PUBLICATIONS OF
THE DAVID DUNLAP OBSERVATORY
UNIVERSITY OF TORONTO

VOLUME II NUMBER 11

SPECTROSCOPIC STUDIES OF 60 Be STARS OVER A PERIOD OF 24 YEARS

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1963

TORONTO, CANADA

PRINTED AT

THE UNIVERSITY OF TORONTO PRESS

SPECTROSCOPIC STUDIES OF 60 Be STARS OVER A PERIOD OF 24 YEARS

By Judith A. Copeland and John F. Heard

Abstract

The spectra of 60 Be stars have been observed with a fair degree of regularity, about once a year, over the past 24 years for the principal purpose of surveying the spectral variations. A brief summary of the spectral characteristics and changes of each of these stars is here presented. For those stars showing double emission, studies of the fluctuations of the relative intensities of the violet and red components (V/R) have been made. For 15 of the stars it was possible to assign periods for these fluctuations; the mean period is about 6.8 years. About half of the stars show shell characteristics at times; the strength of the hydrogen absorption core intensities for about half of these shell stars show a degree of correlation with the V/R variations.

Introduction

Bright-line stars of class B are not uncommon. Merrill and Burwell (1933) in their "Catalogue of Be Stars" and in their two supplements (1943 and 1949) have listed 1088 such stars.

The emission lines in most Be stars are confined to the hydrogen lines, and invariably the emission is weaker as we proceed to the higher members of the Balmer series; indeed many such stars show emission only at Hα. Emission lines other than hydrogen are sometimes observed, e.g. Fe II, Mg II, Si II, Ni II, Cr II, He I. Main sequence B stars more commonly show emission lines than do the more luminous stars, and stars of spectral class B3 include a higher proportion of emission-line stars than do earlier or later classes.

It was shown by early investigations that the emission lines are almost invariably centred, or nearly so, within broad, dish-shaped absorption lines. This led Struve (1931) to the conclusion that the emission lines arise in a disk or ring cast off from rapidly rotating stars. The relatively few stars showing narrow single emission have also relatively narrow underlying absorption; they are explained as rotating stars which are presented "pole-on". The more common broad emissions (super-imposed on very broad absorption) are always double. The two components of the emission, violet (V) and red (R), frequently show variations in relative intensity (V/R) and also in position relative to the underlying absorption. The interpretation of these *V/R* variations and the concomitant velocity shifts has been difficult. McLaughlin (1961), who has observed a number of Be stars over a long period of time, put forward a model of an extensive envelope which both rotates and pulsates in such a way as to give rise to the *V/R* variation. Another model, first suggested by Struve (1931) and re-discussed by McLaughlin (1961), involves gaseous rings which are elliptical in shape. The choice between these two models hinges, in part, upon the observed Doppler shifts of the absorption core and the emission lines. Concerning these Doppler shifts there has been a difference of opinion between McLaughlin and Miss Underhill (1959).

The dark reversal (if it may be so termed) which separates the *V* and *R* components of double emission is sometimes so strong as to resemble the sharp cores in the so-called shell stars. Indeed when these shell-like reversals are marked, other lines, mostly of ionized metals, appear strong and sharp in absorption. The fact that shell characteristics appear in stars with rapid rotation lends support to the idea that the outer regions of the star's envelope, where the absorption cores are produced, are not rotating rapidly. In a number of Be stars the shell characteristic appears to come and go.

It appears that many more data will be required before satisfactory explanations can be found for all the curious features that are observed in the spectra of Be stars.

The Observations

One of us (J.F.H.) in 1938 selected from Merrill and Burwell's (1933) Mount Wilson Catalogue (M.W.C.) a list of 60 Be stars, most of which, at that time, were not being observed at Michigan where most of the detailed long-term observations of Be stars had been made. The writer's intention was to observe these stars once or twice per season over a long period of time in order to add to the store of knowledge of the spectral variations of Be stars. The intention was not fully realized for one reason and another (in particular there was a lacuna during the war years), but nevertheless a considerable collection of spectrograms was built up. For the benefit of other investigators who may be interested in these stars we give in Table I the number of spectrograms in our collection year by year. These spectrograms were taken with the Hilger one-prism spectrograph—

TABLE I

Number of Be-star Spectrograms Year by Year (1900+) in the D.D.O. Collection

M.W.C.	38	39	40	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62
7	3	19		1	1	2																
8	3	1	1			3						1	1	1	1	1	1	1		1	1	
10	5	1	1			1						1	1	1	1	1	2	1	1	3	1	
13	4	1	1			2					4	2	1		1	1	2	3		2	2	
23	3	2	2			3	1	3		1	6	4	1	1	1	1	1	1	2	1	1	
29		3	1			1	1				2	1	1		2	1	1	1	2	1		1
49	2	1	1			2		1		1	9	1	1		2	1	1	1	1	1	1	
61	4					2	1			1	2	1	2	1	1		1				1	
63	3		1			1		1		1		1	1		1	2	1		1	1	1	
68	4						1	1		1	1	1	1	1	1	1	1	1	1	2	1	1
76		3	2			2		1		1	1	1	1	1		2	1	1	1	1		1
79	1	1	1			4	1		1			1	1		1	1	1	1	1	1	1	
82	1	1	2			2		1		1	1	1	1							2	1	
83		2				1			2	1	1		1			2	1		1	1		
86							2					1				1					2	
88	1	1										1			1	2	1			2	1	
93								1		2	1	2			1	1	1		1	1	1	
107	1											1		1		1			1	3	1	
114		1	1						3						1	2	1			1		
115	2								1	1					1					2	1	1
139		2	1			1			1	3	2	9		1		1	1		1			1
140		1												1		2	1		1	1	1	1
146		1												1		1	1			1	1	
156		1												2	2		1			2	1	
159		2							3							2						
164		1							3	2					1	1					1	
174			1						1	1			1			1						1
188		1	1						2	3				1	1					2	1	1
189			1						2	3	1	4		1						1		1
190		1													1	1				1		2
278	2	1				2	1			1	1	1	1	1	1	1	1	1	1	1		
292	1	1				2	1	2	1	1	1	1	1	1	1	1	1	1	1	2	2	
307		1	1			3	2			1	1	1	1	1	2	1		1	1	1	1	
308		2				1	2	1		1	1	1	1	1	1	1	1	1	1	2	1	
310		2				3	1	1		1	2	2	1	2	1	2	1	1	1	2	2	
312		2	2			2	1	1		1	24	1	1	3	1	1	1	1	1	3	1	
317	1	1				6	5	2		3	2	1	2	1	2	2	1	1	2	3	1	
320			3			1	2	2		1	1	1	1	2	1	1		1	1	2	1	
331	1	1				3					1	1	1	1	1	1	1	1	1	2	1	
332		1				2						1	1	1	1	1	2	1	1	3		

