THE Be SPECTRUM VARIABLE PI AQUARII

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ABSTRACT

The spectrum of π Aquarii has been studied on 270 spectrograms taken mainly in the interval 1911–1961. The hydrogen lines have strong emission, several angstroms wide, centrally divided by absorption. Conspicuous variation of the ratio V/R, in cycles ranging in length from from 2 to 6 years, occurred during the intervals 1924–1935, 1941–1942, and 1955–1961. The bright lines were absent during 1936–1937, 1944–1945, and 1950. Total widths of the emission remained approximately constant except for large increases near dates of disappearance and reappearance.

Displacements of the emission and its central absorption accompanied the variations of V/R, with amplitudes up to 150 km/sec and more. Maximum positive displacements accompanied maximum V/R, as in most spectrum variables of this type. The hydrogen central absorption lines often appeared double during the most active variations, especially in 1931–1932. Measures of helium absorption lines indicate that similar structure and variation probably affected them, but emission was too weak to show clearly except at λ 5876, which clearly behaved like the hydrogen lines.

The variations appear best accounted for by the slow rotation of the apsides of an equatorial "shell" with elliptical outline. The significance of measures on emission edges is discussed and the effects of systematic errors are considered. Probably the real variation of position of the emission lines has a smaller amplitude than that of the central absorption, but shifting of apparent absorption borders indicates that the emission is displaced in the same direction as the central absorption. Measurements on microphotometer tracings of β^1 Monocerotis support this conclusion.

INTRODUCTION

About forty of the brighter Be stars have been observed at Ann Arbor for many years. For a few the record starts soon after the beginning of stellar spectroscopic work at this observatory in 1911. One of these is π Aquarii. The variations of its hydrogen lines have been conspicuous, and it best exemplifies the irregular behavior of stars of this type. This paper is intended to be the first of a series on long-term studies of Be spectra. The results will therefore be presented and discussed in considerable detail. Results of earlier studies of π Aquarii have been published by R. H. Curtiss (1925, 1929), C. D. Higgs (1930), W. J. S. Lockyer (1936), and the writer (McLaughlin 1931, 1933*a*, 1937).

GENERAL DESCRIPTION OF THE SPECTRUM

The spectrum of π Aquarii has been classified as B1e. The absorption lines of hydrogen show wide Stark-effect wings, and the helium lines are diffuse and shallow, with profiles of the kind attributed to rapid rotation. Additional complications often occur, making them appear double. The line of Mg II, at 4481 A, can be measured on plates of the best contrast. Other stellar absorption lines are very difficult to detect. The lines appear weaker than simple rotational broadening would make them, as if a faint continuum spread over them. During a stage when the bright hydrogen lines were absent, the absorption lines appeared stronger, as if a veiling continuum had disappeared with the bright lines.

Emission at the hydrogen lines has been strong during the greater part of the 50-year period of observation at Ann Arbor. Scattered observations at the Lick Observatory extend the record of strong emission back to 1893. At Hα and Hβ the bright lines considerably exceed the strength of the continuum. At Hγ the maxima stand only slightly above the continuum, and at Hδ they are relatively weak, though usually readily seen and measured. At Hϵ and Hζ the emission is difficult to see except during phases of great inequality of the components, when the stronger part of the emission is measurable. The over-all widths of the bright lines are several angstroms. The following widths, measured on twenty-eight plates taken during 1955–1960, are typical: Hδ, 6.02 A; Hγ, 5.91 A; Hβ, 7.04 A. Exceptional variations of the emission widths have occurred under special circumstances to be noted later.

Outside of the outer edges of the emission, the wings of the underlying absorption appear at Hβ and higher lines of the Balmer series but are lacking at Hα. At the last-named line the Stark broadening is least, and the underlying absorption is filled in completely by wider diffuse emission wings that are not seen at the higher Balmer lines.

The emission lines are divided approximately centrally by a conspicuous absorption-like minimum. This has never appeared strong, as in shell spectra, but has remained only of moderate strength and usually is fairly well defined, though sometimes weaker and diffuse. It is interpreted as true absorption because its behavior in all the variations of the spectrum is similar to that of the deep, undoubted absorption lines in such shell spectra as that of β^1 Monocerotis.

Weak emission lines of Fe II also occur. The strongest are λ 4233 and λ 4584, which are measurable on the plates of better quality. All other Fe II lines contrast so feebly with the continuous spectrum that few significant measures can be made.

Definite emission appears at λ 5876 He I. Its structure, so far as it can be determined, is similar to that of the hydrogen lines. Incipient emission at the higher members of the helium diffuse triplet series (λ 4472, λ 4026) may be in part responsible for frequent apparent doubling of those lines.

Large variations of the type called V/R have occurred in the hydrogen lines intermittently during the 50-year interval. This type of change consists of a balanced shifting of intensity between the two components into which each wide emission line is divided by the central absorption. Through usage, the terms "violet" and "red" component have become attached to the bright maxima of lesser and greater wavelength, respectively. As the violet component weakens, the red strengthens, and vice versa, so that the sum of the intensities remains roughly constant. Extreme ratios of intensity have been estimated as high as 4. During these variations the passages through the stage of equal components occur rapidly, so that a plot of the ratio V/R is roughly sinusoidal.

The intensity variations are accompanied by changes of wavelength that are interpreted as Doppler effects. Greatest strength of the red component is accompanied by a negative shift of wavelength of the central absorption and also, according to the measurements of emission edges, of the emission as a whole. Both the central absorption and the outer edges of the emission apparently undergo approximately parallel variations of position. The total measured width of the emission remains roughly constant, and the absorption seems to be approximately central in it.

Other interpretations have sometimes been suggested. One of these—that the absorption line is *crowded*, first one way and then the other, by the alternate strengthening of the two emission components—is readily disposed of by analysis of a few good measures. If the "crowding effect" were the main cause of the shifts, the strong emission component should spread outward as well as inward. This would lead to a shift of the emission just the opposite of that shown by the measures. Another suggestion, that the emission remains fixed in position while the absorption oscillates across it, disagrees with the measures, but it requires more critical examination, since the measures themselves might be affected by variable systematic errors. This will be discussed in a later section.

During three different intervals the hydrogen emission lines disappeared for a year or more. Immediately before and after these disappearances, V/R variation was inappreciable.

OBSERVATIONAL MATERIAL

A total of 270 spectrograms were used in this study. Of these, 243 were taken at Ann Arbor, 21 at the Lick Observatory, and 6 at Mount Wilson and Palomar Observatories.

The Ann Arbor spectrograms cover the interval from 1911 to 1961, with a few gaps. The observations from 1911 to 1940 inclusive were obtained with the one-prism spectrograph, dispersion 40 A/mm at Hγ, at the Cassegrain focus of the 37-inch reflector. Beginning in 1941, the one-prism and two-prism spectrographs were used alternately. Many plates of π Aquarii were obtained with the latter instrument, employing a camera of 12 inches in focal length, which gives dispersion of 38 A/mm at Hγ. Since 1952, most of the plates have been taken with the two-prism instrument and 24-inch camera, dispersion 19 A/mm at Hγ. With a few exceptions the Ann Arbor spectrograms recorded only the blue-violet region, $\lambda\lambda$ 3800–5000. Occasionally spectrograms extend to Hα. The spectrograms from other observatories have a considerable variety of dispersions. Most of them also cover only the blue-violet region, but several record the region from Hβ to Hα.

Measurements were made on all features judged to be real, so far as settings were possible. An interrupted reticle was used, which permitted an unobstructed view of weak lines and slight contrasts of density. The most useful measures are those of the hydrogen emission and absorption structure. Measures of the helium absorption lines are discordant, and their interpretation is uncertain.

THE HYDROGEN LINES

At each hydrogen line the positions of the central absorption and the apparent outer edges of the emission were measured. The edges of the central absorption were sometimes measured, especially when these lines appeared unusually wide. On a number of plates the central absorption appeared double, sometimes with equal components, and at other times quite unequal. At Hγ and Hδ the wings of the underlying broad absorption form distinct minima that can be measured like ordinary absorption lines. These were measured whenever they were sufficiently well defined.

On any one spectrogram the velocities of the corresponding features of the different hydrogen lines often show considerable scatter. However, through each season, all show similar trends. The scatter probably is due only partly to accidental errors of measurement. Some of the discrepancies of individual lines may represent real systematic differences, either due to different motions of gases in different parts of the extended atmosphere or as the result of varying effects of the instrumental profile in regions of different dispersion. It is possible that a "crowding" effect of the instrumentally broadened strong emission component operates appreciably at Hβ so as to increase the apparent range of the absorption velocity. The relative weakness of the emission at the higher lines, as well as the greater dispersion at their positions, must make this source of error much less effective at Hγ and Hδ.

Limitations of space prohibit the tabulation of all velocity measures in such a way as to reveal the differences from line to line on each plate. In Table 1 the means of the three lines, Hβ, Hγ, and Hδ, are given for each plate. Table 2, on the other hand, gives means of the measures on several successive plates for Hβ, Hγ, and Hδ separately. These data are plotted in Figures 1, 2, and 3. Additional data of individual line velocities on each plate, for limited intervals of time, are plotted in Figures 4 and 5. These do not appear in any of the tables. Details of measures made on the Lick Observatory spectrograms are given in Table 3.

The ratio V/R was estimated at Hβ and Hγ on all plates that showed these emission lines. These eye estimates have been calibrated approximately by measurements of intensity on microphotometer tracings of nine good standardized spectrograms covering the range of estimated ratios 0.45–2.2. Beyond that range no measures have been made. Table 4 gives the equivalence of eye estimates and measured ratios interpolated from a smooth curve. Because this calibration is tentative, the original eye estimates are tabulated in Tables 1 and 2.

At the extremes of the V/R variation, on a few plates the weaker component was

TABLE 1

MEAN VELOCITIES OF HYDROGEN EMISSION AND ABSORPTION, AND RATIO V/R, IN π AQUARII

Date G.M.T. and U.T.			Emission Edge (VE)	Central Absorption	Emission Edge (RE)	V/R	
						Hγ	Hβ
1911	Sept.	19.74	-243	-28	+200	0.8	1.0
		23.73	-216	-11	+202	0.8	0.7
		27.75	-234	-37	+189	1.0	1.0
	Oct.	11.66	-219	- 2	+210	1.0	0.9
		12.70	-209	-22	+181	0.9	1.0
	Nov.	22.58	-209	-20	+176	0.9	1.0
1912	Oct.	5.68	-201	- 5	+240	1.5	1.3
		19.68	-198	-25	+191	0.7	0.9
1916	Oct.	17.61	-228	- 4	+203	0.7	1.0
1919	Oct.	11.69	-189	-35	+176	1.1	1.1
1921	July	2.83	-189	-10	+215	1.1	1.1
	Sept.	6.72	-246	0	+208	1.0	0.9
1924	Aug.	18.78	-202	+21	+245	1.2	1.3
	Sept.	3.71	-169	+12	+211	0.9	1.3
		22.73	-183	+13	+239	1.6	1.8
1925	Aug.	22.25	-177	+32	+300	1.4	1.8
		24.31	-181	+60	+268	1.5	2.2
		29.31	-178	+55	+280	1.6	1.7
	Sept.	5.26	-184	+50	+249	1.3	2.0
	Oct.	13.17	-211	+31	+285	1.6	2.0
		15.22	-205	+29	+319	1.7	1.9
1926	Aug.	9.31	-188	+29	+226	1.0	1.4
		15.31	-204	+13	+256	0.9	1.3
	Nov.	6.11	-225	+10	+220	0.77	1.0
	Dec.	2.10	-232	-49	+170	0.9	0.9
1928	Aug.	7.33	-214	-74	+125	0.43	0.37
		8.29	-206	-57	+134	0.33	0.36
		12.27	-234	-64	+117	0.45	0.40
		14.24	-204	-38	+124	0.40	0.29
		26.19	-260	-68	+130	0.50	0.36
	Oct.	3.19	-227	-73	+115	0.33	0.33
1929	July	8.35	-319	-78	+140	0.40	0.29
		19.27	-249	-38	+183	0.50	0.45
	Aug.	8.36	-289	-71	+185	0.43	0.40
		13.26	-242	-45	+165	0.62	0.31
		17.25	-257	...	+172	0.67	0.45
		19.20	-244	-69	+147	0.50	0.45
		30.27	-242	-49	+181	0.43	0.43
	Sept.	4.22	-222	-14	+181	0.55	0.50
		14.21	-248	-50	+190	0.62	0.40
		22.12	-220	-52	+168	0.40	0.40

