THE SPECTRA AND ROTATIONAL VELOCITIES OF THE BRIGHT STARS OF DRAPER TYPES A3–G0

ARNE SLETTEBAK
Perkins Observatory

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ABSTRACT

Rotational velocities (v sin i's) have been determined by spectroscopic means for the bright stars of Draper types A3–G0, plus a few standards of spectral type later than G0. The total number of stars considered was 215. Spectral types and luminosity classes on the MK system were estimated for all stars not already MK standards. The principal results of this and a previous investigation for 159 stars which were judged to be normal main-sequence and intermediate-luminosity stars in the range A3–G0 are as follows:

1. As has been generally known, axial rotation decreases along the main sequence from the middle A-type stars to the late F-type and early G-type stars. Main-sequence stars later than about F5 have very little axial rotation.
2. Axial rotation also decreases from the middle A-type to the late F- and early G-type stars of intermediate luminosity but persists to later spectral types than for the main-sequence stars.
3. The stars of intermediate luminosity have generally greater axial rotation than the corresponding main-sequence stars in the range F0–G0. Among the middle A-type stars, the two groups probably have about the same axial rotation.

Axial rotation is also discussed for a number of groups of stars not included in the afore-mentioned discussion, including the luminous giant and supergiant stars, the metallic-line stars, the peculiar A stars, and the stars with composite spectra. The variation of axial rotation across the H-R diagram as determined from the present investigation and two previous investigations by the writer is summarized.

I. INTRODUCTION

The present paper is the last in a series which has as its aim the description of the variation of stellar axial rotation across the H-R diagram. The other papers in this series treated the B8–A2 stars (1954) and the B2–B5 stars (Slettebak and Howard 1955). An earlier investigation dealt with the Be stars (1949).

On the observational side, there has been little interest in stellar axial rotation since the pioneering work of Struve, Shajn, Elvey, and Miss Westgate, until recent years. The recent work of Huang (1953) and of Herbig and Spalding (1953, 1955) is particularly significant. Huang's work is an extension of Miss Westgate's catalogues (1933*a*, *b*, 1934), and includes line widths of 1550 stars. Unfortunately, two-dimensional spectral types are lacking for most of his stars, but his paper contains an enormous amount of material for future statistical studies of stellar axial rotation when MK spectral types and luminosity classes become available for his stars. Herbig and Spalding have determined rotational velocities for 656 stars of spectral types F0–K5 on the MK system. Their work and the present investigation overlap to some extent, and the material in common yields substantially the same results.

II. THE OBSERVATIONS

The observational selection was as follows: spectrograms of all stars with *Henry Draper* spectral types between A3 and G0, brighter than magnitude 5.01, and north of declination -15° were taken. In addition, a number of stars outside these limits were observed as standards of spectral type. The total number of stars observed was 215.

All spectrograms were obtained with the two-prism spectrograph attached to the 69-inch telescope of the Perkins Observatory, giving a dispersion of 21 A/mm at λ 4071, 28 A/mm at $H\gamma$, and 32 A/mm at λ 4481. The first 31 stars observed were taken on

Eastman 103-O plates, developed in D19 for $3\frac{1}{2}$ minutes at 68° F.; the remaining spectra were taken on Eastman II*a*-O plates, developed in Promicrol for 12 minutes at 69° F. All spectrograms were widened to a width of 1.5 mm, with the exception of a very few of the fainter stars; this served the double purpose of enabling a more accurate spectral classification and making possible two independent microphotometer tracings of each stellar spectrum, even when only one usable spectrogram was available. All plates were calibrated in the dome of the Perkins Observatory with the aid of a small spectral sensitometer and were traced with the Perkins Microphotometer, using a magnification of 120.

Figure 1 illustrates the spectrograms employed in this study, showing examples of line broadening by axial rotation for some representative stars.

III. METHODS

1. THE ROTATIONAL VELOCITIES

Equatorial rotational velocities multiplied by the sine of the angle of inclination of the axes of rotation ($v \sin i$) were determined by spectroscopic means for all stars. For the large majority of the stars included, this was done by obtaining profiles of selected

TABLE 1

DATA ON SHARP-LINED STANDARD STARS AND COMPUTED LINE PROFILES

Star	Sp(MK)	Employed for Spectral Types:	Line	u_λ	Equatorial Velocities Corresponding to Computed Profiles (Km/Sec)
θ Leo	A2 V	A3–A7	*Mg* II 4481	0.73	25, 50, 75, 100, 125, 150, 200, 250, 300, 400
γ Vir N γ Vir S	F0 V	A5–F2	*Mg* II 4481	.76	25, 50, 75, 100, 125, 150, 200, 250, 300, 400
σ Boo	F2 V	F0–F5	*Fe* I 4071	.82	25, 50, 75, 100, 125, 150, 200
ι Peg	F5 V	F2–F8	*Fe* I 4071	.84	25, 50, 75, 100, 125, 150
β CVn η Cas	G0 V	F7–G5	*Fe* I 4071	0.87	25, 50, 75, 100, 125, 150

stellar absorption lines and comparing with a sequence of line profiles computed for varying degrees of rotational broadening, following the graphical technique of Shajn and Struve (1929).

