1954ApJ...119..146S

THE SPECTRA AND ROTATIONAL VELOCITIES OF THE BRIGHT STARS OF DRAPER TYPES B8–A2

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Received June 25, 1953; revised July 28, 1953

ABSTRACT

Spectral types and rotational velocities of 179 stars of Draper types B8–A2 brighter than the fifth magnitude have been determined. Spectral types and luminosity classes were assigned to all normal stars on the Morgan-Keenan-Kellman system of classification. Equatorial rotational velocities multiplied by the sine of the inclination of the axis of rotation ($v \sin i$) were determined for all stars by comparing observed profiles of the Mg II 4481 line in each star with a set of profiles computed by the graphical method of Shajn and Struve.

The B8–A2 stars divide into a number of subgroups from the point of view of axial rotation: the supergiant, metallic-line, and peculiar A stars have small axial rotation; the normal stars of intermediate luminosity have moderate axial rotation ($\bar{v}$ = 93 km/sec); and the normal main-sequence stars have the largest axial rotation ($\bar{v}$ = 177 km/sec). The only comparison of the B8–A2 main-sequence stars with stars of other spectral types possible at this time is with the Be stars: the latter have about twice the average axial rotation of the B8–A2 main-sequence stars.

A number of emission-line stars and spectroscopic binaries included in this study are discussed. The variation of equivalent width of Mg II 4481 with spectral type is shown. Three stars were found to exhibit a general weakening of the spectral lines; it is suggested that these stars lie somewhat below the main sequence.

I. INTRODUCTION

The fact that some classes of stars are in rapid axial rotation while others are not is of great importance for the problem of stellar evolution. It is generally known through the researches of Struve, Elvey, Westgate, and others that axial rotation of single stars is limited to those of early type: stars of spectral type later than about F5 do not rotate with appreciable velocities. It is also generally known that among the early-type stars certain classes of stars are conspicuous for their very large or very small axial rotation: the B-emission stars are characterized by very large rotational velocities, while the supergiant stars and some groups of peculiar stars never show large rotations. Among the normal main-sequence and giant stars of early type, however, the dependence of axial rotation on spectral type and luminosity is not altogether clear. In order to obtain this information and further to provide a catalogue of rotational velocities for the brighter stars, the writer plans to investigate axial rotation in the brighter northern stars of early type. The Be stars and the more rapidly rotating B2–B5 stars have already been considered elsewhere.[1] In this paper the brighter stars of Draper types B8–A2 are considered.

II. THE OBSERVATIONS

The observational material was selected to include all stars brighter than magnitude 5.0 with Draper types between B8 and A2 and north of declination −15°. The total number of stars considered was 179. One or more spectrograms of each star were taken with the two-prism spectrograph attached to the 69-inch reflecting telescope of the Perkins Observatory, giving a dispersion of 28 A/mm at $H\gamma$ and 32 A/mm at λ 4481. All spectra were greatly widened, the ratio of spectrum width to the distance between $H\gamma$ and $H\delta$ being 4.5 to 1. This widening served the following purposes: (1) it permitted a more accurate spectral classification to be made, and (2) for those stars for which only one spectrogram was taken or for which only one spectrogram was of usable density, two

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[1] *Ap. J.*, **110**, 498, 1949.

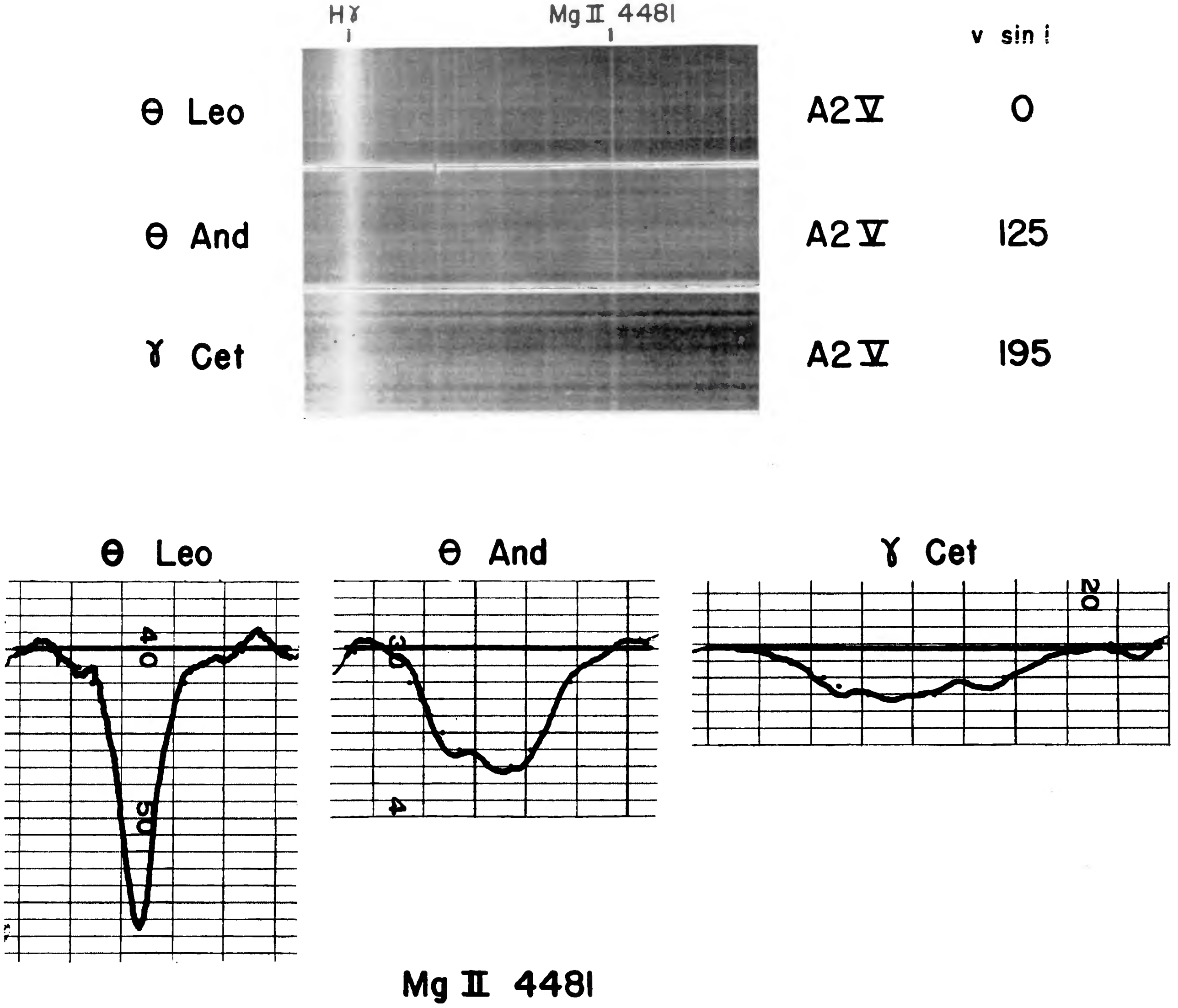

Fig. 1.—Line broadening by axial rotation in some representative A2 main-sequence stars

independent microphotometer tracings were still possible. Eastman 103-O plates treated with D19 developer were used for all stars, with the exception of the last eight stars to be observed, these being taken with Eastman II*a*-O plates developed in promicrol. All plates were calibrated immediately after exposure with a spectral sensitometer located in the 69-inch dome. The sensitometer was calibrated photoelectrically with the very generous assistance of Dr. Robert Hardie. Line profiles were obtained from the plates with the aid of the Perkins microphotometer, a magnification of about 200 being employed. Figure 1, illustrating line broadening by axial rotation in some A2 V stars, shows the spectra employed in this paper and the resulting microphotometer tracings.

III. METHODS

1. THE ROTATIONAL VELOCITIES

The effect of axial rotation on a stellar spectrum is to broaden all spectral lines, the amount of the broadening depending upon the degree of axial rotation and the inclination of the axis of rotation. For single stars a study of line broadening interpreted as due to axial rotation will yield only values of $v \sin i$, where v is the equatorial rotational velocity and i is the angle of inclination between the axis of rotation and the line of sight. The latter quantity is usually unknown for single stars;[2] but for a large, homogeneous group of stars, assumptions can be made about the orientation of the rotational axes, and a mean value of the equatorial rotational velocity for the group can be obtained.

The method of obtaining the $v \sin i$'s is one suggested by Shajn and Struve[3] and was first employed by Elvey.[4] It is based on the assumption[5] that the contour of a line not influenced by rotation is similar to that actually observed in a sharp-line star of similar spectral type. The apparent disk of a star is divided into strips parallel to the axis of rotation, each of which produces the undisturbed contour, in an amount proportional to its relative area, for an undarkened star. An equatorial rotational velocity is then assigned to the star, and the contributions from the various strips, shifted by the necessary amount, are summed to give the rotationally broadened contour. By assigning various values of the equatorial rotational velocity, a series of computed contours is built up. Comparison with an observed contour of the same line in a star of unknown rotation will permit an estimate to be made of $v \sin i$ for the star.

The absorption line, *Mg* II 4481, was chosen for the determination of $v \sin i$ in all stars. It has the advantages of being free from Stark effect, unblended, and one of the strongest lines in the range of spectral types considered. The sharp-line stars, α Canis Majoris (A1 V) and α Lyrae (A0 V), were chosen as nonrotating standard stars, the former for comparison with strong lines and the latter with weaker lines. A set of rotationally broadened contours was then built up from each, using the mean of four independent profiles of *Mg* II 4481 for each standard. A limb-darkened stellar disk was assumed, divided into 40 strips. The value of the monochromatic darkening coefficient at λ 4481 employed was 0.73, obtained from the computations of Münch and Chandrasekhar.[6] This value refers to an A1 main-sequence star with continuous absorption by neutral hydrogen atoms and negative hydrogen ions. Figure 2 illustrates the observed contours of *Mg* II 4481 in α Canis Majoris and α Lyrae and the rotationally broadened line contours derived from them for values of the equatorial rotational velocity from 25 to 400 km/sec.

Two independent profiles were obtained for each of the stars considered. These were adjusted to have the same equivalent width as the appropriate standard profile by mul-

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[2] Exceptions to this appear to exist among the Be stars, where inclination effects can be observed spectroscopically (see n. 1).

[3] *M.N.*, **89**, 222, 1929.

[4] *Ap. J.*, **71**, 221, 1930.

[5] Justified by Carroll, *M.N.*, **93**, 478, 508, 680, 1933.

[6] *Harvard Circ.*, No. 453, 1949.

