

HD 47129: THE MOST MASSIVE BINARY*

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ABSTRACT

Thirty-two coude spectrograms of Plaskett's star have been obtained. These show that the primary star has a stellar wind which is stronger from the following side of the star. New orbital elements are presented for lines of different excitation. Lines of the secondary absorption spectrum are distinguished from shell features, and show an orbital velocity indicating a mass ratio near unity. The mass of each component exceeds $55 M_{\odot}$. Neither star fills its Roche limiting surface, but it appears that both lose mass to the system. The secondary is underluminous for its mass and may be smaller than the primary. He II $\lambda 4686$ emission is not strongly associated with either star, and arises in part between the two.

Subject headings: stars: binaries — stars: early-type — stars: individual

I. INTRODUCTION

Because of present day interest in the evolution of massive binaries, mass exchange and mass loss in such systems, and the general question of the mass scale for the very hot stars, a reexamination of HD 47129 (Plaskett's star) has been undertaken. This system has long been considered to be the highest mass system known, and we have placed special emphasis on the interpretation of the peculiar secondary spectrum and the determination of the masses of the stars. It was of particular interest to determine whether any or all of the secondary spectrum is attributable to a star rather than gas streams.

Earlier studies of the system (Plaskett 1922; Struve 1948; Abhyankar 1959) revealed the high mass function of the primary, but the actual masses of the star have always been in doubt because of the high scatter and peculiar distribution of "secondary" velocities. The primary is an O7 star, with a period of 14.4 days and $f(m) \approx 12.4 M_{\odot}$. Thus for any reasonable primary mass, the secondary is also massive. No eclipses are seen in the system so that an inclination significantly different from 90° , also implying higher masses, is indicated.

II. OBSERVATIONS

Coude plates have been obtained at both Kitt Peak National Observatory and at the Dominion Astrophysical Observatory (DAO). Most observations were made in the blue-violet region, with dispersions between 6 and $20 \text{ \AA mm}^{-1}$. Because all of the lines are extremely broad and shallow, the spectral lines are very difficult to see, so whenever possible exposures were made on the fine-grain IIIaJ emulsion. All plates

were measured on the oscilloscope display machine ARCTURUS at the DAO, greatly increasing the accuracy over previous studies.¹ Rectified intensity tracings were made of the best plates at representative phases throughout the orbit, and the extremely weak secondary absorptions and broad He II emission were studied on these as well.

In Table 1 we present the velocities measured for the primary star for a variety of different ions. Dates of observation, orbital phases, original plate dispersion, and emulsion are also tabulated. The phases have been computed using the ephemeris given by Abhyankar (1959), where T_0 is the time of periastron passage:

$$T_0 = \text{JD } 2,423,039.94 + 14.3961E.$$

Later we give slightly modified orbital elements, but the eccentricity is so small that the time of periastron passage is poorly determined. Thus we decided to keep Abhyankar's phases for simplicity.

As a check on the accuracy of measurement, the strong interstellar H and K lines were measured on all plates. The scatter is somewhat larger than would be expected from coude plates (K line gives $+17.3 \pm 0.8 \text{ km s}^{-1}$). There is no clear phase dependence of these velocities; however, it is possible that small contributions from circumstellar material may increase the observed velocity range beyond that expected for a purely interstellar line.

III. THE PRIMARY

A detailed description of the primary spectrum has been given elsewhere (Abhyankar 1959 and references therein), and we find no basic changes to this. Briefly, the spectrum is that of an O7 I star with the following

* DAO contribution 283.

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¹ This appears to be contradicted by the smaller formal errors in Plaskett's and Abhyankar's elements. However, when their data are run on our orbital program, larger errors are indicated. Therefore, their errors are derived in a different way.

