A STUDY OF THE SPECTRUM OF 25 ORIONIS

HELEN W. DODSON

ABSTRACT

A study of 147 spectrograms of 25 Orionis, covering the interval 1915–1933, has shown simultaneous variations of the velocities of the central absorptions and the emission lines of hydrogen. These changes are nearly synchronous with changes of the ratio V/R of the components of the emission lines. The period shows a consistent decrease from 1817 days to 1025 days, and the velocity amplitude of the central absorptions was subject to a conspicuous decrease followed by an increase, with extreme values of 40 and 120 km/sec.

The central absorption velocities of $H\beta$, $H\gamma$, and $H\delta$ are in phase; but the amplitude increases in the order named. This is true also of the emission velocities. The changes in the emission velocities anticipate those in the central absorptions by about 100 days. The emission ratio V/R shows a marked difference of phase from line to line, $H\delta$ anticipating $H\gamma$ by about 200 days, and $H\gamma$ anticipating $H\beta$.

The emission lines vary conspicuously in width and show two maxima of width in each velocity cycle. These maxima occur at times of maximum and minimum velocity.

The helium lines and the broad hydrogen absorption which underlies the emission show systematic variations of velocity and changes of contour which are definitely related to the velocities of the hydrogen central absorption, but are conspicuously out of phase with the latter.

With the exception of the phenomena of the helium and broad hydrogen absorption, the variations observed find a satisfactory interpretation in terms of the rotating-pulsating nebulous atmosphere suggested by McLaughlin.

Bright $H\beta$ was discovered in the spectrum of 25 Orionis by Mrs. Fleming.[1] Each hydrogen line consists of a broad region of absorption upon which is superimposed a wide emission line, which in turn is divided almost centrally by narrow absorption. R. H. Curtiss[2] found that the two emission components thus formed undergo cyclic variations in relative intensity in a period first announced as 1875 days. Later work by Curtiss[3] showed considerable irregularity in the period. A close correlation between the variations in velocity of the hydrogen emission and central absorption and the changes of intensity ratio of the two emission components was pointed out by McLaughlin in 1931.[4]

The data for the present study were obtained from 141 spectrograms taken at the University of Michigan Observatory and from

[1] *A.N.*, **171**, 139, 1906.

[2] *Pop. Astr.*, **33**, 537, 1925.

[3] *Michigan Obs. Pub.*, **4**, 169, 1932.

[4] *Ibid.*, **4**, 38, 1931.

six spectrograms kindly lent by the Lick Observatory. These plates are all of one-prism dispersion, approximately 40 A/mm at $H\gamma$, with the exception of seven two-prism plates taken at Ann Arbor. Almost all of the plates are of Seed 23 or Eastman 33 emulsion.

The structural features of the hydrogen lines were measured in great detail. The following settings were made, whenever possible:

a) Violet edge of violet absorption border
b) Center of violet absorption border
c) Violet edge of violet emission component
d) Center of violet emission component
e) Center of central absorption
f) Center of red emission component
g) Red edge of red emission component
h) Center of red absorption border
i) Red edge of red absorption border

The mean of settings (*c*) and (*g*) was used to obtain the so-called "emission velocity." Setting (*e*) gave directly the velocity of the central absorption. The mean of settings (*d*) and (*f*) was used in studying the relation between the emission and the absorption velocities, but is not tabulated in this paper.

The helium lines λλ 4009, 4026, 4388, and 4472 were measured on as many plates as possible. At best they are diffuse and difficult to measure; and of the four, λ 4472 seems by far the most reliable. In addition to the measures with the micrometer measuring engine, the lines λ 4026 and λ 4472 were measured for velocity on microphotometer tracings on which the record of the titanium comparison spectrum had been obtained.[5] For very diffuse lines such as these, this method is believed to be fully as reliable as the direct measurement of the spectrogram.

VELOCITIES DERIVED FROM THE HYDROGEN CENTRAL ABSORPTION

The individual measurements on a single plate were in some cases so different that it was considered unwise to take mean hydrogen velocities. Normal places formed from these velocities are given for $H\beta$, $H\gamma$, and $H\delta$ separately in Table I and are plotted as black dots in Figure 1. The curves determined by them are drawn as full lines.

[5] Dodson, *Pub. A.A.S.*, **8**, 7, 1934.

The variations in velocity of $H\gamma$ and $H\delta$ found by McLaughlin[6] during the interval JD 24116–26414 are confirmed. Similar variations occurred over the entire interval studied, and for $H\beta$ as well as for $H\gamma$ and $H\delta$.

