AXIAL ROTATION IN THE BRIGHTER STARS OF DRAPER TYPES B2–B5

ARNE SLETTEBAK AND ROBERT F. HOWARD
Perkins Observatory
Received May 25, 1954; revised July 23, 1954

ABSTRACT

Rotational velocities ($v \sin i$) of the stars of Draper types B2–B5, brighter than 5.51 mag. and north of declination $-20°$, were determined by comparing observed profiles of the *He* I 4471 line with sets of profiles computed by the graphical method of Shajn and Struve. Spectral types and luminosity classes on the MK system of classification were provided by Dr. W. W. Morgan.

The mean true rotational velocity of the main-sequence stars of MK types B2–B5 was found to be 201 km/sec, a value somewhat larger than the corresponding one for the B8–A2 stars. A subdivision of the main-sequence stars into MK types B1–B3 and B5–B7 shows that the B5–B7 stars appear to have the greatest axial rotation, with decreasing rotational velocities for both earlier and later types.

The stars of intermediate luminosity have smaller axial rotation than the main-sequence stars. This was also found to be the case for the B8–A2 stars, but the opposite situation was obtained for the F0–G0 stars.

A number of spectroscopic binaries included in this study are discussed from the point of view of possible synchronism between axial rotation and orbital revolution. The luminosity effect of the forbidden line of *He* I at λ 4470 is briefly discussed.

It is suggested that the observed relation of axial rotation to position on the H-R diagram may be interpreted in terms of the evolutionary sequences recently computed by Sandage and Schwarzschild.

I. INTRODUCTION

The present paper describes the B2–B5 phase in a program of obtaining rotational velocities for the brighter stars with Draper types between B2 and G0. The results for the Be stars (Slettebak 1949) and B8–A2 stars (Slettebak 1954) have been reported earlier, as have the preliminary results of the F0–G0 stars (Slettebak 1953). The ultimate aim of this work is to indicate how axial rotation varies across the H-R diagram and how this bears on problems of stellar evolution.

II. OBSERVATIONS

All stars brighter than 5.51 mag. with Draper types between B2 and B5 and north of declination $-20°$ are included in the present study. Of the total of 185 stars included, 106 have been observed only at the Perkins Observatory, 48 only at the Yerkes Observatory, and the remaining 31 at both observatories.

The Perkins material consists of one or more spectrograms of each star, taken with the two-prism spectrograph attached to the 69-inch telescope, giving a dispersion of 28 A/mm at $H\gamma$ and 32 A/mm at λ 4471. All spectra were considerably widened in order to increase the accuracy of spectral classification and to permit two independent microphotometer tracings to be made even if only one spectrogram was available. Eastman II*a*-O plates, developed for 12 minutes in Promicrol at 69° F, were used for all stars. The plates were calibrated with the spectral sensitometer in the dome of the 69-inch telescope. The Perkins microphotometer, employing a magnification of about 100, was used to derive the line profiles. Figure 1, which shows the extremes in axial rotation measured in this study, illustrates the spectrograms employed.

The Yerkes material was described in detail earlier (Slettebak 1949). It consists of most of the more rapidly rotating bright B2–B5 stars and was originally prepared for purposes of comparison with the Be stars.

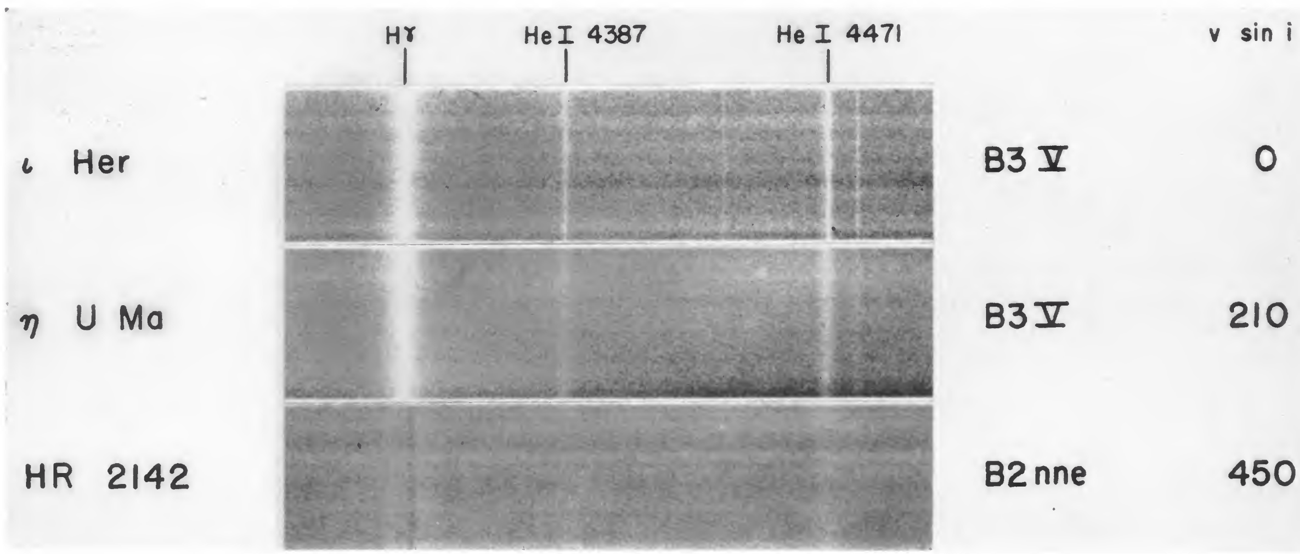

FIG. 1.—Line broadening by axial rotation in three representative B-type stars

III. ROTATIONAL VELOCITIES AND SPECTRAL TYPES

Rotational velocities for all stars were derived from the degree of line broadening with the aid of the graphical method of Shajn and Struve (1929). The method has been used and described by many writers and will not be discussed further here.

The absorption line *He* I 4471 was chosen for the determination of $v \sin i$ for all stars taken at the Perkins Observatory. It has the disadvantage of being subject to Stark effect and is blended with forbidden *He* I 4470 in stars on or near the main sequence, but it is nevertheless probably the most suitable choice with the observational material described above. Values of $v \sin i$ for the stars observed only at the Yerkes Observatory were derived from the *He* I 4026 line.

Two sharp-lined stars were chosen as zero-rotational-velocity standards for all determinations of $v \sin i$: ι Herculis (B3 V) for the stronger lines and ϵ Cassiopeiae (B2p) for the fainter lines. The latter actually has slightly broadened lines, corresponding to a $v \sin i$ of about 10 km/sec; the effect of this will be considered below. Sets of rotationally broadened contours were built up from the above standards, using the average of four independent contours of *He* I 4471 for each standard. A limb-darkened stellar disk was assumed, divided into 40 strips, as described earlier (Slettebak 1949). The inclusion of limb-darkening is probably an unnecessary refinement, however, since the uncertainties in the observed line profiles are large with respect to the small changes introduced by limb-darkening.