TABLE 1
VELOCITIES OF HD 47129

DATE (JD 244,000,000 +)	DISPERSION/ EMULSION	PHASE	BALMER		He I	He II	N III	Si IV	N IV	4485, 4503 (emission)
			γ	HIGH						
2100.84	10 IIIaJ	0.03	135	188	197	220	209	200	...	234, 253
0518.01	10 IIaO	0.08	74	112	150	155	161	159	102(e)	176, 176
0287.70*	6 IIaO	0.09	96	122	161	163	171	167	...	160, ...
1426.70	6 IIaO	0.20	4	-40:	33	28	32	19	...	...
2477.70	10 IIIaJ	0.21	-35	-12	-3	91	...	15	...	...
0304.67*	6 IIaO	0.26	-106	-84	-79	-55	-62	-81	-39	-26, -39
2176.67	17 IIaO	0.30	-158	-113	-106	-100:	-98	-120	...	(+13), -85
1442.70	6 IIaO	0.32	-145	-99	-123	-112	-110	-118	-97	-66, -100
2349.93	10 IIIaJ	0.33	-168	-130	-133	-113	-126	-118	...	-130, ...
2349.96	10 IIIaJ	0.34	-137	-143	-134	-124	-135	-130	...	...
2177.65	17 IIaO	0.37	-159	-164	-169	-159	-158	-161	...	..., -107
2422.94	20 IIaO	0.41	-175	...	-143	-136	-152	...	...	...
2481.68*	10 IIIaJ	0.49	-178	-152	-157	-160	-162	-149	...	...(present)
2482.69	10 IIIaJ	0.56	...	-88	-124	-109	-119	-110	...	...
2007.84	17 IIaO	0.57	-69†	-82	-78	-80	-74	-82	...	-67, ...
2468.66*	10 IIIaJ	0.58	-115†	-70	-101	-86	-85	-103	...	...
2008.04	17 IIaO	0.59	-38	-79	-76	-80	-56	-68	...	...
2339.98	20 IIaO	0.64	-53	-53	-23	-17	-19	-16	...	..., +11
0554.98	15 IIaO	0.65	-33	-35	-39	-30:	-33	-47	11	-57, 0
2009.01	17 IIaO	0.65	-45	-21	-15	-10:	+7	-3	...	...
2498.68	20 IIIaJ	0.67	-1	-6	8	6	1	2	...	0, 33
2312.01	10 IIIaJ	0.70	11	11	25	...	47	85:	...	...
0627.76	15 IIaO	0.71	13	40	44	80	40	60	...	60, ...
2441.69*	20 IIIaJ	0.71	41	43	48	58:	62	47	...	47, 113
2010.00	17 IIaO	0.72	107†	60	65	57:	84	63	...	73
0628.76*	6 IIaO	0.78	76	126	140	150	153	130	...	128, 180
0989.71†	6 IIIaJ	0.85	143	190	202	215	204	191	117	...
2083.88	6 IIaO	0.85	149	141	200	193	208	205	164	194
2098.68*	10 IIIaJ	0.88	90	124:	220	228	216	223	...	201
2127.68	10 IIIaJ	0.90	180	188	232	235	247	239	...	255
2329.93	10 IIIaJ	0.94	187	204:	210	220	233	...	...	228
2344.96	15 IIIaJ	0.99	106	161:	195	238	217	197	...	228

NOTE.—Phases computed from $P = 14^d3961$, $T_0 = 23039.94$ (periastron passage). Average p.e. for He I, N III, Si IV, ~ 10 km s^{-1} ; He II, ~ 15 km s^{-1} .

* Tracings made of these plates.

† Hydrogen lines show weak emission in bottom of line.

‡ He I 3888 shows a sharp component at -500 km s^{-1} .

peculiarities: (1) Of emission lines are seen at $\lambda\lambda 4640$ and 4686 , but are not clearly associated with either star; (2) the unidentified emission lines at $\lambda\lambda 4485$, 4503 are seen, and N IV $\lambda 4058$ absorption is present. These lines show orbital motion similar to the other primary spectrum lines.

We also find that there is a velocity-excitation gradient of the type characteristic of massive OB stars (Hutchings 1976), and indicative of a stellar wind from the primary. The spectrum has several of the mass-loss indicators of Hutchings (1970). These are: Balmer emission (weak), velocity-excitation relation, a Balmer velocity progression, and occasionally He I $\lambda 3888$ shell absorption. We also find that the mass-loss phenomena are phase dependent (see Fig. 1), and are greatest at the phase of maximum velocity of recession, which is also near periastron, in the very slightly eccentric orbit.

Orbital parameters were derived for several sets of spectral lines, of different excitation, and are shown in Table 2. The period was refined by combining our Si IV + N III velocities (chosen for their reliable behavior and high excitation) with those of Plaskett

(1922). In our data the variation in V_0 and K between different sets of lines is evident. The V_0 range shows the stellar wind velocity-line excitation relation, and the range in K shows how the gradient of this relation is greatest near phase 0. In view of this, it is not clear what value of e (if any) should be regarded as real. We adopt the value given by the higher excitation lines, as they presumably arise closest to the stellar photosphere, but note that such a small value may well be spurious. It seems clear that the orbit does not deviate much from circularity.

The unidentified emissions at $\lambda\lambda 4485$, 4503 have a high amplitude and V_0 , similar to absorption lines of high excitation (see Table 2). The few N IV $\lambda 4058$ measures suggest that the absorption moves with the primary, although some of the points indicate a lower amplitude. This is of interest as the Of emissions ($\lambda\lambda 4640$, 4686), as discussed below, do not move in phase with the primary.