The selection of the stellar absorption lines to be used was complicated by the fact that nearly all strong lines are blended for the stars under consideration, with the resolution available at the Perkins Observatory. It was finally decided to use *Mg* II 4481.2, which is blended with *Fe* I 4482.2 for stars of type F0 and later, and *Fe* I 4071.8, which is blended with *Fe* I 4070.8 and *Fe* I 4072.5. The range of spectral types A3–G0 was then broken down into smaller groups, and sharp-lined stars selected in each group to serve as zero rotational velocity standard stars. The latter are listed in Table 1, with their MK spectral types, the range of spectral types for which they were employed, the absorption line used for the $v \sin i$ determinations, the stellar limb-darkening coefficient u_λ (Münch and Chandrasekhar 1949) used in the line-broadening computations, and the values of the equatorial rotational velocities for which the line profiles were computed. Values of $v \sin i$ for the A3–A7 stars had to be interpolated from comparisons of line profiles with A2 and F0 computed profiles, since none of the normal A3–A7 III–V stars included in this study were found to have sharp lines.

For all stars showing any degree of rotational line broadening, then, two independent observed line profiles were obtained and compared with the appropriate set or sets of

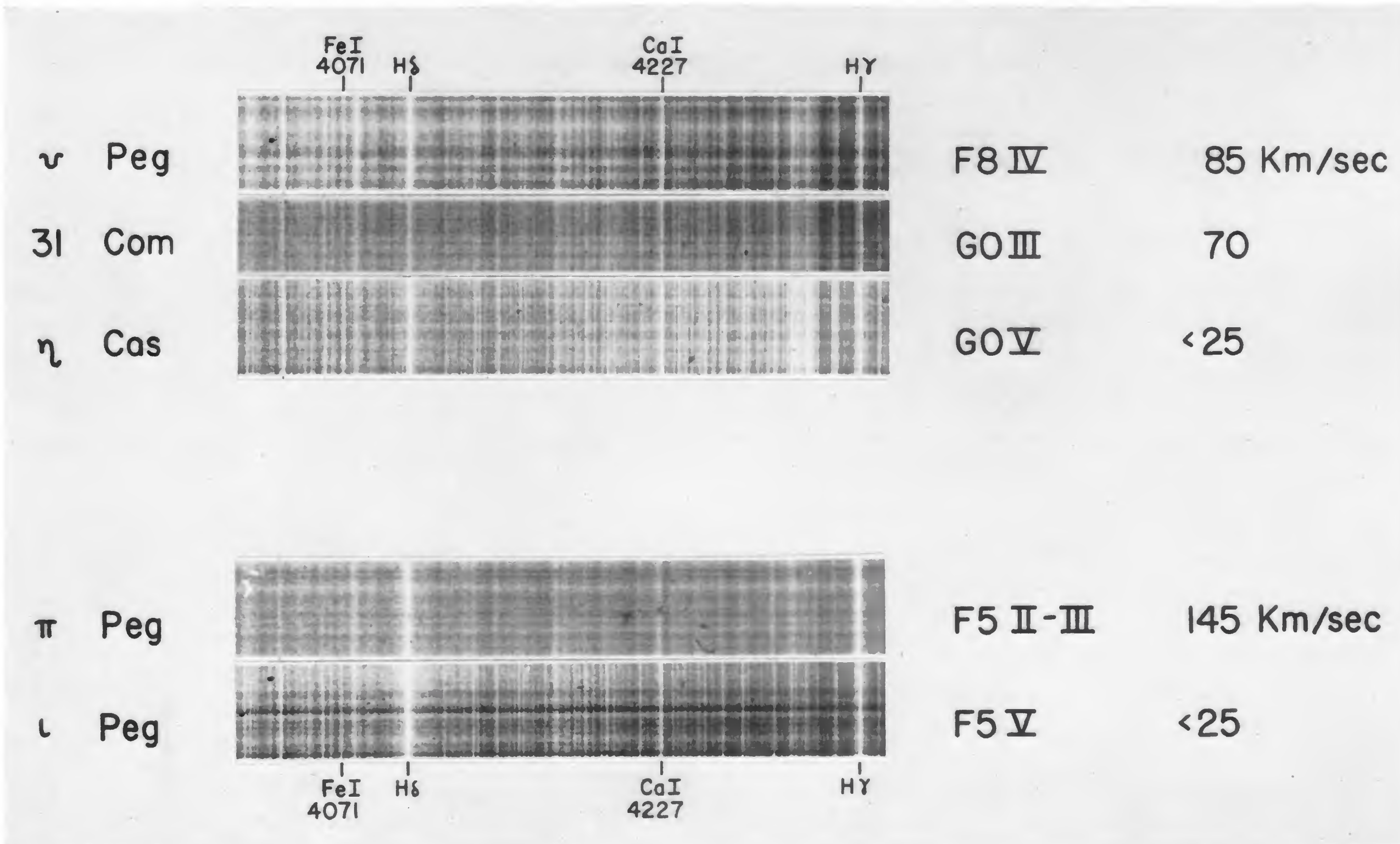

FIG. 1.—Line broadening by axial rotation in some representative F-type and early G-type stars of intermediate luminosity. The sharp-lined standard stars, η Cassiopeiae and ι Pegasi, are shown for comparison.

computed line profiles, after normalization to the same equivalent width as the latter. The average of the two values of $v \sin i$ obtained in this way was recorded as the tentative rotational velocity of the star. The final step was a careful visual inspection and intercomparison of all of the spectrograms involved, great care being taken to use spectrograms of similar density and stars of similar spectral type and luminosity class in making the intercomparisons. This technique was found to be especially valuable for stars with relatively small line broadening, since individual line profiles for one of these stars sometimes gave results which were inconsistent with those of other stars of similar line broadening. All the values of $v \sin i$ determined through the use of line contours define a sort of zero point for the system of rotational velocities; the final visual intercomparison is then a smoothing process, making the individual rotational velocities mutually consistent. The final $v \sin i$ values for all stars are listed in Table 2.

2. THE SPECTRAL TYPES