Two independent line profiles of *He* I 4471 were obtained for each of the stars observed at the Perkins Observatory. In most cases the resultant values of $v \sin i$ were simply averaged to give the rotational velocity of the star. For those stars which were observed both at the Yerkes and at the Perkins Observatory, the average Perkins $v \sin i$ was again averaged with the Yerkes value to give the final rotational velocity of the star. As a final check, all stars were arranged into groups of similar rotational velocity, spectral type, and luminosity class and were intercompared visually, great care being taken to obtain similar density matches. It was then found that a number of sharp-lined stars had been assigned values of $v \sin i$ which were too high, owing to the blending effect of the forbidden *He* I 4470 line. The final values of $v \sin i$ for these stars were determined visually, as were the values for a number of other stars of various degrees of line broadening, whose measured rotational velocities were inconsistent with those of the remainder of the stars. The rotational velocities of all stars are listed in Table 1.

In order to carry out the stated purpose of this investigation, the positions of the stars included must be known on the H-R diagram; that is, accurate spectral types and luminosity classes are required. These were very kindly provided by Dr. W. W. Morgan, of the Yerkes Observatory, and are on the MK system (Johnson and Morgan 1953). They are listed in Table 1. All spectral types and luminosity classes given there are due to him, with the exception of a few which were classified at Perkins. The latter are identified by an asterisk in Table 1.

IV. ACCURACY OF THE ROTATIONAL VELOCITIES

It is difficult to assess the internal accuracy of the set of $v \sin i$ values determined in this paper. This is because of the method employed, in which estimates from line profiles were combined with direct visual estimates to obtain final values of $v \sin i$. The agreement between the two values of the rotational velocity derived from line profiles for each star is good, but this is probably misleading as a gauge of internal accuracy, as direct visual estimates show. As a final check on the internal consistency of a set of $v \sin i$ values, direct visual estimates appear to be rather accurate, provided that the observational material is homogeneous and that comparisons are made between stars of the same spectral type and luminosity class, using spectra of comparable density.

1955ApJ...121..102S

TABLE 1

SPECTRAL TYPES AND ROTATIONAL VELOCITIES OF THE BRIGHTER DRAPER B2-B5 STARS

Star	α(1900)	δ(1900)	m_v	Sp(MK)	v sin i (Km/sec)	Notes
γ Peg	$0^h\ 8^m.1$	$+14^\circ 38'$	2.87	B2IV	0	**
HR 91	0 18.9	+51 28	5.36	B5IV	230	
HR 144	0 30.6	+53 37	5.14	B8V*	60	
ζ Cas	0 31.4	+53 21	3.72	B2V	20	
π And	0 31.5	+33 10	4.44	B5V	≤ 50	1
ξ Cas	0 36.5	+49 58	4.85	B2V	230	
o Cas	0 39.2	+47 44	4.70	B2V	260	2
ν And	0 44.3	+40 32	4.42	B5V	80	3
1 Per	1 45.4	+54 39	5.49	B2V	210	
ε Cas	1 47.2	+63 11	3.44	B2p	10	4
δ Cet	2 34.4	− 0 6	4.04	B2IV	20	5**
35 Ari	2 37.6	+27 17	4.58	B3V	135	
π Cet	2 39.3	−14 17	4.39	B7V	15	
π Ari	2 43.7	+17 3	5.30	B6IV*	75	6
σ Ari	2 46.0	+14 40	5.46	B7V*	195	
HR 890	2 53.7	+51 57	5.42	B7IV*	220	
λ Cet	2 54.4	+ 8 31	4.69	B5III*	150	
30 Per	3 11.1	+43 39	5.38	B8V*	250	
HR 985	3 11.2	+65 17	4.76	B2Ve	360	7
29 Per	3 11.5	+49 51	5.30	B3V	145	
31 Per	3 12.0	+49 44	5.08	B5V	320	
τ Ari	3 15.5	+20 47	5.17	B5Vp?	20	8
HR 1011	3 16.1	+48 51	5.30	B5V	250	
HR 1034	3 20.9	+48 43	4.94	B3V	50	
34 Per	3 22.2	+49 10	4.67	B5V*	180	
ψ Per	3 29.4	+47 52	4.26	B5e	390	9
δ Per	3 35.8	+47 28	3.10	B5III	255	
40 Per	3 36.0	+33 39	5.04	B0.5V	60	
16 Tau	3 38.9	+23 58	5.43	B7IV	235	
17 Tau	3 38.9	+23 48	3.81	B6III	245	10
19 Tau	3 39.3	+24 9	4.37	B6V	140	
20 Tau	3 39.9	+24 3	4.02	B7III	30	
29 Tau	3 40.4	+ 5 44	5.36	B3V	145	11
23 Tau	3 40.4	+23 38	4.25	B6IVnn	315	12
η Tau	3 41.5	+23 48	2.96	B7III	210	13
30 Tau	3 42.8	+10 50	5.03	B3V	20	
HR 1207	3 48.8	+47 35	5.34	B6V	300	
HR 1215	3 50.0	+34 47	5.48	B2V	130	
λ Tau	3 55.1	+12 12	3.8-4.1	B3V	≤ 110	14
35 Eri	3 56.5	− 1 50	5.25	B5V	190	
40 Tau	3 58.5	+ 5 10	5.33	B3V	25	
48 Per	4 1.4	+47 27	4.03	B3Vp	250	15
HR 1288	4 4.8	−16 39	5.45	B3V	40	
HR 1289	4 5.0	+83 34	5.39	B5V	320:	
μ Tau	4 10.1	+ 8 39	4.32	B3V	80	
53 Per	4 14.3	+46 16	4.89	B6III	10	
72 Tau	4 21.3	+22 46	5.41	B6V	230	
HR 1423	4 24.5	−13 16	5.50	B1Vn	340	16
ν Eri	4 31.3	− 3 33	4.12	B2III	40	17**
HR 1469	4 32.1	+ 0 48	5.32	B7V	140	
τ Tau	4 36.3	+22 46	4.33	B3V	220	18
μ Eri	4 40.5	− 3 26	4.18	B5IV	190	
π^4 Ori	4 45.9	+ 5 26	3.78	B2III	40	19
π^5 Ori	4 49.0	+ 2 17	3.6-3.7	B2III	90	20
ψ Eri	4 56.6	− 7 19	4.81	B2*V*	90	

TABLE 1 (Continued)