From the mass-loss calibrations of Hutchings (1976), the primary appears to lose mass at a rate varying from $\sim 2 \times 10^{-6} M_\odot \text{ yr}^{-1}$ at phase ~ 0.5 to $8 \times 10^{-6} M_\odot \text{ yr}^{-1}$ at phase ~ 0.0 . A natural

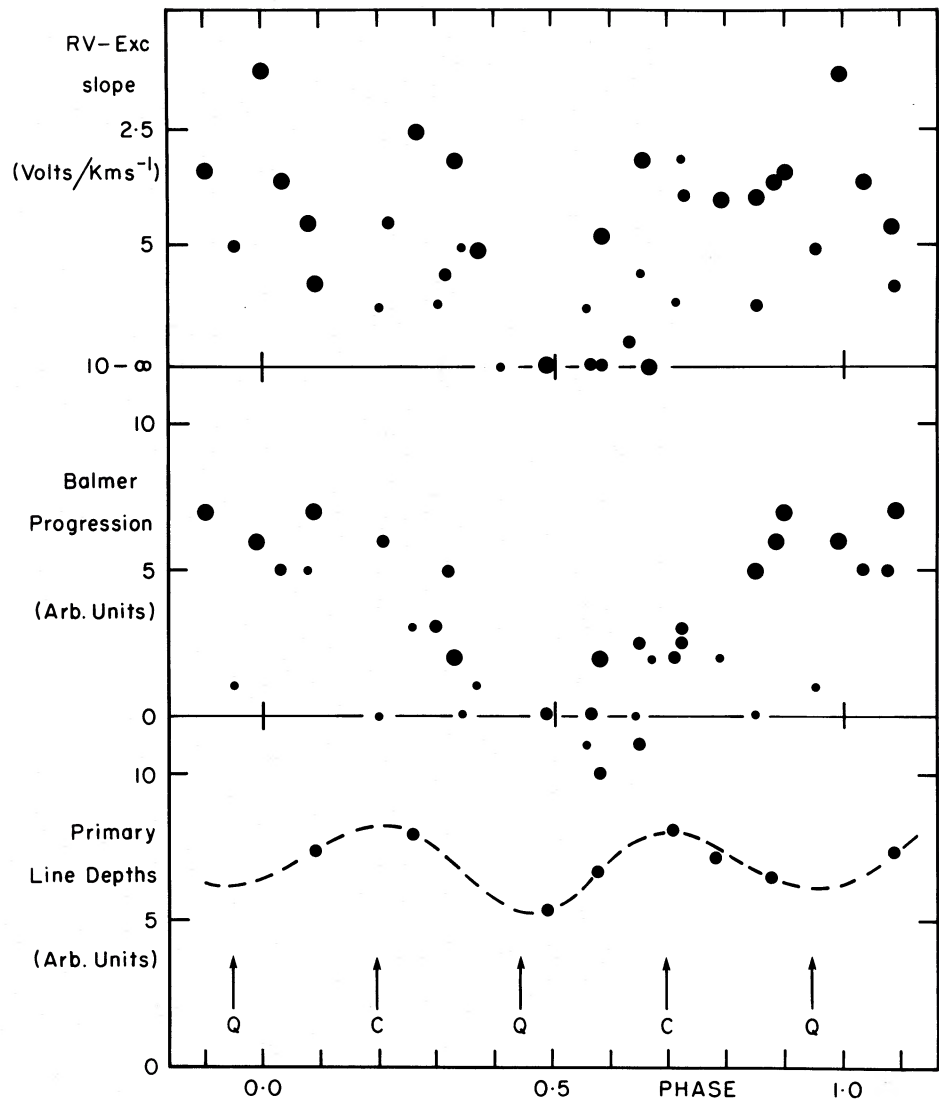


FIG. 1.—Upper, velocity-excitation slope for lines in HD 47129 as a function of phase. Lower slope indicates larger velocity gradient. Size of dots indicates weight. Effect is lowest near phase 0.5. Center, Balmer velocity progression as function of phase. Number in arbitrary units express slope in km s^{-1} /Balmer line in series. Effect measures velocity gradient and is lowest near phase 0.5. Lower, mean depth of spectral lines in primary spectrum as function of phase. *Q* and *C* indicate quadrature and conjunction phases.

TABLE 2
HD 47129 PRIMARY-STAR ORBITAL PARAMETERS
 $P = 14^d39601 \pm 0^a00009$

Lines	K (km s^{-1})	V_0 (km s^{-1})	e	ω (radians)	To 2,442,000+	Fit (km s^{-1} per point)	Exc. (eV)
He II.....	203 ± 4	42 ± 3	0.040 ± 0.025	2.7 ± 0.5	322 ± 1	10	75
Si IV + N III.....	200 ± 3	34 ± 2	0.025 ± 0.014	1.4 ± 0.7	319 ± 2	7	57
He I.....	199 ± 3	27 ± 2	0.019 ± 0.017	1.2 ± 0.9	318 ± 2	8	21
H _{LIMIT}	175 ± 5	14 ± 4	0.045 ± 0.028	1.4 ± 0.7	319 ± 2	12	10
Hy.....	162 ± 8	-6 ± 6	0.060 ± 0.048	2.3 ± 0.9	320 ± 2	21	10
UID emis*.....	199 ± 9	(42)	0.029 ± 0.043	2.7 ± 1.3	321 ± 3	25	high?
Adopt.....	203 ± 4	42 ± 3	0.025 ± 0.015	1.4 ± 0.7	319 ± 2		
Abhyankar 1975...	204 ± 2	29 ± 1	0.024 ± 0.007	1.7 ± 0.3			
Plaskett 1922.....	207 ± 2	23 ± 2	0.036 ± 0.012	3.4 ± 0.4			

* $\lambda\lambda 4485, 4503$.