All spectral types are on the *Revised Atlas* system of spectral classification, or MK system (Johnson and Morgan 1953). As pointed out in the notes to Table 2, several sources for these types were used, but the great bulk came from the afore-mentioned paper, which defines the MK system. These stars were used as standards to classify the remaining stars for which no MK spectral types were available. The spectral classification was carried out at the Perkins Observatory by the writer (with the help of Dr. P. C. Keenan for some of the late-type stars), using the same plates employed for the $v \sin i$ determinations. Because the dispersion of these spectrograms is rather high for spectral classification purposes, all classification was carried out by viewing the plates directly, without aid of magnification, and it was felt that quite accurate results were possible in this way.

IV. THE ACCURACY OF THE OBSERVATIONS

1. THE ROTATIONAL VELOCITIES

An estimate of the probable error of a $v \sin i$ determination is not possible, in view of the method used to arrive at the final $v \sin i$, as described. It is probable that the maximum errors of the measured rotational velocities run about the same as those estimated for the B2–B5 stars (Slettebak and Howard 1955, Table 2).

The smaller rotational velocities, taken individually, are not too reliable, in view of the low resolution employed. In particular, owing to slight differences in the quality of the spectrograms, it was decided not to attempt to distinguish varying degrees of axial rotation below 25 km/sec. There is no question but that the relatively sharp-lined stars must be treated with high dispersion in order to obtain accurate individual values. The writer would like to point out again that the present dispersion, although admittedly inadequate for accurate determinations of $v \sin i$ for the sharpest-lined stars, was chosen for measuring a very wide range of rotational velocities, including values as high as 400 and 500 km/sec.

The "sharp-lined" standard stars at spectral type F0, γ Virginis N and S, and not really sharp-lined stars: γ Virginis N has very slight rotational line broadening, while γ Virginis S has an estimated $v \sin i$ of 30 km/sec. This makes the computed broadened line profiles at F0 broader than they should be for a given rotational velocity, and it tends to underestimate velocities obtained with the use of these profiles. The effect is small for all but the lowest $v \sin i$'s, however, and all discrepancies were adjusted in the visual intercomparison of spectrograms already referred to. Rotational velocities derived from all other sharp-lined standard stars gave consistent results. Values of $v \sin i$ were also obtained from both *Fe* I 4071 and *Mg* II 4481 contours for a number of F0 and F2 stars and were found to be consistent.