TABLE 1--Continued

Date G.M.T. and U.T.	Emission Edge (VE)	Central Absorption	Emission Edge (RE)	V/R	
				Hγ	Hβ
1929 Oct. 16.18	-285	- 2	+183	0.77	....
18.18	-232	- 4	+208	0.83	1.1
Nov. 5.12	-238	-18	+192	1.0	1.0
8.11	-231	-41	+158	1.6	0.67
23.08	-235	-18	+184	1.1	1.0
30.08	-237	-38	+177	1.6	0.77
1930 June 29.34	-151	+79	(+248)	3.0	4.0
July 31.40	-148	+42	(+313)	2.5	3.5
Aug. 13.37	-144	+43	+231	3.0	3.2
22.39	-154	+47	+232	3.0	3.0
Sept. 13.26	-146	+43	+284	3.5	3.5
18.17	-130	+58	+250	3.0	3.0
Oct. 5.06	-141	+51	+277	3.0	3.5
13.12	-158	+47	+229	2.3	4.0
22.06	-135	+56	....	3.5	4.0
26.14	-156	+79	+356	3.5	4.5
Nov. 5.11	-162	+44	+297	3.0	3.5
13.06	-155	+63	+323	3.0	4.0
Dec. 2.04	-170	+38	+299	2.5	3.0
1931 June 1.38	-169	+45	+256	1.5	2.8
July 4.37	-232	+36	+215	0.83	1.1
10.34	-238	+16	+201	1.2	1.1
24.35	-224	-10	+184	0.75	1.0
Aug. 6.37	-281	+12	+199	....	1.0
16.30	-218	- 9	+210	0.71	0.50
22.38	-220	-17	+207	0.52	0.55
30.37	-203	0	+206	0.7	0.36
Sept. 6.23	-208	-12	+182	0.62	0.45
18.26	-318	-28	+197	0.55	0.42
29.25	-388	-57	+168	0.42	0.36
Oct. 10.25	-334	-75	+157	0.45	0.42
18.18	-261	-39	+162	0.33	0.25
Nov. 1.14	-362	-72	+187	0.43	0.40
6.13	-337	-72	+173	0.50	0.40
1932 June 5.38	-188	+11	+238	2.0	1.5
9.37	-220	-18	+171	1.4	1.5
21.37	-218	-14	....	1.7	1.3
24.35	-232	- 2	+206	1.4	1.7
July 8.38	-256	-12	+162	1.2	2.0
19.35	-165	+ 6	+231	2.0	2.5
29.34	-203	+50	+296	2.0	2.4
Aug. 6.40	-188	+19	+310	1.05	1.05
8.33	-196	+48	+244	1.2	1.6
21.40	-189	+51	+231	1.5	2.1

TABLE 1--Continued

Date G.M.T. and U.T.	Emission Edge (VE)	Central Absorption	Emission Edge (RE)	V/R	
				Hγ	Hβ
1932 Sept. 29.14	-200	+75	+310	1.5	2.5
Oct. 8.14	-155	+59	....	1.6	2.5
16.17	-168	+76	+370	2.0	2.4
Nov. 3.14	-184	+60	+343	2.0	2.0
17.11	-170	+79	+303	1.8	2.3
1933 Apr. 27.40	-204	+32	+278	1.2	1.4
June 1.33	-213	+80	+311	0.9	1.5
11.35	-185	+65	+327	0.7	1.5
17.38	-247	+52	+294	1.2	1.3
July 7.37	-208	+66	+319	1.3	1.5
26.23	-268	+33	+274	...	2:
28.31	-233	+21	+289	1.0	1.2
Aug. 6.32	-294	+29	+269	0.9	1.4
Oct. 3.19	-291	-29	+243	1.0	0.83
28.17	-275	-27	+272	0.83	0.83
1934 May 25.38	-289	-20	+206	0.62	0.50
June 1.38	-284*	-37	+191	0.62	0.70
July 19.38	-291	-72	+157	0.40	0.33
Aug. 9.40	....	-74	+202	....	$<$0.5
17.40	....	-65	+198	....	$<$0.5
Sept. 19.13	-237	-73	+161	0.4	0.3
Oct. 1.22	....	-108	+140	0.4	0.29
14.11	....	-82	+113	0.33	....
30.16	....	-92	+135	0.33	0.29
1935 May 24.37	-249	-65	+147	1:	1:
June 12.35	-320*	-62	+108*	....	1:
July 7.28	....	+18	+136*	1:	1:
14.29	-244	-58	....	1.2:	1.4:
26.36	-226	-12	+216	1.4:	1.4:
Aug. 1.36	-208	+16	....	1.4:	1.6:
27.30	-209	+11	+246*	1.4	1.4
Oct. 2.20	-206	+21	+238	0.8	1.0
25.14	-190	+24	+232	1.1	1.2
Nov. 7.13	-228	- 1	+227	0.8	0.8
1936 May 22.38	....	0	....	....	$<$1
June 13.35	....	-35:	....	....	0.8
Aug. 8.36	....	+ 6:	....	....	$<$1
Sept. 23.14	....	- 2:	....	....	....
Nov. 6.04	....	-49	....	....	....
1937 May 31.37	....	-79	....	....	....
June 22.35	....	-22:	....	....	$<$1
July 30.24	....	- 7:	....	....	....
Aug. 14.30	....	-24	....	....	....
Oct. 13.04	....	+22:	....	....	$>$1

TABLE 1--Continued

Date G.M.T. and U.T.			Emission Edge (VE)	Central Absorption	Emission Edge (RE)	V/R	
						Hγ	Hβ
1937	Dec.	1.07	....	- 2	....	....	....
1938	June	5.37	....	+10	....	0.9	1.0
	July	3.37	-308	-28	+267	1.2	1.1
		24.33	-238	-34	+291	....	1.4
	Aug.	9.30	-334*	-21:	+287*	....	1.2
		19.23	-297	-22	+260	....	1.1
		27.20	-262	-20:	+211*	....	1.1
	Sept.	17.15	-338	-40:	+223*	....	1.0
	Oct.	9.20	(-269)	+ 4	....	....	>1
	Nov.	10.13	-296	- 7	+310*	....	0.7
1939	June	25.38	-227*	+22:	+316*	....	1:
	July	3.38	-314*	-32:	+301*	....	0.9
		19.38	....	+ 4:	....	....	....
	Aug.	4.30	-250	- 9	+174*	1.2	1.2
	Sept.	8.15	-257	-10:	+232	1.1	1.0
	Oct.	3.20	-291*	- 2	+229	0.9	0.75
	Nov.	14.06	-212	+ 1	+230	0.9	1:
1940	July	1.33	-209	-11	+209	1.0	0.9
		18.35	-228	-37	+210	0.7	0.9
	Aug.	1.27	-242	- 1	+250	0.8	0.8
	Nov.	13.05	-311	-63	+215	0.9	1.0
1941	July	24.29	-264	-74	+147	0.50	0.33
	Oct.	8.20	-234	-60	+208	1.2	0.7
		22.13	-307	-49	+156	0.62	0.55
	Nov.	16.08	-250	-52	+188	0.7	0.67
1942	June	18.37	-216	+18	+232	1.7	2.1
		25.37	-173	+51	+248	1.8	1.8
	July	28.38	-185	+41	+186	1.6	1.8
	Aug.	22.28	-182	+36	+257	1.5	1.7
		29.33	-135	+18	+183	1.6	2.1
	Oct.	8.13	-170	+20	+357*	2.2	2.2
1943	Aug.	25.24	-229	-25	+212	0.8	1.1
		28.23	-269	-31	+183	0.77	0.8
	Sept.	23.16	-306	-39	+173	....	0.8
		27.16	-256	-53	+168	0.8	....
	Oct.	30.15	-253	-30	+231	1.1	1.1
1944	July	22.23	-345*	+13	+270*	....	<1
	Nov.	14.13	-446*	-51	+140*	....	1:
1946	Jan.	15.99	....	-16	....	....	....
	July	11.32	....	-22	....	....	....
		27.32	....	+32	....	....	....
	Aug.	8.23	....	-19	....	....	....
	Oct.	4.14	....	-21	....	....	....
1947	July	5.36	....	- 6	....	....	....

TABLE 1--Continued

Date G.M.T. and U.T.			Emission Edge (VE)	Central Absorption	Emission Edge (RE)	V/R	
						Hγ	Hβ
1947	Aug.	10.28	-643	-26	+288	1.0:	1.0:
	Oct.	1.14	-285	- 9	+285	1.0:	1.0:
		15.14	-256*	+34	+305*	1.0:	1.0:
	Dec.	22.06	-320*	+ 5	+409*	1.0:	1.0:
1948	July	21.29	-405*	- 2	+376*	....	1.0:
		29.38	-440	+23	+386	....	1:
	Aug.	10.18	-411	-30	+455	....	1:
	Nov.	12.02		Note			
1949	June	8.35	-325*	- 2	+307*	....	1:
	July	8.39	-323*	-30	+325*	....	1:
	Nov.	8.15	....	+40:	....	....	....
1950	May	3.41	....	+23	....	....	....
1951	Apr.	23.42	-245*	- 2:	+411*	....	1.0
	June	12.37	-312*	-19:	+339*	....	1.0
	July	15.35	-274*	-10	+327*	....	1.0
	Aug.	12.26	....	-41	....	....	....
	Sept.	13.27	....	+ 4:	....	....	....
	Nov.	25.18	-261*	+17	+335*	....	1.0
1952	June	2.38	-355*	+ 5	+373*	1.0	1.0
	July	4.38	-285	- 1	+220	1.0	0.8
	Sept.	9.19	-264	-23	+220	1.0	0.9
1953	July	3.33	-232	+12	+217	....	1.2
	Aug.	11.18	-240*	-11	+244*	....	1.0
	Sept.	27.12	-228*	+39:	+254*	....	1.1
		28.12	-233	+ 5	+228	....	1.1
1954	July	16.37	-223	-20	+239	....	0.9
	Aug.	13.16	-257	-37	+231	....	1.0
	Sept.	24.20	-248	+ 2	+186	....	1.1
	Nov.	9.05	-265	- 4	+336	....	1.0
1955	Aug.	9.31	-199	- 8	+205	0.8	1.1
	Oct.	28.07	-203	+ 8	+242	1.2	1.3
1956	July	11.34	-170	+25	+234	1.5	2.0
	Aug.	15.28	-157	+24	+258	1.4	1.7
	Sept.	26.14	-160	+40	+280	1.8	2.2
	Nov.	6.03	-187	+20	+191	1.3	1.3
1957	July	2.35	-206	-17	+200	1.0	1.0
		18.31	-262	-18	+189	0.95	0.85
	Oct.	5.14	-220	-20	+182	1.0	1.0
1958	Aug.	1.33	-217	- 1	+177	0.77	0.77
	Oct.	2.21	-258	-22	+181	0.7	0.6
		21.09	-243	-26	+162	0.7	0.56
	Nov.	19.07	-270	-12	+177	0.67	0.56
1959	June	2.33	-297	-53	+148	0.5	0.33
		3.34	-342	-76	+135	0.37	0.29

TABLE 1--Continued

Date G.M.T. and U.T.			Emission Edge (VE)	Central Absorption	Emission Edge (RE)	V/R Hγ	V/R Hβ
1959	June	19.36	-267	-63	+130	0.5	0.37
		28.34	-314	-67	+156	0.45	0.36
	July	1.36	-272	-48	+134	0.5	0.36
		7.31	-272	-33	+137	0.55	0.43
	Aug.	1.32	-258	-51	+139	0.55	0.38
	Oct.	10.13	-306	-38	+140	0.45	0.4
		20.12	-258	-48	+152	0.55	0.43
	Nov.	12.05	-314	-53	+118	0.62	0.5
	Dec.	8.02	-276	-62	+141	0.55	0.45
1960	July	8.34	-234	-46	+162	0.8	0.75
		27.35	-266	-38	+161	0.8	0.65
	Sept.	29.14	-261	-47	+199	0.8	0.7
	Oct.	7.13	-250	-44	+174	0.9	0.8
		29.09	-272	-45	+164	0.85	0.85
	Nov.	7.02	-254	-23	+184	1.0	0.8
	Dec.	15.00	-253	-28	+217	1.0	1.0
1961	May	14.33	-226	- 5	+232	1.2	1.0
	June	18.32	-211	-38	+199	1.0	1.1
		27.35	-229	-31	+240	0.95	1.0
	July	23.36	-244	-23	+204	1.0	1.1
	Aug.	4.27	-210	- 5	+197	1.1	1.1
		22.29	-220	-20	+194	1.05	1.05
	Sept.	28.24	-241	-14	+196	0.9	0.9
	Oct.	10.17	-220	- 9	+194	1.0	1.0
	Nov.	18.12	-219	+ 4	+212	....	....
		21.12	-198	0	+201	....	....