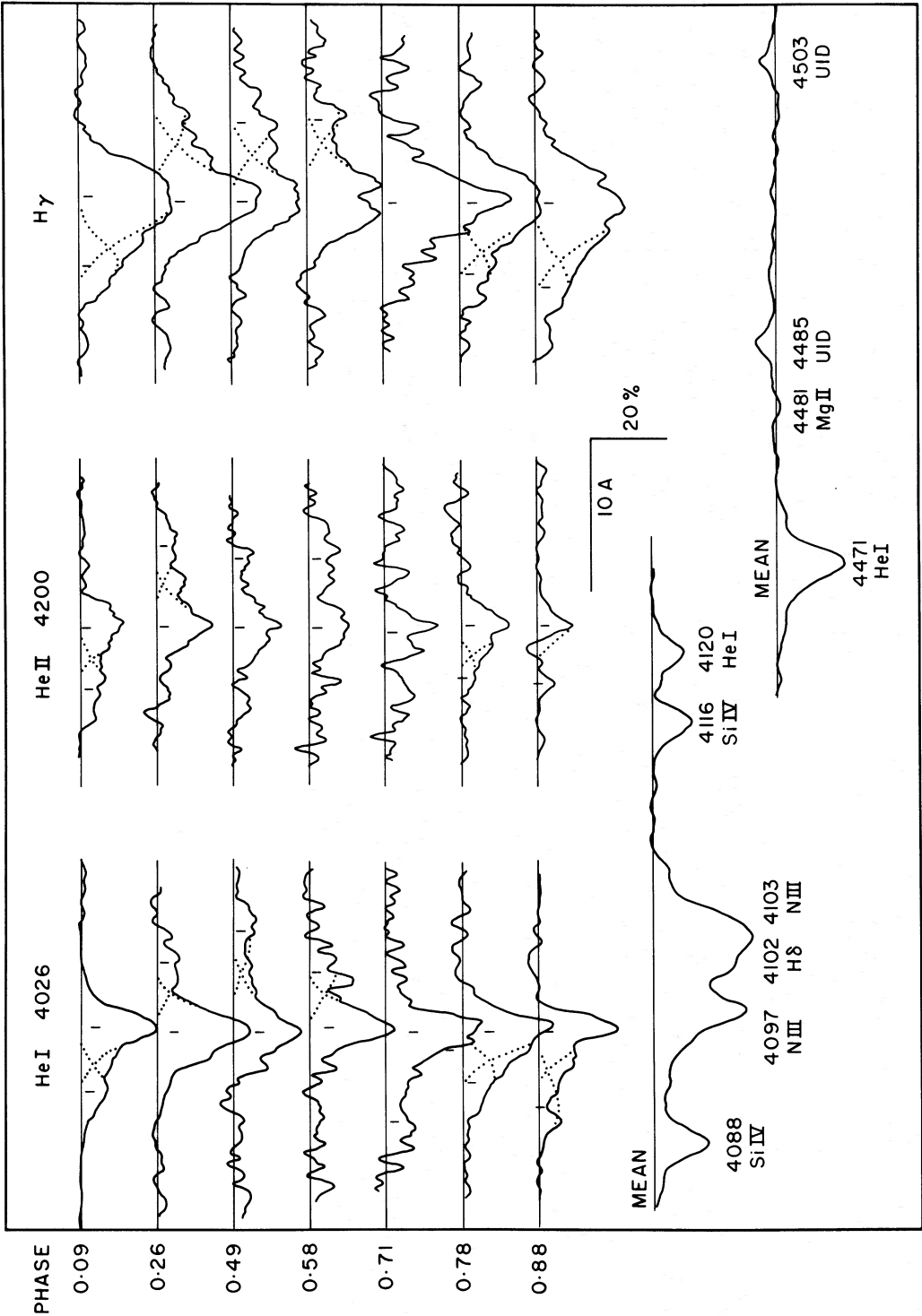


FIG. 2.—Line profiles in HD 47129 at selected phases (*upper*) and averaged through cycle in rest frame of the primary. Line center positions and profile overlaps are indicated.

explanation for this appears to be that mass loss is enhanced by tidal effects at periastron. However, there are several reasons for rejecting this explanation. The size of the orbit indicates that the separation of the stars is at least $100 R_{\odot}$ for any possible mass ratio (see below). This means that the primary underfills its Roche lobe by ~ 50 percent and tidal distortions in the line-forming regions in the envelope will be small, and will vary by an amount unlikely to cause any noticeable change in the mass-loss rate. Changes of the order seen can arise by small perturbations only when the line-forming region is within a few percent of the Roche limiting surface. Further, streaming toward the secondary should then show up as an enhanced mass-loss rate visible at phase ~ 0.25 , and this is not seen. Finally, the uncertainty in e (and ω) make the connection with periastron passage somewhat dubious in any case.