Several comparisons of rotational velocities of stars in common with other investiga

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TABLE 2

SPECTRAL TYPES AND ROTATIONAL VELOCITIES OF THE A3-G0 STARS

	Star	α(1900)	δ(1900)	m_V	Sp(MK)	Source	v sin i (Km/sec)	Notes
1	β Cas	$0^h\ 3^m.8$	$+58^\circ 36'$	2.42	F2IV	1	70	
2	22 And	0 5.1	+45 31	5.08	F2II	1	40	
3	η Cas	0 43.1	+57 17	3.64	G0V	1	<25	
4	HR 244	0 47.1	+60 35	4.93	F8V		<25	
5	θ Cas	1 5.0	+54 37	4.52	A7V	1	110	
6*	φ Cas	1 13.8	+57 42	5.25	F0Ia	1	≤25	
7	δ Cas	1 19.3	+59 43	3.0-3.1	A5V	1	120	
8	ω And	1 21.7	+44 53	4.96	F4IV		75	
9	υ And	1 30.9	+40 54	4.18	F8V	1	<25	
10	χ Cet	1 44.7	-11 11	4.77	F2IV		60	
11	α Tri	1 47.4	+29 6	3.58	F6IV	1	90	S.B., P=$1^d.74$
12	β Ari	1 49.1	+20 19	2.72	A5V	1	70	S.B., P=$107^d.0$
13	λ Ari(br)	1 52.4	+23 7	4.83	F0IV		95	
14	48 Cas	1 53.7	+70 25	4.61	A4V		80	
15	β Tri	2 3.6	+34 31	3.08	A5III	1	80	S.B., P=$31^d.4$
16	14 Ari	2 3.7	+25 28	5.07	F2III	1	150	
17*	ι Cas	2 20.8	+66 57	4.59	A5p		55	
18	12 Per	2 35.9	+39 46	4.99	F9V		<25	S.B., P=$331^d.0$
19	θ Per	2 37.4	+48 48	4.22	F7V	1	<25	
20	μ Cet	2 39.5	+ 9 42	4.36	F0IV	1	55	
21	16 Per	2 44.3	+37 54	4.27	F2III	1	155	
22*	τ Per	2 47.2	+52 21	4.06	Comp.		<25	S.B., P=1516^d
23*	γ Per	2 57.6	+53 7	3.08	Comp.		<25	S.B.
24	ι Per	3 1.9	+49 14	4.17	G0V	2	<25	
25*	ζ Eri	3 11.0	- 9 11	4.90	Am		65	S.B.
26	α Per	3 17.2	+49 30	1.90	F5Ib	1	<25	
27	36 Per	3 25.5	+45 43	5.35	F4III	1	<25	
28*	HR 1129	3 37.3	+63 2	4.96	Comp.		<25	
29	ν Per	3 38.4	+42 16	3.93	F5II	1	30	
30	HR 1242	3 56.1	+58 53	5.07	F0II	1	<25	
31	o^1 Eri	4 7.0	- 7 6	4.14	F2II-III		110	
32	μ Per	4 7.6	+48 9	4.28	G0Ib	1	<25	S.B., P=$283^d.3$
33*	52 Per	4 8.1	+40 14	4.89	Comp.		<25	S.B.
34	46 Tau	4 8.2	+ 7 28	5.35	F3V	1	60	Close V.B.
35	HR 1327	4 11.3	+64 54	5.40	G5III	1	<25	
36*	ω Tau	4 11.4	+20 20	4.80	Am		60	
37	δ Tau	4 17.2	+17 18	3.93	K0III	1	<25	
38	64 Tau	4 18.3	+17 13	4.84	A7V		60	
39	κ Tau	4 19.4	+22 4	4.36	A7V		80	
40	υ Tau	4 20.3	+22 35	4.40	F0III-IV		215	
41	71 Tau	4 20.7	+15 23	4.60	F0V		225	S.B.
42	θ^2 Tau	4 23.0	+15 39	3.62	A7III	1	70	S.B., P=$140^d.8$
43	HR 1427	4 24.8	+15 59	4.84	A7V		60	
44	ρ Tau	4 28.2	+14 38	4.75	F0V		130	
45*	58 Per	4 29.8	+41 4	4.46	Comp.		<25	S.B., P=6270^d
46*	88 Tau	4 30.2	+ 9 57	4.38	Am		<25	S.B., P=$3^d.57$
47	90 Tau	4 32.6	+12 19	4.30	A5V		80	S.B.
48	σ^2 Tau	4 33.6	+15 43	4.85	A5V		130	
49	π^3 Ori	4 44.4	+ 6 47	3.31	F6V	1	<25	
50	ω Eri	4 48.0	- 5 37	4.45	A9IV		170	
51	β Cam	4 54.5	+60 18	4.22	G0Ib	1	<25	
52*	ε Aur	4 54.8	+43 41	3.3-4.1	F0Ia	4	30	S.B., P=$27^y.08$
53	64 Eri	4 55.3	-12 41	4.85	F0IV		190	
54	ι Tau	4 57.1	+21 27	4.70	A7V		130	
55	9 Aur	4 58.9	+51 28	4.99	F0V		<25	

TABLE 2 (Continued)