SPECTRAL TYPES AND ROTATIONAL VELOCITIES OF THE BRIGHTER DRAPER B2-B5 STARS

Star	α (1900)	δ (1900)	m_V	Sp(MK)	v sin i (Km/sec)	Notes
11 Cam	$4^h57^m.5$	+58°50'	5.31	B2*V*:p	125	21
η Aur	4 59.5	+41 6	3.28	B3V	125	
103 Tau	5 2.0	+24 8	5.50	B2V	90	22
λ Eri	5 4.4	- 8 53	4.34	B2IV	325	
τ Ori	5 12.8	- 6 57	3.68	B5III	25	
ρ Aur	5 14.7	+41 42	5.12	B5V	90:	
ν Lep	5 15.4	-12 25	5.29	B7:V*:nn	370	
22 Ori	5 16.7	- 0 29	4.65	B2IV	20	
23 Ori(br)	5 17.6	+ 3 27	4.99	B1V	280	
8 Lep	5 18.9	-14 1	5.17	B2IV	20	
25 Ori	5 19.6	+ 1 45	4.73	B1V	295	23
γ Ori	5 19.8	+ 6 16	1.70	B2III	60	
115 Tau	5 21.3	+17 53	5.31	B5V	160	
ψ Ori	5 21.6	+ 3 1	4.66	B2IV		24
114 Tau	5 21.6	+21 51	4.83	B3V	10	
32 Ori	5 25.4	+ 5 52	4.32	B5IV	190	
υ Ori	5 27.1	- 7 23	4.64	B0V	10	
HR 1861	5 27.6	- 1 40	5.30	B1V	20	
120 Tau	5 27.7	+18 28	5.50	Bp	280	25
121 Tau	5 29.4	+23 58	5.28	B3V	115	
42 Ori	5 30.5	- 4 54	4.65	B2III	105	
ζ Tau	5 31.7	+21 5	3.00	B2IVp	310	26
125 Tau	5 33.5	+25 50	5.00	B2V	60	27
ω Ori	5 33.9	+ 4 4	4.54	B3IIIe	195	28
126 Tau	5 35.5	+16 29	4.87	B3IV	90	29
HR 1952	5 35.8	- 1 11	5.00	B2IV	65	30
133 Tau	5 42.1	+13 52	5.20	B2V	60	
55 Ori	5 46.5	- 7 33	5.32	B2V	145	
139 Tau	5 51.8	+25 56	4.90	B1Ib	≤ 140	
χ^2 Ori	5 58.0	+20 8	4.71	B2Ia	0	
HR 2142	5 59.4	- 6 42	5.12	B2IV,V*nne	450	31
HR 2154	6 1.7	- 4 11	5.37	B5IV	10	
ν Ori	6 1.9	+14 47	4.40	B3V	30	32
ξ Ori	6 6.3	+14 14	4.35	B3V	230	
69 Ori	6 6.3	+16 9	4.92	B5V	310	
HR 2205	6 7.0	- 6 32	5.09	B2V	15	
HR 2266	6 13.9	-19 56	5.31	B2V	75	
7 Mon	6 14.9	- 7 47	5.13	B2V	165	
HR 2284	6 16.8	-11 44	5.49	B1Vep	270	33
10 Mon	6 23.0	- 4 42	4.98	B2V	85	
ν Gem	6 23.0	+20 17	4.06	B7IV	220	34
β Mon A	6 24.0	- 6 58	4.73	B3Vpe	360	35
HR 2395	6 28.6	- 1 9	5.02	B6V	310	
42 Cam	6 40.5	+67 41	5.04	B3IV	140	
43 Cam	6 42.9	+69 0	5.13	B7IV*	205	
HR 2522	6 44.4	-15 2	5.29	B6V	150	
ι CMa	6 51.7	-16 55	4.39	B3II	0	
19 Mon	6 58.0	- 4 6	4.89	B1V	350	
γ CMa	6 59.2	-15 29	4.07	B8II	≤15	
HR 2678	7 2.0	-11 8	5.28	B0.5IV	165	36
HR 2825	7 20.2	-16 0	5.20	B3V	30:	37
16 Pup	8 4.6	-18 57	4.34	B5V	190	
η Hya	8 38.0	+ 3 45	4.32	B3V	135	
κ Hya	9 35.5	-13 53	4.96	B5V	190	
30 Sex	10 25.2	- 0 7	4.95	B6V	115	

TABLE I (Continued)

SPECTRAL TYPES AND ROTATIONAL VELOCITIES OF THE BRIGHTER DRAPER B2-B5 STARS

Star	α(1900)	δ(1900)	m_v	Sp(MK)	v sin i (Km/sec)	Notes
HR 4590	$11^h55^m.7$	$-19^\circ\ 6'$	5.28	B1.5V	135	38
κ Dra	12 29.2	+70 20	3.88	B7p	250	39
α Vir	13 19.9	-10 38	1.21	B1V		40
η UMa	13 43.6	+49 49	1.91	B3V	210	
θ CrB	15 28.9	+31 42	4.17	B7nn	400	41
HR 5780	15 29.0	- 8 51	5.15	B6IV-V	15	
λ Lib	15 47.5	-19 52	5.06	B3V	220	
48 Lib	15 52.6	-13 59	4.68	Bp	400	42
β Sco(ft)	15 59.6	-19 32	5.06	B2V	85	
ν Sco(br)	16 6.2	-19 12	4.29	B2IV?	210	
τ Her	16 16.7	+46 33	3.91	B5IV	20	
χ Oph	16 21.2	-18 14	4.85	B2IV?p	115	43
ζ Dra	17 8.5	+65 50	3.22	B6III	20	
68 Her	17 13.6	+33 12	4.6-5.3	Comp		44
HR 6502	17 22.5	+20 10	5.42	B6V:	250	
ι Her	17 36.6	+46 4	3.79	B3V	0	45
66 Oph	17 55.3	+ 4 22	4.81	B2Ve	≤275	46
67 Oph	17 55.6	+ 2 56	3.92	B5Ib	0	
96 Her	17 58.1	+20 50	5.09	B3V	220	47
102 Her	18 4.5	+20 48	4.32	B2V	20	
HR 6845	18 12.5	+42 8	5.42	B6V:	235	
4 Aql	18 39.8	+ 1 57	5.04	B9V	350	
HR 7119	18 49.0	-15 44	5.04	B5III	10	
HR 7166	18 53.8	-12 59	5.36	B5V	190	48
HR 7202	18 57.2	+26 9	5.50	B5V	300	
HR 7210	18 57.7	+50 23	5.24	B3V	0	
HR 7249	19 2.4	-19 27	5.41	B2Ve?	220	49
ι Lyr	19 3.7	+35 57	5.13	B7IV	310:	
20 Aql	19 7.3	- 8 6	5.37	B3IV	170	
η Lyr	19 10.4	+38 58	4.46	B2IV	10	
1 Vul	19 11.9	+21 13	4.60	B3IV	130	
3 Vul	19 18.8	+26 4	4.92	B6III	45	
2 Cyg	19 20.2	+29 26	4.86	B3IV	155	
8 Cyg	19 28.1	+34 14	4.85	B3IV	10	
ι Aql	19 31.6	- 1 31	4.28	B5III	95	
σ Aql	19 34.3	+ 5 10	5.0-5.2	B3V		50
12 Vul	19 46.8	+22 21	4.91	B3V	300	51
23 Cyg	19 51.2	+57 16	5.04	B5V	150	
22 Cyg	19 52.3	+38 13	4.87	B6III	120	
HR 7628	19 53.8	+40 6	5.43	B5Vp?	115	52
25 Cyg	19 56.3	+36 46	5.15	B3V	230	53
17 Vul	20 2.6	+23 20	5.08	B3V	240:	
28 Cyg	20 5.7	+36 33	4.82	B3V	310	54
HR 7739	20 11.0	+25 17	4.82	B3V	275	
ω^1 Cyg	20 27.0	+48 37	4.89	B2V	185	
ε Del	20 28.4	+10 58	3.98	B6III	40	
τ Cap	20 33.7	-15 18	5.30	B6III	180	55
28 Vul	20 34.2	+23 46	5.04	B5V	330	
51 Cyg	20 39.1	+49 59	5.41	B2V	30	
λ Cyg	20 43.5	+36 7	4.47	B5V	140	56
55 Cyg	20 45.5	+45 45	4.89	B3Ia	0	
57 Cyg	20 49.7	+44 1	4.68	B5V	≤115	57
60 Cyg	20 57.7	+45 46	5.24	B1V	320:	58
υ Cyg	21 13.8	+34 29	4.42	B2Ve	280	59
6 Cep	21 17.3	+64 27	5.18	B3V	150	60

