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THE ORBITS OF THE SPECTROSCOPIC COMPONENTS OF H. D. 216014

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ABSTRACT

This massive binary system was discovered by Dr. J. S. Plaskett upon examining the first plate, on which the spectra of both components appeared, with a large relative displacement.

The spectrum is B0n, the diffuse character of the lines being reflected in the high probable error of an average plate, $\pm 7 \cdot 34$ km.

The orbit was satisfactorily determined from 21 spectrograms, on 18 of which the secondary spectrum was measured. The principal elements are: $P = 2 \cdot 28754$ days, $e = 0 \cdot 086$, $\omega = 289^\circ \cdot 31$, $K_1 = 225 \cdot 0$ km., $K_2 = 258 \cdot 8$ km., and the minimum masses are $14 \cdot 23$ and $12 \cdot 37$ times the sun.

Eddington's theoretical considerations indicate an absolute magnitude of $-2 \cdot 50$, which is in agreement with the value of $-2 \cdot 67$, derived by assigning probable values of surface brightness $-3 \cdot 75$, and density $0 \cdot 08$ with respect to the sun. The corresponding parallax is $0'' \cdot 00095$, a distance of 3,400 light years.

The calcium lines are sharp and give a velocity of $-26 \cdot 28 \pm 0 \cdot 31$ km., while the velocity of the system is $-23 \cdot 10 \pm 1 \cdot 70$ km.

Introduction

The star H.D. 216014, 1900 R.A. $22^h\ 44^m \cdot 2$, Dec. $+64^\circ\ 32'$, vis. mag. $6 \cdot 83$, spectral class B0, was discovered to be a binary by the Director upon examining the first plate. The lines were seen to be double and of wide separation, the relative velocity being approximately 400 kms. The investigation of this star of probable large mass was assigned to the writer who had recently joined the staff and commenced observing on the B-class programme.

The first observations seemed to be satisfied by a period of $6 \cdot 85$ days, which combined with the unusually large amplitude, would make the system a very massive one. The sixth observation, however, demanded the submultiple 1/3 and the shorter period of $2 \cdot 2891$ days was later adopted as the preliminary value.

The Spectrum

The spectrum is classified in the Henry Draper Catalogue as B3, with the following remark: "The line $H\beta$ is not seen as a dark line, and is suspected to be bright." The type, however, is really B0n. Two of the single-lined plates were obtained when the stars were crossing the line of sight, the observed velocity being identical with that of the system. These show a fair spectrum, the lines of which are given in Table I.

TABLE I—THE SPECTRUM OF H.D. 216014—PLATE 11034

I—Lines Measured for Rad. Vel.

Wavelength	Int.	Atom
*4921·929	4	He
*4861·326	8	Hβ
4713·143	3	He
4685·74	4	He+
4650·75	4	C++
4574·737	1	SiIII
4567·824	1	SiIII
4552·611	1	SiIII
4481·230	2	Mg+
*4471·477	5	He
*4387·928	4	He
*4340·467	10	Hγ
4267·16	2	C+
*4143·759	4	He
*4120·812	2	He
4116·104	2	SiIV
*4101·738	9	Hδ
4088·863	3	SiIV
4075·869	2	OII
*4026·189	5	He
4009·267	2	He
*3970·075	8	Hϵ
3968·476	4	Ca+(H)
3933·667	5	Ca+(K)

II—Lines Observed but not Measured

Wavelength	Atom
4676·246	Oxygen
4661·650	"
4649·148	"
4596·189	"
4590·983	"
4437·549	Helium
4416·974	Oxygen
4414·888	"
4349·435	"
4319·647	"
4317·160	"
4253·77	Sulphur
4168·97	Helium
4119·222	Oxygen
4072·156	"
4069·788	" blend

III—Unknown Lines Measured

4428·18	Mg+	(4428·00)
4285·79	S	(4285·13)

