already mentioned, the violetshifted absorption edges of the emissions partake of the motion of the W-R star. An independent orbital solution for the violetshifted absorptions of He I λ3888, which also follow the motion of the W-R component, led to a large value of the eccentricity, of the same order as that derived for the O companion. On the other hand, the resulting value of K was slightly larger than the values of K derived from the He II and C emissions.

The adopted elements are listed in Table 3; they remain unchanged, within the errors quoted, for the range of periods that are indicated in § IV.

VII. THE WOLF-RAYET ATMOSPHERE

Information on the characteristics of the Wolf-Rayet envelope can be derived from the correlation with excitation potential of the different systemic velocities suggested by the violetshifted absorption edges and by the emission lines of different ions, and also from an analysis of the behavior of the violet-shifted He I λ3888 absorption at different phases of the orbital cycle.

1. The systemic velocities of the violetshifted absorptions are inversely correlated with their excitation potentials, as it is shown in Figure 4: the lines with lowest excitation potential yield the most negative systemic velocity. This correlation may also hold in the ultraviolet (Johnson 1978). We interpret it as being due to an outward accelerated atmosphere of the W-R star, and this interpretation agrees with what we know about the velocity fields in other W-R atmospheres (cf. Kuhi 1973; Bappu 1973; Seggewiss 1974, 1975; Niemela 1975). A similar correlation seems to hold for the emission lines (Fig. 5), but here a word of caution is in order because the radial velocities from C II are based only on one line, namely, the one at 4260 Å, which is very broad and asymmetric in nature.

2. The He I λ3888 line displays remarkable variations in intensity and structure which have been reported by several authors (cf. Perrine 1920; Smith 1955; Sahade 1955, 1958; Ganesh and Bappu 1967; de Monteagudo and Sahade 1968, 1970; Rajamohan 1972; Niemela 1973). These variations are phase-dependent and can be summarized as follows (Fig. 6 [Pl. 7]): (*a*) Around the conjunction at which the O9 I star is in front, the violetshifted He I λ3888 absorption is strongest and suggests the effect of diluted radiation; (*b*) at quadratures, the line has a complex structure of several components with different intensities (see illustration in Struve 1956); (*c*) at around the conjunction where the WC8 star is in front, the line has a stellar appearance.

The behavior just described clearly suggests that the layers where the He I λ3888 feature originates are not homogeneous at the different phase angles. Moreover,

TABLE 3

PHYSICAL PARAMETERS[a] OF γ_2 VELORUM[b]

P (days)	78.5002 ± 0.0001
γ (km s^{-1})	12 ± 1
e	0.40 ± 0.01
ω (deg)	256 ± 3
$\mathfrak{M}_{\rm O9\,I} \sin^3 i$ ($\mathfrak{M}_\odot$)	32 ± 6
$\mathfrak{M}_{\rm WC8} \sin^3 i$ ($\mathfrak{M}_\odot$)	17 ± 2
$a_1 \sin i$ (km)	6.7×10^7
$a_2 \sin i$ (km)	1.33×10^8

[a] And probable errors.

[b] Ganesh and Bappu's 1967 values for the masses were $\mathfrak{M}_{\rm O} = 46.3\ \mathfrak{M}_\odot$; $\mathfrak{M}_{\rm WC} = 13.0\ \mathfrak{M}_\odot$.

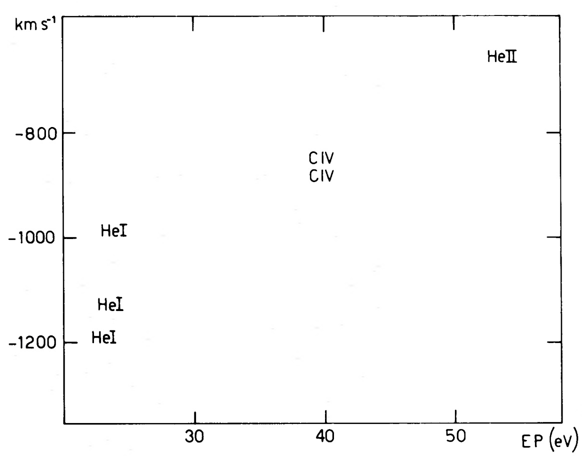

FIG. 4.—Systemic velocity derived from the violetshifted absorption edges against excitation potential of the upper level of the corresponding line. (This figure is similar to Fig. 2 in Niemela and Sahade 1979.)

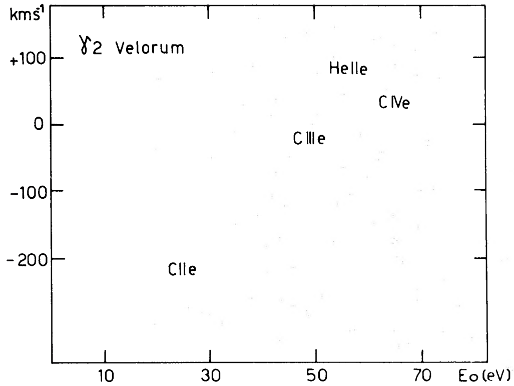

FIG. 5.—Systemic velocity derived from emission lines against the ionization potential of the corresponding ion.

more than one layer must be contributing at particular phase intervals.