We suggest instead that the stellar wind from the primary is enhanced on the following side of the star in its orbit. The reason for this is not clear, and we can only suggest that the phenomenon may be one of suppression of the wind in the forward direction if the orbital plane contains sufficient material (lost from both stars?), which causes a viscous drag on the wind. Struve, Sahade, and Huang (1958) found evidence for a large amount of circumstellar material. It may be relevant to note that the mass-loss rate from the *back* side of the primary is more typical of a star of its spectrum and luminosity than the rate in the forward direction.

Spectrophotometry was done of the selected spectra marked in Table 1. One of the purposes was to estimate the luminosity of the primary by measuring H γ equivalent widths, Ca II K absorption and $\lambda 4430$ diffuse interstellar absorption. Figure 2 shows tracings of some selected spectral regions and the profiles of H γ are shown. The mean H γ equivalent width is $1.8 \pm 0.06 \text{ \AA}$ for the primary, and $0.21 \pm 0.08 \text{ \AA}$ for the secondary. It is difficult to estimate the secondary contribution to the spectrum, as it is peculiar and the star is underluminous. The ratio of line depths for Balmer, He I, and He II lines is about 3 for all so that the secondary does not appear to be of a very different spectral type. However, scaling the secondary H γ equivalent width by this factor yields a

very small absorption strength. It seems safe, therefore, only to say that the secondary contributes not more than one-quarter of the continuum in the blue. The H γ equivalent widths of the primary then lies between 1.2 and 1.6 $\text{\AA}$, and this corresponds to M_v between -7.1 and -6.4 . Putting this on the H-R diagram suggests that the primary is a supergiant of mass 40–60 $M_{\odot}$.

The $\lambda 4430$ central depth is 5 percent and the Ca II K interstellar line equivalent width is $0.28 \pm 0.01 \text{ \AA}$. These both indicate a distance modulus of ~ 9.0 mag. An E_{B-V} of 0.36 then yields a value of $M_v \sim -4$ for the system. However, these are very unreliable numbers and in view of the mass-loss and H γ measurements we assume the system is considerably more luminous than this.

Figure 1 and Table 3 illustrate the variation of line depths with phase, from the tracings made. All lines show similar behavior, being deep at conjunction and shallow at quadrature. We do not consider this to be simply a blending effect, as the secondary is well separated at phases at which changes occur. It is also noteworthy that the lines are deeper at the phase 0.95 quadrature than at phase 0.45—i.e., stronger on the side of enhanced mass loss. This type of variation may result from tidal distortion and gravity darkening, but (1) the amplitude is larger than it should be and (2) inspection of photometric work of the system (Abhyankar and Spinrad 1958; Calder 1936; Stebbins 1928) shows no continuum variation of this amplitude or nature. We conclude again that tidal distortion is small, but that phase-related spectrum variations exist.

Finally, we note that the absence of eclipses in the system indicates that the system is not seen equator-on. If the primary radius is $25 R_{\odot}$ and the secondary is not larger, then a mass ratio near unity constrains i to be less than 65° . If the secondary is half this radius, then $i \leq 72^\circ$.

IV. THE SECONDARY

Weak satellite lines, perhaps attributable to the secondary star, are present at many of the stronger lines. They are most visible at H γ and He I $\lambda 4472$, although they are often seen at other H, He I, and He II lines. One infers nearly the same spectral type

TABLE 3
HD 47129 PRIMARY SPECTRUM LINE DEPTHS, IN PERCENT
OF CONTINUUM

PHASE	Si IV		N III 4097	He II 4541	He I			H γ
	4088	4166			3819	4026	4471	
0.09.....	7	6	14	7	8	10	10	12
0.26.....	8	6	11	8	10	12	12	13
0.49.....	7	5	7	5	7	8	7	8
0.58.....	8	7	10	6	...	11	8	9;
0.71*	9	8	13	7	9	11	9	15
0.78.....	8	6	13	6	7	12	9	10
0.88.....	7	4	12	5	7	11	7;	11

* Secondary spectrum blended?