Note: * One line only (usually Hβ).

1948 Nov. 12. All lines wide double, mean -123, +97.

TABLE 2

NORMAL PLACES OF HYDROGEN LINE VELOCITIES AND EMISSION RATIOS IN π AQUARII

Date	No. of Plates	Hδ			Hγ			Hβ			V/R	
		VE	CA	RE	VE	CA	RE	VE	CA	RE	Hγ	Hβ
1911.77	6	-193	-28	+163	-222	-19	+186	-227	-13	+221	0.90	0.93
1912.78	2	-168	+14	+208	-199	-24	+209	-216	-27	+226	1.1	1.1
1916.80	1	-192	+58	+189	-218	- 6	+197	-256	-21	+216	0.7	1.0
1919.78	1	-197	-64	....	-165	-26	+186	-209	-22	+165	1.1	1.1
1921.59	2	....	+31	(+253)	-218	-21	+199	-216	-10	+214	1.05	1.0
1924.68	3	-175	+ 1	+189	-177	+12	+234	-197	+35	+251	1.2	1.5
1925.70	6	-178	+31	+235	-177	+43	+293	-208	+54	+298	1.5	1.93
1926.61	2	-163	+40	+246	-183	+ 8	+218	-207	+28	+262	0.95	1.35
1926.85	1	-182	-12	+197	-221	+21	+218	-250	+ 9	+234	0.77	1.0
1926.92	1	-239	-65	....	-233	-45	+181	-228	-43	+158	0.9	0.9
1928.64	6	-211	-57	+107	-220	-62	+116	-234	-68	+141	0.41	0.35
1929.59	6	(-270)	-64	+153	-264	-57	+156	-265	-85	+180	0.52	0.39
1929.73	6	(-234)	-31	(+179)	-238	-29	+191	-245	-29	+180	0.60	0.56
1929.88	4	-223	-20	+194	-243	-20	+162	-233	-53	+185	1.32	0.86
1930.58	4	(-149)	+34	....	-143	+56	+254	-156	+64	+251	2.9	3.4
1930.75	5	-121	+37	....	-138	+45	+240	-155	+79	+286	3.1	3.6
1930.86	4	-146	+67	....	-165	+58	+280	-164	+98	+354	3.0	3.8
1931.42	1	-168	+42	+225	-170	+34	+312	-169	+70	+216	1.5	2.8
1931.55	4	....	+15	+196	-238	+32	+199	-246	+ 5	+202	(0.93)	1.05
1931.67	5	(-215)	0	+181	-214	- 9	+179	-254	-15	+230	0.62	0.46
1931.82	5	(-235)	-71	+163	-342	-56	+162	-356	-68	+177	0.43	0.37
1932.47	5	....	- 7	....	-224	-10	+140	-222	- 3	+235	1.54	1.60
1932.59	5	....	+31	....	-182	+59	+262	-195	+31	+268	1.55	1.93
1932.81	5	-184	+34	....	-164	+63	(+262)	-183	+82	+347	1.78	2.34
1933.32	1	....	- 4	....	-173	+48	+198	-234	+38	+357	1.2	1.4
1933.46	4	....	+84	....	-224	+56	+289	-211	+68	+336	1.02	1.45
1933.58	3	....	+32	....	-254	+21	+261	-276	+37	+293	(0.95)	1.53
1933.79	2	....	-40	....	-298	-30	(+308)	-268	-13	+240	0.92	0.83
1934.41	2	....	-42	+192	(-294)	-14	+184	-284	-45	+217	0.62	0.60
1934.59	3	....	-118	....	-348	-60	+216	(-324)	-59	+185	(0.4)	0.4:
1934.77	4	....	-79	+137	....	-82	+132	....	124	+154	0.36	(0.3)
1935.42	2	(-246)	-60	(+208)	(-258)	-50	(+117)	-281	-92	+128	1:	1:
1935.54	3	(-208)	+ 8	....	-242	-13	....	-291	-53	+143	1.2:	1.3:
1935.73	5	-204	- 6	(+278)	-181	+22	(+241)	-238	+13	+229	1.10	1.20
1936.42	2	....	+ 2	....	....	-33	....	....	- 7	....	....	0.8:
1936.67	2	(-176)	+74	(+231)	(-230)	-27	....	....	-12	(+201)	....	....
1936.85	1	....	-65	....	....	-45	....	....	-43	....	....	....
1937.44	2	....	-87	+154	....	-70	....	....	-23	....	....	....
1937.60	2	....	- 2	(+101)	....	-45	....	....	+30	....	....	....
1937.85	2	....	+46	....	....	+16	....	....	-37	....	....	....
1938.55	5	(-235)	-25	....	(-312)	-19	+258	-300	- 4	+270	(1.0:)	1.16
1938.75	4	....	-24	....	-272	- 3	(+211)	-310	-34	(+328)	....	1.0:
1939.64	7	(-212)	- 6	....	(-263)	- 3	(+225)	-248	+ 5	+249	(1.1:)	(1.0)
1940.62	4	(-254)	-24	....	-243	-26	+218	-250	-36	+224	0.85	0.90
1941.75	4	(-272)	-69	(+187)	-284	-57	+175	-249	-50	+175	0.75	0.56
1942.48	3	-200	+23	(+203)	-192	+37	+238	-187	+49	+227	1.70	1.90
1942.71	3	-158	+16	(+137)	-165	+19	(+228)	-161	+68	(+339)	1.8	2.0
1943.72	5	(-252)	-18	(+184)	-267	-42	+185	-258	-41	+201	0.87	0.95
1944.71	2	....	(+25)	....	....	-11	....	-396	-72	+205	....	....
1946.04	1	....	-23	....	....	- 7	....	....	-27	....	....	....
1946.61	4	....	+ 5	....	....	0	....	....	-33	....	....	....
1947.73	5	....	-15	....	(-336)	+ 7	(+338)	-290	- 1	+315	1.0:	1.0:
1948.65	4	....	-10	....	....	-30	....	-419	- 8	+406	....	1.0:
1949.60	3	....	- 7	....	....	+ 7	....	-324	+ 6	+316	....	1.0:
1950.34	1	....	+37	....	....	+17	....	....	+19	....	....	....
1951.58	6	....	-24	....	....	-13	....	-273	+18	+353	....	1.0
1952.54	3	....	- 3	....	-268	- 8	+224	-313	- 7	+269	1.0	0.9
1953.65	4	....	-10	....	(-241)	- 5	(+204)	-236	+32	+249	1.0	1.1
1954.69	4	-228	-33	....	-255	- 5	+240	-240	-15	+256	....	1.0
1955.72	2	(-189)	- 4	(+210)	-205	-20	+235	-201	+12	+220	1.0	1.2
1956.69	4	-168	+18	(+255	-163	+26	+238	-172	+38	+246	1.50	1.80
1957.60	3	(-242)	- 8	+182	-217	-23	+182	-232	-20	+204	0.98	0.95
1958.76	4	....	Note	+163	-246	-14	+167	-252	-29	+186	0.71	0.62
1959.49	7	-324	-49	+150	-272	-60	+132	-292	-52	+145	0.49	0.33
1959.85	4	(-287)	-38	(+149)	-281	-53	+132	-292	-54	+142	0.54	0.45
1960.55	2	....	-50	....	-240	-47	+154	-260	-24	+168	0.8	0.70
1960.80	4	(-251)	-49	(+164)	-263	-35	+175	-256	-39	+188	0.89	0.79
1960.96	1	....	....	....	-276	-31	+217	-230	-22	+216	1.0	1.0
1961.44	3	(-216)	-42	(+218)	-233	-29	+261	-210	- 5	+209	1.05	1.03
1961.60	3	(-246)	+ 2	(+183)	-242	-23	+199	-208	- 9	+202	1.05	1.08
1961.82	4	(-220)	+14	(+233)	-206	-16	+194	-236	+ 1	+200	....	....

Note: 1958.76; Hδ appears double on all plates, mean velocities: -99 (weak); +22 (strong).

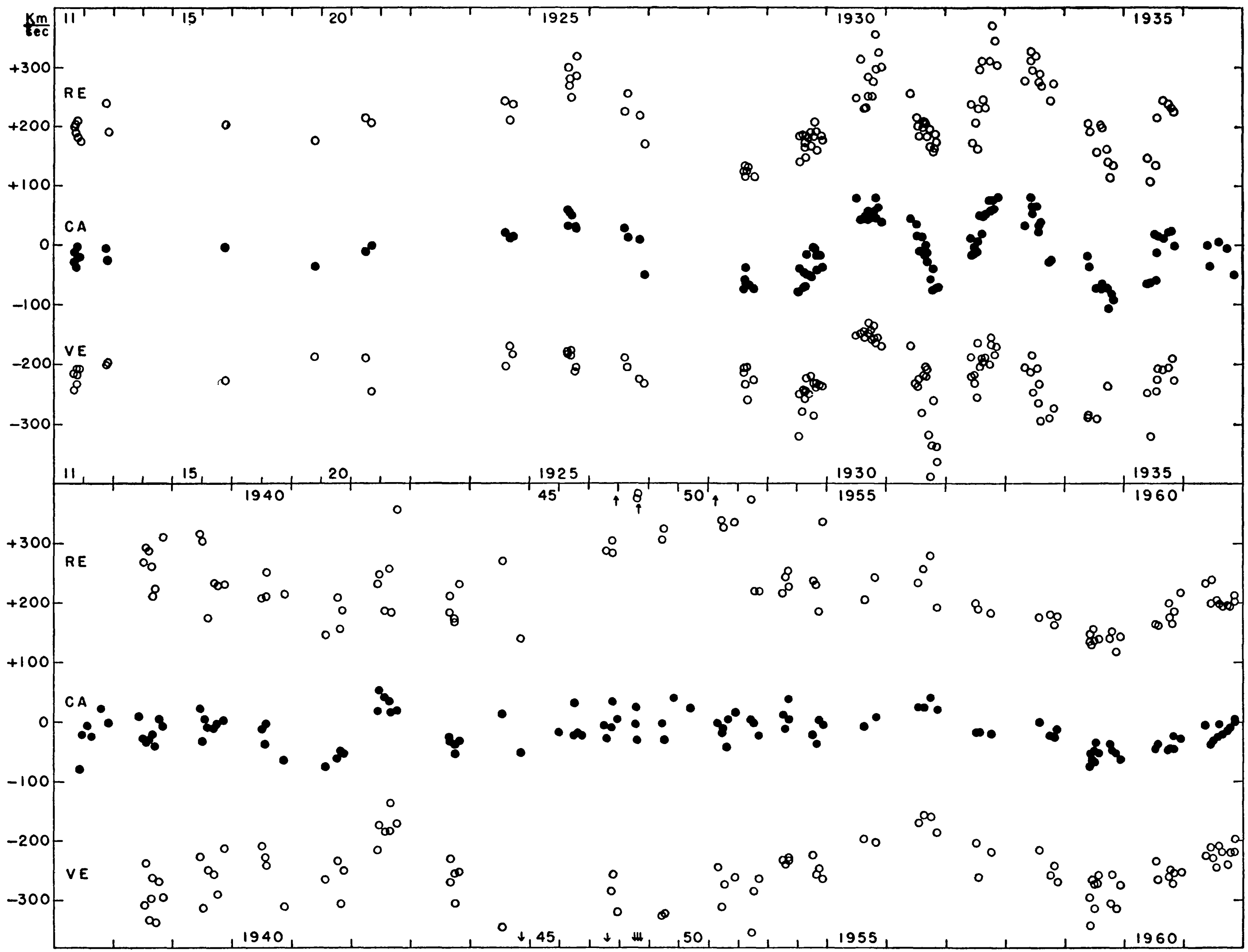

FIG. 1.—Mean velocities of hydrogen emission edges and central absorption lines measured on individual plates of π Aquarii, 1911–1961. The time scale is compressed during the "inactive" stages 1911–1922 and 1945–1954. Data from Table 1. *Open circles:* emission edges (*RE*, red edge; *VE*, violet edge); *filled circles* (*CA*): central absorption. Arrows at top and bottom, 1944–1951, indicate emission edge velocities