TABLE I—*Continued*

M.W.C.	38	39	40	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62
336						2	1					1	1	1	2	1	1	1	1	2	1	
343		1				2						1	2	1	1	1	1	1		2	1	
346		2				2	3			1	3	1	2	1	1	1	1	1	1	3	1	
347	1					3	1			1	1	1	1	1	2	1	1	2		2	1	
350		1				1	1			1	1	1	1	1	1	1		1		2	1	
352	1					2						1	1	1	1	1		1		1	1	
353						1	1			1	1	1	1	1	1	1		1		1		
360	1	1				2						1	1	1	1	1		1		2		
361												2		1	1		1	1	1	2	1	
366	1					2						1	1	1	1	1	1	1	1	2	1	
371	2					2						1	1	1	1	1	1	1	1	2	1	
376	2		1			4	4			3	4	1	2	1	1	1	1	1	1	2	1	
381	3	1				3	3			4	3	1	1	1	1	1		1	1	1	2	
383	1	2	2			2						1	1	1	1	2	1	1	1	3	1	
394	2	1				5	3	1		1	2	1	1	1	1	1	1	1	2	1	1	
395	3					2	2	2		2	2	1	2	2	1	1	2	2	1	3	2	
397						11	43	8	33	2	2		1	1	2	1	1	1		3	1	
402	2	2	3			1	1	2	1	1	1	1	1	2	1	1	1	1	1	1		
407	5					3	1	1		1	1	2	1	1	2	2	1	1		3	2	
409	2	1	1			1	2	2		2	2	1	1	1	1	1	1	1	1	2	1	

most of them at dispersion 33 A./mm., some, especially of the stars fainter than magnitude 8, at dispersion 66 A./mm. Hα does not show on the spectrograms, and little is seen to the violet of λ 3900.

As the spectrograms were being accumulated a card catalogue was maintained listing the main spectral variations. In 1961 the other writer (J.A.C.) undertook a detailed re-examination of all the spectrograms and a tabulation and correlation of the results.

In Table II we list the stars according to both M.W.C. and H.D. numbers, giving R.A. and Dec. for 1900, the visual magnitude, and

TABLE II

SUMMARY OF SPECTRAL FEATURES AND VARIATIONS

M.W.C. 7, H.D. 2905; 0ʰ27ᵐ.3, +62°23′; 4ᵐ.24, cB0eα; κ Cas

No emission has been observed, though Hβ absorption is weak; no spectral variations were noted.

M.W.C. 8, H.D. 4180; 0ʰ39ᵐ.2, +47°44′; 4ᵐ.7, B4neβ; o Cas

In 1938, 1939, 1946 double emission at Hβ appeared faintly with $V = R$, and there was a deep core at Hγ. These features were not visible from 1952 on.

TABLE II—*Continued*

M.W.C. 10, H.D. 6343; $0^h59^m.4$, $+65°26'$; $7^m.10$, B5eβ

Hβ has single emission varying in intensity, particularly strong in 1946, 1958, 1959, Sept. 1960. Hγ shows weak emission when Hβ emission is strongest, but in Nov. 1960 Hγ showed a distinct absorption core and Hβ no emission.

M.W.C. 13, H.D. 9105; $1^h24^m.6$, $+62°51'$; $7^m.46$, cB5(e)

Absorption lines are very sharp; no emission was seen on any of the plates.

M.W.C. 23, H.D. 12302; $1^h55^m.6$, $+59°12'$; $8^m.2$, B3e

There are marked and rapid variations in the intensity and the *V/R* ratio of the double emission lines. Emission lines other than hydrogen appear. Shell characteristics come and go.

M.W.C. 29, H.D. 13661; $2^h08^m.1$, $+54°04'$; $8^m.6$, B(3)ne

The width and *V/R* ratios of Hβ and Hγ vary markedly. He I 4471 absorption is usually sharp but was broad in 1946 and exceptionally so in 1959.

M.W.C. 49, H.D. 15472; $2^h24^m.4$, $+70°30'$; $8^m.0$, B4ne

There are marked intensity and *V/R* changes in the double emission at Hβ and Hγ, and hydrogen absorption cores and other shell characteristics come and go. The relative intensity and sharpness of He I 4471 and Mg II 4481 vary.

M.W.C. 61, H.D. 19243; $3^h00^m.7$, $+62°00'$; $6^m.5$, B2e

There are marked intensity and *V/R* changes in the double emission at Hβ and Hγ. Though the hydrogen emission is broad, the He I absorption is narrow. Weak absorption cores of Hγ and Hδ appeared in 1953.

M.W.C. 63, H.D. 20017; $3^h07^m.9$, $+48°19'$; $7^m.9$, Bne

Hydrogen and He I have very broad absorption, and He I is very weak. The emission at Hβ and Hγ is weak and varies in width. *V/R* changes are noted, but frequently the double emission is difficult to resolve. An absorption core was seen at Hγ in 1938, 1946, 1953, 1955, 1956, 1957.

M.W.C. 68, H.D. 21650; $3^h24^m.6$, $+41°25'$; $7^m.2$, B5ne

There are marked variations of intensity and *V/R* ratios of double emission at Hβ and Hγ. Absorption cores at Hβ and Hγ come and go.

M.W.C. 76, H.D. 23982; $3^h44^m.3$, $+63°11'$; $8^m.1$, B3e

All absorption lines are broad. Weak, narrow, double emission is sometimes seen at Hβ and Hγ with $V = R$. In 1960 and 1962 an absorption core was seen at Hγ.

M.W.C. 79, H.D. 24560; $3^h49^m.3$, $+44°38'$; $7^m.8$, B(3)ne

Absorption lines are broad. Emission is usually absent, though suggested by the weakness of Hβ absorption, but in 1945 and in 1960 and 1961 there was fairly distinct narrow double emission at Hβ with $V \doteqdot R$.