SPECTRAL TYPES AND ROTATIONAL VELOCITIES OF THE A3-GO STARS

	Star	α(1900)	δ(1900)	m_v	Sp(MK)	Source	v sin i (Km/sec)	Notes
56	β Eri	5^h $2^m.9$	$-5°13'$	2.92	A3III	1	200	
57	15 Ori	5 4.0	+15 28	4.86	F2IV		50	
58*	μ Aur	5 6.6	+38 22	4.78	Am		90	
59	λ Aur	5 12.1	+40 1	4.85	GOV	2	< 25	
60	19 Aur	5 13.4	+33 51	5.16	A5II	1	< 25	
61	α Lep	5 28.3	-17 54	2.69	FOIb	1	< 25	
62	49 Ori	5 34.1	- 7 16	4.88	A4IV		190	
63	χ^1 Ori	5 48.5	+20 15	4.62	GOV		< 25	
64	η Lep	5 51.9	-14 11	3.77	FOV		< 25	
65	8 Mon(br)	6 18.5	+ 4 39	4.48	A5IV		125	
66	ξ Gem	6 39.7	+13 0	3.40	F5IV		75	
67	15 Lyn	6 48.6	+58 33	4.54	G5III-IV		< 25	Close V.B.
68*	38 Gem	6 49.0	+13 18	4.70	FOVp		130	S.B.
69	ω Gem	6 56.3	+24 21	5.21	G5II	1	< 25	
70*	ζ Gem	6 58.2	+20 43	3.7-4.1	Cep.		< 25	
71	δ Gem	7 14.2	+22 10	3.51	FOIV		120	
72	ρ Gem	7 22.7	+31 59	4.18	FOV	1	60	
73	o Gem	7 32.6	+34 49	4.92	F3III		90	
74	α CMi	7 34.1	+ 5 29	0.48	F5IV-V	2	< 25	
75	ρ Pup	8 3.3	-24 1	2.88	F6II	4	< 25	
76	ζ Mon	8 3.6	- 2 42	4.41	G2Ib	1	< 25	
77	o UMa	8 22.0	+61 3	3.47	G4II-III		< 25	
78	HR 3459	8 38.8	- 6 52	4.70	G2Ib	3	< 25	
79	ε Hya(A+B)	8 41.5	+ 6 47	3.48	GOIII-IV		< 25	Close V.B.
80	ι UMa	8 52.4	+48 26	3.12	A7V	1	145	
81*	α Cnc	8 53.0	+12 15	4.27	Am		70	
82	HR 3579	8 54.2	+42 11	4.09	F5V	2	< 25	Close V.B.
83	σ^2 UMa	9 1.6	+67 32	4.87	F7IV-V	2	< 25	
84*	15 UMa	9 1.8	+52 0	4.54	Am		30	
85*	τ UMa	9 2.7	+63 55	4.74	Am		< 25	S.B.
86	18 UMa	9 9.0	+54 26	4.89	A5V		175	
87	23 UMa	9 23.7	+63 30	3.75	FOIV	5	150	
88	τ^1 Hya	9 24.1	- 2 20	4.78	F6V		30	
89	24 UMa	9 25.6	+70 16	4.57	G4III-IV		< 25	
90	θ UMa	9 26.2	+52 8	3.26	F6IV	1	< 25	
91	τ^2 Hya	9 26.9	- 0 45	4.50	A3III		70	
92*	o Leo	9 35.8	+10 21	3.76	Comp.		< 25	S.B., P=1
93	ε Leo	9 40.2	+24 14	3.12	GOII	1	< 25	
94	υ UMa	9 43.9	+59 31	3.89	F2IV	1	110	
95	21 LMi	10 1.5	+35 44	4.47	A7V	1	155	
96	ζ Leo	10 11.1	+23 55	3.65	FOIII	1	80	
97	40 Leo	10 14.3	+19 59	4.97	F6IV	1	< 25	
98	30 LMi	10 20.2	+34 18	4.83	FOV		30	
99	36 UMa	10 24.2	+56 30	4.84	F8V	2	< 25	
100	HR 4132	10 27.4	+40 56	4.84	A7IV		140	S.B.
101	37 LMi	10 33.1	+32 30	4.77	GOII		< 25	
102	χ Leo	10 59.9	+ 7 53	4.66	F2III-IV		< 25	
103	δ Leo	11 8.8	+21 4	2.58	A4V	1	200	
104	φ Leo	11 11.6	- 3 6	4.58	A7III-IV		250	
105*	ξ UMa(A+B)	11 12.9	+32 6	3.86	GOV		< 25	Close V.I
106	ι Leo	11 18.7	+11 5	4.03	F2IV	5	< 25	
107*	93 Leo	11 42.8	+20 46	4.54	Comp.		< 25	S.B., P='
108	β Vir	11 45.5	+ 2 20	3.80	F8V	1	< 25	
109	π Vir	11 55.8	+ 7 10	4.57	A4V		70	S.B.
110*	12 Com	12 17.5	+26 24	4.78	Comp.		< 25	S.B., P=