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tiplying percentage absorptions in the line by the necessary scale factor. The comparisons were then made with the set of rotationally broadened profiles corresponding to the standard profile chosen. Finally, the two resulting values of $v \sin i$ were averaged, to give the rotational velocity of the star. These are listed in Table 1.

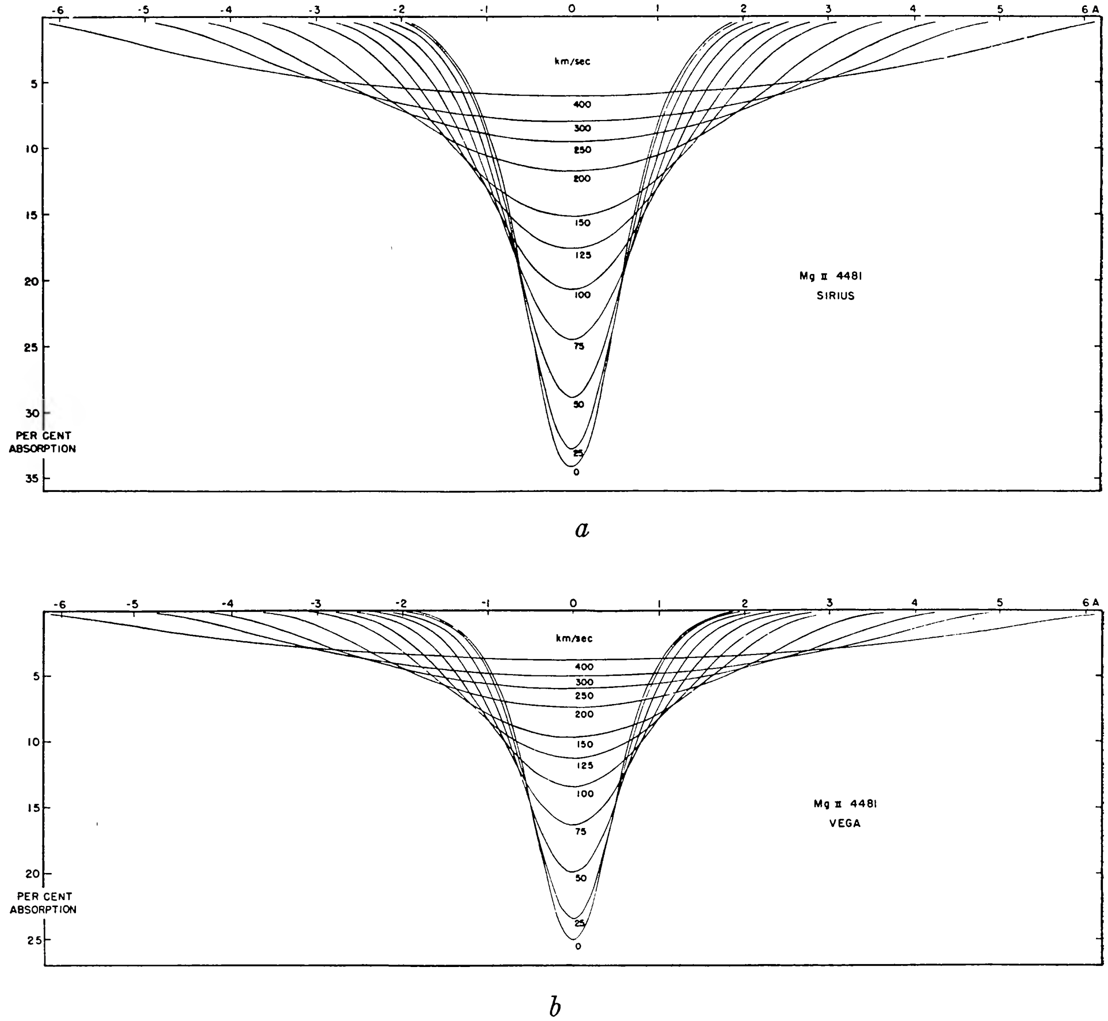

FIG. 2.—*a*, the observed profile of *Mg* II 4481 in α Canis Majoris (0 km/sec) and rotationally broadened line contours derived from it for ten values of the equatorial rotational velocity. *b*, the observed profile of *Mg* II 4481 in α Lyrae (0 km/sec) and rotationally broadened line contours derived from it for ten values of the equatorial rotational velocity.

2. THE SPECTRAL TYPES

The second observational datum which is required to be known accurately in this investigation is the spectral type. Further, for the normal stars a luminosity class must also be assigned, since axial rotation may depend upon luminosity as well as spectral class. A two-dimensional classification on the Morgan-Keenan-Kellman system[7] was attempted for each of the normal stars, using both Perkins and Yerkes plates. The procedure was the following: all stars were first classified as accurately as possible from the Perkins plates and were then classified independently from Yerkes spectrograms of dis-

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[7] *An Atlas of Stellar Spectra* (Chicago: University of Chicago Press, 1943).

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TABLE 1

SPECTRAL TYPES AND ROTATIONAL VELOCITIES OF THE B8-A2 STARS

Star	(1900)	(1900)	m_v	Sp(HD)	Sp(MKK)	v sin i (km/sec)	Δ/2 (km/sec)	Notes
α And	0^h 3^m.2	+28°32'	2.15	A0p	B9p	52	7.5	1
θ And	0 11.9	+38 8	4.44	A2	A2V*	125	0	
σ And	0 13.1	+36 14	4.51	A2	A2V	130	0	
μ And	0 51.2	+37 57	3.94	A2	A5V	80	0	
φ And	1 3.7	+46 43	4.28	B8	B7V	72	7.5	2
υ Psc	1 14.0	+26 44	4.67	A2	A2V	98	2.5	
τ And	1 34.7	+40 4	4.90	B8	B8IV	88	12.5	
γ^1 Ari	1 48.0	+18 48	4.75	A0p	B9V	182	17.5	
γ^2 Ari	1 48.0	+18 48	4.83		A1p	50	20	3
50 Cas	1 54.9	+71 56	4.06	A2	A1V	82	2.5	4
4 Per	1 55.6	+54 0	4.99	B8	B8V	81	1	
α Psc(br)	1 56.9	+ 2 17	4.33	A2p	A2p	92	7.5	5
58 And	2 2.5	+37 23	4.77	A2	A5V	155	15	6
γ Tri	2 11.4	+33 23	4.07	A0	A0V	230	10	
ρ Cet	2 21.1	-12 44	4.90	A0	B9V	230	40	
ξ^2 Cet	2 22.8	+ 8 1	4.34	A0	B9III*	62	7.5	
γ Cet	2 38.1	+ 2 49	3.58	A2	A2V	195	15	7
π Per	2 52.4	+39 16	4.62	A2	A2V	168	17.5	
HR 932	3 1.1	+74 1	4.89	A2	A0V	270	5	
β Per	3 1.7	+40 34	2.2-3.5	B8	B8V*	65	0	8
ζ Ari	3 9.2	+20 40	4.95	A0	A0IV-V	142	7.5	
32 Per	3 14.7	+42 58	4.98	A2	A2V	155	5	
HR 1035	3 21.0	+59 36	4.42	B9p	B9Ia*	<18	7.5	
ξ Tau	3 21.8	+ 9 23	3.75	B8	B8p			9
HR 1040	3 21.9	+58 32	4.76	A0p	A0Ia*	0	0	
HR 1046	3 22.4	+55 6	4.98	A2	A1V*	178	2.5	
17 Eri	3 25.7	- 5 25	4.80	B9	B8V	72	17.5	
γ Cam	3 39.8	+71 1	4.67	A0	A3IV	205	15	
27 Tau	3 43.2	+23 45	3.80	B8	B8III*	160	10	
HR 1204	3 48.6	+62 47	4.87	B9	B9V	110	15	10
ν Tau	3 57.8	+ 5 43	3.94	A0	A1V	70	0	
λ Per	3 59.1	+50 5	4.33	A0	B9V	210	20	
68 Tau	4 19.7	+17 42	4.24	A2	A2IV	15	15	
π^2 Ori	4 45.2	+ 8 44	4.35	A0	A0V	218	7.5	
7 Cam	4 49.3	+53 36	4.44	A2	A1V	42	12.5	11
π^1 Ori	4 49.4	+10 0	4.74	A0	A0p	108	17.5	12
4 Aur	4 52.5	+37 44	4.99	A0	A0V*	92	2.5	
ψ Eri	4 56.6	- 7 19	4.81	B8	B2V			13
11 Ori	4 58.9	+15 16	4.65	B9	A0p	20	5	14
ι Lep	5 7.6	-11 59	4.54	B8	B8V	195	35	
κ Lep	5 8.6	-13 4	4.46	B8	B8V	125	5	
β Ori	5 9.7	- 8 19	0.34	B8p	B8Ia*	<65	10	
β Tau	5 20.0	+28 31	1.78	B8	B7III*	82	12.5	
ζ Lep	5 42.4	-14 52	3.67	A2	A3V	245	5	
134 Tau	5 43.9	+12 37	4.92	B9	B9IV*	8	7.5	
ξ Aur	5 46.5	+55 41	4.92	A2	A2p?	68	17.5	15
136 Tau	5 47.1	+27 35	4.54	A0	A0III	50	10	16
β Aur	5 52.2	+44 56	2.1-2.2	A0p	A2IV*			17
θ Aur	5 52.9	+37 12	2.71	A0p	A0p	48	17.5	18
μ Ori	5 56.9	+ 9 39	4.19	A2	Am	20	15	19
3 Mon	5 57.1	-10 36	4.97	B8	B5IV	80	5	
θ Lep	6 1.5	-14 56	4.67	A0	A1V	215	20	
HR 2209	6 7.8	+69 21	4.73	A0	A0V	308	32.5	
2 Lyn	6 10.8	+59 3	4.42	A0	A2V	0	0	
HR 2244	6 11.2	-13 41	4.99	B9	B8V	235	10	

TABLE 1 (Continued)