M.W.C. 82, H.D. 26420; $4^h05^m.7$, $+41°52'$; $7^m.6$, B3neα

No emission was seen until 1960 when at Hβ double emission appeared with $V = R$; by 1961 both Hβ and Hγ showed $R > V$ and sharp absorption cores.

M.W.C. 83, H.D. 26906; $4^h10^m.1$, $+45°58'$; $8^m.6$, B(3)ne

From 1939 to 1951 Hβ showed strong double emission with $V = R$ and an absorption core at Hγ. On the plate of 1953 the Hβ emission was absent, but seems gradually to have re-appeared between 1956 and 1960 when it occurs as narrow emission to the red of the centre of both Hβ and Hγ, i.e. $R \gg V$.

TABLE II—*Continued*

M.W.C. 86, H.D. 28497; $4^h24^m\!.5$, $-13°17'$; $5^m\!.5$, B3ne

There is double emission at Hβ and Hγ with variations in the intensity, *V/R* ratio, and in the strength of the absorption cores.

M.W.C. 88, H.D. 29866; $4^h37^m\!.3$, $+40°36'$; $6^m\!.1$, B4ne

Emission at Hβ and Hγ is weak and sometimes resolved into double, sometimes not. There are *V/R* variations, and Hγ at times has an absorption core.

M.W.C. 93, H.D. 31293; $4^h49^m\!.4$, $+30°24'$; $7^m\!.5$ var., A0ep; AB Aur

Most plates show fairly wide emission to the red of centre at Hβ, Hγ and Hδ with a strong absorption core to the violet. The cores faded in 1950, returned in 1956, disappeared in 1957 and returned in 1959. The emission strengthened and became more nearly central when the cores disappeared. On the 1961 plate Hβ emission was double with $R > V$, Hγ double with $R = V$.

M.W.C. 107, H.D. 34921; $5^h15^m\!.8$, $+37°55'$; $7^m\!.4$, B0ne

Emission at Hβ and Hγ is double and there are well marked variations of *V/R*.

M.W.C. 114, H.D. 37115; $5^h31^m\!.0$, $-5°41'$; $8^m\!.2$, B5ne

All plates show moderately wide double emission at Hβ with $V = R$. Since 1940 there has been a sharp absorption core at Hγ, and since 1956 there has been double emission at Hγ with $V = R$.

M.W.C. 115, H.D. 37202; $5^h31^m\!.7$, $+21°05'$; $3^m\!.0$, B3e; ζ Tau

This well-known shell star exhibits many changes in the absorption and emission lines. The double emission lines at Hβ show marked variations of *V/R*, and the Hγ core shows variations in intensity along with the other shell lines. Double emission was seen at Hγ in 1955 and 1960 with $V = R$, but in 1961 only the violet component was seen.

M.W.C. 139, H.D. 44637; $6^h17^m\!.7$, $+15°09'$; $7^m\!.7$, B3e

Hydrogen absorption is very broad; He I absorption is moderately strong and sharp. Emission was seen only at Hβ, double with *V/R* varying, but usually with $V \doteq R$. Emission was weakest in 1950.

M.W.C. 140, H.D. 45314; $6^h21^m\!.6$, $+14°57'$; $7^m\!.1$, B2ne

All absorption lines are extremely broad and weak. Double emission with varying *V/R* was seen at Hβ and Hγ except on the last plate (1962) when no emission at all was seen.

M.W.C. 146, H.D. 45995; $6^h25^m\!.6$, $+11°19'$; $5^m\!.8$, B2ne

Absorption lines are broad and diffuse. Double emissions at Hβ and Hγ vary as to *V/R*.

M.W.C. 156, H.D. 50083; $6^h46^m\!.5$, $+5°13'$; $6^m\!.8$, B2e

Both Hβ and Hγ show double emission with *V/R* variations.

M.W.C. 159, H.D. 50209; $6^h47^m\!.1$, $-0°10'$; $8^m\!.3$, B(5)ne

Hydrogen absorption is very strong and broad; the relative strength of He I 4471 to Mg II 4481 varies considerably. Double emissions at Hβ, Hγ and (since 1949) at Hδ vary in width, strength and *V/R*.

M.W.C. 164, H.D. 52721; $6^h57^m\!.2$, $-11°09'$; $6^m\!.6$, B3e

Hydrogen absorption is wide but He I fairly narrow and variable in strength. In 1939 Hβ emission was narrow and fairly strong, and in 1950 Hβ emission was weaker

TABLE II—*Continued*

and Hγ had weak double emission with $R > V$; thereafter emission was apparently absent.

M.W.C. 174, H.D. 57386; 7^{h}15^m.9, −8°15′; 8^m.1, B5ne

Absorption lines are fairly wide and moderately weak. Hβ emission is fairly strong, wide and double with variable V/R. Hγ emission is weak and probably double.

M.W.C. 188, H.D. 65079; 7^{h}51^m.9, +3°14′; 7^m.7, B3ne

Hydrogen and He I absorptions are very broad. Hβ emission was moderately strong and double in 1939; it faded with time and changed slightly as to V/R; it was extremely weak in 1962. Hγ emission is weak, probably double but not always resolved.

M.W.C. 189, H.D. 65176; 7^{h}52^m.4, −1°20′; 8^m.1, B(5)ne

All absorption lines are extremely weak and broad. Weak Hβ emission was seen in 1949 and 1952, it was stronger in 1954 and double, with $V \doteqdot R$; it was weaker in 1960, stronger again in 1962. In 1954 Hγ emission was double, with $R = V$; it was weaker in 1960.

M.W.C. 190, H.D. 65875; 7^{h}55^m.8, −2°36′; 6^m.4, B2e

Hydrogen absorption lines are fairly wide, He I strong and fairly narrow. Hβ and Hγ emissions are narrow but probably double with V/R changes.

M.W.C. 278, H.D. 164284; 17^{h}55^m.3, +4°22′; 4^m.8, B5ne

Hydrogen and He I absorption lines are fairly wide. Weak double Hβ emission appeared at Hβ in 1946, was absent in 1951 and 1955, was very strong in 1959 and 1960. Hγ double emission also appeared in 1953, was absent in 1955 and 1956, was strong in 1959 and 1960. In all cases $V = R$.