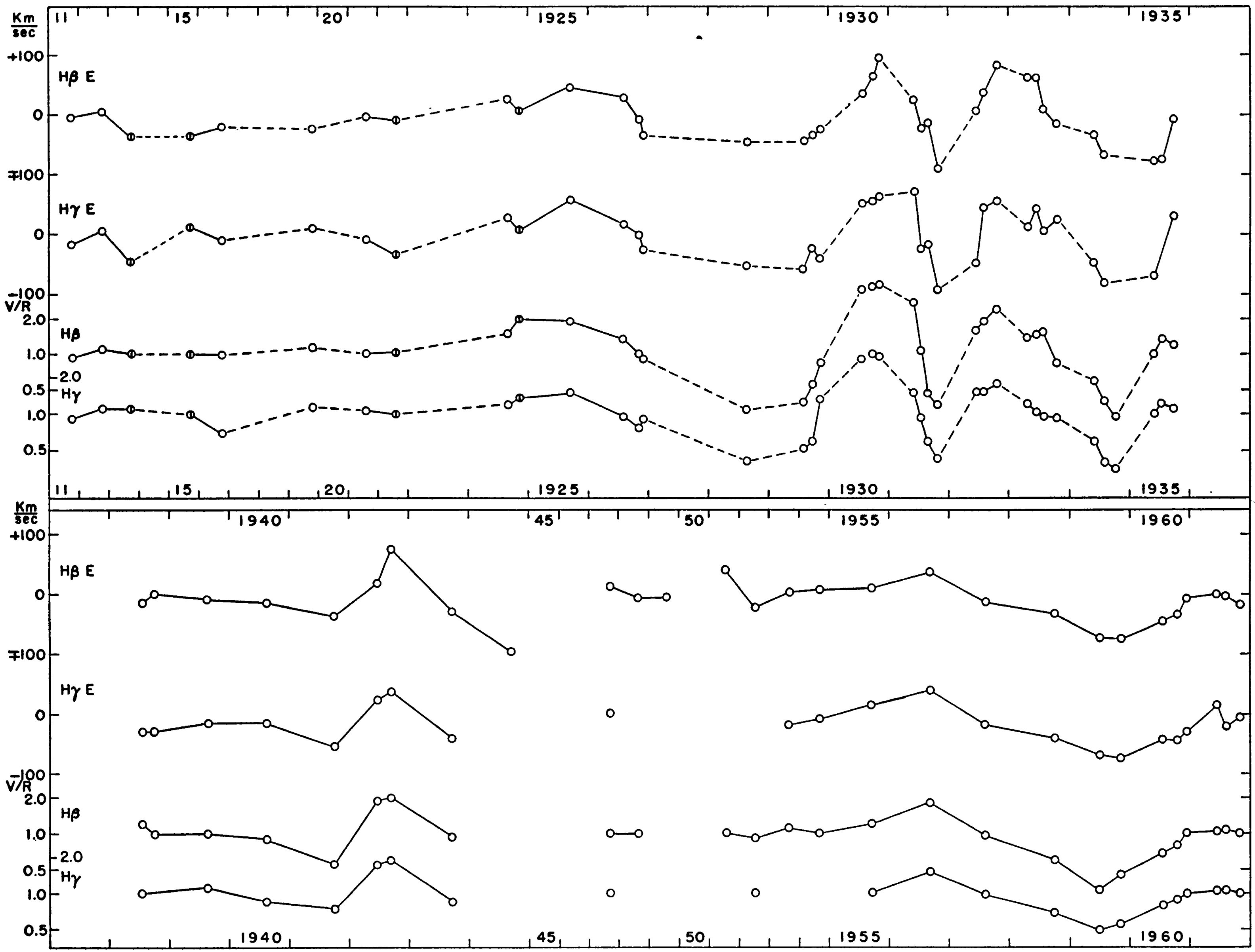

FIG. 2.—Velocities and V/R for Hβ and Hγ emission in π Aquarii, 1911–1961. The time scale is compressed during the "inactive" stages 1911–1922 and 1945–1954. The data are group means based on Table 2. Emission velocities are means of values for red and violet edges. Values of V/R are means as listed in Table 2. Circles with vertical bars (1913 1915, 1922 ,1924) are data from Lick spectrograms.

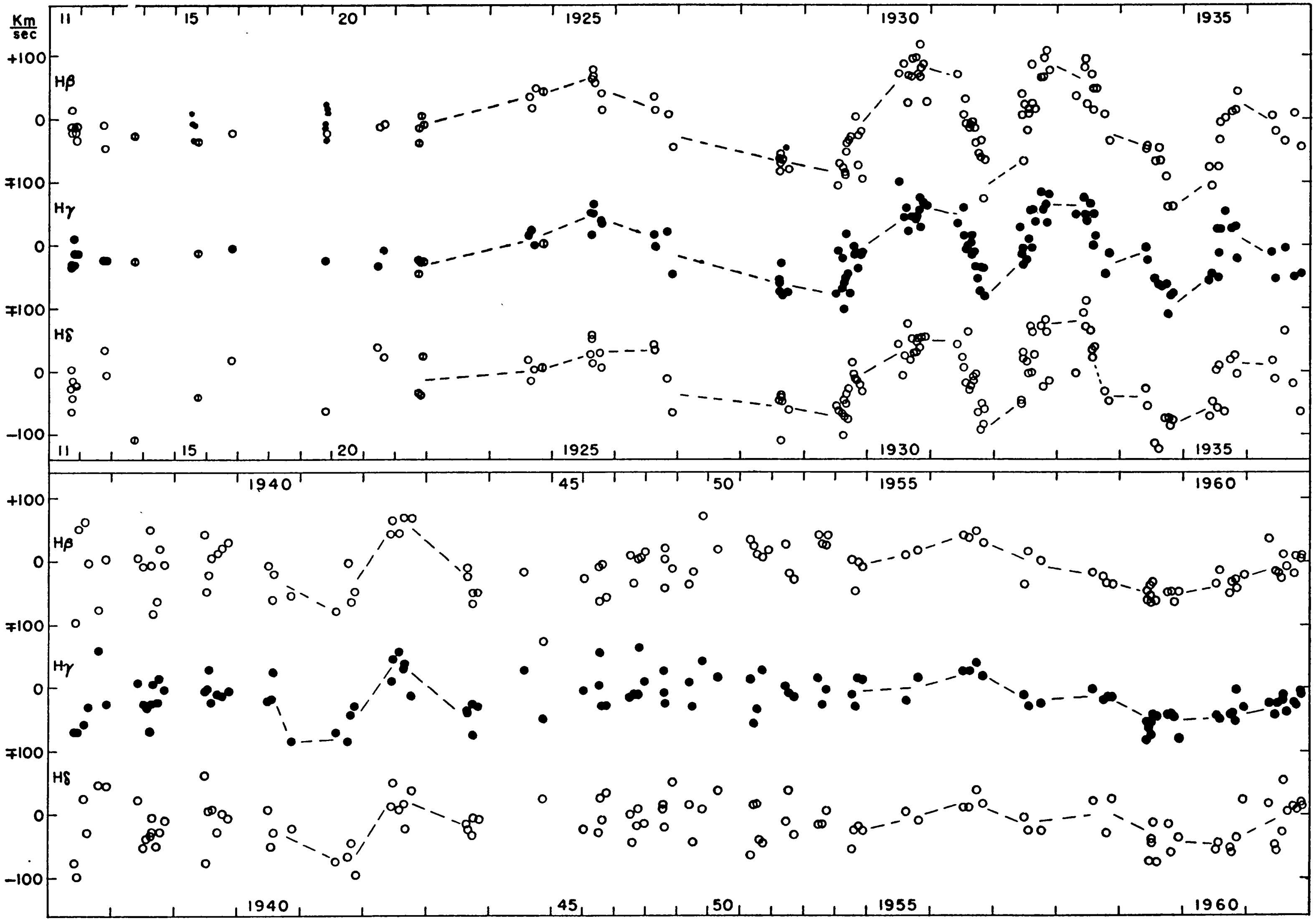

FIG. 3.—Velocities of central absorption at hydrogen lines of π Aquarii, measured on individual plates, 1911–1961. The scale of time is compressed during the "inactive" stages 1921–1922 and 1945–1954. *Open circles:* Hβ (*above*) and Hδ (*below*); *filled circles:* Hγ. Circles with vertical bars (1913, 1915, 1922, 1924) are data from Lick spectrograms. Small black dots plotted with Hβ (1915, 1919, 1928) are Yerkes data (Higgs 1930).