Part I contains the lines measured for determining the radial velocity, together with their intensity and identification. Part II contains the weak lines observed but not measured. Two faint unknown lines were measured for wavelength and are given in Part III. λ4428·18 is very probably due to Mg+, λ4427·995 although no traces of λλ4433·991 or 4390·585 were observed. λ4285·79 may possibly be λ4285·13 which with λ4253·77 are attributed to abnormal sulphur by Lockyer[1]. The absence of the Pickering series and of ionized nitrogen forbids a classification earlier than B0, while the presence of λ4686 He+ fixes the type definitely as B0. As in many B0-B1 stars many lines of oxygen occur, but here the lines are very weak and not suitable for measurement. The diffuse character of the lines is shown in the rather high probable error of an average plate, ±7·34 km. Both components appear to have identical spectra, the asterisks in Table I denoting those lines measured as double in an average plate. The lines of calcium are strong, and compared with the nebulous nature of the other lines, are narrow admitting of accurate measurement, as is shown by the probable error of their mean velocity, ±0·31 km.

The suspected emission of Hβ referred to in the quotation above is not confirmed, it appeared as a good absorption line on all the plates.

[1] The references are on page 178.

The Observations

Before the star became out of reach in the west, nineteen plates were secured with the I-prism spectrograph and IS camera, having a dispersion of 49 A per mm. at Hγ. Two observations with the IM camera, dispersion 29A per mm. at Hγ, are marked with an asterisk in Table II. The emulsion used throughout was Seed 30. The plates were measured on a Toepfer micrometer engine having a binocular eyepiece which was found to be more restful on the eyes than the ordinary single-ocular machine. Four of the plates were remeasured and the means accepted as the final values of the velocities. The measures were difficult, and somewhat uncertain, on account of the diffuse nature of the lines, but in general owing to the large relative velocity the two components were clearly separated. Had the amplitudes been about one-half their actual values, considerable difficulty would have been experienced in obtaining satisfactory measures, as separations of 150 km. would certainly have appeared as single lines.

TABLE II—JOURNAL OF OBSERVATIONS—H.D. 216014

No.	Plate	Julian Date 2,424,000+	Phase from 2,424,076	Brighter Component				Fainter Component				Calcium		
				Vel.	Lines	Wt.	(O-C)	Vel.	Lines	Wt.	(O-C)	Vel.	Lines	(O-M)
1	10891	078·8014	0·5139	−210·9	6	3	+12·8	+168·3	6	1·2	−39·5	−31·5	K	−5·2
2	10905	081·7243	1·1492	+166·5	4	1	+18·6	−222·8	4	0·6	− 3·2	......	......	......
3	10917	092·6841	0·6713	−181·8	7	2	−18·0	+164·3	7	1·2	+25·4	−26·1	K, K	+0·2
4	10920	098·7722	2·1843	− 95·0	5	1	+14·4	+ 68·9	6	0·6	− 7·4	−22·9	H, K	+3·4
5	10925	099·7549	0·8795	− 28·0	11	2	+ 1·9	......	......	......	......	−28·4	H, K	−2·1
6	10934	111·6459	1·3328	+204·1	10	3	− 0·8	−290·0	7	2·0	− 5·0	−27·8	H, K	−1·5
7	10956	116·6446	1·7564	+ 97·4	10	3	−10·4	−209·5	9	1·2	−35·9	−29·0	H, K	−2·7
8	10976	117·5972	0·4215	−237·5	11	3	+ 1·7	+232·2	9	2·0	+ 6·7	−29·2	H, K	−2·9
9	10983	117·7715	0·5958	−213·4	10	2	−15·5	+209·9	10	1·2	+31·9	−29·3	K	−3·0
10	10993	119·5965	0·1332	−228·4	11	2	−23·4	+205·4	10	1·2	+19·5	−30·0	H, K	−3·7
11	11012	127·6626	1·3367	+206·9	10	3	+ 1·6	−274·1	9	2·0	+11·3	−27·4	K	−1·1
*12	11029	128·6875	0·0741	−196·0	10	3	−11·3	+161·8	9	2·0	− 1·2	−18·9	H, K	+7·4
13	11034	138·6536	0·8900	− 26·0	21	3	− 4·0	......	......	......	......	−27·9	K	−1·6
14	11048	139·6557	1·8921	+ 69·2	8	1	+29·0	− 90·2	7	2·0	+ 5·4	−27·6	H, K	−1·3
15	11063	141·6355	1·5844	+172·2	7	3	− 4·2	−239·2	8	2·0	+13·2	−23·3	K	+3·0
16	11083	142·7625	0·4238	−235·3	6	3	+ 3·7	+216·5	6	2·0	− 8·8	......	......	......
*17	11091	143·6048	1·2661	+191·6	8	3	− 0·6	−273·9	8	2·0	− 3·3	−18·6	K	+7·7
18	11114	144·6439	0·0177	−164·8	7	2	− 1·4	+181·6	7	0·6	+43·2	−36·1	K	−9·8
19	11130	155·1264	0·8500	− 52·5	5	1	− 1·7	......	......	......	......	......	......	......
20	11130A	159·1048	0·2534	−236·4	5	1	− 4·2	+244·0	5	0·6	+26·4	−17·0	H, K	+9·3
21	11143	166·0840	0·3699	−227·7	11	3	+13·7	+214·2	10	2·0	−14·0	−20·6	H, K	+5·7