M.W.C. 292, H.D. 168957; 18^{h}17^m.3, +25°01′; 6^m.9, B5e

All absorption lines are narrow. In 1938 emissions at Hβ, Hγ, Hδ, Hϵ were strong and narrow; emission was replaced in 1946 by absorption cores which faded and in 1951 were replaced by emission again. Emission was gone again in 1952, re-appearing in 1954, missing in 1958, replaced by absorption cores in 1959 which then faded in 1961. The alternation of hydrogen emission lines and absorption cores was accompanied by numerous changes in the many other absorption lines, e.g. He II 4686 was quite strong in 1954.

M.W.C. 307, H.D. 174886; 18^{h}47^m.7, −10°21′; 8^m.1, B3e

The hydrogen absorption is moderately wide, He I fairly sharp. Double Hβ and Hγ emissions vary in V/R, width and intensity—weakening in 1951, strengthening then weakening again from 1955 onward. Absorption lines vary considerably in strength and sharpness.

M.W.C. 308, H.D. 175863; 18^{h}52^m.3, +59°53′; 6^m.9, B4e

Hydrogen and He I absorption lines are fairly broad. A narrow single Hβ emission appeared in 1947, faded, and was gone by 1950. It returned in 1951 but was weak or absent later. The 1959 plate seems to show absorption cores at Hγ and Hδ.

M.W.C. 310, H.D. 177648; 19^{h}00^m.5, +23°11′; 6^m.9, B3e

Hydrogen and He I absorptions are fairly broad. Double Hβ emission comes and goes with variable V/R. When Hβ emission is strongest Hγ has an absorption core.

TABLE II—*Continued*

M.W.C. 312, H.D. 180398; $19^h11^m.3$, $+12°56'$; $7^m.7$, B(3)ne

Hydrogen and He I absorptions are broad. Double Hβ emission is always weak and varies as to intensity and *V/R* ratio. Absorption core and signs of emission borders are seen at Hγ when Hβ emission is most distinct.

M.W.C. 317, H.D. 183143; $19^h23^m.0$, $+18°05'$; $6^m.9$, cB9eα

This is a well-known, strongly reddened supergiant which shows the interstellar band at λ4430 very strongly. On our plates Hβ absorption is sometimes strong, sometimes practically filled in, as though variable emission is present. He I 4387 fluctuates in character between nebulous and sharp. On a plate of 1953 Sept. 8 a strong "absorption" feature appeared at λ4447.5; it was gone on 1953 Oct. 16, and was seen on no other plate before or since. The feature may be a flaw in the emulsion, but it gives every appearance of being a strong absorption line. If the line is real the writers can suggest only N II 4447.03 by way of identification.

M.W.C. 320, B.D. $+5°4285$; $19^h41^m.3$, $+5°44'$; $8^m.5$, B5ne

The absorption lines are extremely wide. Hβ and Hγ show double emission with strong cyclical variations in *V/R*.

M.W.C. 331, H.D. 192044; $20^h07^m.8$, $+26°11'$; $5^m.9$, B8ne

Hydrogen and He II absorption lines are wide, nebulous. The Hβ and Hγ emission lines are double, with variations in intensity and *V/R*. Cores show with varying sharpness at Hγ, Hδ, Hϵ.

M.W.C. 332, H.D. 192445; $20^h09^m.8$, $+36°02'$; $7^m.1$, B2ne

Hydrogen and He I absorptions are very wide and weak. Generally the double hydrogen emissions are strong, showing as far as Hϵ; there are cyclical variations in the strength, width and *V/R* ratios. Other emission lines (e.g. Fe II 4383, He I 4471) are seen at times.

M.W.C. 336, H.D. 193009; $20^h12^m.9$, $+32°04'$; $7^m.0$, B0ne

Absorption lines are very wide. Double emission at Hβ and Hγ show cyclical variations in *V/R* ratios. Fe II 4383 is often seen in emission.

M.W.C. 343, H.D. 194335; $20^h20^m.0$, $+37°10'$; $5^m.7$, B3ne

No emission was seen in 1939, but since 1946 double emission at Hβ has displayed *V/R* variations.

M.W.C. 346, H.D. 195407; $20^h26^m.0$, $+36°39'$; $7^m.7$, B3e

Hydrogen and He I absorption lines are broad and weak except at times when shell characteristics appear, producing many sharp absorption cores. Double emissions at Hβ and Hγ vary markedly as to *V/R*. Other double emissions appeared strongly at times (e.g. Fe II 4549 and 4583 in 1954). On several plates since 1952 a wide absorption appeared at about λ4650 (O II?).

M.W.C. 347, H.D. 195592; $20^h27^m.2$, $+43°59'$; $7^m.2$, cB1e

The hydrogen and He absorptions are sharp and strong, and many lines of Si III, N III, Si IV, O II appear. No emission was observed except insofar as Hβ absorption varies somewhat in strength.

M.W.C. 350, H.D. 196712; $20^h34^m.0$, $-2°46'$; $6^m.3$, B9e

The hydrogen absorptions are broad. At times we would classify as B8 or earlier, at other times as B9, as the ratio of He I 4471: Mg II 4481 varies. Hβ shows emission,

TABLE 11—*Continued*

broad and probably double, but never well resolved. Faint Hγ emission was present in 1960.

M.W.C. 352, H.D. 198183; $20^h43^m.5$, +36°07′; $4^m.5$, B6e; λ Cyg

The absorption lines are narrow and strong. No emission was observed and no changes.

M.W.C. 353, H.D. 198478; $20^h45^m.5$, +45°45′; $4^m.9$, cB2eα

This is the supergiant 55 Cyg. No emission was observed and no changes.

M.W.C. 360, H.D. 200310; $20^h57^m.6$, +45°46′; $5^m.2$, B3ne

The hydrogen absorptions are rather narrow, the He I absorptions broad. The 1946 plates showed double Hβ and Hγ emission with $V = R$. No emission was seen in 1952 and later. The 1962 plate showed a sharp core at Hγ.