The appearance of the line at the conjunction where the O9 I component is in front should result from the contribution of a tenuous, expanding envelope that is asymmetrically associated with the system.

When the line is double, the radial velocities seem to suggest that one of the absorption components probably arises from an envelope that surrounds the O9 I star. The material at our disposal is not enough to permit a stronger statement; however, the fact that the radial velocities from He I λ3888 essentially follow the orbital motion of the W-R member of the close pair certainly means that the major contribution to the absorption comes from the outer edges of the accelerated atmosphere of the WC8 star, and the corresponding γ-velocity supports this assertion.

VIII. CONCLUSIONS

We have derived new orbital elements for the system of γ_2 Vel from a large number of moderate dispersion spectrograms. Now, in view of the fact that no eclipses in the continuum have been detected (Moffat 1977), it seems reasonable to adopt as an upper limit for the orbital inclination a value of the order of 70°. Then the lower limit for the masses of the components comes out to be

$$\mathfrak{M}_{\rm O9\,I} = 38\,\mathfrak{M}_\odot\,, \quad \mathfrak{M}_{\rm WC8} = 20\,\mathfrak{M}_\odot\,,$$

and, therefore, the actual mass of the W-R component of γ_2 Vel should be larger than 20 $\mathfrak{M}_\odot$. This is a most important conclusion because of its bearing on the possible evolutionary history of W-R stars. Moreover, it warns against the general practice of considering 10 $\mathfrak{M}_\odot$ as the representative value of the mass of all W-R stars.

More determinations of masses of W-R stars are certainly needed.

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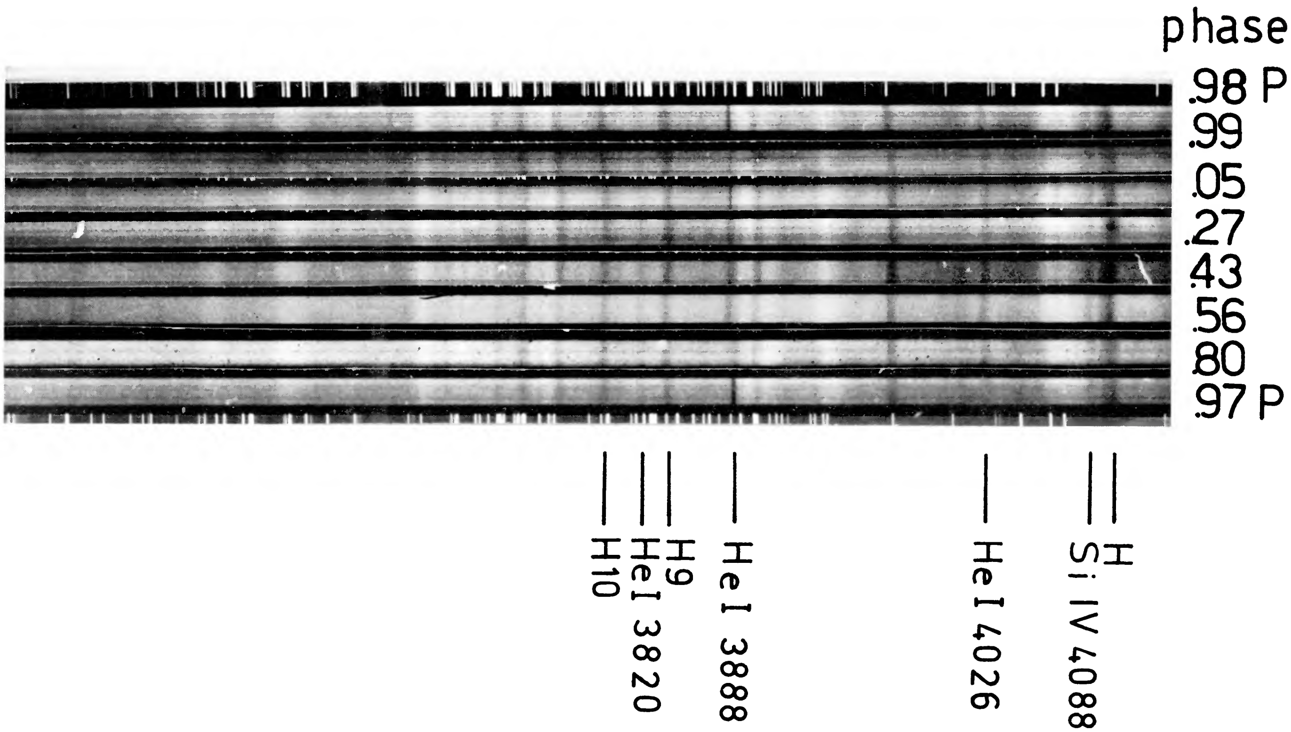

FIG. 6.—Spectra of γ_2 Velorum showing phase-dependent variations of He I λ3888
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