* IM Plates.

The columns of Table II are self-explanatory, but it should be noted that the Julian days of the last three observations are expressed in the "new style", i.e., beginning at Greenwich Civil Noon, and therefore a correction of 0·5000 of a day must be subtracted from the given times in order to harmonize them with the earlier observations.

The Spectroscopic Orbit

The secondary spectrum was measured on eighteen of the twenty-one plates, so that the elements were determined from thirty-nine observations. Preliminary values of the elements were obtained by a graphical method in use at the observatory. It was decided to employ the Lehmann-Filhés method of correcting the elements and to include a correction for a period as the observations only extended over thirty-eight cycles. Mention should be made of the system of weighting adopted as this is very important when large residuals are concerned. The weights assigned depend upon the number of lines measured, the character of the exposure of the plate and the factor 0·6 which expresses the degree of precision of the fainter measures with respect to those of the brighter component. The sum of the weights is 74·4, of which 26·4, or 35 per cent, is due to the secondary. The resulting probable errors of the brighter and fainter components were ±7·34 and ±12·57 km.

TABLE III—OBSERVATION EQUATIONS—H.D. 216014

Primary										
2.......	1	1·000t	+ ·837u	....	+·233w	−·153x	−·153y	−17·312z	− 1·1	= 0
7.......	3	1·000	+ ·953	....	+·199	−·106	−·095	− 6·330	+ 1·9	
11.......	3	1·000	+1·107	....	+·115	−·052	−·032	− 1·632	+ 1·1	
6.......	3	1·000	+1·020	....	+·106	−·047	−·027	− ·937	+ 4·7	
15.......	3	1·000	+ ·885	....	−·162	+·093	+·109	+ 7·045	+ 6·1	
7.......	3	1·000	+ ·555	....	−·214	+·169	+·166	+ 6·584	+ 6·7	
14.......	1	1·000	+ ·296	....	−·155	+·195	+·181	+11·345	−23·5	
4.......	1	1·000	− ·414	....	+·132	+·180	+·164	+ 3·591	−18·9	
18.......	2	1·000	− ·587	....	+·191	+·156	+·146	+ 9·917	+11·9	
12.......	3	1·000	− ·704	....	+·216	+·132	+·129	+ 6·672	+16·9	
10.......	2	1·000	− ·798	....	+·219	+·106	+·109	+ 4·645	+28·0	
20.......	1	1·000	− ·904	....	+·188	+·061	+·073	+ 5·953	+12·1	
21.......	3	1·000	− ·970	....	+·097	−·001	+·019	+ 1·695	−11·4	
16.......	3	1·000	− ·970	....	+·018	−·042	−·020	− 1·288	− 3·8	
8.......	3	1·000	− ·966	....	+·000	−·051	−·029	− 1·162	− 0·6	