SPECTRAL TYPES AND ROTATIONAL VELOCITIES OF THE B8-A2 STARS

Star	(1900)	(1900)	m_v	Sp(HD)	Sp(MKK)	v sin i (km/sec)	Δ/2 (km/sec)	Notes
13 Mon	$6^h27^m.5$	+ 7°24'	4.50	A0p	A0Ib*	<12	12.5	
γ Gem	6 31.9	+16 29	1.93	A0	A0IV*	48	12.5	
α CMa	6 40.8	-16 35	-1.6	A0	A1V*	0		20
θ Gem	6 46.2	+34 5	3.64	A2	A3III*	130	20	
16 Lyn	6 50.3	+45 13	4.80	A2	A2V	195	20	
δ Mon	7 6.8	- 0 20	4.09	A0	A0IV	155	15	
HR 2751	7 10.9	+49 39	4.80	A2	A3III-IV	210	10	
λ Gem	7 12.4	+16 43	3.65	A2	A3V*	150	5	
21 Lyn	7 19.2	+49 25	4.45	A0	A1IV	0	0	
β CMi	7 21.7	+ 8 29	3.09	B8	B8V*	260	50	21
α Gem A	7 28.2	+32 6	1.99	A0	A1V*	0	0	22
α Gem B	7 28.2	+32 6	2.85		Am	15	15	
24 Lyn	7 34.6	+58 57	4.96	A2	A3III	212	27.5	
φ Gem	7 47.4	+27 1	4.99	A2	A3V	165	5	23
27 Lyn	8 0.9	+51 48	4.87	A2	A2V	162	7.5	
HR 3314	8 20.7	- 3 35	3.95	A0	A0V*	120	0	
δ Hya	8 32.4	+ 6 3	4.18	A0	A0V	270	30	
γ Cnc	8 37.5	+21 50	4.73	A0	A1V	85	0	
ρ Hya	8 43.1	+ 6 12	4.42	A0	A0V	142	7.5	
θ Hya	9 9.2	+ 2 44	3.84	A0	A0V*	100	5	
38 Lyn	9 12.6	+37 14	3.82	A2	A3V*	160	10	24
26 UMa	9 28.0	+52 30	4.65	A0	A2V	180	5	
υ² Hya	10 0.3	-12 35	4.72	B8	B8V	70	10	
η Leo	10 1.9	+17 15	3.58	A0p	A0Ib*	<55	5	
α Sex	10 2.8	+ 0 7	4.50	A0	A0III	0	0	
α Leo	10 3.1	+12 27	1.34	B8	B7V*	352	7.5	
λ UMa	10 11.1	+43 25	3.52	A2	A2IV*	35	0	
HR 4072	10 16.9	+66 4	4.92	A0	A0p	8	7.5	25
ω UMa	10 48.2	+43 43	4.84	A0	A1V	15	15	26
54 Leo(br)	10 50.2	+25 17	4.51	A0	A1V	188	2.5	27
β UMa	10 55.8	+56 55	2.44	A0	A1V*	32	2.5	
60 Leo	10 57.0	+20 43	4.42	A0	Am	28	27.5	28
θ Leo	11 9.0	+15 59	3.41	A0	A2V*	0	0	
σ Leo	11 16.0	+ 6 35	4.13	A0	B9V	70	10	
θ Crt	11 31.6	- 9 15	4.81	B9'	B9V	192	7.5	
β Leo	11 44.0	+15 8	2.23	A2	A3V*	110	12.5	
γ UMa	11 48.6	+54 15	2.54	A0	A0V*	165	5	29
δ UMa	12 10.5	+57 35	3.44	A2	A3V*	178	2.5	
η Vir	12 14.8	- 0 7	4.00	A0	A2V	0	0	30
23 Com	12 29.9	+23 11	4.78	A0	A0IV	65	0	31
ρ Vir	12 36.8	+10 47	4.95	A0	A0V	175	25	
ε UMa	12 49.6	+56 30	1.68	A0p	A0p	30	10	32
α² CVn	12 51.4	+38 51	2.90	A0p	A0p	42	17.5	33
θ Vir	13 4.8	- 5 0	4.44	A0	A1V	0	0	
ζ UMa(br)	13 19.9	+55 27	2.40	A2p	A2V*			34
ζ UMa(ft)	13 19.9	+55 27	3.96	A2	Am	75	0	35
78 Vir	13 29.1	+ 4 10	4.93	A2p	A2p	25	0	36
ζ Vir	13 29.6	- 0 5	3.44	A2	A3V*	178	7.5	
τ Vir	13 56.6	+ 2 2	4.34	A2	A3III	165	15	
α Dra	14 1.7	+64 51	3.64	A0p	A0III*	0	0	37
HR 5313	14 7.2	+ 2 53	4.90	A0p	B9p	102	2.5	38
λ Boo	14 12.6	+46 33	4.26	A0	A0p	95		39
π Boo(br)	14 36.0	+16 51	4.94	A0	B9p	0	0	40
109 Vir	14 41.2	+ 2 19	3.76	A0	A0V*	335	35	
β Lib	15 11.6	- 9 1	2.74	B8	B8V*	230	30	

TABLE 1 (Continued)

SPECTRAL TYPES AND ROTATIONAL VELOCITIES OF THE B8-A2 STARS

Star	(1900)	(1900)	m_v	Sp(HD)	Sp(MKK)	v sin i (km/sec)	Δ/2 (km/sec)	Notes
γ UMi	$15^{h}20^{m}.9$	+72°11'	3.14	A2	A3II-III*	185	5	
α CrB	15 30.5	+27 3	2.3-2.4	A0	A0V*	132	7.5	41
γ CrB	15 38.6	+26 37	3.93	A0	A0III-IV	100	0	42
β Ser	15 41.6	+15 44	3.74	A2	A2IV*	202	27.5	
μ Ser	15 44.4	- 3 7	3.63	A0	A0V	80	2	
ε Ser	15 45.8	+ 4 47	3.75	A2	Am	35	0	43
ζ UMi	15 47.6	+78 6	4.34	A2	A3V	225	25	
ι CrB	15 57.4	+30 8	4.91	A0	A0p	0	0	44
π Ser	15 58.0	+23 5	4.82	A2	A3V	110	10	
υ Her	15 59.7	+46 19	4.64	B9	B9p	0	0	45
φ Her	16 5.6	+45 12	4.26	B9p	B9p	0	0	46
ψ Sco	16 6.5	- 9 48	4.91	A2	A2V	25	0	
ω Her	16 20.8	+14 16	4.53	A0p	A1p	0	0	47
υ Oph	16 22.4	- 8 9	4.68	A2	Am	65	5	48
λ Oph	16 25.9	+ 2 12	3.85	A0	A1V	142	7.5	49
15 Dra	16 28.2	+68 59	4.98	B8p	B9IV	150	0	50
σ Her	16 30.9	+42 39	4.25	A0	B9V	285	15	
52 Her	16 46.3	+46 9	4.86	A2p	A2p	52	2.5	51
ι Oph	16 49.3	+10 20	4.29	B8	B8V	102	22.5	52
ε Her	16 56.5	+31 4	3.92	A0	A0V	90	5	53
δ Her	17 10.9	+24 57	3.16	A2	A3IV*	305	15	
69 Her	17 14.2	+37 24	4.80	A2	A2V*	155	5	
ν Ser	17 15.2	-12 45	4.35	A0	A1V	125	10	
ρ Her(br)	17 20.2	+37 14	4.52	A0	A0p	90	5	54
μ Oph	17 32.4	- 8 3	4.65	B8	B8V	140	15	
o Ser	17 35.8	-12 49	4.39	A2	A2V	135	15	55
γ Oph	17 42.9	+ 2 45	3.74	A0	A0V*	212	12.5	
68 Oph	17 56.7	+ 1 18	4.44	A2	A1V	232	7.5	
ο Her	18 3.6	+28 45	4.1-4.2	A0	B9V	138	27.5	
δ UMi	18 4.6	+86 37	4.44	A0	A1V	180	20	
φ Dra	18 22.2	+71 17	4.24	A0p	A0p	95	10	56
39 Dra	18 22.5	+58 45	4.9	A2	A1V*	180	10	
α Lyr	18 33.6	+38 41	0.14	A0	A0V*	0		57
γ Lyr	18 55.2	+32 33	3.30	A0p	B9III*	90	5	
ζ Aql	19 0.8	+13 43	3.02	A0	B9V	365	35	
λ Aql	18 1.0	- 5 2	3.55	B9	B8V	155	5	
π Dra	19 20.2	+65 31	4.63	A2	A2IV	30	0	
ι Cyg	18 27.2	+51 31	3.94	A2	A5V	210	15	
9 Vul	19 30.2	+19 33	4.88	B8	B7V	235	5	
δ Cyg	19 41.9	+44 53	2.97	A0	B9.5III*	128	7.5	
13 Vul	19 49.2	+23 49	4.50	A0	A0III	42	7.5	
ρ Aql	20 9.7	+14 54	4.96	A0	A2V	160	12.5	
30 Cyg	20 10.2	+46 31	4.96	A2	A3III	150	0	
29 Cyg	20 10.8	+36 30	4.98	A0	A2p	85	5	58
κ Cep	20 12.3	+77 25	4.40	B9	B9III	0	0	
ν Cap	20 15.1	-13 4	4.84	A0	B9V	0	0	
ζ Del	20 30.6	+14 20	4.69	A2	A3V	118	7.5	
29 Vul	20 34.1	+20 51	4.78	A0	A0V	48	7.5	
α Del	20 35.0	+15 34	3.86	B8	B9V*	160	10	
α Cyg	20 38.0	+44 55	1.33	A2p	A2Ia*	<18	17.5	
ε Aqr	20 42.3	- 9 52	3.83	A0	A1V*	105	5	
ν Cyg	20 53.5	+40 47	4.04	A0	A0V	245	5	
σ Cyg	21 13.5	+38 59	4.28	A0p	B9Ia*	<20	20	
ν Cep	21 42.6	+60 40	4.46	A2p	A2Ia*	<25	25	
ι Aqr	22 1.0	-14 21	4.35	B8	B8V	150	25	59

TABLE 1 (Continued)

SPECTRAL TYPES AND ROTATIONAL VELOCITIES OF THE B8-A2 STARS

Star	(1900)	(1900)	m_V	Sp(HD)	Sp(MKK)	v sin i (km/sec)	Δ/2 (km/sec)	Notes
θ Peg	$22^{h}\ 5^{m}.2$	$+\ 5^{\circ}42'$	3.70	A2	A2V	122	7.5	60
γ Aqr	22 16.5	- 1 53	3.97	A0	A0V	75	0	
32 Peg	22 16.7	+27 50	4.88	B8	B8V	68	17.5	
4 Lac	22 20.5	+48 58	4.64	B8p	B9Iab*	<25	25	
σ Aqr	22 25.4	-11 11	4.89	A0	A0IV	22	22.5	
α Lac	22 27.2	+49 46	3.85	A0	A2V	155	15	
η Aqr	22 30.2	- 0 38	4.13	B8	B8V	288	12.5	
ζ Peg	22 36.5	+10 19	3.61	B8	B8V*	210	10	
ο Peg	22 37.1	+28 47	4.85	A0	A1V	0	0	
ρ Peg	22 50.2	+ 8 17	4.95	A0	A1V	100	5	
α Peg	22 59.8	+14 40	2.57	A0	B9.5III*	155	5	
κ Psc	23 21.8	+ 0 42	4.94	A2p	A2p	42	7.5	61
ι And	23 33.2	+42 43	4.28	B8	B8V*	88	7.5	
κ And	23 35.5	+43 47	4.33	A0	B8V	195	0	

NOTES TO TABLE I

* These stars have been classified by Dr. W. W. Morgan and have been used as standards in this study.