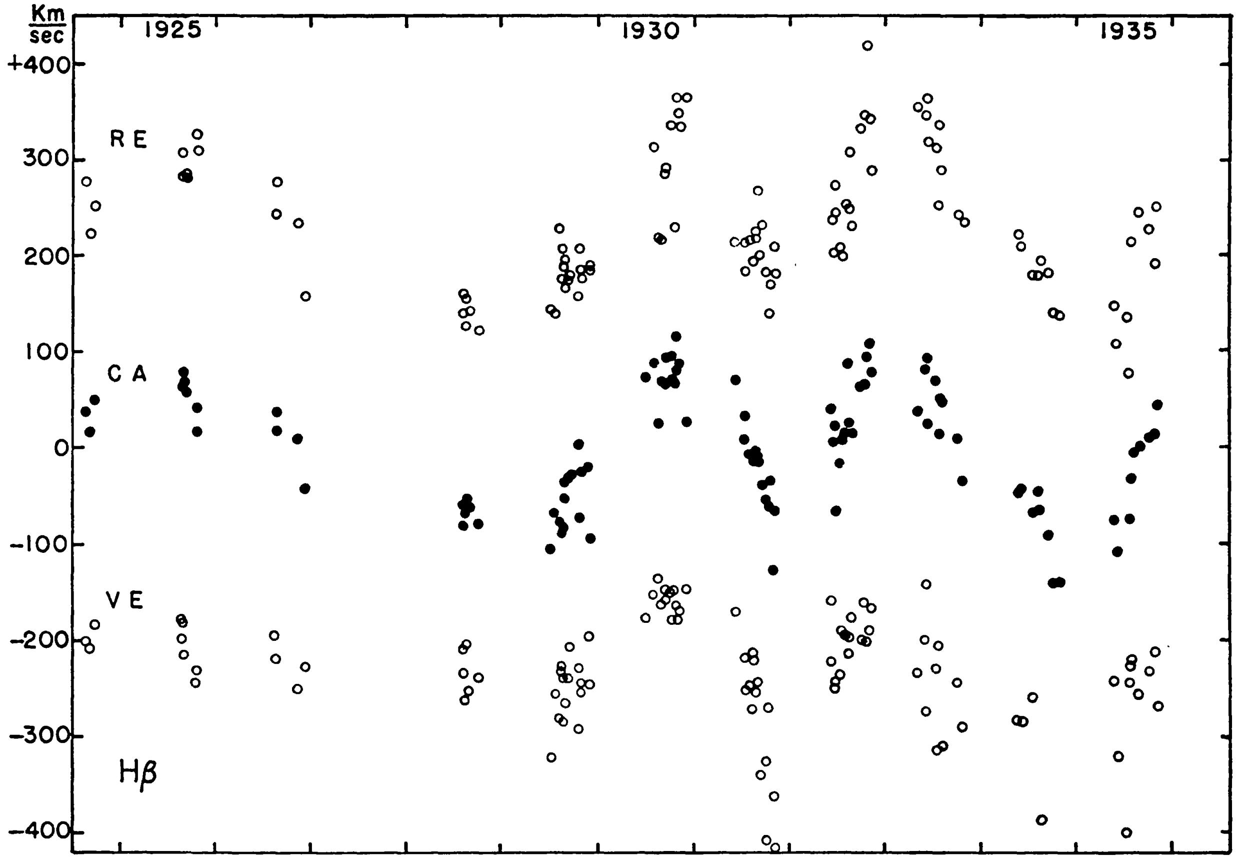

FIG. 4.—Measured velocities of emission edges and central absorption lines at Hβ on individual spectrograms of π Aquarii during the "active" period 1924–1935. *Open circles:* emission edges (*RE*, red edge; *VE*, violet edge); *filled circles* (*CA*): central absorption velocities.

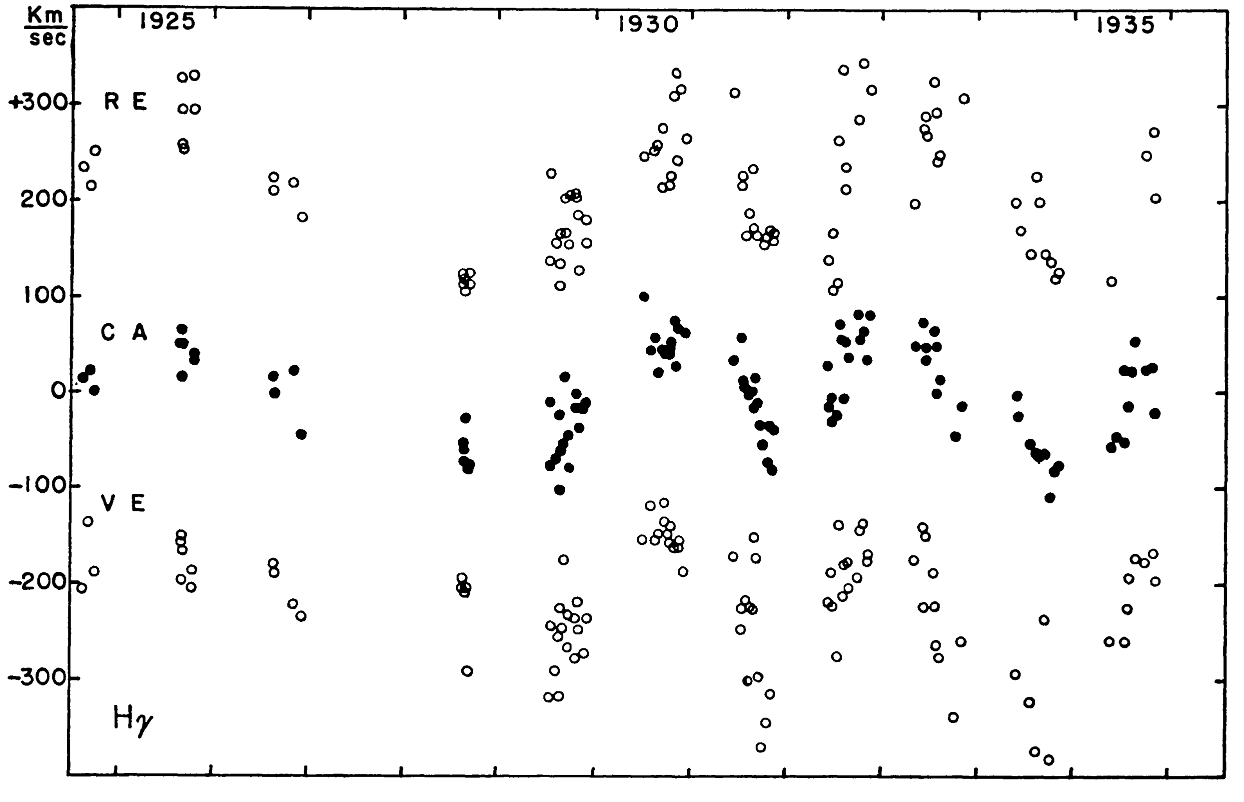

FIG. 5.—Measured velocities of emission edges and central absorption lines at Hγ on individual spectrograms of π Aquarii during the "active" period 1924–1935. Symbols have the same meaning as in Fig. 4.

difficult to distinguish or apparently absent. Thus, in 1930 a "reversed P Cygni" structure was apparent at the hydrogen lines when the violet emission was strongest. During October, 1934, the spectrum somewhat resembled that of P Cygni.

DISCUSSION OF THE HYDROGEN-LINE VARIATIONS

The most obvious result that can be seen by inspection of Figures 1–5 is the marked irregularity in the variations of π Aquarii. Constancy and variation of V/R have alternated during the 50-year interval, and at times the emission line has disappeared. The velocity amplitudes are large, reaching 200 km/sec for the Hβ emission in 1930–1931. The record before 1911 is fragmentary, but the scattered Lick Observatory plates show that the spectrum and velocity did not vary conspicuously during the interval 1893–1911.

Changes were small or non-existent from 1911 to 1923. The seasonal means of velocity

TABLE 3

RADIAL VELOCITIES OF HYDROGEN-LINE FEATURES OF π AQUARII ON LICK OBSERVATORY SPECTROGRAMS*

Date G.M.T.	Disp.	Hδ			Hγ			Hβ			V/R	
		ve	ca	re	ve	ca	re	ve	ca	re	Hγ	Hβ
1893 Oct. 12....	1p†	.....	.....	.....	−248	+18	+229	.....	.....	.....	0.8	.....
25....	1p†	.....	.....	.....	−188	+35	+242	.....	.....	.....	1.0	.....
1896 July 6....	3p	.....	.....	.....	−212	−17	+177	.....	.....	.....	1.0	.....
1897 Aug. 17....	3p	.....	.....	.....	−172	−14	+166	.....	.....	.....	1.0	.....
1911 June 13....	1p	.....	.....	.....	.....	.....	.....	−248	− 5	+280	.....	1.0
21....	1p	.....	.....	.....	.....	.....	.....	−298	+ 4	+246	.....	1.0
1912 June 14....	1p	.....	.....	.....	.....	.....	.....	−189	− 7	+217	.....	1.0
July 27....	1p	.....	.....	.....	.....	.....	.....	−292	−40	+229	.....	1.0
Aug. 19....	3p	.....	.....	.....	.....	.....	.....	−222	−31	+193	.....	1.1
25....	3p	.....	.....	.....	.....	.....	.....	−238	− 6	+188	.....	1.2
1913 Sept. 23....	1p	−345	−109	+341	−346	−28	+256	−267	−26	+199	1.1	1:
1915 Sept. 21....	1p	.....	− 41	.....	−209	−13	+233	−247	−33	+178	1.0	1.0
1922 Sept. 22....	1p	.....	− 34	.....	−214	−23	+141	−176	−38	+238	1.0	1:
Oct. 2....	1p	.....	.....	.....	−260	−47	+185	−241	−14	+243	1.0	1:
Nov. 9....	1p	.....	− 37	.....	−261	−27	+175	−290	+ 4	+250	1.0	1.0
22....	1p	−177	+ 24	+179	−237	−27	+202	−283	− 8	+201	1:	1.1
1924 Nov. 10....	1p	−181	+ 6	+175	−178	+ 2	+194	−221	+44	+234	1.4	2.0

* In the table the columns labelled "ve," "ca" and "re" refer to the "violet" edge of emission, the central absorption, and the "red" edge of emission, respectively.

† Only Hγ comparison line.

TABLE 4

CALIBRATION OF EYE ESTIMATES OF V/R

Eye Estimate	Measured Ratio	Eye Estimate	Measured Ratio
0.45........	0.35	1.00........	1.00
.50........	.42	1.20........	1.23
.60........	.53	1.50........	1.60
.70........	.67	1.80........	2.00
.80........	.78	2.0........	2.4
0.90........	0.90	2.2........	2.8

lie close to the middle of the large range seen in later years, and throughout that interval the red and violet emission components were essentially equal. Observations made at the Yerkes Observatory in 1915 and 1919 (Higgs 1930) reinforce this conclusion.

Variation set in about 1924. The first cycle was probably long, but there is a little doubt because of a lack of observations in 1927. It is possible, though rather unlikely, that a rapid rise to a maximum and a return to minimum took place during the gap in the observations between December, 1926, and August, 1928. Be that as it may, relatively rapid changes of V/R and velocity with a large amplitude took place in 1929–1935. Cycles were 2–3 years in length, and the last had an amplitude considerably less than those that preceded it.

In 1935 the emission lines had become relatively weak; in May, 1936, only a feeble trace remained at Hβ. By July it had disappeared completely, and it was not seen again distinctly until June, 1938. It then remained relatively stable, with equal components and without large velocity variations through 1941. A conspicuous maximum of V/R and velocity occurred in 1942, followed by a return to equality and mean velocity in 1943. In 1944–1946 the emission was again absent. A brief reappearance of apparently much wider emission occurred in 1947–1948, after which it again weakened and did not return until 1951. After a few years of constancy at equality and mean velocity, variation set in again, and about one cycle was completed between 1955 and 1961.

The lines are sufficiently accordant to define the variations individually, but distinct systematic differences appear, and various aspects of the variation are slightly out of phase. In Figure 2 we see that changes in V/R distinctly preceded changes of velocity. In 1930, 1932, and 1935, V/R had already attained nearly its maximum value, while the emission velocity was still not far from the middle of its range. Discrepancies are less evident at the minima of the curves.

Figure 3 shows differences between the absorption velocities of Hβ, Hγ, and Hδ.The ranges of Hγ and Hδ are about equal, but that of Hβ is clearly greater, possibly due to a "crowding" effect of the stronger emission component. Phase differences are slight, but Hδ seems to anticipate Hγ in the most rapid passages from positive to negative velocities.

Systematic differences between the emission velocity-curves are irregular (Fig. 2). In 1930, Hγ anticipated Hβ in rising to maximum, and there is some indication of the same effect in 1932. In 1933, however, Hβ declined ahead of Hγ. In the changes of V/R the higher lines anticipate Hβ. On some plates near passage through equality, the inequality of components at Hγ is opposite to that at Hβ.

MEASURES OF Hα

Only a few Ann Arbor plates show the Hα region, and, because of the low dispersion at that line, they were not measured for velocity. The Hα emission and its central absorption were measured on several Lick and Mount Wilson spectrograms. Some of these show weaker wings that extend to considerably greater widths than the structures measured at Hβ and higher lines of the series. With proper exposure, however, the narrower structure is not seriously confused by these wings and can be measured.

Four one-prism spectrograms taken at Lick Observatory in 1911–1912 show both Hα and Hβ. Means of the measures on these four plates are given in Table 5. Considering the low dispersion, the results for Hα and Hβ are fairly accordant. The central absorption was not measurable at Hα.