1.......	3	1·000	− ·868	....	−·143	−·122	−·109	− ·195	− 5·2	
9.......	2	1·000	− ·782	....	−·196	−·155	−·142	− 5·806	+16·6	
3.......	2	1·000	− ·586	....	−·236	−·200	−·200	− 3·146	+29·0	
19.......	1	1·000	− ·190	....	−·155	−·241	−·234	−18·161	−11·1	
13.......	3	1·000	− ·022	....	−·086	−·247	−·270	−16·635	+ 0·3	
5.......	2	1·000	+ ·032	....	−·063	−·247	−·271	− 6·175	+14·3	
Secondary										
2.......	0·6	1·000	....	− ·837v	−·268	+·176	+·176	+ ·840	−14·4	
7.......	2·0	1·000	....	− ·953	−·228	+·122	+·109	+ 7·272	+ 6·8	
11.......	2·0	1·000	....	−1·017	−·132	+·059	+·037	+ 1·875	− 9·6	
6.......	2·0	1·000	....	−1·020	−·122	+·054	+·031	+ 1·077	+ 5·6	
15.......	2·0	1·000	....	− ·885	+·187	−·107	−·125	− 8·094	−10·4	
7.......	1·2	1·000	....	− ·555	+·246	−·194	−·191	− 7·564	+45·2	
14.......	2·0	1·000	....	− ·296	+·178	−·224	−·208	−13·034	− 7·0	
4.......	0·6	1·000	....	+ ·414	−·152	−·207	−·189	− 4·125	+17·2	
18.......	0·6	1·000	....	+ ·587	−·219	−·179	−·168	−11·394	−50·5	
12.......	2·0	1·000	....	+ ·704	−·248	−·152	−·148	− 7·665	+ 0·8	
10.......	1·2	1·000	....	+ ·798	−·252	−·121	−·125	− 5·337	−19·9	
20.......	0·6	1·000	....	+ ·904	−·216	−·070	−·084	− 6·840	−31·0	
21.......	2·0	1·000	....	+ ·970	−·111	+·001	−·022	− 1·948	+15·7	
16.......	2·0	1·000	....	+ ·970	−·021	+·048	+·022	+ 1·480	+13·4	
8.......	2·0	1·000	....	+ ·966	−·000	+·059	+·033	+ 1·335	− 3·4	
1.......	1·2	1·000	....	+ ·868	+·164	+·141	+·120	+ ·224	+35·1	
9.......	1·2	1·000	....	+ ·782	+·226	+·177	+·163	+ 6·671	−28·5	
3.......	1·2	1·000	....	+ ·586	+·271	+·229	+·230	+ 3·614	−33·5	

The symbols in the thirty-nine observations equations given in Table III and in the normal equations have the following significance:

$$t = \delta\gamma \qquad x = -1000\,\delta\omega$$
$$u = \delta K_1 \qquad y = 1000\,\frac{\delta T.\mu}{(1-e^2)^{3/2}}$$
$$v = \delta K_2$$
$$w = 1000\,\delta e \qquad z = -1000\,\frac{\delta\mu}{(1-e^2)^{3/2}}$$

The observation equations give rise to the following normal equations:

+74·400t	− 6·027u	+ 2·493v	− ·210w	−1·629x	−1·625y	− 68·867z	+ 18·186 = 0
	+29·616	+ ·202	− ·013	+ ·072	+ ·027	− 19·512	− 37·523
		+18·648	− ·011	+ ·156	+ ·116	− 4·719	− 23·123
			+2·075	+ ·266	+ ·296	+ 6·930	+ 11·804
				+1·337	+1·299	+ 58·067	− 9·901
					+ ·028	+ 1·417	− 2·067
						+614·946	+1167·704

These yielded the following values of the unknowns:

$t = -\ 2·1876$ whence	$\delta\gamma = -2·19$		±1·70 km.
$u = +\ 0·0018$	$\delta K_1 = 0·00$		±2·66 km.
$v = +\ 0·3231$	$\delta K_2 = +0·32$		±3·33 km.
$w = -\ 13·9441$	$\delta e = -0·014$		±0·007
$x = -\ 75·2245$	$\delta\omega = +4°·31$		±4°·80
$y = +169·9290$	$\delta T = +0·06098$		±0·03252 days
$z = -\ 1·8989$	$\delta P = -0·00156$		±0·00047 days

In order to see whether the inclusion of the less certain measures of the fainter component materially contributed in defining the elements, or whether they produced a detrimental effect, a second solution was carried out for the brighter component only. Using the same symbols as before (v omitted of course) we have the six normal equations:

+48·000t	− 6·027u	+ ·511w	−1·460x	−1·162y	− 17·682z	+207·200 = 0
	+29·347	+ ·068	+ ·021	+ ·013	− 16·154	− 26·238
		+1·175	+ ·2645	+ ·278	+ 9·896	+ 2·880
			+ ·826	+ ·827	+ 38·220	− ·254
				+ ·015	+ ·588	− 1·660
					+411·686	+490·440

These resulted in:

$t = -\ 3·9490$ whence	$\delta\gamma = -3·95$	±2·13 km.
$u = +\ 0·2571$	$\delta K_1 = +0·26$	±2·41 km.
$w = -\ 6·6601$	$\delta e = -0·007$	±0·012
$x = -102·0932$	$\delta\omega = +5°·84$	±6°·09
$y = +157·33$	$\delta T = +0·05646$	±0·03899 days
$z = -\ 1·1913$	$\delta P = -0·00098$	±0·00052 days

K_2 with its probable error was found to be

$\delta K_2 = +0·92$ ±3·47 km.

Applying these corrections to the preliminary elements we obtain the final ones given in Table IV.

TABLE IV—ELEMENTS OF THE ORBIT—H.D. 216014

	Preliminary		1st Solution Both Components		2nd Solution Brighter Component only	
Period..................	P	2·2891 days	2·28754	±0·00047 days	2·28812	±0·00052days
Eccentricity.............	e	0·10	0·086	±0·007	0·093	±0·012
Longitude of periastron...	ω_1	285·0	289·31	±4·80	290·84	±6·09
" " ..	ω_2	105·0	109·31	±4·80	110·84	±6·09
Semi-amplitude of primary..................	K_1	225·0 km.	225·0	±2·66 km.	225·26	±2·41 km.
Semi-amplitude of secondary..................	K^2	258·5 km.	258·8	±3·33 km.	259·42	±3·47 km.
Periastron passage........	T	J.D.2,424,076·940	−4077·0010	±0·0325	−4076·9965	±0·0389
Velocity of the system....	γ	−20·82 km.	−23·10	±1·70 km.	−24·79	±2·13 km.
Velocity of calcium.......	Ca+	−26·28 km.	−26·28	±0·31 km.	−26·28	±0·31 km.

The elements of solution II differ little from those of solution I, but they are defined with much greater precision by the first solution, and so the inclusion of the fainter measures was justifiable, as we would expect from theory. We are here, however, dealing with diffuse lines and not with well-defined ones, and it is questionable whether in this case the solution would have been improved had the factor of precision been, perhaps, 0·4.

The elements of solution I are therefore considered as the elements of the orbit, and they were used in computing the ephemeris for the velocity curve. ΣPvv was reduced from 17958·82 to 14398·54, or by 20 per cent. The probable error of an observation of weight unity is ±14·3 km., and of a single plate is ±7·34 km.