TABLE I

NORMAL PLACES: VELOCITIES AND EMISSION RATIOS FOR HYDROGEN IN 25 ORIONIS

Julian Day	Central Absorption Velocity in Km/Sec			Emission Velocity in Km/Sec			Emission Intensity Ratio: log V/R				No. of Plates
							Eye Est. McL.		Microph. Est. Dodson		
	$H\beta$	$H\gamma$	$H\delta$	$H\beta$	$H\gamma$	$H\delta$	$H\beta$	$H\gamma$	$H\gamma$	$H\delta$	
2400000+											
20827..	+ 6	+17	+19	+ 8	+16	+ 44	−.04	−.11	−.06	−.16	4
21562..	.....	+14	+16	+21	+49	......	−.15	−.11	−.05	.00	1
22301	+55	+84	+78	+51	+67	+ 84	+.42	+.28	+.28	+.07	5
22383		+52	+56	+28	+51	+ 63	+.27	+.15	+.11	+.02	4
22661..	.....	+24	+18	+31	+10	.....	.00	−.08	−.05	−.28	2
22720..	+24	+15		+21		+ 23	−.16	−.17	−.13		8
23094..	− 9	−45	−44	−11	−44	− 45	−.42	−.36	−.32	−.08	4
23361..	....	+16	+36	.....	+40	......	.00	+.08	.00	.00	1
23497..	....			+42	+32	+ 53	+.23	+.23	+.12	+.28	2
23778..	+55	+59	+49	+44	+63	.....	+.40	+.36	+.23	+.30	5
23847..	+61	+68	+87	+57		+114	+.35	+.32	+.18	+.34	12
24153..	+54	+54	+43	+47	+47	+29	+.25	+.17	+.20	+.13	4
24225..	+34	+58	+46	+30	+57		+.17	+.13	+.16	−.07	4
24458	+21	+19	+21	+ 8	+16	− 6	−.19	−.17	−.16	−.20	7
24527		+ 2	+ 9	+16	− 5	......	−.24	−.25	−.27	−.32	5
24832..	−10	− 6	+ 1	+ 4	−19	− 21	−.28	−.24	−.20	−.12	7
24867..	+ 5	− 3	−29	+10	− 3	− 27	−.30	−.15	−.02	+.03	5
25265..	+31	+13	.....	+29	+35	......	+.08	+.14	+.14	......	7
25561..	+30	+27	+32	+18	+39	+ 40	+.11	+.08	+.13	......	7
25909..	− 4	−10	−19	− 1	−22	− 13	−.32	−.28	−.22	−.22	5
26005..	−37	−23	−21	− 2	−30	− 30	−.28	−.15	−.18	......	6
26276..	+38	+35	+29	+34	+37	+ 20	+.25	+.19	+.20	+.11	6
26373..	+58	+47	+52	+33	+45	+ 26	+.38	+.40	+.19	+.48	5
26657..	+39	+48	+54	+30	+49	+ 30	+.26	+.21	+.09	+.10	7
26752..	+38	+45	+57	+30	+36	+ 21	+.19	+.17	+.10	−.16	5
27011..	+26	+31	+21	+24	+29	+ 17	+.01	−.01	.00	−.09	9
27109..	+32	+22	+24	+36	+28	+ 33	+.01	−.01	.00	−.03	9

The velocity curves vary in a similar manner in period, amplitude, and form. There has been a consistent decrease in period during the interval of observation. Starting with the maximum of JD 22100,

[6] *Op. cit.*, p. 39.

we have the following approximate values for the length of a cycle:

	Length of Cycle in Days			
	Hβ	*Hγ*	*Hδ*	Mean
Maximum to maximum	1825	1875	1750	1817
Minimum to minimum	1650	1625	1750	1675
Maximum to maximum	1500	1550	1600	1550
Minimum to minimum	1250	1300	1125	1225
Maximum to maximum	950	1000	1125	1025

This evidence alone is sufficient to discount finally any attempt to explain the variations in terms of binary motion.

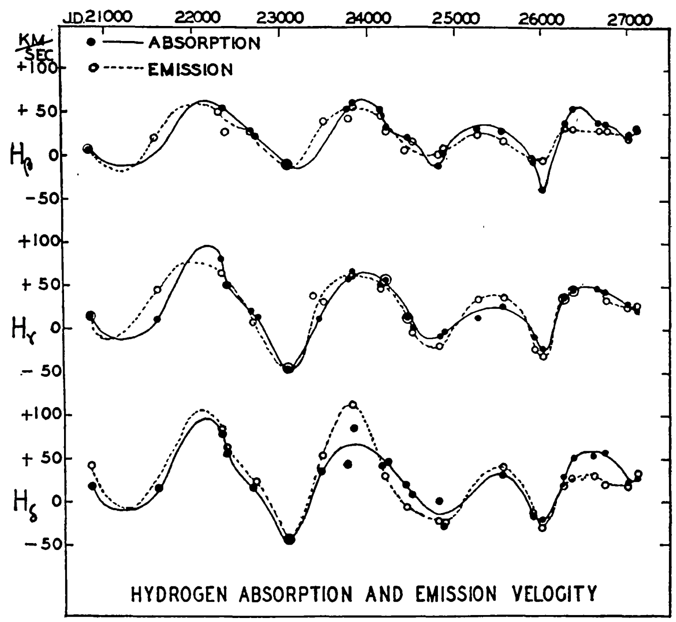

FIG. 1.—Velocity-curves of 25 Orionis

The amplitudes of the three central absorption velocity-curves differ systematically; the range is greater for the lines of shorter wave-length. This difference is small and is probably of questionable significance between $H\gamma$ and $H\delta$, but it is very marked between $H\beta$ and $H\gamma$. There has been a conspicuous change of amplitude from cycle to cycle, as is shown by the following approximate values of the range of velocity:

		Range in Km/Sec		
Cycle	JD	$H\beta$	$H\gamma$	$H\delta$
(I)	21300–23100	75 (−12 to +63)	120 (−20 to +100)	121 (−15 to +106)
(II)	23100–24800	76 (−11 to +65)	111 (−45 to + 66)	115 (−45 to + 70)
(III)	24800–26000	50 (−16 to +34)	40 (−14 to + 26)	45 (−11 to + 34)
(IV)	26000	98 (−40 to +58)	74 (−23 to + 51)	83 (−25 to + 58)

There seems to be no prescribed shape for the velocity-curves; each cycle has been unique, and the last one shows a maximum of a distinctly new form. It can perhaps be stated that the minima are generally sharper than the maxima. There is little or no evidence of a lag in phase between the three curves of hydrogen central absorption, and the conclusion seems justifiable that they pass simultaneously through maximum and minimum values.

Central absorption and emission velocities had previously been measured by McLaughlin on 57 of the 147 spectrograms. A comparison of his measures and those of the writer showed a high degree of accordance. During each season there was a wide scattering of the velocities given by individual plates. A comparison of the differences, plate *minus* normal place, for Dodson and McLaughlin showed a close agreement. This demonstrated that the variations during any season were actually inherent in the plates, although this does not fully establish their physical reality as attributes of the star.

Efforts to find a period for these more rapid changes met with little success. For the most part the data were too far apart in time to give conclusive results. For $H\gamma$, data for single seasons could be fairly well represented by periods of from 25 to 39 days. For five different seasons the periods found are as follows:

1923–24	39 days	1930–31	30 days
1926–27	25	1931–32	39
1929–30	39		

More data would be needed before definite conclusions could be reached concerning the existence of a short period.

VELOCITIES DERIVED FROM THE HYDROGEN EMISSION LINES

Normal places of the emission velocities of $H\beta$, $H\gamma$, and $H\delta$ are tabulated in the fifth, sixth, and seventh columns of Table I, and are plotted in Figure 1 as open circles. The curves based on them are drawn as broken lines.