TABLE 2 (Continued)

SPECTRAL TYPES AND ROTATIONAL VELOCITIES OF THE A3-GO STARS

	Star	α(1900)	δ(1900)	m_V	Sp(MK)	Source	v sin i (Km/sec)	Notes
111	β CVn	$12^h29^m.0$	$+41°54'$	4.32	GOV	1	< 25	
112	γ Vir N	12 36.6	− 0 54	3.65	FOV	1	< 25	
113	γ Vir S	12 36.6	− 0 54	3.68			30	
114	31 Com	12 46.8	+28 5	5.07	GOIII	1	70	
115	78 UMa	12 56.4	+56 54	4.89	F2V	1	90	
116	β Com	13 7.2	+28 23	4.32	GOV	1	< 25	
117*	20 CVn	13 13.1	+41 6	4.66	FOII-IIIp		< 25	
118	80 UMa	13 21.2	+55 31	4.02	A5V	1	240	
119	HR 5110	13 30.3	+37 42	4.96	F2IV		< 25	S.B., P=2^d.61
120	24 CVn	13 30.4	+49 32	4.63	A4V		160	
121	25 CVn	13 33.0	+36 48	4.92	A7III		240	Close V.B.
122	τ Boo	13 42.5	+17 57	4.51	F7V	2	< 25	
123	η Boo	13 49.9	+18 54	2.80	GOIV	1	< 25	S.B., P=495^d
124*	12 Boo	14 5.8	+25 34	4.22	F8IV		< 25	S.B., P=9^d.60
125	κ Boo(br)	14 9.9	+52 15	4.60	A7IV		135	
126	ι Vir	14 10.8	− 5 31	4.16	F7III-IV		< 25	
127	ι Boo	14 12.6	+51 50	4.78	A7V		130	
128	θ Boo	14 21.8	+52 19	4.06	F7V	1	30	
129	γ Boo	14 28.1	+38 45	3.00	A7III	1	135	
130	σ Boo	14 30.3	+30 11	4.48	F2V	1	< 25	
131	μ Vir	14 37.8	− 5 13	3.95	F3IV		50	
132	16 Lib	14 52.0	− 3 56	4.59	FOIV		120	
133	45 Boo	15 2.9	+25 16	5.03	F5V	1	35	
134	μ Boo(br)	15 20.7	+37 44	4.47	FOV		90	
135*	β CrB	15 23.7	+29 27	3.72	FOp		< 25	S.B., P=10^y.5
136	δ Ser(br)	15 30.0	+10 52	4.23	FOIV		80	
137	λ Ser	15 41.6	+ 7 40	4.42	GOV	2	< 25	
138	χ Her	15 49.2	+42 44	4.61	F9V	2	< 25	
139	γ Ser	15 51.8	+15 59	3.86	F6V	1	< 25	
140	HR 5960	15 55.4	+55 2	4.96	FOIV		135	
141	ξ¹ Sco	15 58.9	−11 6	4.16	F5IV		< 25	Close V.B.
142	θ Dra	16 0.0	+58 50	4.11	F8IV-V	2	30	S.B., P=3^d.07
143	σ Ser	16 17.0	+ 1 16	4.80	FOV		80	
144	γ Her	16 17.5	+19 23	3.79	A9III	1	140	
145	ζ Her	16 37.5	+31 47	3.00	GOIV	1	< 25	Close V.B.
146	HR 6237	16 43.4	+56 58	4.88	F2V		55	
147	20 Oph	16 44.3	−10 36	4.73	F5IV-V		< 25	
148	19 Dra	16 55.5	+65 17	4.82	F6V		< 25	S.B., P=52^d.1
149	60 Her	17 0.7	+12 53	4.91	A3IV		115	
150	HR 6493	17 21.3	− 5 0	4.61	F3V		50	S.B., P=26^d.3
151	β Dra	17 28.2	+52 23	2.99	G2II	1	< 25	
152*	ν¹ Dra	17 30.2	+55 15	4.98	Am		65	
153*	ν² Dra	17 30.3	+55 14	4.95	Am		50	
154	α Oph	17 30.3	+12 38	2.14	A5III	1	240	
155	ω Dra	17 37.5	+68 48	4.87	F5V		< 25	S.B., P=5^d.28
156	μ Her	17 42.6	+27 47	3.48	G5IV	1	< 25	
157	ψ Dra(br)	17 43.7	+72 12	4.90	F5IV-V		< 25	
158	ν Her	17 54.7	+30 12	4.48	F2II	1	< 25	
159	ζ Ser	17 55.2	− 3 41	4.60	F3V	2	75	
160	72 Oph	18 2.6	+ 9 33	3.73	A4V		75	
161	χ Dra	18 22.9	+72 41	3.69	F7V	1	< 25	S.B., P=280^d.5
162	γ Sct	18 23.5	−14 38	4.73	A3V		260	
163	45 Dra	18 30.9	+56 58	4.95	F7Ib	3	< 25	
164	δ Sct	18 36.8	− 9 9	5.0-5.2	F3III-IV		35	S.B.
165*	ζ Lyr(br)	18 41.3	+37 30	4.29	Am		30	S.B., P=4^d.30