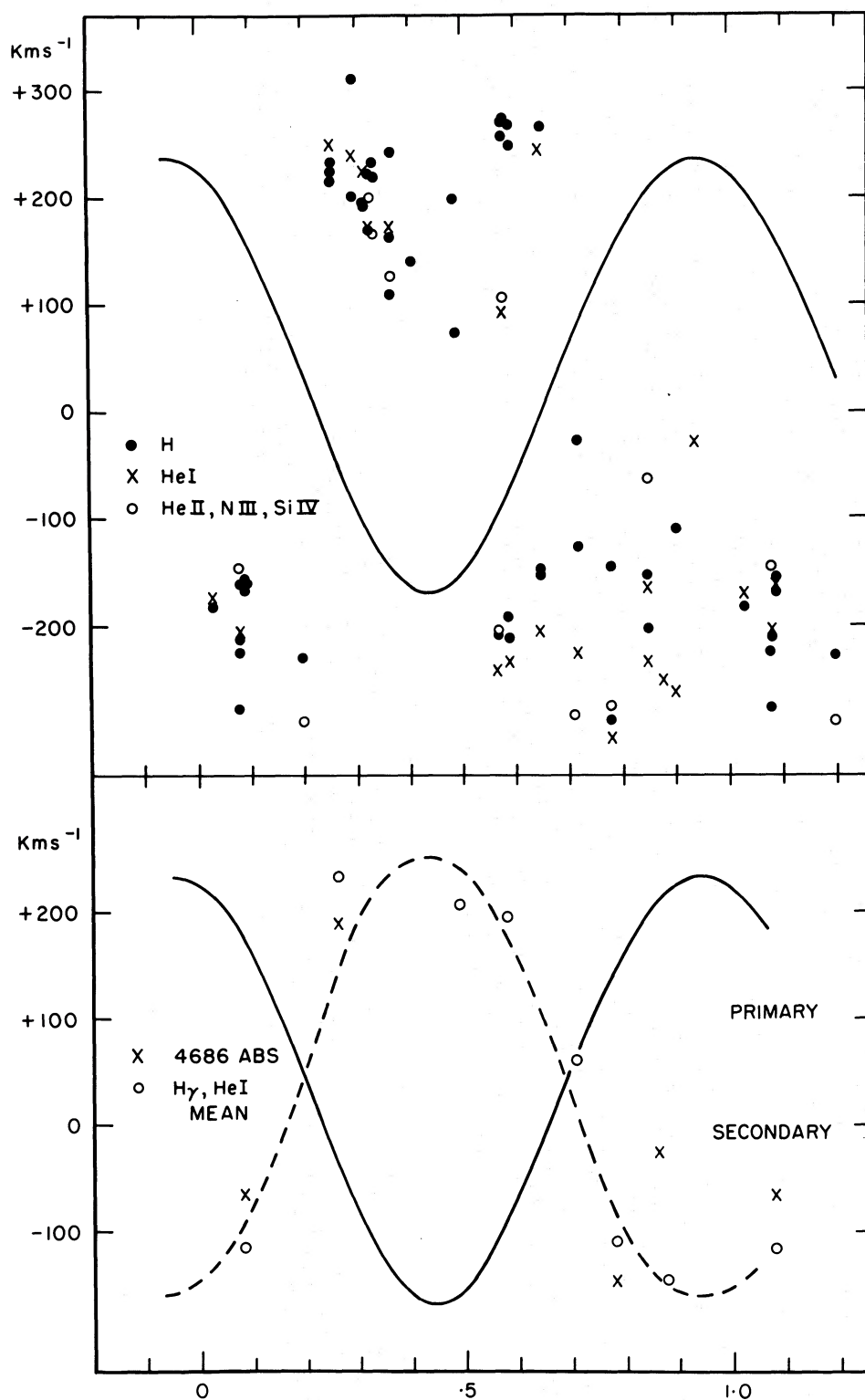


FIG. 3.—*Top*, velocities of “secondary” absorptions as measured on the oscilloscope-display machine. The weakness of the features causes a very large scatter, although gas streams within the system greatly distort the velocities at some phases. *Bottom*, velocities of the “secondary” absorption (large circles) derived from careful inspection of tracings of the best plates. They appear to come from the secondary star and imply a mass ratio near 1. The point at $\phi = 0.26$ lies high; it is discussed in the text. The computed orbit for the primary based on the He II absorptions is shown as a smooth curve. The dotted curve is fitted through the secondary velocities illustrated. Also shown, as crosses, are the best $\lambda 4686$ absorptions which lie within the emission. They probably are associated with the secondary.

for the secondary as for the primary, although the weakness of the lines makes careful classification difficult. We find, as have other workers, that the secondary lines are strongest at the phase when the second star is approaching the observer. This curious effect is found in other hot binaries and most probably is related to the same nonuniform mass loss as has been shown above for the primary, or to some gas streams in the system.

The relative luminosity of the secondary has been mentioned above as being not more than one-quarter that of the primary. The value of $\frac{1}{3}$ assumes similar spectral characteristics. In view of its apparent mass, this is likely. Since the Of emission is apparently not associated with the primary, it is strong compared with the considerably weaker continuum of the secondary. However, the secondary is probably underluminous by at least 1 mag, as discussed below.