1. Manganese star; spectrum variable. Also spectroscopic binary, P = 96.7 days.

2. A double star with $4^{m}.5$ and $6^{m}.0$ components separated by about $0''.3$. No trace of the fainter component is visible on either blue- or red-sensitive plates. Also, an emission-line star, MWC 420. See section VI, 2.

3. γ^{2} Arietis is the fainter component of an 8" binary. It is a peculiar A star and spectrum variable. Peculiar features include chromium, europium and silicon.

4. Listed as having two spectra in the "Bright Star Catalogue". Only one spectrum is visible on the Perkins plate.

5. This star has a $5^{m}.23$ component 3" distant. The brighter component is a peculiar A star, with abnormally strong chromium and silicon.

6. Listed as having two spectra in the "Bright Star Catalogue". Only one spectrum is visible on the Perkins plate.

7. A double star with $3^{m}.7$ and $6^{m}.2$ components about 3" apart.

8. Algol. Morgan (Ap. J., 81, 348, 1935) and others have reported doubling of the Mg II 4481 line at and in the vicinity of primary light minimum. The Perkins spectrograms, taken out of primary light minimum, show Mg II 4481 as a single line.

9. ζ Tauri was observed to have variable radial velocity by Campbell in 1908 (L. O. B. 5, 62, 1908) and to show two spectra in 1928 (Lick Obs. Pub., 16, 43, 1928). A series of Perkins spectrograms taken in late 1951 confirms the aforementioned composite spectrum. Although not many lines are visible, the Ca II K-line and the Mg II 4481 line are clearly double on several plates. Two plates taken on October 12, 1951 appeared to show the widest splitting of the K-line recorded in the Perkins series: the separation was found to correspond to a radial velocity difference of 160 km/sec between the two components. A period of four days or less is indicated, although this is based on a very incomplete series of spectrograms. The components of the lines which appear double are about equal in strength and very sharp, indicating little or no rotational broadening. Both components are of spectral type B8. The spectrum appears to be peculiar, however, in the sense that the Helium lines are relatively broad and shallow, suggesting moderate axial rotation, at all phases, even when the K-line and Mg II 4481 line appear single and very sharp.

10. Emission-line star, MWC 77. See section VI, 2.

11. Spectroscopic binary, P = 3.9 days. See section VI, 3.

NOTES TO TABLE 1 (Continued)

12. Weak-line star. See section VI, 5.

13. No rotational velocity measured for this star. It will be considered in a fort coming study of axial rotation in the B2-B5 stars.

14. Peculiar A star. Silicon is abnormally strong.

15. A possible weak-line star. See section VI, 5.

16. Spectroscopic binary, P = 6.0 days. Secondary spectrum visible but very faint, according to L. O. B. 199, 1911. Only one spectrum is visible on the Perkins plate. See section VI, 3.

17. Spectroscopic binary, P = 4.0 days, with two spectra visible. Both spectra are visible and of equal intensity on the Perkins plate. All lines are very narrow, indicati little or no component of axial rotation in the line of sight.

18. Peculiar A star and spectrum variable. Silicon is abnormally strong.

19. Metallic-line star: A3 K-line and A7 metallic spectrum. Also, spectroscopic binary, P = 4.4 days; visual binary with $4\overset{\mathrm{m}}{.}3$ and $6\overset{\mathrm{m}}{.}6$ components separated by $0\overset{''}{.}2$.

20. Standard zero rotational velocity star.

21. Emission-line star, MWC 178. See section VI, 2.

22. α Gem B, the fainter of this 5" binary, is a metallic-line star; A1 K-line and A5 metallic spectrum. Both A and B are spectroscopic binaries, with periods of 9.2 and 2.9 days, respectively. See section VI, 3.

23. Two spectra, according to the "Bright Star Catalogue". Only one spectrum is vi ible on the Perkins plate.

24. Visual binary with $4\overset{\mathrm{m}}{.}0$ and $5\overset{\mathrm{m}}{.}9$ components 3" apart.

25. The spectrum is peculiar and most nearly resembles in its over-all features the spectrum of the manganese-star, φ Herculis. In particular, the unidentified line at λ3984 which is found in the manganese-stars is present in HR 4072. It is uncertain whethe manganese is actually present in the spectrum of HR 4072. Mn II 4253 and possibly 4137 appear to be present but are on the threshold of visibility. If manganese is present, i is decidedly weaker than in the spectrum of φ Herculis. HR 4072 is also a spectrosc binary with P = 11.6 days.

26. Spectroscopic binary with P = 15.8 days. See section VI, 3.

27. Visual binary, with $6\overset{\mathrm{m}}{.}30$ companion at 6" distance.

28. Metallic-line star: A1 K-line and A5 metallic spectrum.

29. Reported to be emission-line star; MWC 583. See section VI, 2.

30. Spectroscopic binary with P = 71.9 days, and two spectra, as first pointed out by Frost and Adams (Ap. J., 17, 152, 1903). Only one spectrum appears on the Perkins pla

31. Listed as having two spectra in the "Bright Star Catalogue". Only one spectrum visible on the Perkins plate.

32. Peculiar A star and spectrum variable. Peculiar features include chromium and europium.

33. Peculiar A star and spectrum variable. Peculiar features include chromium, europium and silicon.

34. Mizar, visual binary with 14" separation. The brighter component is a spectros copic binary, P = 20.5 days, with two spectra visible. The Perkins plate shows both spec the lines are about equal in strength and quite narrow, indicating little or no componen of axial rotation in the line of sight.

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NOTES TO TABLE 1 (Continued)

35. The fainter component of Mizar is a metallic-line star: A2 K-line and A7 metallic spectrum.

36. Peculiar A star and spectrum variable. Peculiar features include chromium and europium.

37. Spectroscopic binary, P = 51.4 days. See section VI, 3.

38. Peculiar A star of the silicon-type and spectrum variable.

39. Weak-line star; see section VI, 5. A v sin i determination from the contour of Mg II 4481 was impossible because of the weakness of that line. The value given was obtained from visual estimates of the broadening of the K-line.

40. Peculiar A star of the manganese-type and spectrum variable. The fainter component of this 6" binary is a metallic-line star.

41. Spectroscopic binary, P = 17.4 days. See section VI, 5.

42. A visual binary of less than 1" separation, with components of magnitude 4.0 and 7.0. Also, listed as having two spectra in the "Bright Star Catalogue". Only one spectrum is visible on the Perkins plate.

43. Metallic-line star: A3 K-line and F0 metallic spectrum.

44. The spectrum of ι Coronae Borealis is almost identical with that of HR 4072, described in note 24.

45. Peculiar A star of the manganese type.

46. Peculiar A star of the manganese type.

47. Peculiar A star: chromium is very strong.

48. Metallic-line star: A2 K-line and A7 metallic spectrum.

49. Visual binary: $4^{m}.0$ and $6^{m}.1$ components of about 1" separation.

50. Classified as B8p in the Henry Draper with the remark that the K-line is strong and the spectrum resembles that of β Orionis, although the lines are not as narrow. The Balmer lines appear relatively weak on the Perkins plate, suggesting that 15 Draconis does lie above the main sequence.

51. Peculiar A star: strontium and chromium are abnormally strong.

52. Listed as having two spectra in the "Bright Star Catalogue". Only one spectrum is visible on the Perkins plate.

53. Spectroscopic binary, P = 4.0 days. Also, composite spectrum (Adams, Ap. J., 18, 69, 1903), with lines of secondary reported rather weak. Only one spectrum is visible on the Perkins plate. See section VI, 3.

54. The brighter component of the visual binary ρ Herculis is a peculiar A star. The general level of excitation corresponds roughly to an A0 star, but the K-line is weak and silicon is strong. The fainter component, of magnitude 5.5 and 4" distance, is a B9V star in rather rapid rotation.

55. Listed as having two spectra in the "Bright Star Catalogue". Only one spectrum is visible on the Perkins plate.

56. Visual binary: $4^{m}.5$ and $6^{m}.2$ components, separated by less than 1". Reported to have two spectra, the Perkins plate shows only one: that of a peculiar A star of the silicon type.

57. Standard zero rotational velocity star.

58. Weak-line star. See section VI, 5.

59. Listed as having two spectra in the "Bright Star Catalogue". Only one spectrum is visible on the Perkins plate.

60. Listed as having two spectra in the "Bright Star Catalogue". Only one spectrum is visible on the Perkins plate.

61. Peculiar A star: chromium is abnormally strong.

persion 65 A/mm at $H\gamma$; any stars which then showed differing spectral types or luminosity classes were reclassified from the Perkins plates to give the final type. The writer owes a deep debt of gratitude to Dr. Morgan for making the Yerkes plates available, for providing standard stars, and for many stimulating conversations. The spectral types determined are listed in Table 1.

IV. THE ACCURACY OF THE OBSERVATIONS

1. THE ROTATIONAL VELOCITIES

As has been previously mentioned, two profiles for each star were measured, and the mean of the two values was taken as the $v \sin i$ of the star. In Table 1 the column $\Delta/2$ is a measure of the accidental errors involved in the $v \sin i$ determination of one star: $\Delta/2$ is the difference in rotational velocity between the mean and either of the two measured values. From an examination of Figure 2, one might expect the errors to increase as one goes to larger velocities, since the resolution decreases. A study of the $\Delta/2$'s bears this out, as Table 2, which tabulates the probable errors for different velocity ranges, shows.

TABLE 2

PROBABLE ERRORS OF MEASURED ROTATIONAL VELOCITIES

$v \sin i$ (Km/Sec)	No. of Stars	P.E. (Km/Sec)	$v \sin i$ (Km/Sec)	No. of Stars	P.E. (Km/Sec)
0–100	60	± 7	201–300	22	±14
101–200	58	± 9	>300	5	±19

The probable error listed in Table 2 is that of the mean $v \sin i$ for one star. It should be mentioned that a number of stars, primarily supergiant and peculiar stars, have been omitted from the foregoing discussion by virtue of having observed profiles which are narrower than the standard zero-velocity profiles. Inclusion of these would have led to a smaller probable error, which would have been spurious.

An examination of Figure 2 also shows that very little difference exists between the zero and the 25-km/sec contours. It follows that rotational velocities below 25 or 30 km/sec have little meaning other than indicating a very small axial rotation.

A number of stars had measured equivalent widths of *Mg* II 4481 roughly equidistant between those of the standard stars. For these, comparisons with both sets of computed contours were made and showed good agreement.