The emission velocity-curves are very similar to those for the central absorption lines. The minima are sharper than the maxima, and there is no evidence of lag in phase between the three curves. As in the case of the absorption, the range of velocity is greater for the lines of shorter wave-length, as is shown in the following table:

	Max.	Min.	Range in Km/Sec
Hβ	+55	−10	65
Hγ	75	45	120
Hδ	+110	−45	155

Comparing the absorption and the emission velocity-curves, it is evident that there is a phase difference between the two sets. For each line the emission velocity anticipates the absorption velocity by as much as 100 days. There is also a difference of amplitude of emission and absorption. For $H\beta$ and $H\gamma$ the range is greater for the absorption than for the emission. This, combined with the difference in phase, results in a slight asymmetry in the position of the central absorption line. During the increase of velocity the absorption lies slightly to the violet side of the center of the emission; at maximum emission velocity it is truly central; and during decreasing velocity it is on the redward side of the emission center. Considering normal places, the greatest observed deviation of the absorption from the center of the emission amounts to about 4 per cent of the width of the emission line.

THE WIDTHS OF THE EMISSION LINES

The widths of the emissions at $H\beta$, $H\gamma$, and $H\delta$ undergo variations of more than an angstrom unit. Normal places formed from the measures of width are given in the second, third, and fourth columns of Table II, and are plotted in Figure 2, where the velocity curve of the $H\gamma$ central absorption is displayed at the top for purposes of comparison. In the main, the widths of all three emission

TABLE II

NORMAL PLACES: WIDTHS OF EMISSION LINES AND VELOCITIES OF EMISSION EDGES FOR HYDROGEN

Julian Day	Emission Widths in Angstroms			Velocities of Emission Edges in Km/Sec					
				$H\beta$		$H\gamma$		$H\delta$	
	$H\beta$	$H\gamma$	$H\delta$	Red Edge	Violet Edge	Red Edge	Violet Edge	Red Edge	Violet Edge
2400000+									
20827	5.9	5.2	4.8	+192	−176	+192	−163	+195	−140
21562	7.0	5.4	......	232	198	234	136	......	......
22301	6.4	5.0	5.6	250	145	240	107	290	116
22383	5.8	5.1	4.3	209	149	228	124	222	96
22661	5.6	5.4	......	208	136	190	182	......	......
22720	6.4	5.3	4.7	213	182	195	173	165	150
23094	7.0	5.9	5.4	205	227	165	245	138	242
23361	......	5.5	......	......	......	230	151	......	......
23497	5.6	5.4	4.3	219	128	221	149	211	105
23778	5.6	4.7	......	215	130	198	112	......	127
23847	6.5	5.5	5.6	260	139	256	115	318	99
24153	6.0	4.8	4.4	231	139	212	119	192	130
24225	5.9	5.1	5.1	216	146	235	120	231	147
24458	6.2	4.7	5.1	199	184	179	148	177	192
24527	5.7	5.8	5.3	192	161	183	201	183	214
24832	5.8	5.1	4.7	180	177	164	196	159	184
24867	5.7	4.9	4.9	187	166	167	173	153	206
25265	5.2	4.8	(2.2)	191	132	193	140	40	121
25561	5.4	5.5	5.2	185	148	231	136	231	137
25909	6.5	5.1	4.6	192	206	154	198	156	182
26005	6.9	5.8	5.3	205	218	177	228	166	251
26276	6.6	5.4	4.8	243	165	222	149	201	144
26373	6.4	5.3	......	230	163	228	139	......	123
26657	7.0	5.6	6.0	243	185	270	144	256	172
26752	6.3	5.5	5.3	223	163	226	153	214	172
27011	5.9	5.2	4.9	207	158	211	152	199	166
27109	6.8	5.9	5.1	+244	−175	+230	−179	+218	−146

lines vary together, and exhibit maxima of width at both maxima and minima of velocity, and minima of width at the times near median velocity. The only marked exception to this rule occurs at about JD 25400, when the maximum of velocity is unusually low. The plates which furnish the discordant data are the two-prism spectrograms, most of which are underexposed.

A closer insight into the nature of the variations is gained from a study of velocities of the separate emission edges. These are given

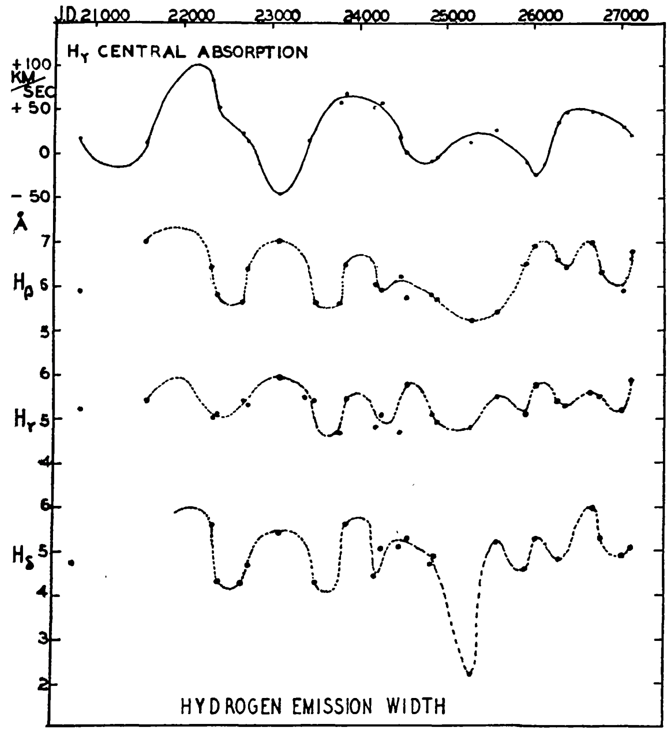

FIG. 2.—Hydrogen emission widths in 25 Orionis

in the last six columns of Table II and are plotted in Figure 3. For each hydrogen line, the velocity curve for the red edge is plotted above that for the violet edge, so that changes in the distance between the two curves indicate (but are not proportional to) changes of the width of the line. In general, the violet edges show sharp minima at the times of velocity minima, but rather blunt maxima at the times of velocity maxima. The red edges, however, show the reverse effect: sharp maxima at velocity maxima and blunt minima at velocity minima, although the differences are less pronounced. It is thus suggested that the variations of emission width are caused by a flaring-out of the weak violet edge of the emission at velocity minima and a flaring-out of the weak red component at velocity maxima. This rather striking phenomenon has an important bearing on the interpretation of the variations in terms of a physical model, which will be discussed in a later section.