M.W.C. 361, H.D. 200775; $21^h00^m.4$, +67°47′; $7^m.2$, B5e

Hydrogen absorptions are very broad, but He I and Mg II 4481 are fairly sharp. Strong double emissions at Hβ and Hγ show variations of V/R; "shell" absorption cores at Hγ and Hδ vary in intensity. An unidentified emission feature at λ4286 appeared on the 1955 plate.

M.W.C. 366, H.D. 203374; $21^h16^m.7$, +61°25′; $6^m.6$, B0ne

Hydrogen and He I absorptions are broad. Double emissions at Hβ and Hγ vary slightly as to V/R.

M.W.C. 371, H.D. 205060; $21^h27^m.7$, +42°16′; $7^m.1$, B5(n)e

In 1938 and 1946 hydrogen and He I absorptions were broad with "shell" cores, but no emission was seen. Since 1952 double emissions at Hβ and Hγ have appeared, varying in intensity and V/R ratio.

M.W.C. 376, H.D. 206773; $21^h39^m.3$, +57°17′; $7^m.0$, B0ne

The spectrum of this star is about the most interesting of our list, showing remarkable variations. In 1938 there were strong narrow central emissions at Hβ, Hγ, Hδ within broad weak absorptions. By 1940 Hβ and Hγ showed wide double emission ($V < R$), and Hδ was practically continuous. Thereafter the hydrogen emission doubles varied markedly in intensity, width and V/R. In 1951 the emission doubles were more like borders to strong absorption cores; He I lines shared this appearance with the hydrogen lines as far as they could be seen (to Hζ). In 1953 the doublets were narrow, and V was barely visible at Hγ and Hδ; in 1957 the V/R ratios were reversed; by 1958 the emission doublets were wider again and equal. Similar variations continued.

M.W.C. 381, H.D. 208682; $21^h52^m.9$, +64°52′; $5^m.8$, B3ne

Hydrogen and He I absorptions are broad and weak. Double hydrogen emissions vary in intensity and V/R. Other emissions, e.g. He I 4471, Fe II 4383 are present at times. Hydrogen absorption cores vary in strength.

M.W.C. 383, H.D. 209296; $21^h57^m.2$, +56°14′; $8^m.1$, B(5)e

On early plates hydrogen absorptions were broad and deep, He I weak, Mg II 4481 stronger than He I 4471; type was then more like B9 than B5. No emission was seen until 1952 when (and thereafter) double emissions with $V = R$ were present at Hβ and Hγ. By 1961 He I 4471 was much stronger than Mg II 4481. Hβ had an absorption core in 1946 which remained until 1956.

TABLE II—*Continued*

M.W.C. 394, H.D. 217050; 22^{h}52^m.7, +48°09′; 5^m.2, B3ne

The spectrum is that of a typical shell star with very sharp, strong hydrogen cores and many faint metal lines. Hβ and Hγ show double emissions with slight variations of *V/R*. Some other emissions show at times.

M.W.C. 395, H.D. 217543; 22^{h}56^m.3, +38°10′; 6^m.4, B3ne

The spectrum shows marked variations. On the 1938 plates strong hydrogen absorption cores appeared as far as Hζ on broad underlying absorptions; He I absorptions were broad and strong; the only emission was a suggestion of borders at Hβ. By 1946 the emission borders at Hβ were stronger, Mg II 4481 was nearly as strong as He I 4471, and numerous metal lines were appearing in absorption. In 1947 emission at Hβ was strong ($V = R$) and shell characteristics were more marked. By 1953 the emission at Hβ was weak or absent and the metal absorptions were very weak. In 1954 Hβ emission was stronger with $V > R$. Thereafter there were variations in the hydrogen emissions (intensity and *V/R*) and in the hydrogen core intensities, but the metal lines did not return in strength.

M.W.C. 397, H.D. 218393; 23^{h}02^m.6, +49°40′; 6^m.8, Ave

This well-known star, although classified as A-type, sometimes resembles a late B-type. It has a most peculiar spectrum, showing marked variations in both the absorption and emission lines. Our plates from 1938 to 1949 were studied in some detail by Halliday (1950) who discussed the coming and going of the α Cygni metal lines and the rhythmic variations in the radial velocities. The hydrogen absorptions are usually sharp, and there are usually double emissions at Hβ and Hγ at least. The *V/R* ratios do not show the common pattern of variations; instead, the variations are rapid and seemingly erratic, and more often than not the red component is much the stronger. It is when the emission doublets are nearly equal in intensity that the metal absorptions are the strongest and sharpest; they practically disappear when $R \gg V$.

M.W.C. 402, H.D. 223501; 23^{h}45^m.0, +61°39′; 8^m.2, B3e

Hydrogen absorptions are very broad, He I somewhat narrower. Hβ and Hγ were seen as double emissions on most plates with *V/R* variations. A weak Hγ absorption core was seen in 1938.

M.W.C. 407, H.D. 224559; 23^{h}53^m.8, +45°52′; 6^m.5, B3ne

Hydrogen and He I absorptions are very broad. Emission doublets at Hβ and Hγ are generally narrow, but vary in width and *V/R*. Hydrogen absorption cores vary in strength.

M.W.C. 409, H.D. 225095; 23^{h}58^m.3, +55°00′; 7^m.6, B1e

Hydrogen absorptions are wide, He I narrow. Hβ emission appears single, but Hγ and Hδ show emission doublets with *V/R* and intensity variations. He I 4471 varies in width and strength and an absorption core was seen at Hγ in 1960.

Mount Wilson spectral type. For each star there is a brief summary of the more detailed descriptions of the spectrum and spectral variations which are on our cards.

THE *V/R* VARIATIONS

Approximately 60 per cent of the Be stars in our list showed *V/R* variations. An attempt was made to study these for periodicity as follows: For both Hβ and Hγ, if possible, the *V/R* was estimated and classified according to the following scheme:

V/R Class	1	$V \ll R$
	2	$V < R$
	3	$V = R$
	4	$V > R$
	5	$V \gg R$

For each suitable line on each spectrogram the *V/R* classification was estimated three times and the mean taken. These classification numbers were then plotted as ordinates against time as abscissae, and the points were simply joined by straight lines.