The presence of systematic errors will best be shown by comparisons with other $v \sin i$ determinations of common stars. Two such comparisons are possible for the stars in question. The first is with Elvey's values,[4] illustrated in Figure 3. Elvey was the first to apply the graphical method of Shajn and Struve, using it for a number of bright stars of representative type. He also used the *Mg* II 4481 line for his velocity determinations. Fourteen stars (excluding three supergiants) are in common, and these show scatter of about the expected amount, with no apparent systematic difference in our velocities. It should be pointed out that Elvey's computed contours were based on the assumption of an undarkened star and that his values might therefore be expected to run somewhat lower than those of the present paper. The effect of limb darkening on the line contour is quite small, however, and is probably masked by the various errors which go into a $v \sin i$ determination. The second comparison is with the values of Miss Westgate[8] and is shown in Figure 4. Miss Westgate's velocities were obtained by measuring *Mg* II 4481 line widths and converting these into rotational velocities by comparing with Elvey's values. Figure 4 shows considerable scatter, plus a systematic difference in the sense that the values here reported run higher than those of Miss Westgate.

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[8] *Ap. J.*, **78**, 46, 1933.

2. THE SPECTRAL TYPES

Quoting W. W. Morgan: "Spectra of classes B9–A2 are most difficult of all to classify accurately. All lines with the exception of the Balmer series are weak, and the broad-line stars show few spectral features that can be used."[7] A luminosity classification for these stars is especially difficult, since the chief criterion is the appearance of the wings of the Balmer lines.

With regard to the spectral types, the maximum error for any given star is probably one-tenth of a spectral class on the MKK system. On the basis of the quality of the plates used, it is difficult for the writer to conceive of assigning, for example, a type of B8 or A2 to an A0 star, no matter how large the rotational broadening. Errors in the luminosity classification are much more difficult to evaluate; the writer can only say that he did as careful a job as possible with the help of a set of excellent standards provided by Dr. Morgan. Nevertheless, the differences in the spectra of the stars of intermediate and lower luminosities (classes III–V) are exceedingly subtle, and it is possible that another investigator might make somewhat different luminosity classifications.

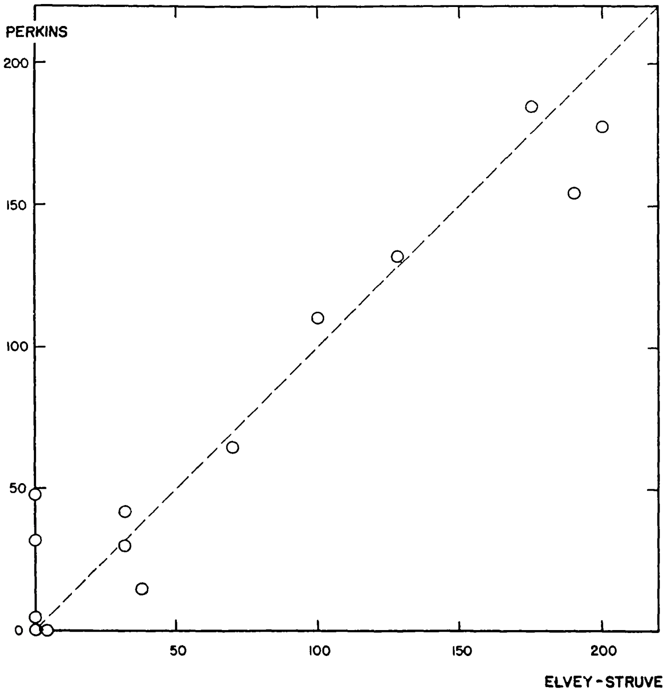

Fig. 3.—Comparison of rotational velocities measured at Perkins with those measured by Elvey and Struve.

It will be shown (Sec. V, 4) that the B8–A2 stars of intermediate luminosity have less axial rotation than the corresponding main-sequence stars, while the reverse appears to be true for the stars of type F (see n. 14, below). Since this result may be of cosmogonical significance, the question as to whether the spectroscopic criteria of luminosity might depend to some extent upon axial rotation is a legitimate and important one. Because the grouping into luminosity classes among the F-type stars is more reliable than among the stars near A0, this question should be carefully considered for the B8–A2 stars. The negative absolute-magnitude effect shown by the Balmer lines is the chief luminosity criterion for the stars near A0. In the opinion of the writer, this effect is quite pronounced, regardless of the rotational broadening of the lines. The effects of axial rotation on the

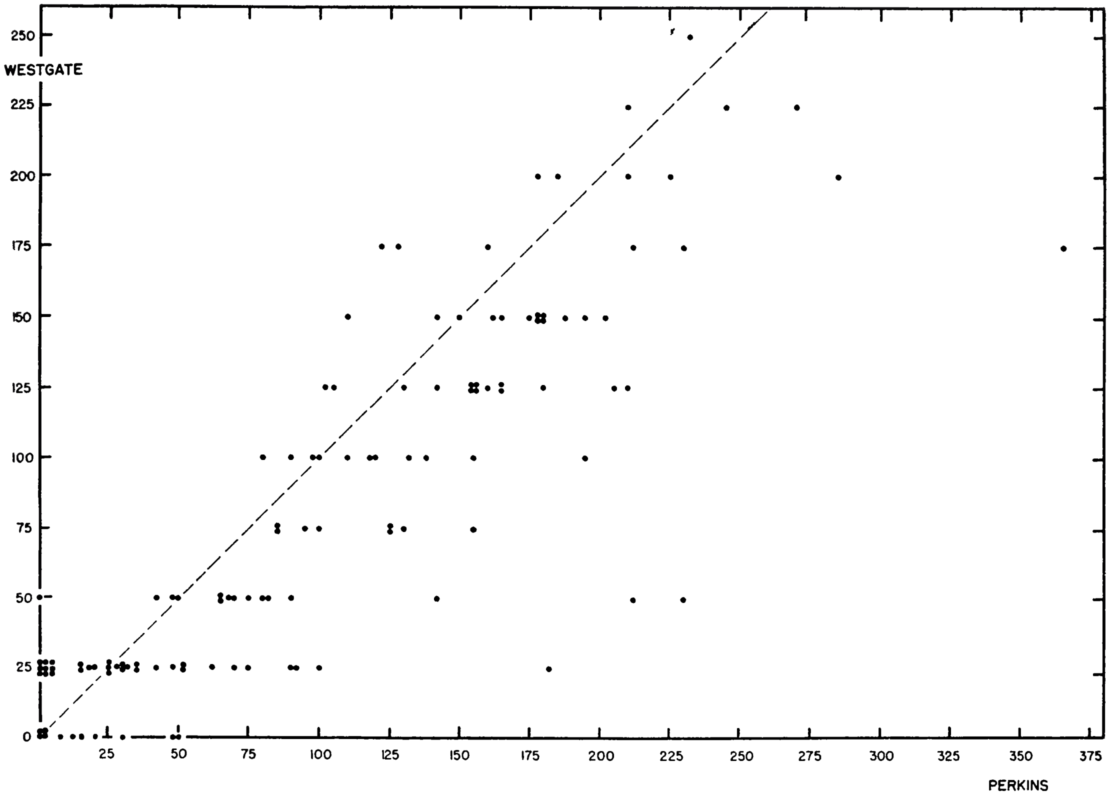

FIG. 4.—Comparison of rotational velocities measured at Perkins with those measured by Miss Westgate.

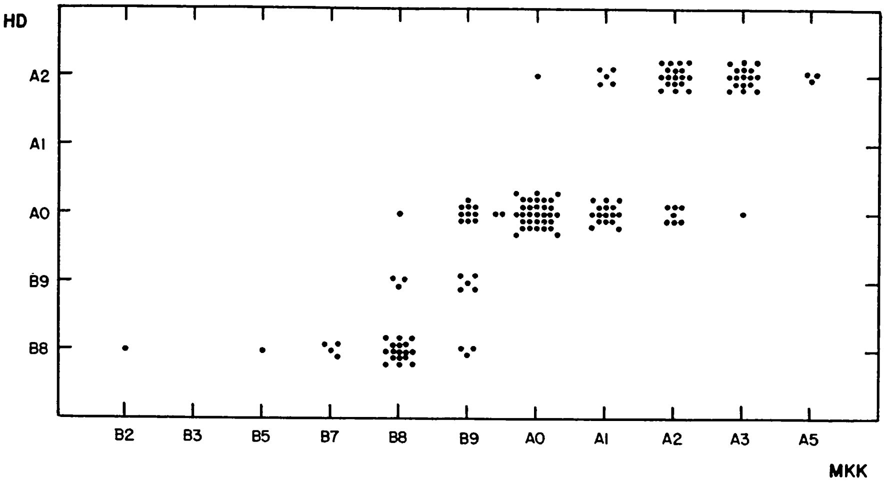

FIG. 5.—Comparison of spectral types assigned on the Morgan-Keenan-Kellman system with corresponding Henry Draper types, for the normal stars.

profiles of the Balmer lines were minimized in estimating luminosity classes by examining the spectrograms without magnification; it was felt that estimates of intensities of the Balmer lines could be made rather accurately in this way. The luminosity classification of these stars remains a very difficult and subtle problem, however, which should not be underestimated.

A comparison of the present MKK types for the normal stars with the corresponding Draper types is shown in Figure 5.

V. THE INTERPRETATION OF THE OBSERVATIONS

An inspection of Table 1 shows that the B8–A2 stars divide into a number of subgroups from the point of view of axial rotation. This is brought out more clearly in Table 3. Thirty-seven stars have been omitted from this table by virtue of being earlier in type than B8, later than A2, or having spectra which are peculiar in some manner. The third column gives the mean observed $v \sin i$, and the fourth column gives the mean true equatorial rotational velocity under the assumption that the axes of rotation are randomly distributed.[9] The latter quantity is probably not too meaningful for certain of the groups listed, in view of the small number of stars comprising the group. Again, the breakdown of the B8–A2 main-sequence stars into individual types is for the sake of completeness; it is not suggested, for example, that the apparent rapid drop in axial rotation at A1 is real, because of the small samples employed. A brief discussion of the subgroups follows.

TABLE 3

AXIAL ROTATION OF SUBGROUPS COMPRISING THE B8–A2 STARS

Type	N	$\overline{v \sin i}$ (Km/Sec)	$\bar{v}$ (Km/Sec)	Type	N	$\overline{v \sin i}$ (Km/Sec)	$\bar{v}$ (Km/Sec)
B8 V	18	152	193	B8–A2 V	87	139	177
B9 V	11	177	225	B8–A2 III–IV	24	73	93
A0 V	20	165	210	Peculiar A	16	41	52
A1 V	20	99	126	Metallic-line	6	40	51
A2 V	18	120	153	Supergiant	9	<26	<34

1. THE PECULIAR A STARS[10]

Sixteen of the stars listed in Table 1 are well-known peculiar A stars, while three more [HR 4072, ι Coronae Borealis, and ρ Herculis (brighter)] have been found to be peculiar in this study. In the following discussion, only the aforementioned sixteen will be considered.