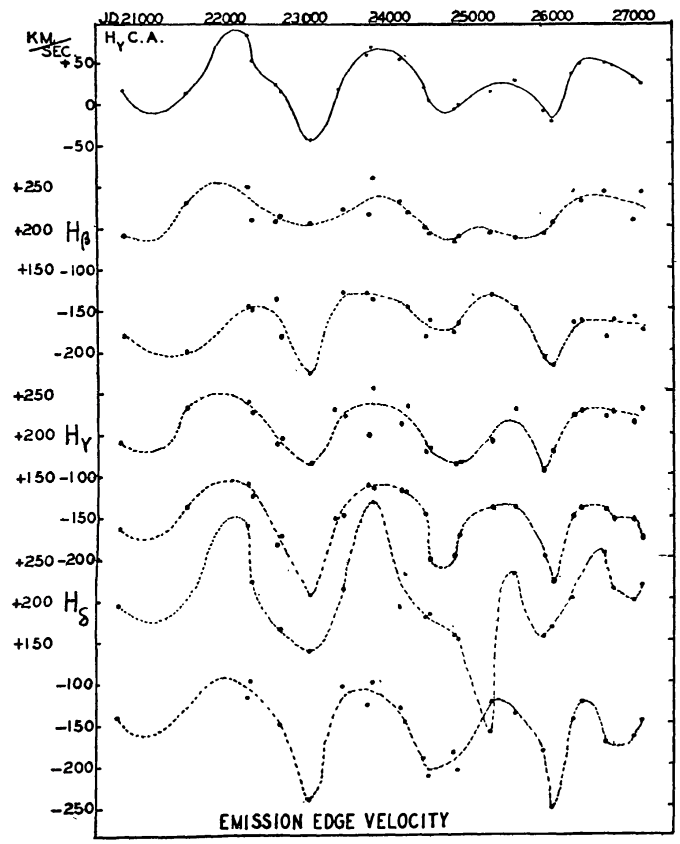

FIG. 3.—Velocities of hydrogen emission edges in 25 Orionis

Line widths, when caused by Doppler shift, should be proportional to the wave-lengths, if the widths are given in wave-length units. Mean values based on all the normal places, except those of JD 25265, are as follows:

$H\beta$	6.2 A	382 km/sec
$H\gamma$	5.3	367
$H\delta$	4.8	351

The agreement seems satisfactory, and the systematic change with wave-length is in the right direction and of the right order of magnitude to be accounted for by the effect of the slit-width in increasing the apparent width of the emission.

THE RATIO OF INTENSITY OF THE VIOLET TO THE RED EMISSION COMPONENTS

Values of the ratio of intensity of the two emission components of $H\gamma$ and $H\delta$ were estimated from the microphotometer tracings.

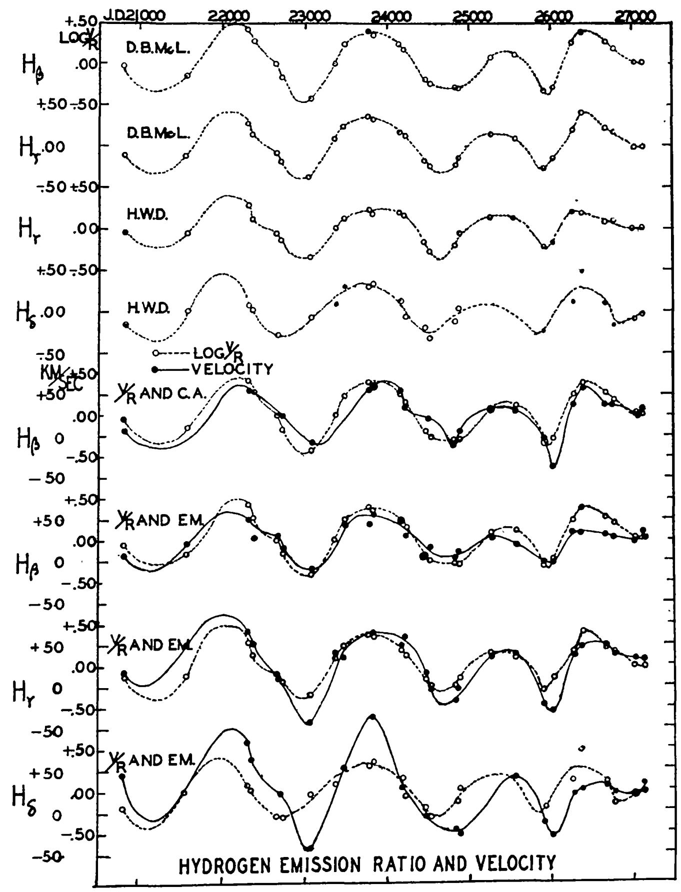

FIG. 4.—25 Orionis. In the lower half of the diagram the figures nearest the margin are log V/R; the others are velocities.

Normal places of these data are given in the tenth and eleventh columns of Table I, in the form of logarithms of V/R. Similar data by McLaughlin, determined by eye estimates from the spectrograms, are given for $H\beta$ and $H\gamma$ in the eighth and ninth columns. The resulting curves are plotted in Figure 4. The close agreement of the two curves for $H\gamma$ obtained by different observers and by quite different methods furnishes a convincing check on the accuracy of the data.

McLaughlin has pointed out that the curves of V/R show a close similarity to the velocity curves. A comparison of his curves for $H\beta$ and $H\gamma$ shows a slight difference in phase: changes of $H\gamma$ slightly precede the corresponding changes of $H\beta$. A comparison of the writer's curves for $H\gamma$ and $H\delta$ shows a conspicuous difference of phase in the same direction; $H\delta$ anticipates $H\gamma$ by 200–300 days. This difference is so conspicuous that it is unquestionably real, and unpublished observations by McLaughlin show this effect strikingly in π Aquarii. On some plates of that star the inequalities of the components at $H\beta$ and $H\gamma$ are opposite in direction, and the appearance of $H\gamma$ predicts the change which is about to occur at $H\beta$.