Those plots which demonstrated clear evidence of periodicity for Hβ and/or Hγ *V/R* ratios are shown in figures 1 to 4 which include 15 of the 60 stars. (The ordinates of the plots are *V/R* classes as defined above.) It is apparent that the variations are not strictly periodic, and not every plot lends itself to an estimate of period; but an effort was made to assign a period to each star in the following manner: First we averaged the intervals between successive crossings of *V/R* class 3 ($V = R$); we noted that the Hβ periods tend to be longer than the Hγ periods for those stars for which both are available. Using a method of linear regressions, we then assigned to each star a period (the "adopted" period) which we believe to be a mean period for Hβ and Hγ suitably adjusted for the observed tendency of the Hβ period to be longer than the Hγ period. The Hβ, Hγ, mean, and "adopted" periods are given in Table III.

The "adopted" periods range from 875 to 3955 days (2.4 to 10.8 years). A histogram of these periods, shown in figure 4, demonstrates that the most frequent period is of the same order as the average period, namely 6.8 years. In assessing the significance of these results, however, one must remember that the stars selected are those which are in a stage of active *V/R* variability; by our method we may have automatically rejected stars which have slower fluctuations and which, over the past 24 years, have shown little variation of *V/R*.

A search for a correlation between period and spectral type yielded no positive result.

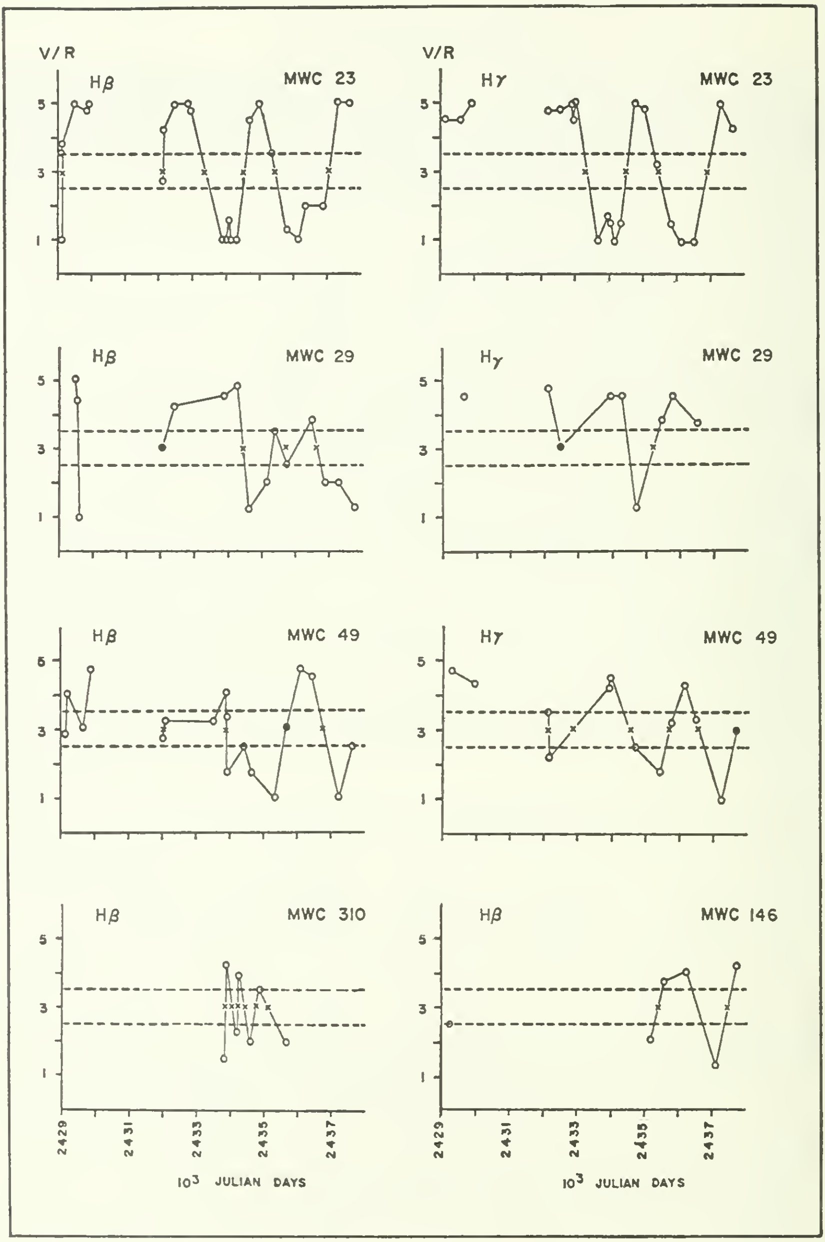
V/R
Hβ
MWC 23
Hγ
MWC 23
Hβ
MWC 29
Hγ
MWC 29
Hβ
MWC 49
Hγ
MWC 49
Hβ
MWC 310
Hβ
MWC 146
5
3
1
2429
2431
2433
2435
2437
10³ JULIAN DAYS