As a group, the peculiar A stars possess small axial rotation. The largest observed $v \sin i$ is 102 km/sec, measured in the "silicon star" HR 5313.[11] The stars, φ Draconis and α Piscium, have measured velocities of 95 and 92 km/sec, respectively. All the others have $v \sin i$'s of the order of 50 km/sec and lower. The "manganese stars" appear to be

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[9] The relation between the moments of the true and observed frequency distributions, allowing the mean of the true rotational velocities to be determined directly from the mean of the observed distribution of $v \sin i$, is due to Chandrasekhar and Münch, *Ap. J.*, **111**, 142, 1950.

[10] A number of the peculiar A stars considered have been announced as spectrum variables. It should be pointed out that the use of the *Mg* II 4481 line as a measure of axial rotation in these stars is justified by the fact that this line has not been observed to be variable.

[11] This star has recently been announced as a spectrum variable by Deutsch, *Ap. J.*, **116**, 536, 1952. Assuming that the period of spectrum variation is equal to the rotation period and that the radius of HR 5313 is $1.9 R_{\odot}$, Deutsch finds that a $v \sin i$ of 170 km/sec gives satisfactory agreement with his observed profile of *Mg* II 4481.

among the sharpest-lined representatives of the peculiar A stars. The point to be stressed is that a comparison of the peculiar A stars with stars of similar temperature and absolute magnitude shows that the former are characterized by relatively small rotational velocities and should be considered separately from the point of view of axial rotation.

2. THE METALLIC-LINE STARS

Only six metallic-line stars are included in this study. Like the peculiar A stars, this group has small axial rotation, the observed *v* sin *i*'s ranging from 75 to 15 km/sec. The sample is undeniably small, but the above conclusion has been verified by visual inspection of spectrograms of a larger number of metallic-line stars. It should be emphasized that the measured rotational velocities for these stars give only an order of magnitude; all have quite large *Mg* II 4481 equivalent widths, making necessary a large extrapolation to the computed line contours. These stars should perhaps be more properly included in a forthcoming investigation of axial rotation in the brighter *Henry Draper* A3–G0 stars. The conclusion that the metallic-line stars possess small axial rotation as a group remains valid, however.

3. THE SUPERGIANT STARS

Nine supergiant stars have been considered, and all have small rotational velocities. This is in agreement with the conclusion of Struve that "supergiants of early or late type never show conspicuous rotations."[12] The *v* sin *i*'s listed for the supergiants are to be regarded as upper limits; axial rotation, if any exists among the supergiants, must be extremely small. That turbulence is a more important broadening agent than axial rotation in these stars is evident from a visual inspection of the line contours on the spectrograms. All show the deep bell-shaped contours characteristic of small-scale turbulence, with the exception of the B8 I*a* star, β Orionis. This star exhibited the largest line broadening of the group, corresponding to a rotational velocity of 65 km/sec under the assumption that axial rotation is the sole broadening agent. Even here, however, it is possible that some sort of large-scale turbulence is contributing to the line broadening, as has been suggested by Struve for the O-type and early B-type supergiants.[13]

4. THE NORMAL B8–A2 STARS OF INTERMEDIATE LUMINOSITY

A total of 24 stars were judged to be of luminosity classes III and IV. The observed rotational velocities ranged from zero to 202 km/sec, the latter for the A2 IV standard, β Serpentis. As indicated in Table 3, the mean observed rotational velocity for the group was found to be 73 km/sec, corresponding to a mean true rotational velocity of 93 km/sec. This indicates that the normal B8–A2 stars of intermediate luminosity possess considerably less axial rotation than the corresponding main-sequence stars and that they, like the groups considered above, should be treated separately with respect to axial rotation.[14] This luminosity dependence of axial rotation is perhaps best seen by a com-

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[12] *Pop. Astr.*, **53**, 211, 1945. However, Dr. Struve points out (private correspondence) that this earlier statement must probably be modified, since we now know a number of highly luminous early B-type stars which do possess appreciable, though never excessively large, rotational velocities (cf. Huang and Struve's paper on ρ Leonis, *Ap. J.*, **118**, 463, 1953).

[13] *Pub. A.S.P.*, **64**, 118, 1952.

[14] A totally different relation between axial rotation and luminosity appears to exist for the stars of later spectral type. At the time of writing (June, 1953), spectrograms have been taken of some thirty stars with spectral types between A7 and G0, as determined by Morgan (Johnson and Morgan, *Ap. J.*, **117**, 313, 1953). Of the eighteen main-sequence stars included, only four show some degree of rotational line broadening, the others having very sharp lines. On the other hand, ten of the thirteen stars of intermediate luminosity exhibit rotational line broadening as against only three sharp-line stars. The F5 V star, 45 Bootis, is the main-sequence star of latest spectral type in the sample considered which shows any degree of axial rotation. Among the stars of intermediate luminosity, however, axial rotation appears to exist to G0 at least, as evidenced by the broadened lines in the spectrum of the G0 III star, 31 Comae.

Note added October 10, 1953: The foregoing conclusions have been strengthened by the addition of a considerable amount of additional observational material and presented as a paper at the August, 1953, parison of the histograms of observed rotational velocities for the stars of intermediate luminosity and the main-sequence stars, as shown in Figure 6. The frequency distributions of the two groups are seen to be quite different. It should be pointed out that the above conclusion rests upon two assumptions: (1) that the luminosity classifications are accurate, and (2) that the relatively small sample considered is representative of the B8–A2 stars of intermediate luminosity as a whole.

5. THE NORMAL B8–A2 MAIN-SEQUENCE STARS

After the various subgroups treated above were eliminated, an unfortunately small number of normal main-sequence stars remained—87. It was thus impossible to investigate the dependence of axial rotation upon spectral type in the B8–A2 range. The breakdown has been made in Table 3, but it is probably without physical significance. Considering the group as a whole, a mean observed rotational velocity of 139 km/sec was obtained, corresponding to a mean true rotational velocity of 177 km/sec. The largest rotational velocity measured for this group was 365 km/sec for the B9 V star, ζ Aquilae.

Figure 6 illustrates the observed distribution of rotational velocities for the B8–A2 main-sequence stars. Although Brown[15] has pointed out that it is hazardous to attempt to distinguish between different forms of the distribution of true rotational velocities unless large numbers of observations are available, the writer feels that the derivation of the distribution of true rotational velocities according to the method of Chandrasekhar and Münch[9] may be of some interest, if only for a comparison with the frequency distributions derived in the latter paper.

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 7. The parameters of $f(v)$ are listed in Table 4, following the notation of Chandrasekhar and Münch.

TABLE 4

PARAMETERS OF ROTATIONAL VELOCITY DISTRIBUTION OF B8–A2 MAIN-SEQUENCE STARS

$\overline{v \sin i}$ (km/sec)	139	$\bar{v}/(2[\overline{v^2} - \bar{v}^2])^{1/2}$	1.37
$\overline{v^2 \sin^2 i}$ (km/sec)^2	26,480	j^{-1} (km/sec)	134
$\bar{v}$ (km/sec)	177	v_1 (km/sec)	174
$\overline{v^2}$ (km/sec)^2	39,720		

It is apparent that a discussion of axial rotation as a function of spectral type has little meaning if the various subgroups at any given spectral type, having intrinsically different axial rotations, are all combined and treated as a homogeneous group. This is illustrated in Figure 6, where the histogram labeled "All B8–A2" includes main-sequence, giant, supergiant, peculiar A, metallic-line, and peculiar stars. A comparison of this histogram with that for the main-sequence stars alone shows that the former is built up by

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meeting of the American Astronomical Society at Boulder, Colorado. This paper was read by title, but an abstract will appear in a forthcoming issue of the *Astronomical Journal*. In July of this year Dr. Struve called my attention to the work of Dr. George Herbig, who had independently arrived at substantially the same conclusions. Dr. Herbig and Mr. J. F. Spalding, Jr., reported on their research at the June meeting of the Astronomical Society of the Pacific and published an abstract in the *Pub. A.S.P.*, **65**, 192, 1953. I am indebted to Dr. Herbig for sending me a copy of his paper in advance of publication.

[15] *Ap. J.*, **111**, 366, 1950.

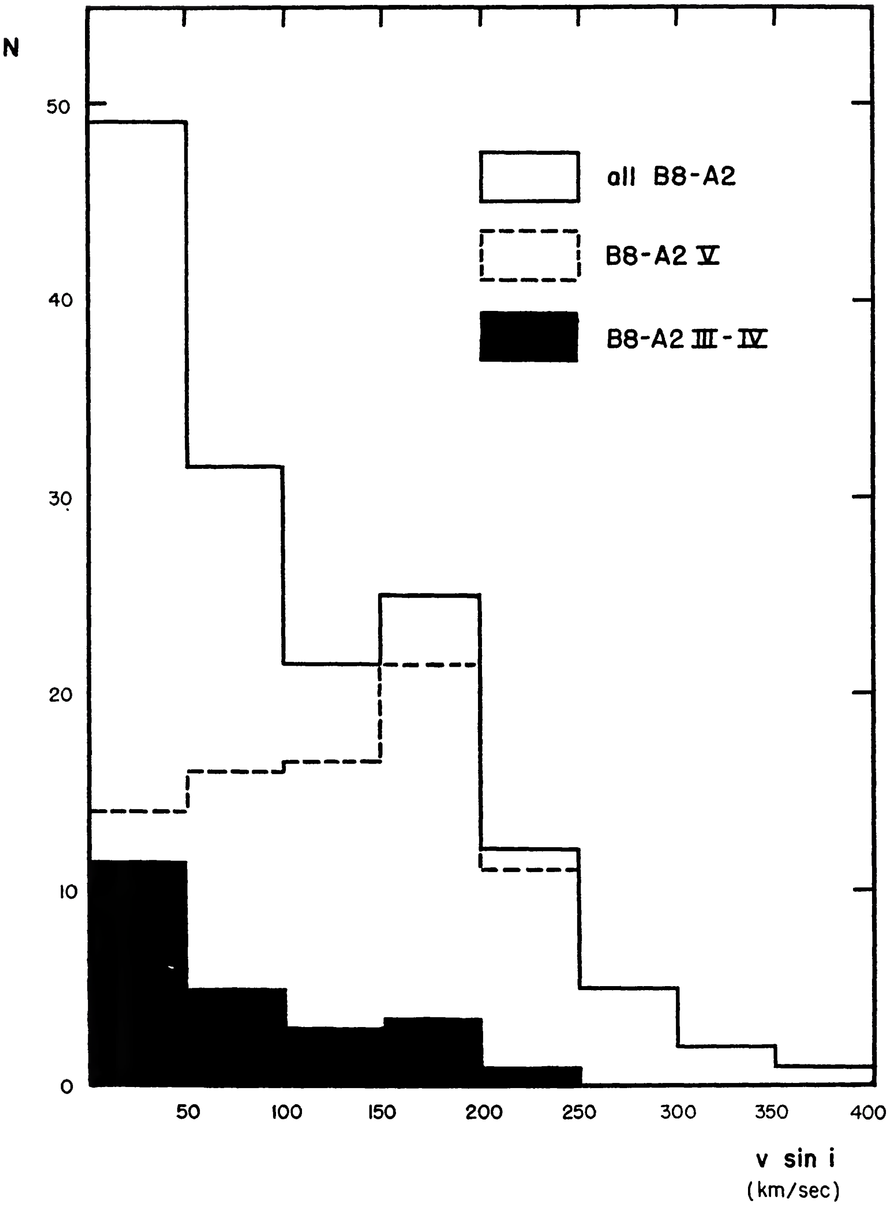

FIG. 6.—The distribution of observed rotational velocities for the B8–A2 stars. The histogram labeled "all B8–A2" includes supergiant, metallic-line, and peculiar A stars in this spectral range, as well as giant and main-sequence stars.

adding intrinsically slowly rotating subgroups to the more rapidly rotating main-sequence group.