Three grating spectrograms with dispersion 77 A/mm obtained at Lick Observatory in 1958 show the narrower Hα emission structure very well. Measures of these plates are listed individually in Table 6, and, for comparison, velocities of Hβ and Hγ as measured on Ann Arbor plates on neighboring dates are also given. Since the velocities and V/R were near the middle of their ranges during the interval covered, the comparison is not particularly conclusive.

Two Mount Wilson spectrograms were obtained at extremes of the variation in 1932 and 1941, respectively. Measures of Hα on these plates and of Hβ and Hγ on Ann Arbor plates of neighboring dates are compared in Table 7. Though the velocities individually are not highly accordant, the changes are large and in the same direction for all the lines. Measures of λ 5876 He I will be discussed subsequently.

WIDTHS OF HYDROGEN EMISSION LINES

During most of the 50-year interval of the Ann Arbor observations, the over-all widths of the emission lines showed only small variations that are difficult to separate from accidental errors. No tabulation is given, but the velocities of the edges in Tables 1 and 2 yield the widths in velocity units that are plotted in Figure 6.

In 1933 the widths appeared significantly greater than in neighboring years. When the emissions reappeared in 1938, they were appreciably wider than before. Again, in 1948, the widths were much greater than usual, and this was true also when the emissions reappeared in 1951. Evidently unusually great width of the bright-line structure was associated with each reappearance after an absence. These wider emissions were rather weak and ill defined. When they finally stabilized later in 1955, they had returned to approximately the width that was measured during the greater part of the 50-year interval, and their strength was nearly as great as had been recorded at any time.

DOUBLING OF HYDROGEN CENTRAL ABSORPTION

On a number of plates the central absorption of one or more of the hydrogen lines definitely appeared double. The greatest frequency of doubling affected Hδ in 1931 and Hγ in 1932, but a few sporadic occurrences were noted in nearly every year. Doubtless some of these were caused by accidental grain effects, but the majority are believed to

TABLE 5

VELOCITIES OF Hα AND Hβ ON LICK SPECTROGRAMS, 1911–1912 (KM/SEC)

	Violet Emission Edge	Central Absorption	Red Emission Edge
Hα	−300	....	+248
Hβ	−257	−12	+243

TABLE 6

VELOCITIES OF Hα ON LICK SPECTROGRAMS, COMPARED WITH VELOCITIES OF Hβ AND Hγ ON MICHIGAN SPECTROGRAMS OF NEIGHBORING DATE

Lick Observatory				Michigan Observatory						
Date 1958	Hα			Date 1958	Hβ			Hγ		
	ve	ca	re		ve	ca	re	ve	ca	re
Aug. 17	−237	+ 1	+197	Aug. 1	−220	−19	+192	−241	− 3	+172
24	−233	− 1	+189							
Sept. 3	−278	−38	+240	Oct. 2	−274	−24	+190	−241	−21	+172

TABLE 7

VELOCITIES OF Hα AND λ 5876 ON MOUNT WILSON SPECTROGRAMS, COMPARED WITH VELOCITIES OF Hβ AND Hγ ON MICHIGAN SPECTROGRAMS ON NEIGHBORING DATE

	ve	ca	re	ve	ca	re
	Mount Wilson					
	1932 Nov. 18.2 (33 A/mm)			1941 Nov. 4.2 (20 A/mm)		
Hα.........	−106	+74	+235	−265	−12	+207
λ 5876......	−157	+81	+334	−348	−41	+229
	Michigan					
	1932 Nov. 17.1			1941 Nov. 16.1		
Hβ.........	−167	+78	+290	−220	−50	+190
Hγ.........	−168	+80	+317	−279	−30	+187

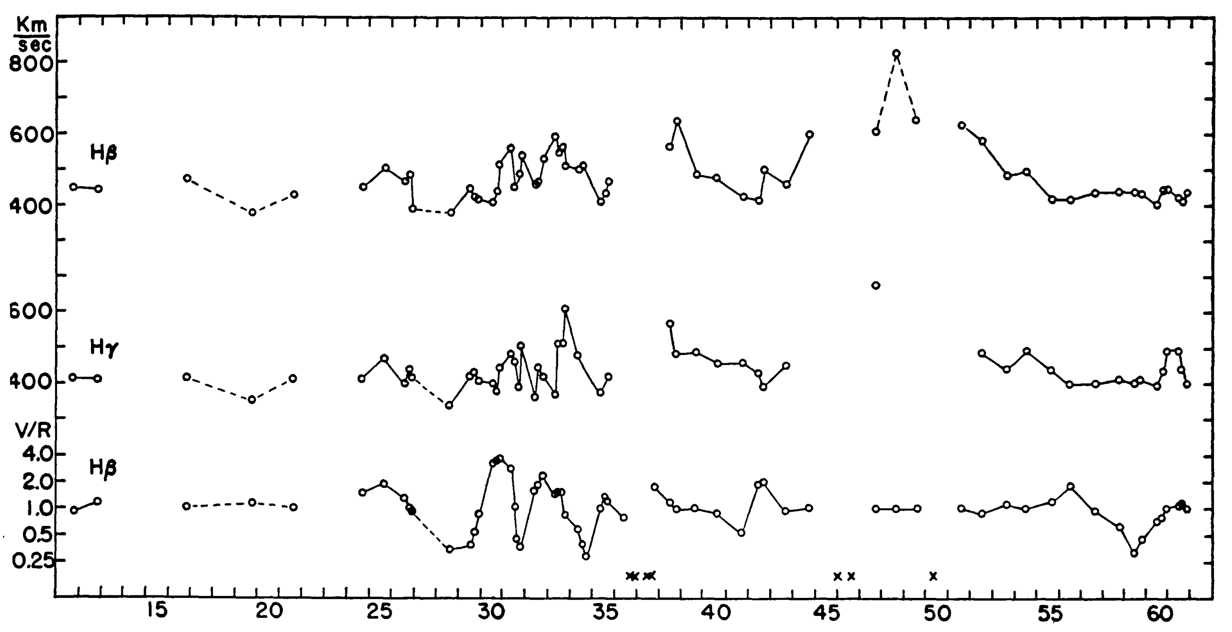

FIG. 6.—Widths, in km/sec, of Hβ and Hγ emission of π Aquarii for the interval 1911–1961. The data plotted are group means obtained from group means of edge velocities in Table 2. At the bottom are plotted group means of V/R at Hβ (Table 2). Crosses below the curve indicate absence of emission.

represent real complications in the line profiles. Separations lie mainly in the range 100–150 km/sec. Doubling and asymmetry on a smaller scale are well known in the better-defined absorptions of "shell" spectra.

Duplicity of more than one line on the same plate seemed to occur about as frequently as would be expected from chance coincidence. A comparison of measures of Hγ and Hδ shows that when one line was single and the other a double with practically equal components, the mean velocity of the double usually agreed with that of the single line. When the double was clearly unequal, its stronger component usually agreed with the single line. These correspondences have been assumed to hold in all cases for purposes of computing the means in Tables 1 and 2.

VARIATIONS OF THE HYDROGEN ABSORPTION BORDERS

The emission lines of hydrogen are flanked by the wings of the Stark-broadened underlying absorption. Though these features are often rather diffuse, micrometer settings can be made on them on spectrograms of low dispersion. Whenever possible they were measured at Hγ and Hδ.

Large variations of intensity of these borders accompany the *V/R* variations of the emission. When the emission components are equal, the borders appear nearly equal. When the emissions are very unequal, the border adjoining the stronger component is invariably the stronger, and the weaker border is often invisible. Similar effects appeared in 25 Orionis (Dodson 1936). Qualitatively, these changes are consistent with an oscillation of the emission, which alternately covers and uncovers the borders, but the cause may be more complicated than this.

In Figure 7 the measured velocities of the borders at Hγ during the most active varia-

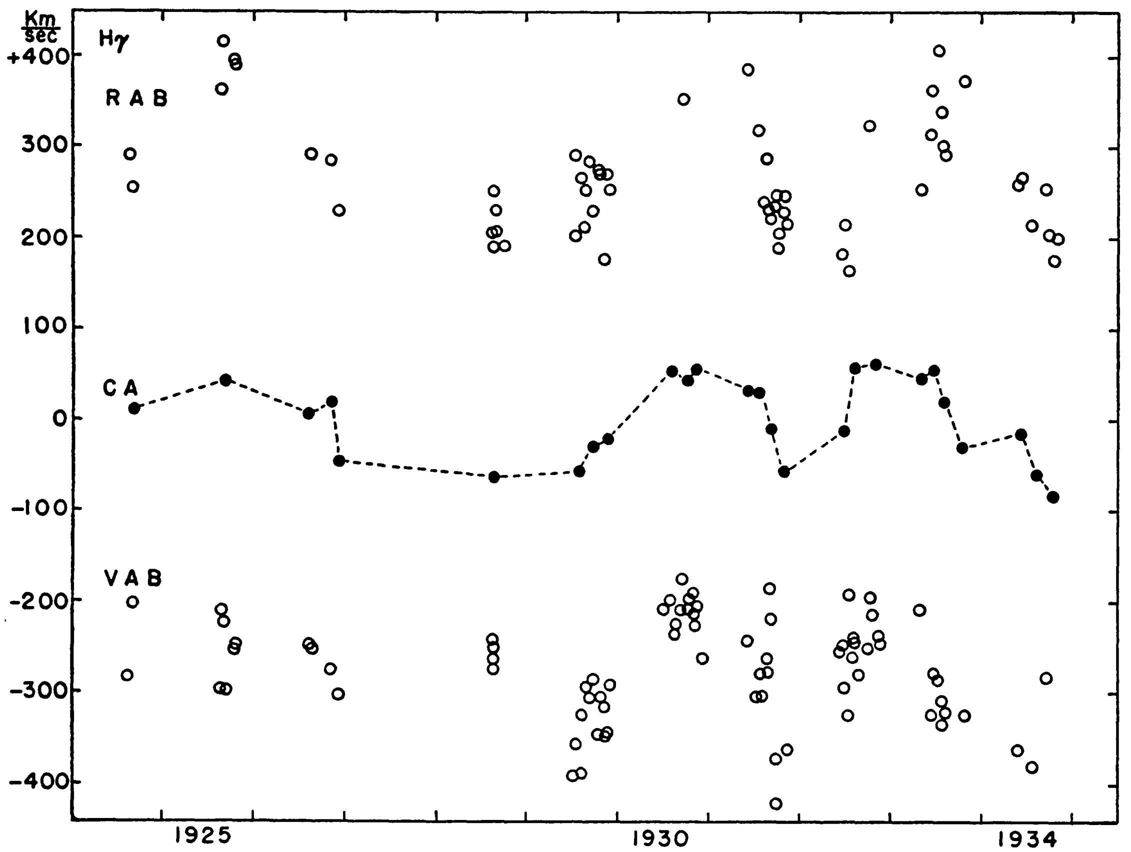

FIG. 7.—Measured velocities of red (*RAB*) and violet (*VAB*) absorption borders of Hγ on individual spectrograms of π Aquarii, 1924–1934. Filled circles (*CA*) are group means of Hγ central absorption velocity (from Table 2), for comparison of trends.

tions of π Aquarii are plotted with the velocity-curve of the central absorption for comparison. It is seen that the borders shifted approximately in phase with the central absorption and with similar amplitudes.

EMISSION AND ABSORPTION OF FE II

The lines of Fe II showed structure similar to that of the hydrogen lines during the times when hydrogen emission was strong, and they disappeared with the hydrogen emission. At best, the Fe II lines were so weak that measurement was difficult except on plates of the best quality. Only λ 4233 and λ 4584 were measured occasionally, but the scattered data show definitely that their widths and velocities were subject to approximately the same variations as the hydrogen lines.

VELOCITIES OF HELIUM LINES

Two Mount Wilson plates, fortunately taken near extremes of velocity and V/R in 1932 and 1941, show the emission-absorption structure at λ 5876 He I very well. Velocities of edges and central absorption measured on these plates are listed in Table 7, with data from Hα on the same plates, as well as velocities of Hβ and Hγ on Ann Arbor spectrograms taken on neighboring dates. A general similarity between the shifts of helium and hydrogen is evident. The displacements are so large that, in spite of the small amount of data, they justify the conclusion that λ 5876 behaves in a manner similar to the hydrogen lines.