Rather interesting relationships result from a comparison of the curves of emission ratio and of velocity. The maxima and minima of the former occur earlier than corresponding phases of the central absorption velocities, and the difference in phase is greatest for $H\delta$. (For $H\beta$, see curve 5, Fig. 4.) The relation of the curves of emission ratio to those of emission velocity is shown in the last three curves of Figure 4. At $H\beta$ the two curves are practically in phase; at $H\gamma$ the emission velocity curve lags about 100 days with respect to the curve of emission ratio; and at $H\delta$ the lag is about 250 days in the same sense.

VELOCITIES DERIVED FROM THE HELIUM LINES

Measurements of the helium lines in this spectrum are very uncertain. The lines are broad and diffuse; and the difficulty of measurement is further complicated by apparent structure, doubling, or marked asymmetry. The lines λ 4026 and λ 4472 were measured independently with the micrometer measuring engine and on microphotometer tracings. Normal places formed separately for λ 4026 and λ 4472 for the two methods are given in Table III. The individual velocities are plotted in Figure 5 as small dots and the normals as circles.

In spite of the large scattering of the individual values, the normal places for λ 4472 measured by the two methods are in satisfactory accord. The same, unfortunately, cannot be said concerning λ 4026. In view of the more diffuse character of the latter line and the weaker exposure of that region, it seems best to regard the data obtained from it as inconclusive. The curves for λ 4472 show a cyclic varia-

TABLE III

NORMAL PLACES: HELIUM AND HYDROGEN BORDER ABSORPTION VELOCITIES; TYPE OF CONTOUR FOR HELIUM

Julian Day	Helium Velocities in Km/Sec				Hydrogen Border Absorption Velocity in Km/Sec		Type of Contour for Helium	
	λ 4472		λ 4026					
	Measur. Eng.	Micro-photom.	Measur. Eng.	Micro-photom.	Measur. Eng.	Micro-photom.	λ 4472	λ 4026
2400000+								
20827	−10	−27	+10	+ 6	+27	+ 62	−3.2	−0.8
21562	....	....	+58	+20	....	144	....	+2.0
22326	− 8	−33	− 5	−16	+67	127	+0.6	+1.0
22708	−21	−19	+ 6	−19	+19	126	−2.1	−0.6
23094	+30	+19	−16	−12	−16	161	0.0	−0.3
23439	+58	+21	+26	− 8	....	108	+2.5	+2.0
23827	+ 6	− 9	− 4	+ 9	+81	157	+3.1	+2.1
24189	−19	−36	+ 8	+30	+51	49	−1.2	−1.3
24487	−32	−29	+ 7	+ 5	+89	51	−3.1	−0.7
24847	+ 8	− 8	+12	+ 6	+ 8	99	+0.7	−0.5
25265	....	−14	....	....	....	....	....	....
25561	− 1	−42	−14	−13	+49	39	−3.7	−0.5
25961	+24	+10	+18	− 2	−63	77	−1.6	−0.3
26320	+ 4	−16	+41	+ 3	+15	116	+3.6	+0.8
26657 26752	+22 −32	−35 −33	+37	−13	+38	109	+1.6	+0.3
27011 27109	−26 + 8	−23 −17	− 4	−17	+31	+102	0.0 −2.8	−1.0

tion of velocity with an amplitude of about 70 km/sec. The relation between these velocities and those of the hydrogen central absorption is evident from Figure 6, where the latter are reproduced at the top of the chart and the curve for λ 4472 is the second from the top. The two variations have similar periods, but are conspicuously out of phase. Maxima and minima of the helium velocity occur at least one-third of a period before those of the hydrogen velocity. The lag of the hydrogen velocity amounts to as much as 600 days in cycles I and II, and 400 days in cycles III and IV.

One unfamiliar with the behavior of Be spectra might find it easy to dismiss this difference of phase as an indication that the observations are without meaning. On the contrary, other Be spectra show that it must have some very great significance, for in only one Be

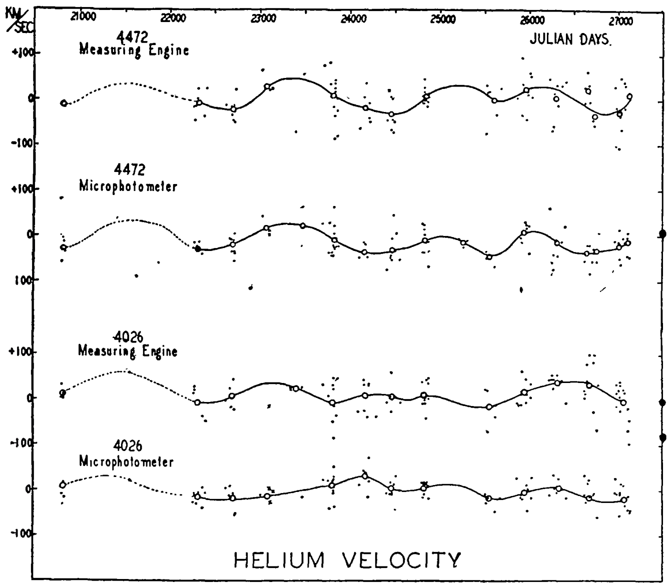

FIG. 5.—25 Orionis

star so far investigated has the helium been found to vary in phase with the hydrogen.[7]

[7] BD $+11^{\circ}$ 4673: helium anticipates hydrogen by roughly one-fifth of a period (Merrill, *Ap. J.*, **69**, 351, 1929).

ζ Tauri: helium is almost opposite in phase to hydrogen (Losch, *Michigan Obs. Pub.*, **4**, 20, 1931).

β Monocerotis: helium velocities are contradictory; mean for all lines is nearly constant (at maximum?), while hydrogen is still increasing (Hawes, *Vassar Pub.*, No. 4, p. 35 [Pl. II], 1934).