Walter,[16] in a rediscussion of Miss Westgate's data,[8] finds that the distribution of rotational velocities for the A-type stars shows two maxima. He suggests that his group of slowly rotating stars be identified with Eggen's[17] "dwarfs" and "bright blue-dwarfs" and his rapidly rotating stars with Eggen's "blue-dwarfs" and possibly some "bright dwarfs." If Walter's double maximum frequency-curve is real, it would appear more likely to the

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[16] *Zs.f. Ap.*, 29, 9, 1951.

[17] *Ap. J.*, 111, 65, 81, 1950.

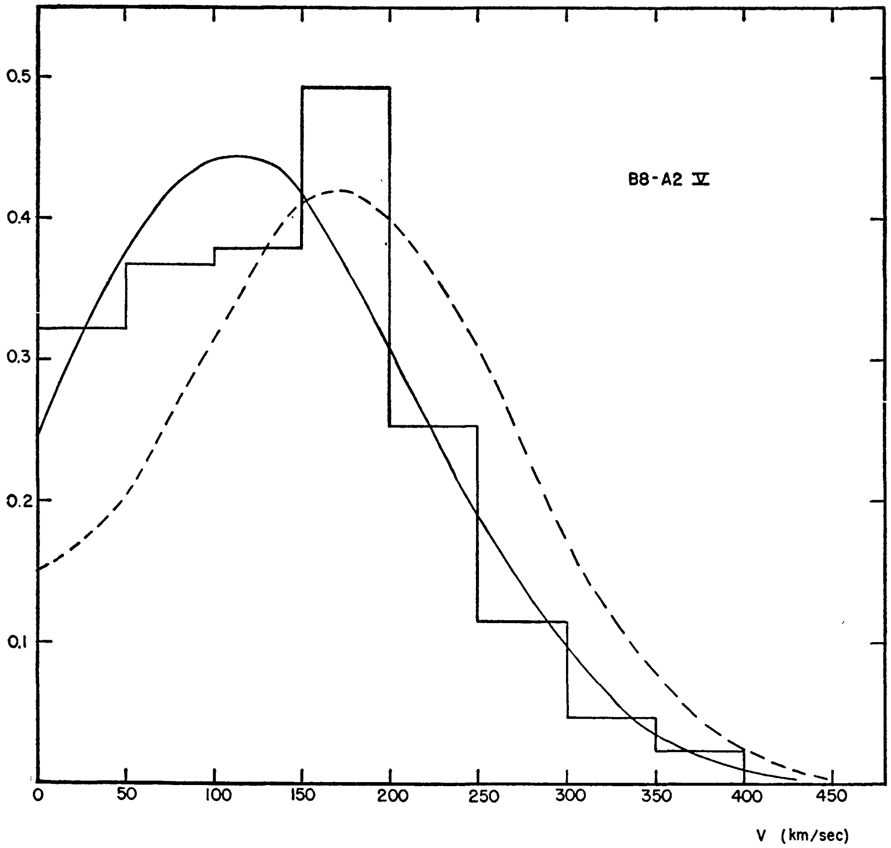

FIG. 7.—Comparison of the distribution of the observed rotational velocities of the B8–A2 main-sequence stars with those derived on the assumption of a true distribution of velocities of the form given in the text and for values of the parameters listed in Table 4. The observed distribution of $v \sin i$ 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.

writer that it is due to the addition of the slowly rotating subgroups listed above to the more rapidly rotating main-sequence group.

The only possible comparison of the B8–A2 main-sequence stars with early-type stars of other spectral types at this time is with the B2–B5 emission stars.[1] The latter, with a value of $\bar{v}$ equal to 348 km/sec,[9] have twice the average axial rotation of the B8–A2 main-sequence stars. The difference in the distribution-curves of true rotational velocities for the two groups is even more striking.

VI. MISCELLANEOUS REMARKS

1. DISTRIBUTION OF THE AXES OF ROTATION

The assumption that the axes of rotation are randomly distributed, supported by the work of Struve and others, is again supported in this investigation. A plot of $v \sin i$ versus galactic latitude and longitude for the main-sequence stars shows no conspicuous correlation. There is thus no reason to suspect that the rotational axes are not distributed in a random fashion.

2. EMISSION-LINE STARS

Four of the main-sequence stars considered are listed in the Mount Wilson catalogue of Be and Ae stars.[18] In view of the fact that axial rotation is undoubtedly associated

[18] Merrill and Burwell, *Ap. J.*, **78**, 87, 1933; **98**, 153, 1943; **110**, 387, 1949.

with the observed emission in these stars, it may be of some interest to consider them individually. Since there are only four, however, a comparison of axial rotation between the emission and the nonemission stars is not possible.

a) *HR 1204 = MWC 77.*—This star was reported to have a faint central *H*α emission component in 1932. The only Perkins plate available for study was a 103-O plate taken in December, 1951, which shows a normal B9 V spectrum with no trace of emission. In view of the relatively low rotational velocity measured (110 km/sec), it appears that HR 1204 is being viewed nearly pole-on; assuming the critical velocity for rotational instability in a B9 V star to be of the order of 350–400 km/sec, the angle of inclination would be about 15°–20°. The weak dark cores in the higher members of the Balmer series reported by Miczaika on plates taken in 1948 are not visible on the Perkins 1951 plate.

b) *β Canis Minoris = MWC 178.*—This B8 V standard star was announced to have double *H*α emission on Mount Wilson spectrograms taken in 1930 and 1932. Plates taken at Perkins in 1936, 1947, 1949, and 1950 show *H*α in emission and *H*β in absorption. A 103-O plate taken in December, 1950, reveals *H*β and *H*γ as broad absorption lines with weak central absorption cores. It is thus evident that the star is seen through at least a portion of its shell. Making the assumption that the critical rotational velocity of a B8 V star is of the order of 350–450 km/sec and employing the observed $v \sin i$ of 260 km/sec for β Canis Minoris, the inclination i would lie between 35° and 50°.

c) *ϕ Andromedae = MWC 420.*—Bright *H*α was discovered in this B7 V star in 1940 and confirmed in 1943. A Mount Wilson spectrogram of December, 1944, revealed a very weak narrow emission line at *H*β centrally superposed on broad absorption, other lines being dark. Miczaika reported that *H*β was free of emission in September and October, 1948. A 1-N plate taken at the Perkins Observatory in September, 1949, shows *H*α as an emission line, while *H*β appears to have a very weak narrow emission core on a 103-O plate taken in October, 1950. In view of the small measured rotational velocity of 72 km/sec, ϕ Andromedae is probably being viewed nearly pole-on. The spectrum appears perfectly normal, however, and shows none of the pole-on effects which have been observed in other sharp-line Be stars.

d) *γ Ursae Majoris = MWC 583.*—This A0 V standard star was announced to have variable *H*α emission in 1938. A re-examination of old Perkins plates shows that if any emission is present at *H*α, it is extremely faint and narrow. On a 1-N plate taken in April, 1950, *H*α is a strong absorption line, while a 103-O plate taken in February, 1950, reveals a normal A0 main-sequence star with no trace of emission.

Five of the stars considered in this paper have measured rotational velocities in excess of 300 km/sec: ζ Aquilae (365 km/sec), α Leonis (352 km/sec), 109 Virginis (335 km/sec), HR 2209 (308 km/sec), and δ Herculis (305 km/sec). Since these stars must be rotating with a velocity near that required for rotational instability, it seemed relevant to examine all available Perkins spectrograms for possible traces of *H*α emission. Red plates were available for three of the above stars, but the results were negative: ζ Aquilae has *H*α as a pure absorption line in 1938, 1946, and 1947; *H*α shows no trace of emission in α Leonis in 1936, 1938, 1943, 1944, 1946, and 1950; *H*α appears without emission in δ Herculis in 1950.

3. SPECTROSCOPIC BINARIES

Fifteen of the stars listed in Table 1 are also listed in the Lick Observatory *Fifth Catalogue of the Orbital Elements of Spectroscopic Binary Stars.*[19] Of these, four have peculiar spectra, and two show two spectra on Perkins plates. The remaining nine are normal stars, in the sense that they can be placed uniquely on the H-R diagram and, further, show only one spectrum on Perkins plates. The latter are listed in Table 5, with the writer's spectral types and the corresponding visual absolute magnitudes and effective temperatures as determined by Keenan and Morgan in their recent calibration.[20]

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[19] *Lick Obs. Bull.*, No. 521, 1948.

[20] *Astrophysics*, ed. J. A. Hynek (New York: McGraw-Hill Book Co., 1951), chap. i.

1954ApJ...119..146S

The fifth column of Table 5 lists the computed radii[21] of the nine stars, and the next column their measured rotational velocities. In the last two columns, the computed rotational period divided by the sine of the inclination is compared with the orbital period as listed in the Lick catalogue.[19] Of particular interest is the eclipsing system β Persei, for which sin i is known and which may be said to be synchronized, within the errors of observation. It is also possible that synchronism may occur in the 7 Camelopardi and 136 Tauri systems if the inclinations are not too great. On the other hand, the α Coronae Borealis and ϵ Herculis systems do not appear to be synchronized: even for sin $i \simeq 1$, the difference between orbital and rotational periods remains appreciable. Nothing can be said about synchronization for the remaining four stars, because of the indeterminancy of their rotational velocities.