On nearly all the Ann Arbor plates, λ 4026 and λ 4472 were measured for radial velocity. These data are not tabulated here, but the velocities for the interval 1928–1934 are plotted in Figure 8. Only scattered measures were made on other helium lines, all of which are weaker. Both 4026 and 4472 appear single on some plates and double on others. The statistics of duplicity or singleness are presented in Table 8. Evidently the two lines correlate poorly, one being double and the other single on the same plate. Coincidence of duplicity of both lines, however, seems to be a little more frequent than chance. The lower frequency of duplicity of 4472 may reflect the lower dispersion at its position. Coincident duplicity of either helium line and any hydrogen line on the same plate was investigated and found to occur only as frequently as the result of pure chance.

Separations of the components of the apparent double lines range from about 120 to over 250 km/sec. The components sometimes appear equal, sometimes very unequal in strength. When one line is single and the other double, the velocity of the single line is usually in rough agreement with the stronger member of the double, but in a fair proportion of cases there is closer agreement with the weaker. Occasionally the velocity of the single line falls near the mean velocity of the pair. When both lines appear double, more often than not we find roughly matching velocities in the two pairs but not always matching relative strengths. When both lines are single, the velocities still correlate poorly, often disagreeing by more than 40 km/sec and occasionally by as much as 100 km/sec.

The poor correlation between 4026 and 4472 is doubtless due in part to plate grain effects and to accidental errors, but large real disturbances in the positions of one or both lines are believed to occur. Since there is conspicuous emission at 5876, traces of emission may occur at 4472 and 4026. Their greater strength at the former line could be an important cause of discrepancies between velocity measurements.

The plots of helium velocities in Figure 8 at first convey the impression of random scatter. Closer inspection reveals clusterings and trends that are probably significant, especially when they are compared with the hydrogen velocities. The radial velocities of 4026 (Fig. 8, *a*) show no appreciable correlation with those of the central absorption lines of hydrogen, except for a marked clustering in 1929 and an apparent trend in 1933–1934. Single and double lines are not clearly related to the phase of the hydrogen varia-

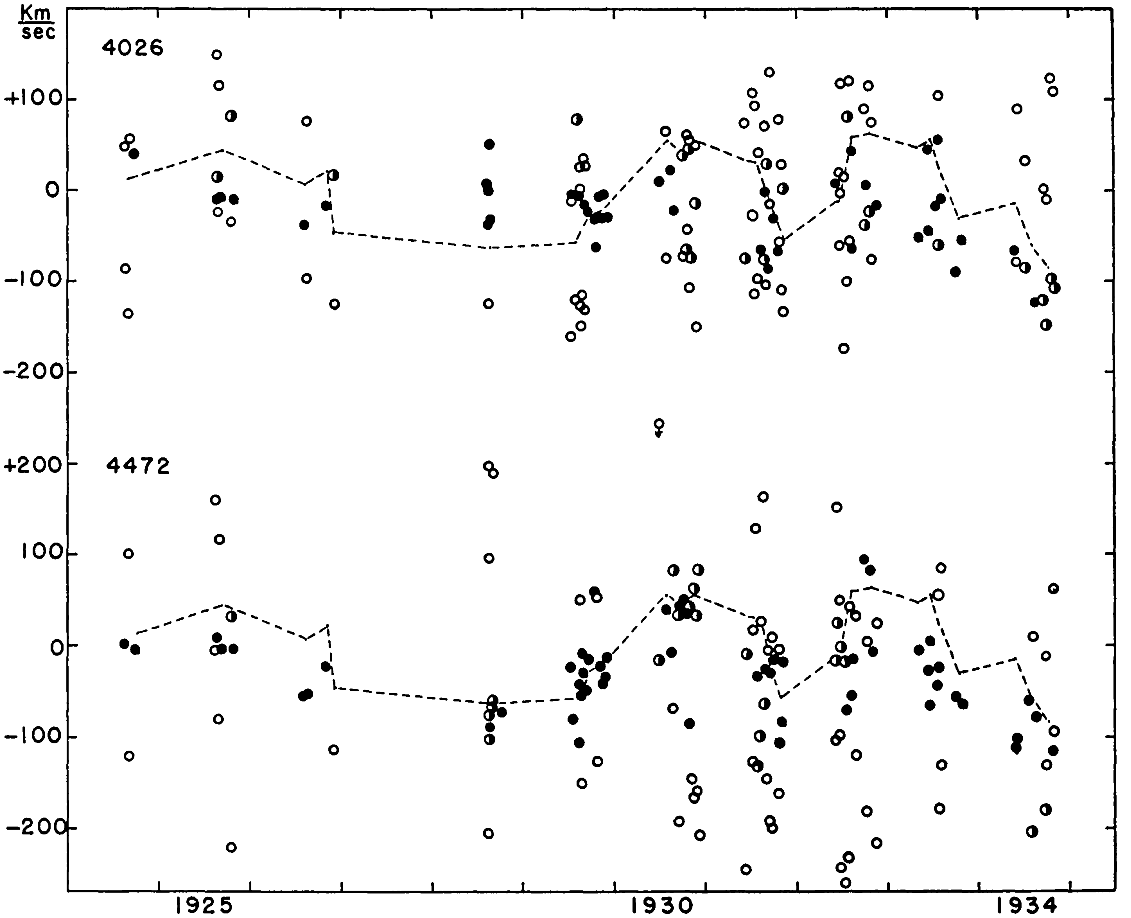

FIG. 8.—Velocities of helium absorption lines λ 4026 and λ 4472 on individual spectrograms of π Aquarii during the "active" period 1924–1934. Filled circles represent single lines; half-filled circles, stronger components of unequal apparent double lines; open circles, components of apparently equal doubles and weaker components of unequal doubles. The dashed curves show the run of Hγ central absorption velocities (Table 2), for comparison with trends of strong helium components.

TABLE 8

STATISTICS OF DOUBLING OF HELIUM LINES OF π AQUARII

λ 4472	λ 4026		
	Single	Double	Not Measured
Single	67	59	14
Double	29	42	12
Not measured	3	1	5

tion but usually seem to alternate in a random manner. However, during the seasons of 1931 and 1932, while the hydrogen lines were shifting rapidly in the negative and positive directions, respectively, the scatter of the velocities of 4026 was unusually large and the incidence of duplicity unusually high. All but 10 of 30 plates showed 4026 double in these years. The greatest frequency of doubling of the hydrogen lines also occurred in 1931 and 1932. By contrast, the discordances of helium velocities from plate to plate were least in 1929. In that year only 6 of 16 plates showed 4026 double, and all of these were in the first half of the season. The mean velocity in that year is accordant with that for hydrogen.

In 1933 and 1934, nearly all the plotted velocities of strong components of 4026 lie in a band that slopes from −30 km/sec in 1933 to −120 km/sec near the end of 1934. This closely parallels the trend of hydrogen absorption velocities during the same interval, though it is shifted about 60 km/sec toward negative values relative to hydrogen. It is possible that during this interval the measures were strongly influenced by a helium absorption line produced in the outer shell. Accordant velocities of 4472 tend to support this interpretation.

The behavior of 4472 was somewhat more systematic. Though it showed duplicity nearly as often as 4026 and had just as large a scatter in some seasons, its velocities often cluster near those of the hydrogen central absorption. From 1928 through 1930, most of its single lines or stronger components of pairs plot in well-defined groups that show the same trend from season to season as the hydrogen lines. In 1931 and 1932 a number of points also cluster in the neighborhood of the hydrogen velocities, but additional lines of larger negative displacement somewhat confuse the picture. Then in 1933 and 1934 the velocities show the same trend already remarked in connection with 4026.

It is concluded that a faint emission-absorption structure like that of the hydrogen lines was sufficiently prominent at 4472 to influence strongly the velocity measures on that line but that the effect of the corresponding structure at 4026 was inappreciable except during 1933 and 1934.

THE RADIAL VELOCITY OF THE STAR

Direct observation of the radial velocity of the star is difficult because most of the measurable features in the spectrum either originate in the external envelope or are contaminated by features produced there. The Mg II line alone seems to be free of such disturbance. During the times when the emission lines were absent, the hydrogen absorption lines may be attributed entirely to the stellar reversing layer. The occurrence of apparent duplicity, however, raises questions regarding the interpretation of hydrogen velocities even at those times. Selection of plates on which the lines appeared single seemed to be the safest course. The helium lines must be considered unreliable for the stellar radial velocity during the period of active variations. During the quiescent stages, even when hydrogen emission was present, they might be expected to show the radial velocity of the star. Table 9 lists the measured radial velocities based on these several sources of data.

During the stable phases, when V/R and velocity showed no large changes, it might be supposed that the central absorption or even the mean of the emission edges would yield the radial velocity of the star. The possibility of undetected asymmetries of the emission, as well as of slow systematic outward flow of absorbing gases, however, renders such measures suspect. The most reliable results from measurements of these features are listed in Table 10.

The mean velocity from the Lick spectrograms of 1913–1922 differs enough from the others to arouse a suspicion that they record some activity of the star. Four of the plates were taken in 1922, and variation had certainly begun by 1924. For this reason, means have been formed both with and without those plates.

Considering the diversity of the features measured, the means of Tables 9 and 10 agree satisfactorily. The figures in the last lines of the tables appear the most reliable. Accordingly, we have

$$\text{Radial velocity of } \pi \text{ Aquarii} = -12.4 \pm 0.3 \text{ km/sec} .$$

INTERSTELLAR LINES

The H and K lines of Ca II were measured whenever possible. In some Be spectra these lines have had components that originated in the shell, in addition to lines produced in interstellar space. In π Aquarii, throughout the 50 years covered by the Ann Arbor observations, the velocities give no indication whatever of components other than the interstellar ones.

A Mount Wilson coudé plate, dispersion 2.9 A/mm, taken August 31, 1942, shows three components at H and K with the following velocities in km/sec: −12.6 (strong), −1.5 (weak), +19.6 (trace). On plates of lower dispersion the components are unresolved, and the resultant velocity should lie between −12.6 and −1.5 km/sec but nearer the former. The results are given in Table 11.

The D lines of Na I were measured on two Mount Wilson plates, with the following

TABLE 9

RADIAL VELOCITIES OF π AQUARII BASED ON ABSORPTION LINES

Lines Measured	Velocity (km/sec)	No. of Plates
Hβ, non-emission phases, single lines	−12.3	16
Hγ, non-emission phases, single lines	−10.6	15
He I 4026, inactive phases 1937–1955	−17.8	28
He I 4472, inactive phases 1937–1955	−25.4	45
Mg II 4481, all measures	−11.1	40
Mean of all measures, equal weights	−15.4±1.5	
Mean of hydrogen and Mg II only	−11.5±0.3	

TABLE 10

RADIAL VELOCITIES OF π AQUARII BASED ON EMISSION EDGES AND CENTRAL ABSORPTION

SPECTROGRAMS	NO. OF PLATES	ABSORPTION		EMISSION	
		Hγ	Hβ	Hγ	Hβ
Lick 3-prism, 1896–1897	2	−15.5	....	−10	....
Lick 3-prism, 1912	2	−18.5	....	−20	....
Lick 1-prism visual, 1911–1912	4	....	−12.0	....	− 7
Lick 1-prism, 1913–1922	6	−27.5	−19.2	−28	−17
Michigan 1-prism, 1911–1921	12	−19.7	−16.3	−10	− 9
Yerkes, 1915	4	−11.5	....	−12	....
Means, all measures	....	−19.8	−16.3	−15.2	−10.8
Means, omitting Lick, 1913–1922	....	−17.5	−15.2	−11.4	− 8.5
Mean of all lines, all plates	....	−15.7±0.4			
Mean, omitting Lick 1913–1922	....	−13.3±0.4			

results: November 18, 1932 (33 A/mm): D_2, −11.6; D_1, −1.5; November 4, 1941 (20 A/mm): D_2, −4; D_1, −11.