11 Camelopardalis: helium is approximately opposite in phase to hydrogen (*ibid.*, p. 45).

β Piscium: helium and hydrogen are opposite in phase (*ibid.*, p. 48).

χ Opiuchi: helium anticipates hydrogen by about one-quarter of a cycle (Cleminshaw, unpublished thesis, University of Michigan, 1934).

HD 33232: "helium velocities apparently have no relationship to the curve for hydrogen" (Merrill, *Ap. J.*, **79**, 347, 1934).

φ Persei: helium is in phase with hydrogen (Dustheimer and Schiefer, unpublished theses, University of Michigan, 1927 and 1929).

VARIATIONS OF CONTOUR IN THE HELIUM LINES

Because of this apparently significant, though confused, character of the helium variations, it was considered worth while to study in greater detail the behavior of the helium lines. Microphotometer tracings show that the helium lines are asymmetrical and that the asymmetry changes. These changes were studied by

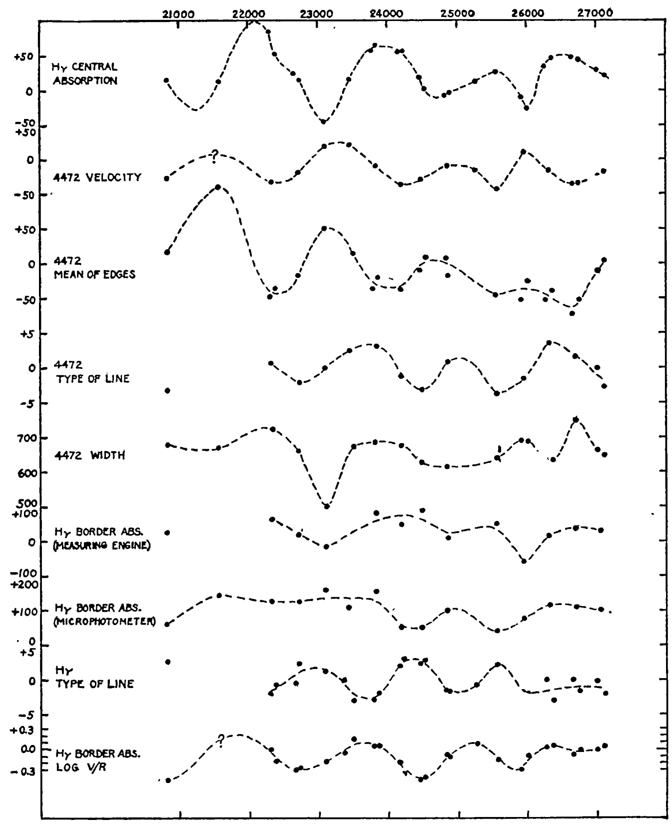

FIG. 6.—25 Orionis

classifying the lines according to degree and direction of asymmetry. The type of line was called positive when the side of greater wave-length showed the steeper gradient, negative when the contour was steeper on the side of shorter wave-length, and zero when the contour was symmetrical. Degree of asymmetry was indicated by the numbers 1–5. These estimates of type of line for λ 4472 show cyclic variations with a period similar to that of the helium and hydrogen velocity curves but out of phase with both of them. The values are given in Table III and are plotted in Figure 6.

The helium velocities from both the microphotometer and measuring engine data were determined from settings on what was considered to be the center of density of the line. This measure was undoubtedly influenced by the radical changes in the contour of the line. If the change in line contour had been the sole cause of the apparent variation in the helium velocity, then the type-of-line curve and the velocity curve should have been in phase. These curves are not in phase; instead, the greatest asymmetry occurs at times of median velocity. The edges of λ 4472 were measured separately, and the mid-point of the line was determined by taking the average of the two measures. Normal places formed from these measures are plotted in the third curve of Figure 6. The mid-point of the line has undergone cyclic shifts in position and is of exactly opposite phase to that of the $H\gamma$ central absorption velocity. The helium velocity curve (center of density measure) is now seen to be the resultant of two separate effects: a shift of the line as a whole, and a variation in the asymmetry of the line.

Normal places of the widths of λ 4472, based on the measures of apparent edges, are given in Table IV and are plotted in curve 5 of Figure 6. This curve shows that the helium lines tend to be narrower when shifted toward the red than when displaced in the opposite direction.

Individual spectrograms differ widely from the seasonal means, and time-averages may have distorted certain relationships between contour, mid-position, and width of line. Accordingly, the data were regrouped by values of these characteristics. In general, when the line λ 4472 was deep on the violet side, it was narrow and the mean of the edges was displaced redward. When symmetrical, it had average width and position. When the absorption was more intense on the redward side, it was wide and the mid-position was displaced toward the violet.

THE UNDERLYING HYDROGEN ABSORPTION

It was thought that the broad underlying absorption lines of hydrogen probably originated in the same region of the stellar atmosphere as the helium absorption, and that similar behavior should therefore be expected. Accordingly, these lines were investigated by measuring their apparent edges on the spectrograms and microphotometer tracings. The normal places obtained from these measurements are given in the sixth and seventh columns of Table III. Both

TABLE IV

NORMAL PLACES: EMISSION RATIO AND ABSORPTION BORDER RATIO FOR $H\gamma$; VELOCITY OF MEAN OF EDGES AND WIDTHS OF HELIUM λ 4472

Julian Day	$H\gamma$ Emission Ratio: Log V/R	$H\gamma$ Abs. Border: Log V/R	Type of Contour $H\gamma$ Abs. Border	Helium λ 4472	
				Velocity of Mean of Edges in Km/Sec	Width in Km/Sec
2400000+					
20827	−.06	−.45	+2.7	+17	680
21562	−.05	......	......	+110	671
22301	+.28	.00	−2.0	−48	726
22383	+.11	−.18	−0.7	−36	
22661	−.05	−.30	−0.5	−18	660
22720	−.13	−.27	+2.3		
23094	−.32	−.18	+1.3	+50	500
23361	.00	−.05	0.0	......	......
23497	+.12	+.15	−3.0	+14	674
23778	+.23	+.04	−2.8	−36	686
23847	+.18	+.06	−1.8	−20	
24153	+.20	−.19	+2.0	−37	677
24225	+.16	−.36	+3.0		
24458	−.16	−.43	+2.4	−10	628
24527	−.27	−.41	+2.8	+8	
24832	−.20	−.08	−1.5	+8	616
24867	−.02	−.11	−1.6	−18	
25265	+.14	+.08	−0.7	......	......
25561	+.13	−.15	+2.2	−46	642
25909	−.22	−.29	−1.8	−52	691
26005	−.18	−.10	−2.0	−25	686
26276	+.20	+.03	0.0	−52	631
26373	+.19	+.05	−3.0	−39	636
26657	+.09	−.07	0.0	−72	748
26752	+.10	−.02	−1.6	−52	
27011	.00	−.01	−0.2	−9	664
27109	.00	+.04	−2.0	+4	651