Figure 1

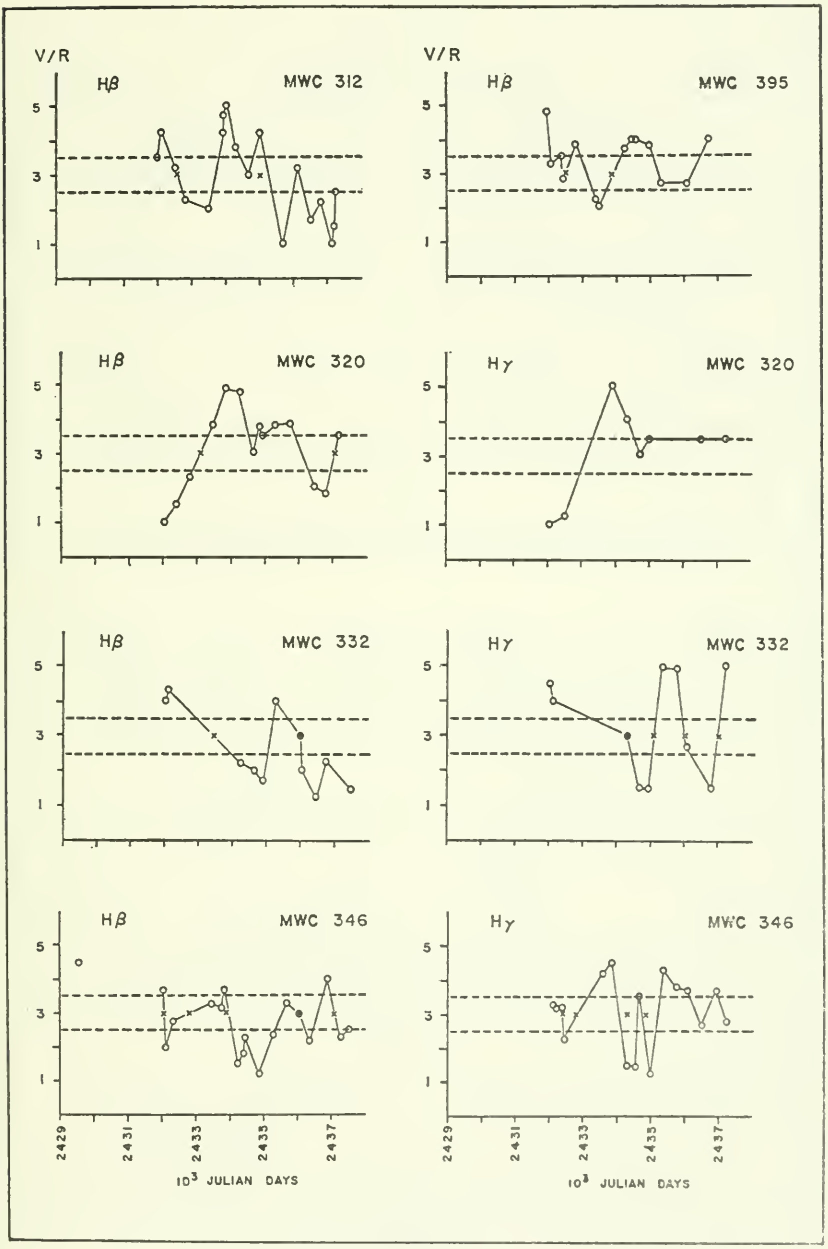
V/R
Hβ
MWC 312
V/R
Hβ
MWC 395
Hβ
MWC 320
Hγ
MWC 320
Hβ
MWC 332
Hγ
MWC 332
Hβ
MWC 346
Hγ
MWC 346
5
3
1
2429
2431
2433
2435
2437
10³ JULIAN DAYS

FIGURE 2

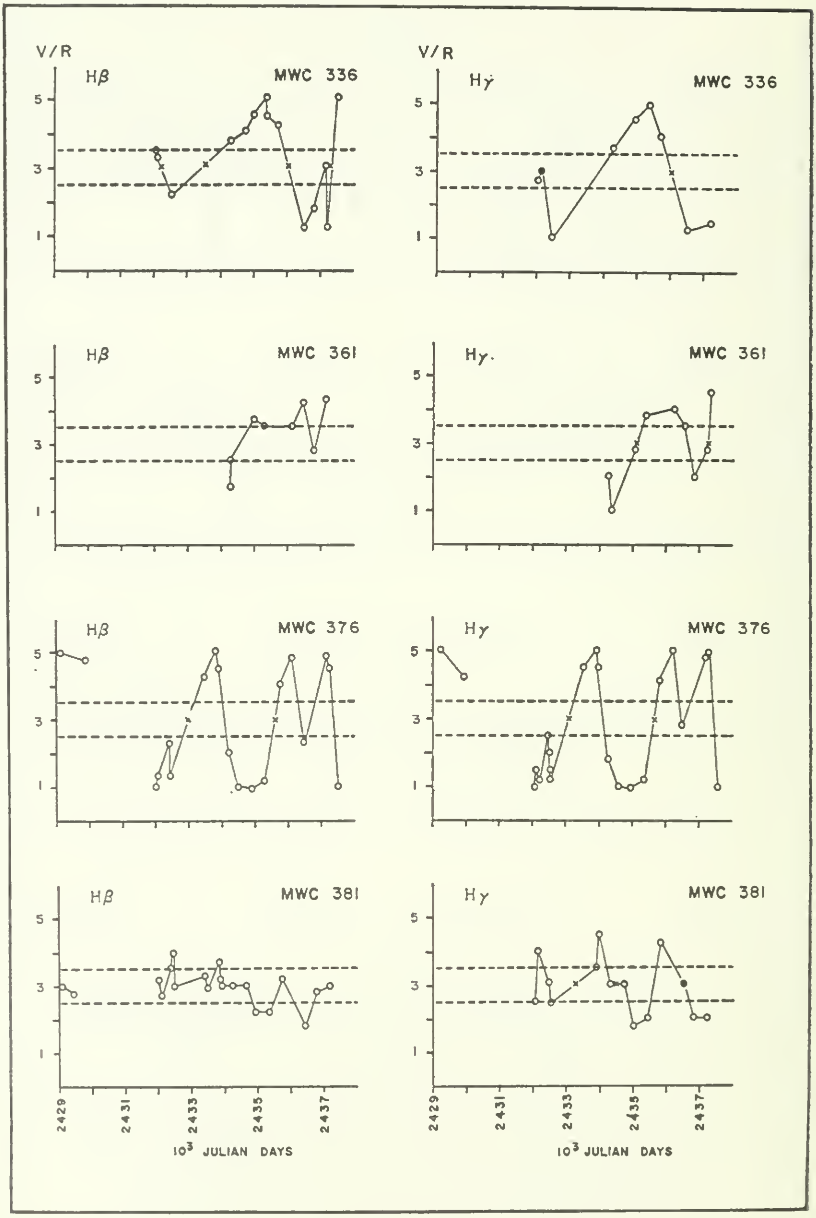
V/R
Hβ
MWC 336
Hγ
MWC 336
Hβ
MWC 361
Hγ
MWC 361
Hβ
MWC 376
Hγ
MWC 376
Hβ
MWC 381
Hγ
MWC 381
5
3
1
2429
2431
2433
2435
2437
10^3 JULIAN DAYS