The Mass of the System

The projected semi-axis major and the minimum masses computed from the elements are:

$$(a_1 + a_2) \sin i = 15{,}162{,}000 \text{ km.} = 22 \text{ solar radii.}$$
$$m_1 \sin^3 i = 14{\cdot}23 \odot$$
$$m_2 \sin^3 i = 12{\cdot}37 \odot$$
$$(m_1 + m_2) \sin^3 i = 26{\cdot}60 \odot$$

But these minimum masses must be divided by $\sin^3 i$, the average value of which is 0·65, so that the actual masses may be considerably larger. The system is among the six most massive systems thus far determined.[2]

The Absolute Magnitude

In attempting to compute the absolute magnitude and thus determine the distance, we shall take the minimum mass and assign conservative values for this type of star. Adopting for the surface brightness $j = -3 \cdot 75$, a mean between the values of Russell[3] and Hertzsprung[4], and a temperature of 20000°, which is below the estimates of Russell[5] and Fowler and Milne[6], and a density $\rho = 0 \cdot 08$, given by Seares[7] for a B0 giant of mass ten times the sun, we have by the luminosity method M = $-2 \cdot 67$. Reducing the bolometric absolute magnitude as given by Eddington[8] to the visual absolute magnitude we find for these conditions M = $-2 \cdot 50$. Combining the mean M = $-2 \cdot 58$ with the apparent magnitude m = $7 \cdot 53$ the resulting parallax is $0'' \cdot 00095$, over 1050 parsecs or more than 3400 light years.

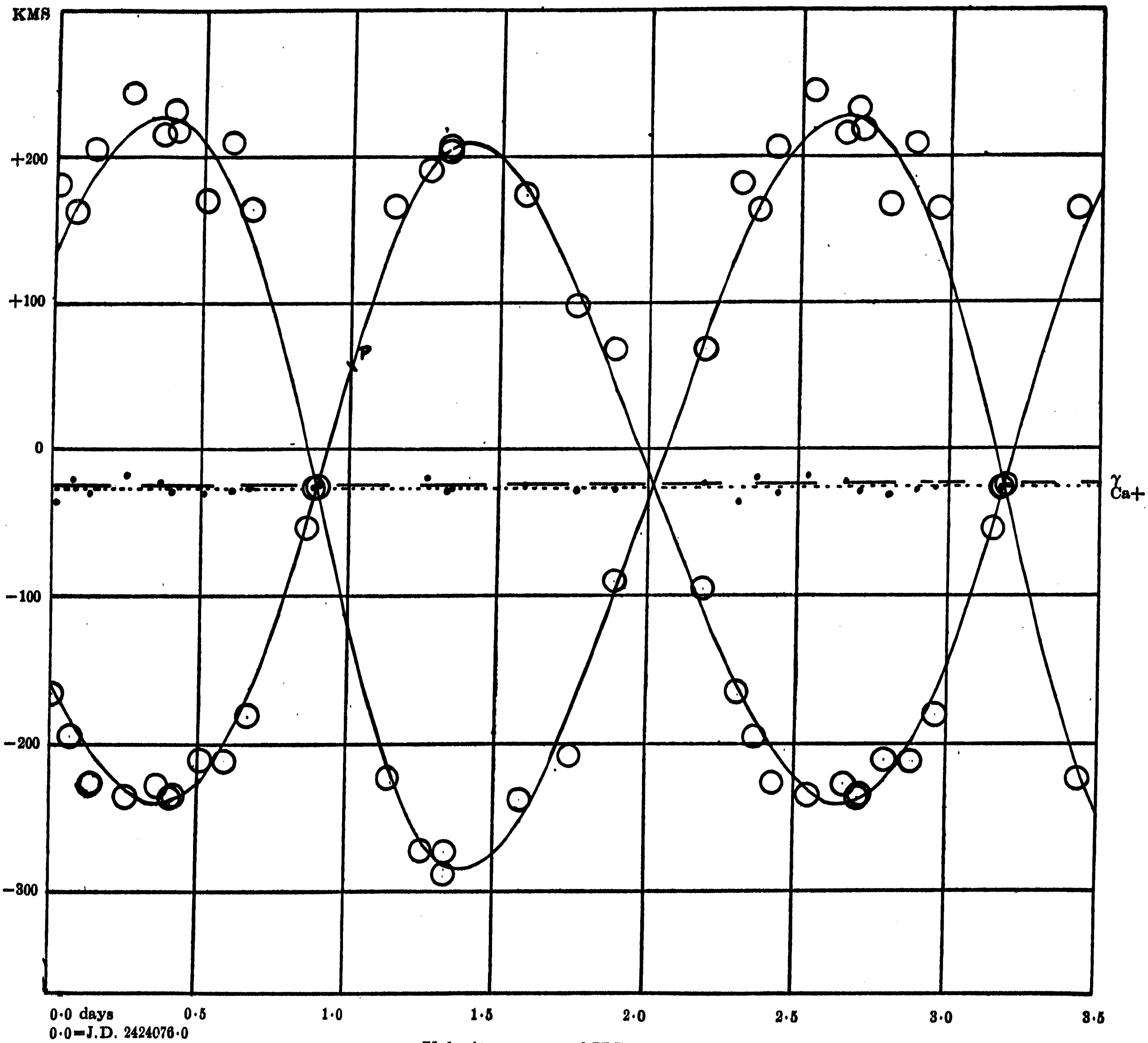
The theoretical diameter as computed by the formulae of Russell[9] or Seares[10] is $0'' \cdot 000048$, which when combined with the linear diameter of $5 \cdot 40 \odot$, 4,667,000 miles, gives the same parallax.