GENERAL DISCUSSION

Basically, the phenomena of stable Be spectra, both "shell" and non-shell types, are satisfactorily accounted for by an extensive lenticular or disklike envelope in the equatorial plane of a rapidly rotating star. Such a structure was proposed by Struve (1931), and it is supported by the work of Burbidge and Burbidge (1953). The picture may be elaborated a little further (McLaughlin 1961*a*). The emission probably originates in the inner parts of the disk, extending out to a distance of several stellar radii. Outside this inner H II region the hydrogen is mainly neutral, and in these outer parts of the disk the central absorption is produced. In order to have strong shell absorption, the disk must be viewed almost precisely edgewise. A view several degrees from the edgewise direction will give a weaker central absorption line, as in π Aquarii. So long as the disk remains circular and stably rotating with uniform velocity, the emission has equal components and the absorption bisects it and yields a radial velocity nearly equal to that of the star.

TABLE 11

VELOCITIES OF INTERSTELLAR CALCIUM LINES OF π AQUARII

Observatory	Date	Dispersion (A/mm)	K		H	
			Velocity (km/sec)	No. of Plates	Velocity (km/sec)	No. of Plates
Michigan	1911–1951	26	− 8.0	150	− 6.3	77
Michigan	1952–1960	13	− 7.8	29	− 6.8	24
Mt. Wilson	1936, July 29	23	−13	1	−16	1
Mt. Wilson	1945, Oct. 24	10	−10.1	1	−12.8	1
Mt. Wilson	1950, June 1	10	− 8.3	1	− 7.3	1

Interpretation of the phenomena of V/R variation has been discussed elsewhere (McLaughlin 1933*b*, 1961*a*) and will not be repeated here at length. In the rotating-pulsating model, alternate expansion and contraction are superimposed on the rotation. Expansion is coincident with $V/R < 1$, and contraction with $V/R > 1$. However, this model only partially accounts for the associated changes of V/R and velocity. Its principal defects are (1) the absorption would be expected to shift across the emission, which is contrary to the evidence of the measures; (2) the long periods of these stars require enormous motions of the gases, and the long-continued contracting phase especially is difficult to admit; (3) accumulation of great amounts of ejected gas after a long phase of expansion should produce large variations in the strengths of the absorption lines, which are not observed or which occur at the wrong phases when they are found. Intermittent expansion also fails as a general explanation. The slowness of V/R changes is a major difficulty in this sort of model, as it is with the rotating-pulsating model (McLaughlin 1961*a*).

The hypothesis of an eccentric envelope made up of rotating elementary rings whose apsides advance in periods of a few years agrees fairly well with the observed phenomena, especially the shifting of the emission with the central absorption. The variation of V/R is accounted for by the relative rarefaction of the gaseous rings near periastron and increased density near apastron. When periastron is presented toward us, the strength of shell absorption should be a minimum, and changes of this type actually are observed in β^1 Monocerotis (McLaughlin 1958, 1961*b*). This model appears to be quantitatively possible, since the periods of apse rotation to be expected are of the same order as the durations of V/R cycles (Johnson 1958).

If Be stars are rotating at the verge of instability, we may speculate that the beginning of V/R variation after a long-enduring constant phase is due to an upset of the stability of the gaseous rings caused by the addition of material newly ejected from the star. The inner portion of the envelope would be disturbed first, and turbulent interaction between the inner and outer ring elements could give rise to large irregularities in the lengths of cycles and to secondary variations superimposed on those of longer period. The apparent doubling of the central absorption lines may be due to the simultaneous presence of two systems of outer elliptical rings of absorbing gases whose major axes have very different orientations.

On each occasion when the emission lines reappeared after an absence, they were much wider than usual. Gradually the widths decreased to the "normal" values. These changes are consistent with the ejection of a new ring which expanded slowly with conservation of angular momentum and finally stabilized at a certain distance from the star. The disappearances, however, seem not to have involved a further narrowing that would indicate the loss of the ring by continued expansion. In 1944, before one of its disappearances, the Hβ emission was abnormally wide. Possibly a collapse of the ring into the star is indicated.

Unfortunately, only the one-prism plates are available during the most active phases of π Aquarii. Study with higher dispersion might yield clues to the meaning of many puzzling aspects of this spectrum. The available series of plates with dispersion of 19 A/mm at Hγ shows too few examples of marked anomalies to permit the drawing of conclusions regarding their nature.

Those who have investigated Be spectra are not in complete agreement as to the interpretation or the validity of measurements made on the edges of emission features (McLaughlin 1961*c*; Underhill 1961). Until the uncertainties that are the basis of the disagreement can be resolved, the physical picture of V/R variation itself will remain in doubt.

Measurement of the position of an emission edge involves a subjective judgment as to where the contribution of the emission to the photographic density either ceases or decreases rapidly. If a gradient of density with linear distance on the plate is too gentle, a measurement may be practically impossible. Obviously, low dispersion steepens the gradient of an edge; but this is a doubtful advantage, for the contribution of the instrumental profile seriously distorts the original emission profile when the wavelength equivalent of slit width plus the diffraction pattern becomes an appreciable fraction of the width of the feature itself. At best, then, the measurements of emission edges on plates of low dispersion are subject to appreciable systematic errors and do not define absolutely the position of the bright line.

Variations of position, however, may still be established if they are large enough, and in stars such as π Aquarii this condition is met. Changing strength of the components may influence the measurer's judgment as to the location of the edge. From experience with photographic materials, one expects the edge of a very strong emission component to be measured farther from the center than the edge of a weak one. That is, the outer edge of a strong "red" component would show a spurious shift toward greater wavelength. Now the fact is that the measurements indicate a shift in the opposite direction. This agrees with the direction of displacement of the central absorption. Such a shift must be in large part real, that is, it occurs in the direction measured, though the measurement may be affected by systematic errors that are a function of the shift itself.

Ideally we might hope to get more meaningful measures from microphotometer tracings. However, exact correspondence between features on the tracings and on the spectrograms is quite difficult to establish, since the comparison lines that give the wavelength scale are not impressed on the tracings. An added drawback is the fact that the tracing cannot be a true record of the spectrogram. The optical system of the microphotometer and the finite width of the illuminated slit that is imaged on the spectrogram introduce an additional instrumental profile. The steepest density gradients on the original plate therefore appear less steep on the tracing. A perfectly sharp discontinuity of density would be traced merely as a steep gradient. After laborious correction for the instrumental profile, doubt would still remain.

The only feature in the hydrogen lines on the spectrogram that can be identified with some confidence on the tracing is, because of some approach to symmetry, the central absorption line. Where its profile is nearly symmetrical, the micrometer setting was probably made midway between equal densities on the two limbs of the profile. Then, from the known magnification from plate to tracing, the positions of micrometer settings on the emission "edges" can be located.

The relative weakness of the central absorption line makes π Aquarii poorly suited to the application of this method. Also the plates of that star that show the greatest variation were taken only with one-prism dispersion. The spectrum of β^1 Monocerotis with its deep shell absorption offers greater possibilities, and numerous spectrograms with dispersion of 19 A/mm have been obtained. These do not yet cover a full cycle of the variation, but they do cover the full range of V/R and velocity. As part of a study that is not yet completed, tracings of Hβ on 30 spectrograms of β^1 Monocerotis have been correlated with the micrometer settings. The results can be summarized as follows:

1. The position measured as the "edge" of a strong emission component is that of the steepest gradient of density. This applies to intensities ranging from the greatest to appreciably less than the strength at the phase of equal components. That is, a component is "strong" even when it is the weaker of the two, with the ratio strong:weak ≤ 1.5.
2. The measured "edge" of a weak emission is at the steepest gradient when appreciable variation of gradient occurs. However, most weak components show a rather uniform gentle gradient; in this case the setting is made close to the half-intensity point of the profile.
3. Weaker emission with gentler gradient extends a considerable distance beyond the measured "edge" of a strong component.
4. The problem is complicated by real changes in the profiles that are not accounted for by shifts or changes in strength of the central absorption.
5. Assuming that the position of the absorption line has been correctly identified, measurements on the tracings yield velocities of the extreme outer limits of emission, as well as of the outer limits of the stronger emission. The results in general confirm the conclusion stated by Merrill (1952) that "the emission as a whole shifts in the same direction as the core, but by a smaller amount." Specifically, in β^1 Monocerotis, the amplitude of emission velocity appears to lie between 60 and 70 per cent of that of the absorption velocity.

The result in 5 disagrees quantitatively with that based on the micrometer measurements, which show the emission velocity amplitude approximately equal to the range of absorption velocity. Evidently, some source of systematic error that is a function of the emission ratio operates on the micrometer measures. The explanation probably lies in 2, the tendency to measure the "edge" of a weak component at the half-intensity point, when the profile has been so modified that there is no longer a steep gradient. So long as a component is strong, the setting is made on the steepest density gradient. This is not the true *outer* edge; for (see 3, above) weaker emission extends beyond it. When the same component is weak, the setting is made at the half-intensity point, which is then *farther out in the wing* and probably at a variable position which is a function of the intensity. As a result, although the emission as a whole does shift less than the central absorption, this systematic error operates to increase the apparent amplitude of emission velocity. In π Aquarii some of the emission velocity amplitudes seem to exceed those of the absorption, but probably they do not actually. The separate plots of emission edges show some tendency for the velocity maxima of the red components and the minima of the violet components to be more pointed than the opposite extremes of the curves. A similar effect can be seen in the curves for 25 Orionis obtained by Miss Dodson (1936). Very probably these sharp cusps are not real in either star but are caused by the systematic error just described.

The behavior of the hydrogen absorption borders gives some of the most direct evidence against fixity of the emission. These borders are believed to be largely or entirely parts of the profile of the underlying Stark-broadened absorption line that originates in the stellar reversing layer. If the emission did not shift at all, we should expect the appearance of these borders to remain unchanged as the "central" absorption shifts, since the amplitude of its motion is less than half the emission width. However, the changes in strength of the borders alone are consistent with shifting of the emission. When the "red" emission component is strongest and the absorption shift is greatest in the negative direction, the "red" absorption border appears stronger, while the "violet" border is very weak and difficult to measure or often entirely absent, as if the emission had shifted and covered it. Similarly, a strong "violet" emission is accompanied by weakening of the "red" absorption border.

The measures of position of the absorption borders show that they are subject to apparent shifts that parallel the measured displacements of emission edges (see Fig. 7). Now, if the emission remained fixed while the central absorption shifted across it, there would be nothing in that change to influence the positions of these bordering minima of the profile, whose positions can be measured like those of any absorption lines. Their measured displacements therefore support the idea that the emission actually does shift.

The displacements of the emission in π Aquarii are altogether too large to be attributed wholly to systematic errors. Such errors do indeed operate, but the emissions do shift in the directions shown by the measures, though probably with a smaller amplitude. Thus it is likely true that in most V/R variables the absorption moves off the exact center of the emission in the direction that will aid in explaining the changing relative strengths of the emission components.

Very probably the phenomena are more complicated than a simple oscillation of the emission and its central absorption, with accompanying variations in intensity of the two components of the bright line. Multiple or diffuse absorption may overlie the weaker emission component throughout its width. One type of complication that may occur is illustrated by the recent variations of ζ Tauri (Herman and Duval 1961). Several high-dispersion plates taken in 1960–1961 at the Observatoire de Haute Provence show very narrow absorption-like minima centrally placed on each emission component of Hβ. Since these observations were published, Michigan spectrograms of ζ Tauri with dispersion 19 A/mm at Hγ have shown this structure still present at the end of 1961, though these features are nearly at the limit of resolution on our plates.

I am grateful to the directors of the Lick Observatory and of Mount Wilson and Palomar Observatories for the use of spectrograms of π Aquarii. Reductions of my measurements over a period of years have been carried out by a large number of student assistants at the University of Michigan.

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