TABLE 2 (Continued)

SPECTRAL TYPES AND ROTATIONAL VELOCITIES OF THE A3-G0 STARS

Star	α(1900)	δ(1900)	m_v	Sp(MK)	Source	v sin i (Km/sec)	Notes
166 110 Her	$18^h41^m.4$	$+20°27'$	4.26	F6V	1	<25	
167 β Sct	18 41.9	− 4 51	4.47	G5II	1	<25	S.B., $P=834^d$
168 111 Her	18 42.6	+18 4	4.37	A3V		80	
169* 113 Her	18 50.5	+22 31	4.56	Comp.		<25	S.B., $P=245^d$
170 θ Ser(br)	18 51.3	+ 4 4	4.50	A5V		130	
171 δ Aql	19 20.5	+ 2 55	3.44	F0IV		80	S.B.
172 ν Aql	19 21.4	+ 0 8	4.86	F2Ib	1	<25	
173 θ Cyg	19 33.8	+49 59	4.64	F4V		<25	
174 α Sge	19 35.6	+17 47	4.37	G0II	1	<25	
175 α Aql	19 45.9	+ 8 36	0.89	A7IV,V	2	240	
176 ψ Cyg	19 53.1	+52 10	4.90	A3IV,V		300	
177* 15 Vul	19 57.0	+27 29	4.74	Am		<25	
178 33 Cyg	20 11.1	+56 16	4.32	A3IV,V		300	S.B.
179 α^1 Cap	20 12.1	−12 49	4.55	G3Ib	3	<25	
180* o^2 Cyg	20 12.4	+47 24	4.16	Comp.		<25	S.B., $P=1170^d$
181 γ Cyg	20 18.6	+39 56	2.32	F8Ib	1	<25	
182 41 Cyg	20 25.3	+30 2	4.09	F5II	1	<25	
183* θ Cep	20 27.9	+62 39	4.28	Am		40	S.B.
184* 47 Cyg	20 30.0	+34 54	4.85	Comp.		<25	
185 β Del	20 32.9	+14 15	3.72	F5IV	5	70	Close V.B.
186 δ Del	20 38.8	+14 43	4.53	A7III		35	
187 HR 7955	20 42.9	+57 13	4.63	F8IV-V	5	<25	
188* μ Aqr	20 47.3	− 9 22	4.80	Am		50	
189* γ Equ	21 5.5	+ 9 44	4.76	F0p		<25	
190 δ Equ	21 9.6	+ 9 36	4.61	F7V		<25	Close V.B.
191 τ Cyg	21 10.8	+37 37	3.82	F0IV		95	S.B.
192* α Equ	21 10.8	+ 4 50	4.14	Comp.		<25	S.B.
193 α Cep	21 16.2	+62 10	2.60	A7IV,V	2	240	
194 β Aqr	21 26.3	− 6 1	3.07	G0Ib	1	<25	
195 ξ Aqr	21 32.4	− 8 18	4.78	A7V		165	
196 μ Cyg(br)	21 39.7	+28 17	4.73	F6V		<25	
197 κ Peg	21 40.1	+25 11	4.27	F5IV		35	Close V.B.
198 α Aqr	22 0.7	− 0 48	3.19	G2Ib	1	<25	
199* ξ Cep(br)	22 0.9	+64 8	4.57	Am		50	
200 ι Peg	22 2.4	+24 51	3.96	F5V	1	<25	S.B., $P=10^d.2$
201 π Peg	22 5.6	+32 41	4.38	F5II-III		145	
202 ε Cep	22 11.3	+56 33	4.23	F0IV	1	85	
203* ζ Aqr(A+B)	22 23.7	− 0 32	3.74	F2IV		≤55	Close V.B.
204 9 Lac	22 33.3	+51 2	4.83	A7IV		90	S.B.
205 η Peg	22 38.3	+29 42	3.10	G2II-III	2	<25	S.B., $P=818^d$
206 ξ Peg	22 41.7	+11 40	4.31	F7V	2	<25	
207 σ Peg	22 47.3	+ 9 18	5.30	F7IV	1	<25	
208* π Cep	23 4.7	+74 51	4.56	G2III		25	S.B., $P=556^d$
209 7 And	23 8.0	+48 52	4.62	F0V		65	S.B.
210 τ Peg	23 15.7	+23 12	4.65	A5IV		150	
211 υ Peg	23 20.4	+22 51	4.57	F8IV	1	85	
212 ι Psc	23 34.8	+ 5 5	4.28	F7V	1	<25	
213 λ Psc	23 37.0	+ 1 14	4.61	A7V	5	60	
214* ρ Cas	23 49.4	+56 57	4.4-5.1	pec.		<25	
215 ω Psc	23 54.2	+ 6 19	4.03	F4IV		30	S.B.