TABLE 1 (Continued)

SPECTRAL TYPES AND ROTATIONAL VELOCITIES OF THE BRIGHTER DRAPER B2-B5 STARS

Star	α(1900)	δ(1900)	m_v	Sp(MK)	v sin i (Km/sec)	Notes
70 Cyg	$21^h23^m.3$	+36°41'	5.20	B3V	135	
7 Cep	21 25.8	+66 22	5.42	B7	300:	
ε Cap	21 31.5	-19 55	4.72	B3V*:p	290	61
9 Cep	21 35.2	+61 38	4.87	B2Ib	0	
π^1 Cyg	21 38.6	+50 44	4.78	B3V	120	
π^2 Cyg	21 43.1	+48 51	4.26	B3III	35	
16 Peg	21 48.5	+25 27	5.05	B3V	150	62
o Aqr	21 58.2	- 2 38	4.66	B8V	300	63
38 Aqr	22 5.3	-12 3	5.40	B6III:	10	
30 Peg	22 15.4	+ 5 17	5.35	B5III	30	
31 Peg	22 16.6	+11 42	4.93	B2V	130	64
2 Lac	22 16.9	+46 2	4.66	B6IV		65
6 Lac	22 26.2	+42 37	4.54	B2IV	75	
12 Lac	22 37.0	+39 42	5.18	B2III	80	66**
HR 8731	22 52.7	+48 9	5.20	B2:p	340	67
o And	22 57.3	+41 47	3.63	B6*p	330	68
β Psc	22 58.8	+ 3 17	4.58	B5pe	145	69
ψ^2 Aqr	23 12.7	- 9 44	4.56	B5V	350	
HR 8926	23 25.4	+58 0	4.9-5.0	B3*V*	160	70
σ Cas	23 53.9	+55 12	4.93	B1V	190	

NOTES TO TABLE 1

1. Variable radial velocity, P = 144 days, two spectra. There are indications of two spectra on the Perkins plate. The He I 4471 line is shaded slightly to the violet and it is possible that the rotational velocity of 50 Km/sec is slightly too large.

2. MWC 8.

3. Variable radial velocity, P = 4.3 days, two spectra. Only one spectrum is visible on the Perkins plate.

4. Sharp-line standard star. Morgan (Morgan, Keenan and Kellman 1943) has called attention to the peculiar spectrum of this star, pointing out that the lines He I 4026 and 4471 are considerably weaker than in stars of similar type, while the broad H wings observ for stars of luminosity class V are not observed.

5. Variablo radial velocity, P = 0.15 days.

6. Variable radial velocity, P = 3.9 days.

7. MWC 65. Also variable radial velocity, P = 4.5 years.

8. He I 4026 abnormally strong?

9. MWC 69. Shell star.

10. MWC 72.

11. Variable radial velocity, two spectra. Only one spectrum is visible on the Perkin plate.

12. MWC 73.

13. MWC 74.

14. Variable radial velocity, P = 4.0 days, two spectra. Some evidence of secondary spectrum on the Perkins plate, but the He I lines appear to be single.

15. MWC 81. Pole-on star.

16. MWC 86.

17. Variable radial velocity, P = 0.19 days.

18. Variable radial velocity, P = 1.5 days.

19. Variable radial velocity, P = 9.5 days.

20. Variable radial velocity, P = 3.7 days.

21. MWC 96. Pole-on star.

22. Variable radial velocity, P = 58.4 days.

23. MWC 110.

24. Variable radial velocity, P = 2.5 days, two spectra. The spectrum is composite the Perkins plate.

25. MWC 111. Pole-on star?

26. MWC 115. Shell star. Variable radial velocity, P = 133 days.

27. Variable radial velocity, P = 27.9 days.

28. MWC 117.

29. Close binary, $5^{m}_{.}5$ and $5^{m}_{.}7$ components. Only one spectrum visible on the Perkin plate.

30. Variable radial velocity, P = 27.2 days.

31. MWC 133

32. Variable radial velocity, P = 131 days.

33. MWC 138.

34. MWC 141.

35. MWC 143. Shell star.

36. Close binary, $5^{m}_{.}6$ and $6^{m}_{.}8$ components. The He I lines appear to be single on t Perkins plate.

37. MWC 177. Pole-on star.

38. Variable radial velocity, P = 3.0 days.

39. MWC 222. Variable radial velocity, P = 0.89 days.

40. Variable radial velocity, P = 4.0 days, two spectra. The spectrum is composit on the Perkins Plate.

41. MWC 237.

42. MWC 239. Shell star.

43. MWC 241. Pole-on star.

44. Variable radial velocity, P = 2.05 days, two spectra, eclipsing system. The spectrum is composite on the Perkins plate.

45. Sharp-line standard star. Variable radial velocity, P = 0.14 days?

46. MWC 278. Two spectra. The helium lines are very broad on the Perkins plate a it is uncertain whether there was doubling at that phase.

47. Variable radial velocity, P = 50.2 days?

48. Close binary, $5^{m}_{.}9$ and $6^{m}_{.}4$ components.

49. MWC 311.

50. Variable radial velocity, P = 2.0 days, two spectra, eclipsing system. The spectrum is composite on the Perkins Plate.

NOTES TO TABLE 1 (Continued)

51. MWC 323.

52. Hydrogen lines too strong?

53. MWC 624.

54. MWC 329. Variable radial velocity, P = 226 days.

55. Close binary, $5^{m}_{.}6$ and $6^{m}_{.}9$ components.

56. MWC 352. Close binary, $4^{m}_{.}8$ and $6^{m}_{.}1$ components. The helium lines appear single on the Perkins plate.

57. Variable radial velocity, P = 2.9 days, two spectra. Only one spectrum is visible on the Perkins plate.

58. MWC 360.

59. MWC 364. Pole-on star.

60. MWC 367.

61. MWC 373. Shell star.

62. MWC 644.

63. MWC 384.

64. MWC 387.

65. Variable radial velocity, P = 2.6 days, two spectra. The spectrum is composite on the Perkins plate.

66. Variable radial velocity, P = 0.19 days.

67. MWC 394. Shell star.

68. Shell star.

69. MWC 396. Pole-on star.

70. Eclipsing variable, AR Cassiopeiae, P = 6.1 days.

** These stars are β Cephei or β Canis Majoris stars. Struve ("The Present State of Our Knowledge of the β Canis Majoris or β Cephei Stars", Ann.d'ap.,15,157-168,1952) has shown that the members of this class of stars show variations in line broadening. The values of v sin i given here are based on one plate only, and therefore are measures of the line broadening at a particular phase.

The fact that one of the sharp-lined standard stars, ϵ Cassiopeiae, has slight rotational line broadening should tend to give values of $v \sin i$ for slowly rotating stars that are a trifle small and should have little effect on the more rapidly rotating stars. As was mentioned above, however, the rotational velocities for the stars with small line broadening were largely determined by visual inspection. For the more rapidly rotating stars, the agreement between rotational velocities estimated from computed line contours derived from ι Herculis and from ϵ Cassiopeiae was good.