FIGURE 3

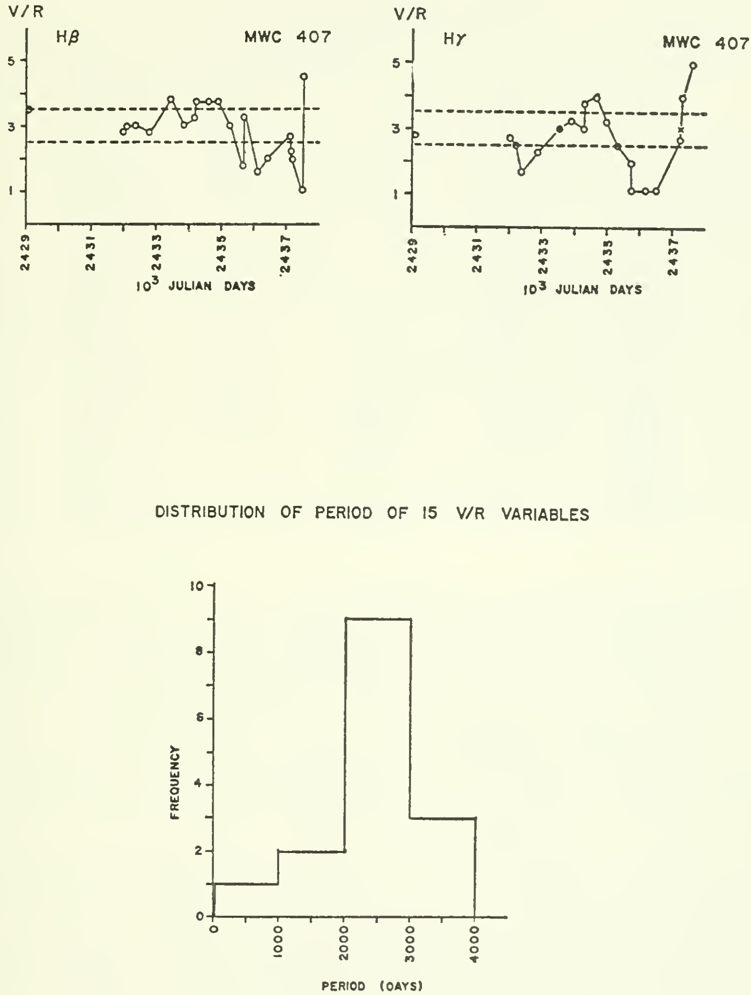
V/R
Hβ
MWC 407
5
3
1
2429
2431
2433
2435
2437
10^3 JULIAN DAYS
V/R
Hγ
MWC 407
5
3
1
2429
2431
2433
2435
2437
10^3 JULIAN DAYS
DISTRIBUTION OF PERIOD OF 15 V/R VARIABLES
10
8
6
4
2
0
FREQUENCY
0
1000
2000
3000
4000
PERIOD (DAYS)

FIGURE 4

TABLE III

V/R PERIODS OBTAINED FOR 15 STARS

Periods in days

MWC	Hβ	Hγ	Mean	Adopted
23	2461	2296	2379	2360
29	2850	2720	2785	2798
49	3097	2291	2694	2702
146	2160			1980
310	1052			875
312	2425			2250
320	3890			3720
332	2580	1790	2185	2145
336	3805	3830	3818	3955
346	2813	1950	2382	2360
361		2090		2340
376	2440	2540	2490	2472
381		2155		2390
395	1500			1325
407		3660		3610

There does appear to be a tendency for the Hγ V/R amplitudes to be greater than the Hβ amplitudes: of the 11 stars for which the data are sufficient, seven show Hγ amplitudes to be the greater, one shows Hβ amplitude the greater, and three show equal amplitudes. In a qualitative way this tendency might find an explanation on the rotating–pulsating model: the Hγ central absorption, being formed at a lower level in the envelope might be expected to be subjected to wider velocity oscillations and so give rise to more notable V/R variations in the emission doublets.

For four out of the 15 stars, the phase wherein $V \gg R$ is definitely longer than that for $R \gg V$, whereas for the other 11 stars there is no noticeable asymmetry of this sort. On the rotating–pulsating model $V \gg R$ corresponds to the contracting phase of the shell; it would thus appear that in some stars this phase lasts longer than the expanding phase.

STARS WITH SHELL CHARACTERISTICS

For practically all the stars which show definite V/R variations we have noted variations in the intensities of the hydrogen absorption cores (shell characteristics). Eye estimates of these core intensities were made and plotted alongside the V/R curves. No exact correlation was apparent, but, generally speaking, the strongest core intensity very frequently coincided with the $V \gg R$ phase or followed it by an interval of less than one quarter of the V/R period.

Taking account of all 60 of the stars investigated, 29 were noted as showing shell characteristics (in the hydrogen lines at least) at some time during the period of observation. These stars are M.W.C. 8, 10, 23, 49, 63, 68, 76, 82, 88, 93, 114, 115, 159, 292, 310, 312, 331, 346, 352, 360, 361, 371, 376, 381, 383, 394, 395, 397, 407. All but four of these stars are of Mount Wilson spectral types B3, B4 or B5; the exceptions are: M.W.C. 93 (A0), M.W.C. 331 (B8), M.W.C. 352 (B6), M.W.C. 397 (A). This clustering of shell spectra about B3–B5 types confirms an observation by Struve (1942). We further noted, by simple averaging of spectral types, that the shell Be stars in our sample are very close to B4, whereas the non-shell Be stars are close to B3. The difference, we believe, is significant, indicating therefore a tendency for the shell characteristic to be somewhat rarer in the earlier-type Be stars.

Conclusions

Our conclusions from a sample of 60 Be stars chosen without reference to known spectral characteristics and observed over a period of 24 years may be summarized as follows:

Fifty-four of the stars have shown emission at Hβ. Of the remaining six, five are supergiants.

Of the 54 stars showing emission at Hβ, 36, that is, 67 per cent, have been classed as V/R variables.

Periods have been determined for 15 of the V/R variables. The mean period is 6.8 years.

Twenty-nine of the stars showed, at some time or other, shell characteristics. These were nearly all of spectral types B3 to B5, and on the average were a little later than the Be stars which did not show shell characteristics. Fifteen of the shell stars are V/R periodic variables; among most of these stars maximum absorption core intensity tends to coincide with the phase $V \gg R$, or follow it by a small fraction of the period.

Acknowledgments

This investigation was supported by the National Research Council of Canada by research grants for obtaining the spectrograms and for financial aid to one of us (J.A.C.) as a graduate student in a Master's programme at the University of Toronto.

We thank Mr. Michael Copeland for his help in preparing the diagrams.

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Richmond Hill, Ontario
January 15, 1963