TABLE 5

COMPARISON OF ORBITAL AND ROTATIONAL PERIODS FOR NINE SPECTROSCOPIC BINARIES

Star	Sp.	M_v	T_{eff}	$R/R_\odot$	v sin i (Km/Sec)	P_{rot}/sin i (Days)	P_{orb} (Days)
β Per	B8 V	−0.5	12,800	3.5	65	2.7	2.9
7 Cam	A1 V	+0.7	10,300	2.6	42	3.1	3.9
136 Tau	A0 III	−1.1	11,000	5.5	50	5.6	6.0
α Gem A	A1 V	+0.7	10,300	2.6	0	....	9.2
ω UMa	A1 V	+0.7	10,300	2.6	15	8.7:	15.8
η Vir	A2 V	+1.2	9,700	2.3	0	....	71.9
α Dra	A0 III	−1.1	11,000	5.5	0	....	51.4
α CrB	A0 V	+0.3	11,000	2.9	132	1.1	17.4
ϵ Her	A0 V	+0.3	11,000	2.9	90	1.6	4.0

4. EQUIVALENT WIDTHS OF *Mg* II 4481

As has been pointed out earlier, equivalent widths of *Mg* II 4481 were measured on all plates, and these were reduced to the equivalent widths of one of the sharp-line standard stars, in order to derive the rotational velocities. The equivalent widths for individual stars are not included in the present paper, because the writer feels that the dispersion employed in this study is not sufficient to permit accurate individual values. Thus, among the B8–A3 main-sequence stars, the probable error of an equivalent-width determination for a single star is about 0.03 A. The uncertainty is particularly great for rotationally broadened lines, since it is difficult to ascertain the correct position of the continuous spectrum. Figure 8 illustrates the variation of equivalent width of *Mg* II 4481 with spectral type among the B7–A5 main-sequence stars included in this study. It will be seen that the scatter is enormous; this may be due largely to errors of measurement; but a visual comparison of spectrograms of stars of the same spectral type and rotational broadening shows that an intrinsic dispersion at a particular spectral type is also present. Figure 8 also shows a definite increase in equivalent width of *Mg* II 4481 with spectral type among the B7–A5 main-sequence stars. This is perhaps brought out more clearly in Table 6, in which the average equivalent width for each spectral type is listed. In so far as the small number of stars representing some of the spectral types permits drawing any conclusions, the equivalent width of *Mg* II 4481 appears to increase to A5 at least. This is in agreement with the earlier findings of Elvey.[4] A forthcoming study of rotational broadening among the bright *Henry Draper* A3–G0 stars should permit the establishment of the position of the maximum strength of the *Mg* II 4481 line on the HR diagram.

A number of other groups of stars of some interest have been included in Table 6. The supergiant and metallic-line stars have, of course, rather larger equivalent widths of

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[21] Russell, Dugan, and Stewart, *Astronomy*, **2**, 738, 1938.

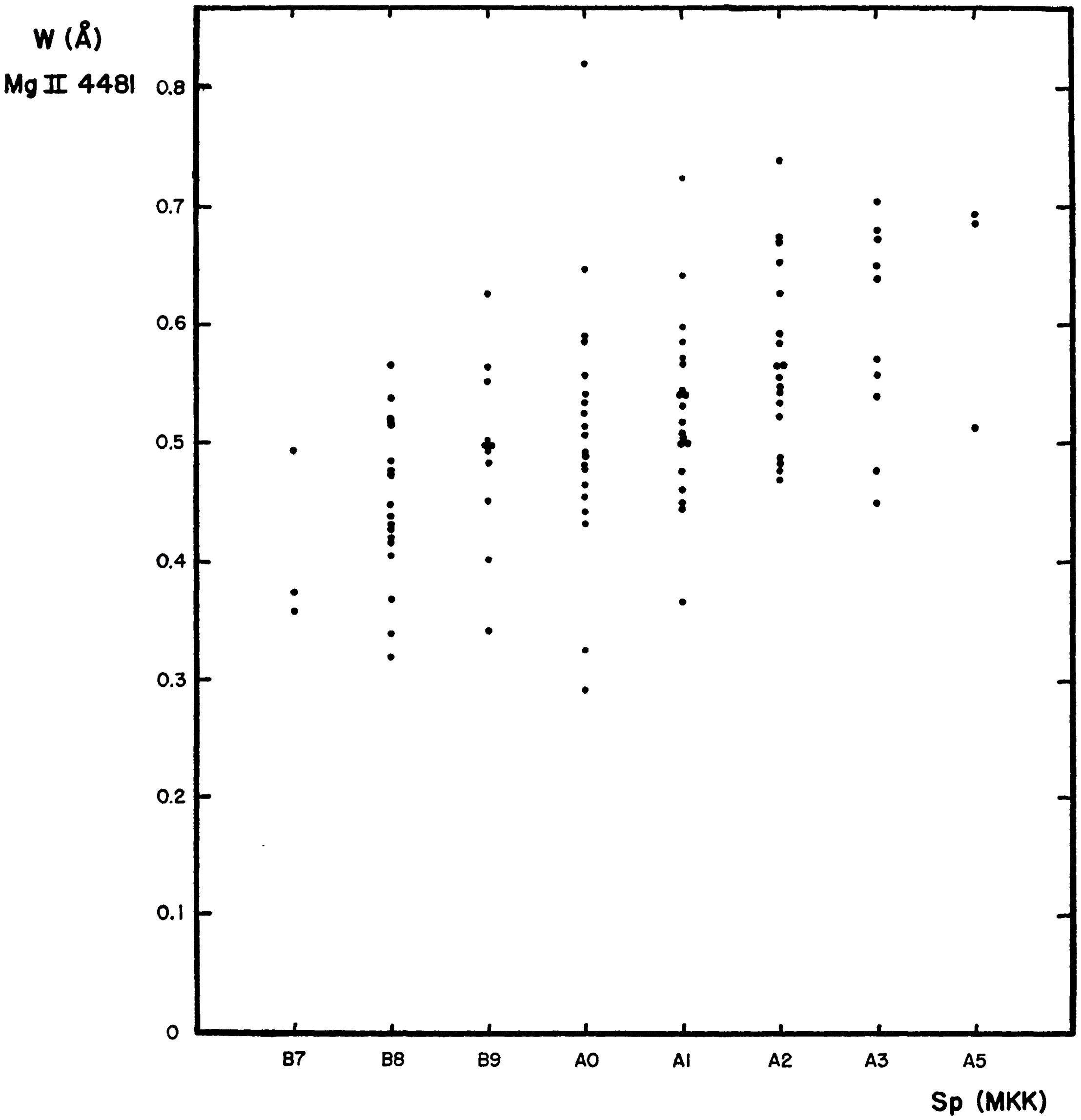

FIG. 8.—The variation of equivalent width of *Mg* II 4481 with spectral type for the B7–A5 main-sequence stars.

Mg II 4481 than the other stars included in this study. The peculiar A stars, on the other hand, have *Mg* II 4481 weaker than corresponding normal stars; and the manganese stars have particularly sharp and weak lines. The group with the weakest lines is the last group in Table 6, which is discussed in further detail in the next section.

5. THE WEAK-LINE STARS

Three of the stars included in this study are characterized by a general weakening of the spectral lines.[22] These stars are listed in Table 7. One of these, λ Bootis, was pre-

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[22] A fourth star, ξ Aurigae, also appears to have weakened lines, but the effect is not nearly so pronounced as in the three stars considered above.

viously announced by Morgan, Keenan, and Kellman.[7] The spectrum of another, 29 Cygni, has been described elsewhere.[23] The spectral types listed in Table 7 are based essentially on the strength of *Ca* II K and the Balmer lines; the remaining metallic lines are then considerably weakened relative to a normal star of corresponding type. This weakening is not a result of rotational broadening, as the rotational velocities show; all three stars have only moderate axial rotation. Trigonometric parallaxes are available for two of the stars, λ Bootis and 29 Cygni; in both cases, they indicate that the stars are located somewhat below the main sequence. Further, the spectral peculiarities of the weak-line stars are similar to those exhibited by the subdwarfs of type A, although not so pronounced. It is tempting to regard the weak-line stars as located just below the main sequence on the H-R diagram, intermediate between the main-sequence stars and the true subdwarfs. In support of this is the fact that the colors of these stars are too red for their spectral types, as is indicated in Table 7. The color types of λ Bootis and 29 Cygni were obtained from the six-color photometry of Stebbins and Whitford.[24] The color type of π^1 Orionis was very kindly obtained for the writer by Dr. Robert Hardie, using the 69-inch reflector of the Perkins Observatory. These colors suggest that the weak-line stars have been classified systematically too early, a result predicted on theoretical grounds for the A-type subdwarfs by Chamberlain and Aller.[25] The space motions of these stars are not unusual, however: the largest is 18 km/sec, for λ Bootis, while the velocities of the other two are under 10 km/sec.

TABLE 6

THE AVERAGE EQUIVALENT WIDTH OF *Mg* II 4481 FOR SOME GROUPS OF STARS

Type	No. of Stars	$\overline{W}$ (A)	Type	No. of Stars	$\overline{W}$ (A)
B7 V	3	0.41	A5 V	3	0.63
B8 V	18	.45	Supergiants	9	.71
B9 V	11	.49	Metallic-line	6	.71
A0 V	20	.51	Peculiar A (all)	16	.39
A1 V	20	.53	Peculiar A (Mn stars)	4	.31
A2 V	18	.57	Weak-line stars	3	0.20
A3 V	10	0.59			

TABLE 7

THE WEAK-LINE STARS

Star	Sp.	$v \sin i$ (Km/Sec)	W of *Mg* II 4481 (A)	Color Type
π^1 Ori	A0 p	108	0.22:	a2–3
λ Boo	A0 p	95	.18:	a4
29 Cyg	A2 p	85	0.20:	a7

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[23] *Ap. J.*, **115**, 575, 1952.

[24] "The Colors of 238 Stars of Different Spectral Types," *Ap. J.*, **102**, 318, 1945.

[25] *Ap. J.*, **114**, 52, 1951.

It is a pleasure to express my thanks to Dr. W. W. Morgan for his kind co-operation and advice on matters of spectral classification, and to Dr. R. H. Hardie for his generous assistance in several photometric problems. I am also indebted to Dr. Morgan and Dr. Otto Struve, and to my associates at the Perkins Observatory, for reading this paper in advance of publication and for valuable suggestions. Finally, I would like to thank Mrs. Mary Fenwick, Mr. Robert Howard, and my wife, for assistance in the reduction of the observations.