A rough estimate of the accidental errors involved in the $v \sin i$ determinations is given in Table 2, in which the probable maximum errors are given for different values of the measured rotational velocities.

A word should be added concerning the effect of finite resolving power on the observed rotational velocities. With the dispersion employed in this study there is very little difference in the broadening of line contours corresponding to rotational velocities of 0 and 25 km/sec. Therefore, values of $v \sin i$ listed in Table 1 which are less than 25 km/sec

TABLE 2

PROBABLE MAXIMUM ERRORS OF MEASURED ROTATIONAL VELOCITIES

$v \sin i$ (Km/Sec)	Probable Maximum Error (Km/Sec)	$v \sin i$ (Km/Sec)	Probable Maximum Error (Km/Sec)
0–50........	±20	205–300......	±50
55–100.......	±30	>300........	±75
105–200.......	±40		

should be treated cautiously. Coudé spectrograms would be required to give a reliable distribution of the rotational velocities of slowly rotating stars. On the other hand, the present resolution is quite adequate to handle the moderately and rapidly rotating stars, since the line contours computed by the Shajn-Struve graphical method are insensitive to the standard zero-rotational-velocity line contour for large values of $v \sin i$. Since the B-type stars are characterized by values of $v \sin i$ ranging up to 400–500 km/sec, the present moderate resolution is sufficient for a statistical study of axial rotation in these stars as a group, even though it provides only approximate values of $v \sin i$ for the slowly rotating stars.

A comparison of the rotational velocities of stars which were observed both at the Perkins and at the Yerkes Observatory is shown in Figure 2. The agreement is quite good, although there appears to be a tendency for the Yerkes values to run slightly higher. The star which is considerably off the left side of the diagram (Perkins, 50 km/sec; Yerkes, 250 km/sec) is π Andromedae, which is a double-lined spectroscopic binary. It is probable that the two-line phase was observed at Yerkes, thus giving too high a value of $v \sin i$.

Figure 3 illustrates the Perkins rotational velocities versus those of Miss Westgate (1933). In addition to a rather considerable scatter, the values of Miss Westgate are seen to run systematically lower than the Perkins values.

A similar comparison made with the recent observations of Huang (1953) is shown in Figure 4. The agreement here is satisfactory, but two points should be noted. First, the Perkins values of $v \sin i$ are systematically slightly larger than those of Huang for values in excess of about 200 km/sec. Second, Huang's rotational velocities are systematically larger for values of $v \sin i$ less than about 75 km/sec. As was mentioned above, the Perkins line-profile values were also found to run systematically higher than the direct visual estimates for many slowly rotating stars, and this was interpreted as being due to the blending effect of the forbidden *He* I 4470 line. It appears probable that this same effect may have influenced Huang's measures of line widths for the stars with small line broadening.

V. DISCUSSION

Of the 185 stars in Table 1, only stars which could be located uniquely on the H-R diagram by spectroscopic means and which have noncomposite spectra on the Perkins

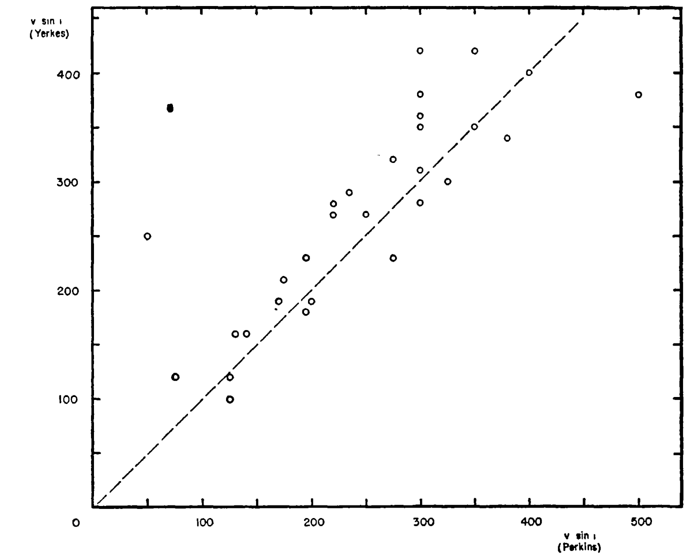

FIG. 2.—Comparison of rotational velocities measured at Perkins with those measured at Yerkes

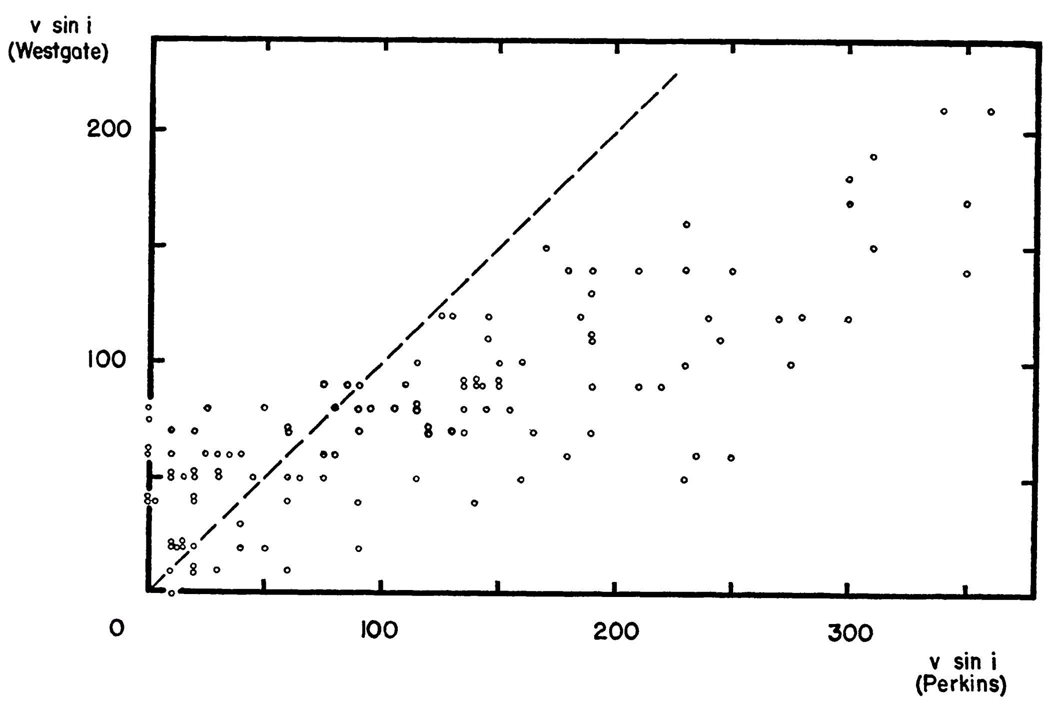

FIG. 3.—Comparison of rotational velocities measured at Perkins with those measured by Miss Westgate.

plates were included in the following statistical discussion. Thus a total of 12 stars has been eliminated because of difficulties of spectral classification, most of these being shell stars or pole-on stars. In addition, seven stars show some evidence of secondary spectrum on the Perkins plates and have also been eliminated. The remaining stars, plus one B2, one B5, and four B7 stars, whose rotational velocities were measured in a previous study (Slettebak 1954), are considered below.