The distance and other M_v estimates of the primary are consistent with its being of normal mass for its luminosity, which implies that the secondary is underluminous for its mass. We consider it less likely that the primary is overluminous, with the secondary of normal luminosity. However, the uncertainties in the estimates do not rule out this possibility altogether.

It has been shown in earlier papers that although the velocity of the secondary absorption spectrum is roughly out of phase with the primary, the following conditions hold: (1) there is a high scatter in the velocities; (2) the velocities are not always the same from cycle to cycle; (3) the mean velocity is more negative than the γ for the primary; and (4) the absorptions show some velocity peaks which are inconsistent with any possible motion of the secondary. Additionally we note that on some plates, especially near phase 0.6, some lines may have a positively displaced component while others show a negative one. The velocities of the secondary, as measured on the oscilloscope display machine, are plotted in Figure 3 (*top*). Because these values are so scattered, the interpretation is very uncertain, so we decided to examine the secondary lines in detail on the best plates at a variety of phases. In Figure 3 (*bottom*) we plot the mean of the velocities obtained for H γ , He I $\lambda\lambda 4472, 4026$, and He II $\lambda 4200$ (when visible). We note that at phase 0.56 the "secondary" lines are sharper than on other plates and may not represent the stellar velocity. At phase 0.26 the strength of the helium secondary lines is about half what it is on all of the other tracings. Because of this anomaly in the intensities at this phase, the line may not be purely stellar. The phase is just beyond the conjunction when the primary is behind, and this could represent material moving from the secondary to the primary. However, it is not clear what would drive such a stream since the stars do not fill their Roche lobes. Below we give other evidence that there may be considerable material between the stars.

Adopting the mean of the secondary velocities as derived from the tracing (and not using those from phase 0.26), we find a mass ratio near 1.02 ± 0.10 and a center-of-mass velocity $V_0 = 38 \pm 5$, which is

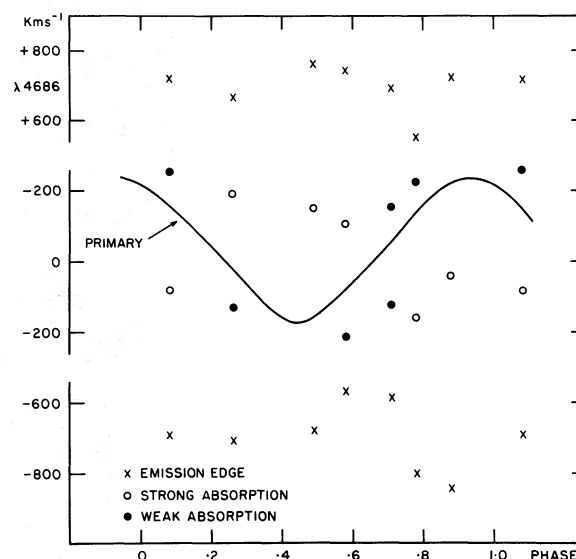


FIG. 4.—Velocities of He II $\lambda 4686$ derived from intensity tracings. Crosses represent emission edges. Absorptions with the broad emission are shown by large and small circles, depending on their intensities. There is some suggestion the stronger absorptions are from the secondary star, while the weaker may be from the primary. The uncertainty in velocity is large.

close to that of the high-excitation lines of the primary (see Fig. 3b).

Emission lines.—The broad weak emissions of He II $\lambda 4686$ and the N III $\lambda 4640$ blend have also been examined on the tracings. Both emission features are too weak and broad to measure satisfactorily on the oscilloscope machine, but the tracings clearly show $\lambda 4686$ to be a variable, weak emission some 20–25 Å wide ($\sim \pm 700 \text{ km s}^{-1}$ which is probably due to both rotation and expansion). We have measured the emission edges with respect to the nearby He I $\lambda 4713$ and find that the emission does not move significantly, in absolute radial velocities. Generally the broad emission shows a weak central reversal and occasionally a second absorption as well. These can be identified with the secondary and primary star velocities, respectively. In Figure 4 we plot the velocity of the emission edges, as well as the velocity of the absorptions within the emission. Measurements of the width and equivalent width of the emission show it to be some 10–15 percent narrower between phases 0.58 and 0.78 (secondary behind) and to be about 50 percent weaker as well. It is probable that the primary occults some of the emission region during these phases. This suggests that i is probably not less than $\sim 60^\circ$. It is significant that there is no weakening of the emission half a cycle later, when the primary is behind. This argues for a smaller radius for the secondary, in spite of its large mass.

Finally, if we adopt the three best defined 4686 absorptions as secondary lines (see Fig. 3b) we reduce the mass ratio M_1/M_2 to ~ 0.9 , which is within the error of our previous estimate.