sets of normals are plotted in Figure 6 as the sixth and seventh curves. Mere random discordance would have been less disturbing than the obviously systematic difference that is shown by the two curves. The curve determined from the measures of the spectrograms is in phase with that for the central absorption; the curve based on the microphotometer tracings is apparently in phase with the velocity curve for λ 4472.

In face of the necessity of choosing between the two curves or dismissing both as meaningless, it appears logical to accept that based on the microphotometer tracings. The line contour on the tracing is a definite and measurable feature; the apparent "edge" of the absorption as seen by the eye on the spectrogram is a thing impossible to define. The large positive velocity of the measures from the tracings is doubtless produced by the influence on the contour of four faint lines of *O* II to the redward of $H\gamma$, but this should not affect the validity of the observed variations of position.

McLaughlin[8] made the qualitative observation that the absorption border on the side of the strong emission component is greatly strengthened, while the other border often nearly disappears. He suggested that this may be due to a motion of the emission as a whole across a stationary underlying absorption, with consequent uncovering of the strong central core. The writer made estimates from microphotometer tracings of the ratio V/R for the absorption borders of $H\gamma$. Normals of these are tabulated in the third column of Table IV and are presented graphically at the bottom of Figure 6. The curve appears well determined and shows that, in general, a strong emission component is flanked by a strong absorption border (since this curve is nearly in phase with that of the hydrogen central absorption velocity and consequently with the curve of emission ratio). McLaughlin's observation is thus confirmed qualitatively, but more accurate study shows that the ratio V/R of the absorption borders reaches its maximum and minimum values about one-sixth of a cycle before the corresponding phases of the emission velocity. There is thus some cause other than a mere uncovering of the deeper portion of the absorption contour with the shift of the emission.

Just as in the case of the helium lines, the microphotometer tracings show that the exposed portions of this underlying hydrogen absorption are unsymmetrical and that the asymmetry changes. In order to make estimates of the type of line, it was necessary to extend the exposed portions of the contours until they intersected. The

[8] *Op. cit.*, p. 48.

normal places of the estimates thus made are given in Table IV, column 4, and are shown graphically in Figure 6, curve 8.

This type-of-line curve for $H\gamma$ sheds some light on the changes in intensity of the two absorption borders. In the main, the change of contour alone would account qualitatively for the change of the ratio V/R of the absorption borders. As the absorption is becoming deep on the violet side (negative type of line), the ratio V/R is seen to approach a maximum. The coincidence is not exact, however, and the ratio V/R for the absorption borders continues to increase for about 100 days after the type-of-line minimum. By an intercomparison of the curves of Figure 6, this difference is found to be satisfactorily accounted for by the further uncovering of a deeper part of the line contour as the emission line shifts toward the red. Similar phenomena occur at the time of maximum asymmetry in the opposite sense.

THE IRON EMISSION

An examination of the tracings shows the presence of broad and faint emission at λ 4584. There are some indications that it became weaker after about JD 27000. It is interesting to note that there was some evidence of a fading of the hydrogen emission at the same time. Prior to JD 25500 the $H\gamma$ emission was consistently stronger than the continuous spectrum of the region, but after JD 27000 it usually appeared distinctly weaker than the continuous spectrum.

DISCUSSION

It is hardly to be expected that all details of the very complex behavior of the spectrum of 25 Orionis will be immediately explained by a simple physical model, but the problem is by no means hopeless. The cyclic variations of velocity and emission intensity constitute the nucleus of the problem. The variations of φ Persei are repeated with such regularity that it was natural to attempt an explanation in terms of orbital motion and attendant phenomena. Such an explanation, however, cannot be valid for Be spectra in general, since several of them are utterly irregular in their behavior. The changes of period of 25 Orionis and π Aquarii[9] definitely rule out the binary hypothesis.

[9] McLaughlin, *Ap. J.*, 77, 224, 1933.

The suggestion that the changes are due to a type of pulsation is due to R. H. Curtiss.[10] A further advance was made by Struve,[11] who pointed out that the diffuse character of the absorption lines indicated rapid rotation and suggested that the emission lines arise from a ring of gas ejected by the rapidly rotating star. This hypothesis, while accounting for the duplicity of the emission, did not satisfactorily explain the relations of velocity and emission ratio.

Recently, Gerasimovič[12] has suggested that Be spectrum variations can be accounted for by a stellar atmosphere in which, for hydrogen, the outward acceleration due to radiation pressure is greater than gravitation. As a result, there is a dissipation of material. This outflow continues until the optical thickness of the expanding chromosphere is sufficient to produce an inward flux of radiation in the dangerous frequencies which will stop the outflow. When this material has been sufficiently dispersed as an expanding shell of gas, the outflow of material will begin again. This mechanism gives a very satisfactory and plausible explanation of the variations in the relative intensities of the red and the violet hydrogen emission components, but is not so successful in explaining the variations in hydrogen absorption and emission velocities.

McLaughlin,[13] working from the similarities of Be spectra to those of novae, suggested an extensive stellar atmosphere, pulsating as well as rotating. Two atmospheric levels are distinguished: an inner emitting atmosphere where the atoms are frequently photoelectrically ionized by the stellar radiation and recombine, giving the emission lines; and an outer atmosphere shielded from the ionizing radiation by the absorption of atoms below it, and therefore acting mainly to produce the absorption superimposed on the emission. The rotation of the atmosphere accounts for the breadth of the emission. In a stage of atmospheric expansion the receding gases on the far side of the star give the strong red component of the emission, which is not subject to absorption by the approaching gases on the near side of the star because of the Doppler shift due to their relative veloci-

[10] *Michigan Obs. Pub.*, **4**, 174, 1932.