1. MAIN-SEQUENCE STARS

A total of 78 stars with MK types in the range B2–B5 V has been found. The mean observed rotational velocity of this group is given in Table 3, with the mean true rotational velocity. The derivation of the latter quantity, given the former and assuming a random distribution of the axes of rotation, is due to Chandrasekhar and Münch (1950).

Included in the 78 B2–B5 V stars are 16 stars of type Be. Taken separately, these stars have a $\bar{v}$ of 284 km/sec—significantly larger than the value obtained for the corresponding non-emission stars, as has been shown previously. The Be stars have been included in this discussion because it appears likely from the work of Wilson (1941) and Smith (1947) that there is no significant difference in the luminosities of the emission and non-emission stars. Also, the spectra of Be stars in a non-emission phase appear no different from those of normal B-type stars of corresponding type. In this sense a Be star is probably a normal B-type star in rotational instability.

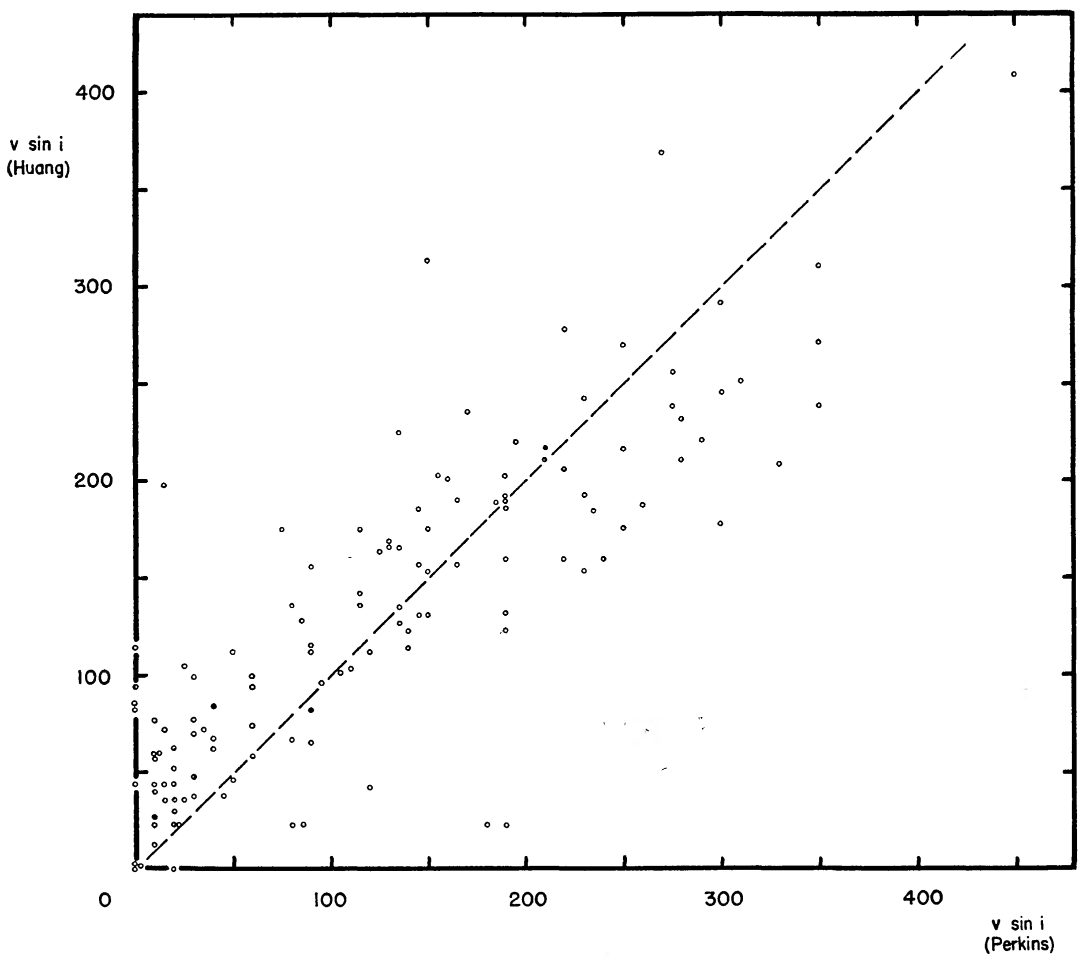

FIG. 4.—Comparison of rotational velocities measured at Perkins with those measured by Huang

The value of $\bar{v}$ of 201 km/sec for the B2–B5 V stars obtained here may be compared with the corresponding value, obtained by one of us (1954), for the B8–A2 V stars: 177 km/sec. The reality of the somewhat larger axial rotation found for the B2–B5 V stars is questionable. Besides errors arising from the relatively small number of stars considered, a systematic error of 25 km/sec between the two determinations is entirely possible and would be enough to obliterate the difference. It is safe to say that axial rotation at these two positions on the H-R diagram is not very different, with the B2–B5 V stars probably having somewhat greater rotation than the B8–A2 V stars.

Since a number of stars with MK types earlier than B2 and later than B5 are included in Table 1, an attempt to gain resolution on the main sequence was made by dividing the B1–B7 stars into two groups and comparing their axial rotation. Table 3 lists the mean observed rotational velocity and the mean true rotational velocity of the two groups, the B1–B3 V stars and the B5–B7 V stars. This grouping would tend to indicate

TABLE 3

AXIAL ROTATION OF THE B-TYPE STARS

Spectral Type (MK) and Luminosity Class	No. of Stars	$\overline{v \sin i}$ (Km/Sec)	$\bar{v}$ (Km/Sec)
B2–B5:			
V	78	158	201
IV	23	112	143
III	14	86	110
B1–B3:			
V	67	157	200
IV	17	110	139
III	8	81	102
B5–B7:			
V	35	203	257
IV	13	177	225
III	17	91	116

that the largest axial rotation among the B-type stars occurs in the B5–B7 V range, with the values dropping off as one goes to both earlier and later types. Again, it must be cautioned that the numbers of stars involved are relatively small.

It may be of some interest to derive the distribution of the true rotational velocities from the distribution of observed rotational velocities for the B2–B5 V stars, following the methods of Chandrasekhar and Münch (1950), although the physical significance of the derived true-rotational-velocity distribution is questionable with only 78 stars involved (Brown 1950).

Assuming random orientation of the axes of rotation and a frequency function for the true rotational velocities of the form

$$f(v) = \frac{j}{\sqrt{\pi}} \left[e^{-j^2(v-v_1)^2} + e^{-j^2(v+v_1)^2} \right] ,$$

the predicted distribution of $v \sin i$ is compared with the observed distribution of $v \sin i$ in Figure 5. The parameters of $f(v)$ are listed in Table 4, following the notation of Chandrasekhar and Münch (1950). Figure 5 may be compared with similar frequency-curves for the B8–A2 stars (Slettebak 1954) and for other groups of stars (Chandrasekhar and Münch 1950).

2. STARS OF INTERMEDIATE LUMINOSITY

A total of 55 stars was estimated to be of luminosity classes III and IV in the range of MK spectral types B1–B7. These are differentiated and broken down into groups of B2–B5, B1–B3, and B5–B7 stars in Table 3. In all cases the stars of intermediate luminosity have significantly less axial rotation than the corresponding main-sequence stars. This was also found to be the case among the B8–A2 stars (Slettebak 1954), but the opposite was found for the F0–G0 stars by Herbig and Spalding (1953) and independently by Slettebak (1953).