The adoption of higher values of the surface brightness, lower density and of the possible mass of $21 \cdot 9 \odot$ for the brighter component, corresponding to the average value of the inclination would, of course, place the system at a greater distance. Indeed, the density is very probably lower than $0 \cdot 08$, since the ratio of the radiation pressure of gravitational pull $(1-\beta)$ is approximately $0 \cdot 617$[8]. It is sufficient, however, to establish by using the minimum mass and the conservative assumptions above, that the parallax cannot exceed $0'' \cdot 00095$, which makes the minimum distance 3400 light years.

The Velocity of Calcium

In contradistinction to the diffuse hydrogen and helium lines the H and K lines of ionized calcium are strong and sharp, giving a constant velocity of $-26 \cdot 28 \pm 0 \cdot 31$ km. This value is very close to that found for the velocity of the system, $-23 \cdot 10 \pm 1 \cdot 70$ km., and raises the question as to the location of the calcium vapour. In the case of this massive binary of short period, it is reasonable to expect that the lines, if due to a calcium envelope enshrouding the pair of stars, should exhibit a measurable oscillation, on account of the very high rotational velocity, whereas no such oscillation was observed. If considered as an interstellar cloud in space, quite apart from the spectroscopic binary, the observations indicate that this vapour has a velocity of approach of 15 km. per sec., as the component of the solar motion in this direction is $-11 \cdot 40$ km. only. Differences of this order and even greater, between the velocity of calcium and the component of the solar motion, do not appear to be unusual among the O-and B-type stars, as has been shown by Dr. Plaskett [11], Young and others[12], so that this view is quite plausible.

An alternative explanation is to place the calcium cloud within the star's gravitational domain, at a distance of 40 to 50 astronomical units say. It would then hardly be expected to show the motions of the rotating binary, and the resulting lines would be stationary, possessing approximately the velocity of the system. This alternative location for the ionized calcium is not inconsistent with the well established hypothesis of Dr. Plaskett[11] in regard to stationary clouds of calcium and sodium vapour.



Velocity curves of H.D. 216014

The observations are shown in the graph as circles of radius 7 km., the round dots represent the velocities of the H and K lines, the dotted line is the calcium axis, while the γ axis is shown by the broken line.

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[1] Lockyer, Roy. Soc., Proc., LXXX, 50, 1908.
[2] Pub. D.A.O., II, p. 154.
[3] Pub. A.S.P., *32*, 307; *34*, 92.
[4] Mt. W. Cont. *10*, 399.
[5] R.A.S.C., XVIII, 153.
[6] M.N., LXXXIV, 505.
[7] Mt. W. Cont. *10*, 404.
[8] Pub. D.A.O., II, p. 329, Table XIV.
[9] Pub. A.S.P., *32*, 315, Table IV.
[10] Mt. W. Cont. *10*, 402.
[11] Pub. D.A.O., II, No. 16.
[12] Pub. D.A.O., I, No. 17.