[11] *Ap. J.*, **73**, 100, 1930.

[12] *M.N.*, **94**, 737, 1934; *Observatory*, **58**, 115, 1935.

[13] *Proc. Nat. Acad.*, **19**, 44, 1933.

ties. The violet component, produced by approaching gases, is weakened by absorption by the approaching gases of the absorbing layers. At this phase the central absorption, originating between the observer and the star, is produced by approaching gases and is shifted in the negative direction. Opposite effects occur when the expanded atmosphere collapses. However, it is not to be supposed that the velocities observed indicate the extent of the expansion. The observed velocities refer to individual atoms streaming outward or inward, while the region of origin of the emission is considered to undergo only a relatively small change of size.

From the account just given, it should be clear that the general features of the spectral variations of 25 Orionis are satisfactorily accounted for by McLaughlin's hypothesis. It is therefore important to examine the finer details of the behavior of the spectrum.

The hydrogen central absorption velocity curves indicate an increase in range of velocity with decrease in wave-length. Since we may assume that $H\beta$ originates at a higher effective level than $H\gamma$, and $H\gamma$ higher than $H\delta$, this means, in terms of the proposed model, that the maximum velocities attained by the atoms are greater in the inner absorbing atmosphere than in the outer. Such a state of affairs appears reasonable; as the atoms recede from the star, we may expect them to be retarded by gravitational attraction, and the maximum velocity observed for atoms in the outer regions should be less than that in the inner layers. Similarly, during collapse the gravitational acceleration should lead to the greatest velocities in the inner absorbing layers, just before the atoms begin to be checked by radiation pressure as they enter the region where screening is no longer complete. This aspect of the observed velocities is therefore distinctly favorable to the proposed hypothesis.

If the central star were small compared with the gaseous envelope, so that no appreciable occultation of atmosphere by the star occurred, then there should be no variation of emission velocity. As expansion and contraction occurred, there should be symmetrical increases and decreases of width of the emission without change of position. If the model is correct, the fact that the emission lines oscillate indicates that significant occultation occurs. During expansion some of the most rapidly receding gases are occulted, with resultant shift of the emission toward the violet (in the same direction as the central absorption) because of the cutting-off of its red edge. We should expect that a larger percentage of the gases at lower levels would be occulted, i.e., that the effect would be greatest for $H\delta$ and least for $H\beta$. The observations show a greater range of emission velocity for $H\delta$ than for $H\gamma$, and least of all for $H\beta$. These data, therefore, are also favorable to the model.

The variation of emission widths furnishes additional convincing evidence. Whether occultation and its accompanying variation of emission velocity occurs or not, there should be marked changes in the widths of the emission lines if the inward and outward motions of the atoms exceed the rotational velocities. According to the model, greatest emission width should occur at the times of fastest expansion and fastest collapse, i.e., twice during a cycle. The observed emission widths exhibit precisely this behavior. The study of the separate emission edges shows that the increase of width at velocity minimum (fastest expansion) is due to the addition of large velocities of approach on the side of the weak violet component of the emission. Light from the atoms having the greatest velocities of recession fails to reach us on account of occultation by the star. It should be noted that these observations of variation of the emission width are not unique. Schiefer and Dustheimer[14] observed changes of emission widths in φ Persei. The relation between emission width and velocity was precisely that observed in 25 Orionis.

The observed central absorption velocity curves show no difference in phase between $H\beta$, $H\gamma$, and $H\delta$, even though these lines presumably originate at different effective levels. The cause of their velocity changes must therefore act practically simultaneously throughout the extensive absorbing outer atmosphere. This points toward radiation pressure and gravitation as the forces controlling the motions of the gases. A similar interpretation is to be placed on the lack of difference in phase between the emission velocity curves.

The slight phase difference of the central absorption and emission velocities and the great difference in the minima of the emission ratio and the hydrogen velocities cannot be so readily explained without some rather arbitrary assumptions as to the extent of the

[14] Unpublished theses, University of Michigan, 1927 and 1929.

various layers, the values of the outward acceleration at different levels in the atmosphere, and the law of rotational velocities as a function of distance from the star. The observed differences in phase of V/R and the velocity curves suggest a compressional wave beginning at the photosphere and traveling outward through the extensive nebulous atmosphere about the star, but this attractive hypothesis appears incompatible with the low densities required and with radiation pressure as the postulated cause of the outward acceleration.

If we consider the screening effect of the atoms, the acceleration acting on the atoms of the inner absorbing layers (the $H\delta$ level) should be much greater than that acting on the atoms higher up (the $H\beta$ level). Therefore, we might expect that the $H\delta$ shell would attain its maximum rate of expansion more quickly than the higher layers, and that it would be more quickly checked during the collapsing phases. This difference is in the direction actually observed for the emission ratio V/R ($H\delta$ anticipates $H\gamma$, and $H\gamma$ anticipates $H\beta$), but it is difficult to believe that it would account for so large a lag in phase as that observed. If we accepted this interpretation, then we should find it difficult to account for a lack of phase difference between the velocity curves for the several lines, either in emission or absorption. We must therefore admit this as a difficulty in connection with the hypothesis proposed by McLaughlin.

The interpretation of velocity variations shown by the helium and the underlying hydrogen absorption is obscure. These variations do not fit directly into the mechanism suggested by McLaughlin. However, the model proposed by Gerasimovič requires that all absorption lines in the spectrum show cyclic variations in velocity and in a manner such that, when the red emission component is weaker than the violet (when the hydrogen lines are shifted toward the red), the spectrum lines other than those of hydrogen should be displaced toward the violet. Regardless of which measure—the mean of the edges or the center of density—be accepted as the helium velocity, it can be said that the helium lines in 25 Orionis show cyclic displacements which are distinctly out of phase with the hydrogen velocities. To what extent the variable asymmetry of the helium lines can be accounted for by variable weak emission is uncertain. Further work will have to be done before any definite conclusions can be reached from the study of these lines.

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Whitin Observatory
Wellesley, Massachusetts
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