Table 3 shows further that axial rotation among the B-type stars appears to be smallest in the giant stars and increases with decreasing luminosity to the subgiant and finally to the main-sequence stars. As in the case of the main-sequence stars, the largest axial

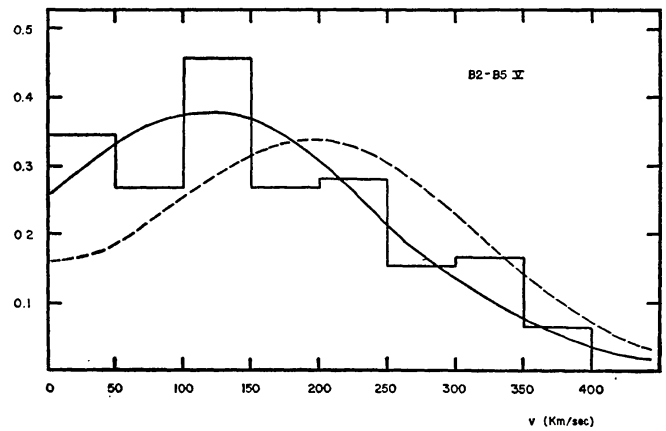

FIG. 5.—Comparison of the distribution of the observed rotational velocities of the B2–B5 main-sequence stars with that derived on the assumption of a true distribution of velocities of the form given in the text and for values of the parameters listed in Table 4. The observed distribution of $v \sin i$ is represented by the histogram, while the full-line curve represents the predicted distribution of $v \sin i$ for a true distribution of v given by the dashed curve.

TABLE 4

PARAMETERS OF ROTATIONAL-VELOCITY DISTRIBUTION OF B2–B5 MAIN-SEQUENCE STARS

$\overline{v \sin i}$ (km/sec)	158	$\bar{v}/[2(\overline{v^2} - \bar{v}^2)]^{1/2}$	1.33
$\overline{v^2 \sin^2 i}$ [(km/sec)^2]	34,560	j^{-1} (km/sec)	164
$\bar{v}$ (km/sec)	201	v_1 (km/sec)	197
$\overline{v^2}$ [(km/sec)^2]	51,840		

rotation among the stars of intermediate luminosity occurs in the B5–B7 range, the velocities decreasing as one goes to both earlier and later types. The B-type giants and subgiants probably have generally larger rotational velocities than the corresponding B8–A2 stars, but this result must be viewed with caution for two reasons: (1) the possibility of systematic errors in the two determinations and (2) the difficulty of accurate luminosity classification in the B8–A2 stars.

3. SUPERGIANT AND LUMINOUS GIANT STARS

Seven stars in Table 1 are in the range of luminosity classes I*a*–II. Of these, all but one were judged to have extremely small axial rotation, though the lines in some appear to be turbulence-broadened. The B1 I*b* star, 139 Tauri, has rather broad lines which have the appearance of being rotationally broadened. The observed rotational velocity of this supergiant star is 140 km/sec, under the assumption that the line broadening is entirely due to axial rotation. It is possible that large-scale turbulence may also be an important broadening agent, however, as has been suggested by Struve (1952) for the early-type supergiant stars. The similarity in appearance of line profiles broadened by axial rotation and those broadened by large-scale turbulence has been pointed out by Huang and Struve (1953).

VI. MISCELLANEOUS REMARKS

1. SPECTROSCOPIC BINARIES

Of the stars listed in Table 1, twenty-one are also listed in the Lick Observatory "Fifth Catalogue of the Orbital Elements of Spectroscopic Binary Stars" (1948). Of these, six show evidence of secondary spectrum on the Perkins plates and have been eliminated from the following discussion. The remaining fifteen are listed in Table 5 with their MK spectral types and the corresponding visual absolute magnitudes and effective temperatures, determined from the calibration by Keenan and Morgan (1951).

The fifth column of Table 5 lists the computed radii (Russell, Dugan, and Stewart

TABLE 5

COMPARISON OF ORBITAL AND ROTATIONAL PERIODS FOR FIFTEEN SPECTROSCOPIC BINARIES

Star	Sp (MK)	M_v	T_{eff} (° K)	$R/R_{\odot}$	$v \sin i$ (Km/Sec)	$P_{rot}/\sin i$ (Days)	P_{orb} (Days)
ν And.......	B5 V	−1.3	15,600	4.2	80	2.7	4.3
π Ari.......	B6 IV	−2.0	14,500	6.2	75	4.2	3.9
λ Tau......	B3 V	−2.0	18,000	5.1	≤110	≥2.4	4.0
τ Tau.......	B3 V	−2.0	18,000	5.1	220	1.2	1.5
π^4 Ori......	B2 III	−4.1	20,300	12.4	40	15.6	9.5
π^5 Ori.......	B2 III	−4.1	20,300	12.4	90	7.0	3.7
103 Tau.....	B2 V	−2.6	20,300	6.2	90	3.5	58.3
125 Tau.....	B2 V	−2.6	20,300	6.2	60	5.2	27.9
HR 1952....	B2 IV	−3.3	20,300	8.6	65	6.7	27.2
ν Ori.......	B3 V	−2.0	18,000	5.1	30	8.6	131.3
HR 4590....	B1.5 V	−2.9	21,400	6.9	135	2.6	3.0
28 Cyg......	B3 V	−2.0	18,000	5.1	310	0.9	226.0
57 Cyg......	B5 V	−1.3	15,600	4.2	≤115	≥1.8	2.9
π^2 Cyg......	B3 III	−3.7	18,000	11.3	35	16.3	72.0
HR 8926....	B3 V	−2.0	18,000	5.1	160	1.6	6.1

1938) of the fifteen stars and the sixth column their measured rotational velocities. In the seventh and eighth columns the computed period of rotation divided by the sine of the inclination is compared with the orbital period as listed in the Lick catalogue (1948).

Synchronism between axial rotation and orbital revolution appears to be ruled out for seven of the systems in Table 1: 103 Tauri, 125 Tauri, HR 1952, ν Orionis, 28 Cygni, π^2 Cygni, and HR 8926. The latter is the eclipsing system AR Cassiopeiae, for which Luyten, Struve, and Morgan (1939) reached a similar conclusion. On the basis of the measured rotational velocities, synchronism also appears improbable for λ Tauri and 57 Cygni. However, it is possible that the secondary spectrum influenced the $v \sin i$ measures; hence synchronism should not be ruled out for these two systems.

2. THE FORBIDDEN LINE OF HELIUM, λ 4470

As has been mentioned previously, the forbidden line of *He* I at λ 4469.92 (2^3P-4^3F) is visible on the Perkins spectrograms of a number of stars. Since only moderate dispersion was available and the line is intrinsically diffuse, it is not completely resolved from *He* I 4471 but, rather, appears as a fuzzy violet asymmetrical edge on the Perkins plates.

Further, it was distinctly visible only for stars with observed rotational velocities less than about 50 km/sec; greater line broadening blends the two lines hopelessly.