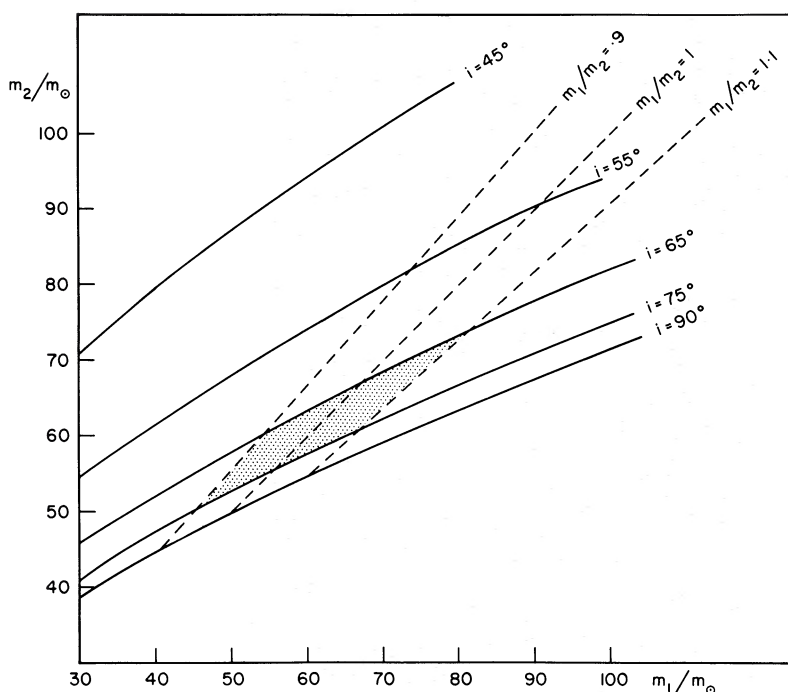


FIG. 5.—Possible masses in HD 47129 for the derived mass function $f(M) = 12.40$. The crosshatched region is the most probable region for the two components to lie since no eclipses are observed and our derived mass ratio is 1.0 ± 0.1 .

V. MASSES OF THE INDIVIDUAL STARS

In Figure 5 we plot M_2 versus M_1 for the derived mass function [$f(M) = 12.40$] with curves of constant i and M_1/M_2 overlaid. Assuming that $i \sim 70^\circ \pm 5^\circ$ and $M_1/M_2 = 1.0 \pm 0.1$, we find $58 < M_1/M_\odot < 100$ and $64 < M_2/M_\odot < 90$. The high mass limits of these ranges seem less likely in view of the apparent luminosity of the primary.

Careful photometry during successive cycles may reveal some ellipsoidal variations, shallow eclipses, or heating effects which would give an estimate of the inclination. However, it appears that irregular outbursts in the system make this a very difficult job. Further, the apparently large separation of the stars means that such effects would be small (of the order of 0.01 mag).

VI. EVOLUTION AND MASS EXCHANGE

The system is unique in several ways. The stars are the most massive known in a binary system (although there is good evidence that stars more massive than $60 M_\odot$ exist: see Conti and Burnichon 1975). In systems where extensive mass exchange has occurred, it is normal to find that the original primary is undermassive for its luminosity, as the core He burning is unaffected by loss of its outer layer. In this system we have a secondary which is underluminous. At its mass and in this size orbit, the star can only be an OB supergiant or a collapsed object.

The second alternative explains the low luminosity, although accretion at the Eddington limit would produce energy comparable with that of the primary,

which may emerge at other wavelengths. It is not clear whether the visible radiation emerging from a thick accretion disk surrounding such an object would have the observed optical qualities of the secondary. More difficult is the evolutionary history of such an object. The high masses involved imply that the collapsed object must have been formed, presumably in a supernova explosion, less than 10^5 years ago. We may thus question whether there is any sign of such an event (SNR, high systemic velocity). We must also consider the likelihood of such a system forming a pair at a separation large enough to allow the initial primary to evolve while retaining so much mass. We consider that this possibility is an unlikely one.

If the secondary is an unevolved star, we can explain its underluminosity by high differential rotation or the presence of a thick disk. Both of these mask radiation in and near the orbital plane. Both phenomena also usually require considerable mass accretion from the companion. This can be reconciled with the near equality of the two masses, if the present primary has lost mass and is the more evolved star. This in turn requires the initial separation of the star to have been smaller, and it is not clear why the primary no longer fills its Roche lobe.

A final alternative is that the system is in a stage of primary mass exchange, from the secondary to the primary. The stellar wind from the primary may prevent accretion onto it, so that mass is lost from the whole system from both objects. The underluminosity of the secondary (and its small size) are still puzzling. We can only suggest that high rotation may form a

thick equatorial disk before the Roche lobe is filled by the star and that it blankets much of the radiation from the photosphere.

From spectroscopic evidence, and the lack of any period change, the rate of mass exchange does not appear to be high. This supports the conclusion that neither star fills its Roche lobe. We suggest that investigation in other wavelengths and careful photo-

metric monitoring may help understand the evolutionary state of this unique bright system.

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