The luminosity dependence of the forbidden λ 4470 line was first shown by Struve (1929): the smaller the luminosity of the star, the stronger the electric fields operating in its atmosphere and the greater the intensity of the line. The stars of high luminosity did not show the λ 4470 line on the Perkins plates, and the line was very weak in the spectra of the few luminosity class III stars in which it was present. All slowly rotating stars of luminosity classes IV and V of spectral type B5 or earlier showed some trace of λ 4470 on the Perkins plates, but no clear separation of the two luminosity classes could be made in terms of the strength of the line. Thus two of the stars with the strongest λ 4470 are the B2 IV stars δ Ceti and γ Pegasi. Again, although a number of main-sequence stars showed the forbidden line conspicuously, others of similar type and rotational broadening had it only weakly present on the Perkins spectrograms.

It should be emphasized that the above remarks are strictly qualitative, in view of the limited visibility of λ 4470 with the present resolution. A quantitative study of the λ 4470 line in the B-type stars with high dispersion plates would be very desirable.

VII. INTERPRETATION

The present investigation, as well as similar studies of the B8–A2 and F0–G0 stars described earlier, have brought out the following relationships between stellar axial rotation and position on the H-R diagram.

1. Axial rotation on the main sequence appears to reach a maximum in the range of spectral types B5–B7 and decreases as one moves to both earlier and later types. In view of the relatively small numbers of stars employed and the possibility of systematic errors, the possibility that the average axial rotation is approximately constant along the main sequence from B2 to A2 cannot be rejected. In any case, there is no question that stellar axial rotation on the main sequence has declined sharply in the early F-type stars and is, for all practical purposes, nonexistent in stars of spectral type F5 and later. The nature of the decline will be considered in a forthcoming paper concerning axial rotation in the A3–G0 stars.

2. Among the B2–A2 stars, axial rotation is greatest for the main-sequence stars and decreases as one goes to higher luminosities. The F0–G0 stars, on the other hand, show the greatest axial rotation in the stars of intermediate luminosity, with less rotation for the main-sequence stars. Further, the giants and subgiants exhibit rotational line broadening to spectral type G0, at least, while axial rotation on the main sequence stops at about F5, as mentioned above. The luminosity dependence of axial rotation in the A3–A7 stars will be considered in a forthcoming paper.

It is tempting to attempt to explain these results in terms of the evolutionary sequences computed recently by Sandage and Schwarzschild (1952). These authors have considered an initially homogeneous star with a convective core and radiative envelope (Cowling model), which is assumed to experience no mixing between the core and envelope and starts to exhaust the hydrogen supply in its core. The subsequent early stages of the evolution were computed by Schönberg and Chandrasekhar (1942). The core finally exhausts its hydrogen and becomes isothermal. The nuclear energy production is then confined to a shell between the exhausted core and the radiative envelope, and the burning continues outward until the core reaches the Schönberg-Chandrasekhar limit. During this process the star moves up about one magnitude from the main sequence, while its effective temperature remains approximately constant.

At this point, Sandage and Schwarzschild assume that a gravitational contraction of the core occurs, which results in a great expansion of the envelope. The star thus evolves rapidly to the right in the H-R diagram, into the giant region.

Following this picture, a main-sequence B- or A-type star with a given rotational velocity will first evolve into a subgiant star of the same spectral type, with a consequent decrease in axial rotation, due to the conservation of angular momentum. It will then move to the right in the H-R diagram, keeping about the same luminosity while approaching later spectral types. The resultant increase in radius will lead to a further decrease in axial rotation.

The observed decrease in axial rotation in the B2–A2 stars of intermediate luminosity then follows as a result of the evolution of these stars from more rapidly rotating main-sequence stars of similar spectral type (resulting in subgiant stars) and of earlier spectral type (resulting in giant stars). Among the F-type stars, on the other hand, the stars of intermediate luminosity have evolved from rapidly rotating A-type main-sequence stars and therefore still exhibit considerable axial rotation, while the corresponding F-type main-sequence stars, for reasons as yet unknown, have intrinsically small axial rotation.

Perhaps the chief objection to the above interpretation concerns the assumption that no mixing occurs between the core and the envelope of stars with equatorial rotational velocities up to several hundreds of kilometers per second. However, Chandrasekhar (1951) has pointed out that, even if large-scale circulatory currents exist, keeping the envelope well mixed, the rigid-body rotation of the core would prevent mixing between it and the envelope. More recently, Mestel (1953) has shown that the nonsymmetrical distribution of matter set up by the mixing currents in rapidly rotating stars will have a large choking effect on the mixing. He concludes that, if the mixing zone is to extend at all into the radiative envelope, the angular velocity of the star must be so great that the centrifugal force at the surface equator nearly equals gravity.

We are extremely grateful to Dr. W. W. Morgan for generously supplying the spectral types which were used in this study. Thanks are also due our associates at the Perkins Observatory, particularly Dr. Geoffrey Keller, for many informative discussions.

REFERENCES

Brown, A. 1950, *Ap. J.*, **111**, 366–374.
Chandrasekhar, S. 1951, in J. A. Hynek (ed.), *Astrophysics* (New York: McGraw-Hill Book Co., Inc., chap. xiv.
Chandrasekhar, S., and Münch, G. 1950, *Ap. J.*, **111**, 142–156.
Herbig, G. H., and Spalding, J. F., Jr. 1953, *Pub. A.S.P.*, **65**, 192–193.
Huang, Su-Shu. 1953, *Ap. J.*, **118**, 285–303.
Huang, Su-Shu, and Struve, O. 1953, *Ap. J.*, **118**, 463–476.
Johnson, H. L., and Morgan, W. W. 1953, *Ap. J.*, **117**, 313–352.
Keenan, P. C., and Morgan, W. W. 1951, in J. A. Hynek (ed.), *Astrophysics* (New York: McGraw-Hill Book Co., Inc.), chap. i.
Luyten, W. J., Struve, O., and Morgan, W. W. 1939, *Pub. Yerkes Obs.*, Vol. **7**, Part IV.
Mestel, L. 1953, *Observatory*, **73**, 217–218.
Moore, J. H., and Neubauer, F. J. 1948, "Fifth Catalogue of the Orbital Elements of Spectroscopic Binary Stars," *Lick Obs. Bull.*, No. 521.
Morgan, W. W., Keenan, P. C., and Kellman, E. 1943, *An Atlas of Stellar Spectra* (Chicago: University of Chicago Press).
Russell, H. N., Dugan, R. S., and Stewart, J. Q. 1938, *Astronomy* (Boston: Ginn & Co.), Vol. **2**, chap. xxi.
Sandage, A. R., and Schwarzschild, M. 1952, *Ap. J.*, **116**, 463–476.
Schönberg, M., and Chandrasekhar, S. 1942, *Ap. J.*, **96**, 161–172.
Shajn, G., and Struve, O. 1929, *M.N.*, **89**, 222–239.
Slettebak, A. 1949, *Ap. J.*, **110**, 498–514.
———. 1953, *A.J.*, **58**, 228.
———. 1954, *Ap. J.*, **119**, 146–167.
Smith, B. 1947, *Ap. J.*, **105**, 489–491.
Struve, O. 1929, *Ap. J.*, **70**, 237–242.
———. 1952, *Pub. A.S.P.*, **64**, 118–119.
Westgate, C. 1933, *Ap. J.*, **77**, 141–152.
Wilson, R. E. 1941, *Mt. W. Contr.*, No. 646; *Ap. J.*, **94**, 12–20.