NOTES TO TABLE 2

The sources for the spectral types listed are the following:

1. Johnson and Morgan, Ap. J. 117, pp. 320-322 (Table 2), 1953. These are the standard stars which define the MK system of spectral classification.
2. Johnson and Morgan, Ap. J. 117, pp. 323-327 (Table 3), 1953.
3. Morgan and Roman, Ap. J. 112, pp. 363-364, 1950.
4. Morgan, Keenan and Kellman, "An Atlas of Stellar Spectra" (Chicago: University of Chicago Press 1943).
5. Morgan, private correspondence or conversation.

All stars not designated as due to one of the above sources were classified at the Perkins Observatory on the MK system.

* Stars noted by asterisks:

6. ϕ Cas: The extent of line broadening by axial rotation as against turbulence is unknown.

17. ι Cas: Peculiar A star of the strontium type. The spectral type is due to Morgan (1943).

22. τ Per: Composite spectrum. The K-line is somewhat weaker than H, and Hδ appears fuzzy. The early type component is probably of type A, while the late type component appears to be a giant in the neighborhood of G5.

23. γ Per: Composite spectrum. A5 + G5III, according to Morgan (1943).

25. ζ Eri: Metallic-line star: A2 K-line and A7 metallic spectrum.

28. HR 1129: Composite spectrum. Approximately A1 + G2III.

33. 52 Per: Composite spectrum. Approximately A2 + G5Ib.

36. ω Tau: Metallic-line star: A2 K-line and F2 metallic spectrum.

45. 58 Per: Composite spectrum. A-type star + G5Ib-II.

46. 88 Tau: Metallic-line star: A3 K-line and A7 metallic spectrum.

52. ϵ Aur: The extent of line broadening by axial rotation as against turbulence is unknown.

58. μ Aur: Metallic-line star: A4 K-line and F2 metallic spectrum.

68. 38 Gem: Metallic spectrum corresponds approximately to an F0V star, but the Balmer lines are too weak for this type, while the K-line is similar to that of an A8 star.

70. ζ Gem: Cepheid variable, P = 10.15 days. The spectrum, taken October 11.45, 1953, is that of an F9Ib star.

81. α Cnc: Metallic-line star: A3 K-line and A7 metallic spectrum.

84. 15 UMa: Metallic-line star: A2 K-line and F2 metallic spectrum.

85. τ UMa: Metallic-line star: A5 K-line and F6 metallic spectrum.

92. o Leo: Composite spectrum. Approximately A2 + F6II-III, according to Morgan (1943).

105. ξ UMa(A+B): Both components are spectroscopic binaries, with periods of 669 and 4 days, respectively. The lines appear single and sharp on the Perkins plate.

107. 93 Leo: Composite spectrum. A + G5III-IV, approximately. The K-line is slightly weaker than H , and Hδ appears fuzzy.

110. 12 Com: Composite spectrum. Approximately A5 + G5III. The spectrum is similar to that of 93 Leo, but the A-type spectrum is weaker in the latter star. Herbig and Miss Turner (1953) have made a very careful study of this system, and conclude that the components have spectral types of A3V and G0III-IV.

NOTES TO TABLE 2 (Continued)

117. 20 CVn: Mg II 4481 is abnormally strong.

124. 12 Boo: Two spectra visible on the Perkins plate; both sets of lines are quite sharp.

135. β CrB: Peculiar A-F star, of the chromium-europium type. The spectral type is due to Morgan (1943).

152. ν^1 Dra: Metallic-line star: A4 K-line and A7 metallic spectrum.

153. ν^2 Dra: Metallic-line star: A2 K-line and F2 metallic spectrum.

165. ζ Lyr(br): Metallic-line star: A4 K-line and F0 metallic spectrum.

169. 113 Her: Composite spectrum. Approximately A5 + G5III.

177. 15 Vul: Metallic-line star: A6 K-line and F2 metallic spectrum.

180. o^2 Cyg: Composite spectrum. The late type component is about K5Ib-II, according to P.C. Keenan (private conversation).

183. θ Cep: Metallic-line star: A6 K-line and F2 metallic spectrum.

184. 47 Cyg: Composite spectrum. The late type component is about K4Ib, according to P.C. Keenan (private conversation).

188. μ Aqr: Metallic-line star: A4 K-line and F2 metallic spectrum.

189. γ Equ: Peculiar A-F star, of the strontium-europium type. The spectral type is due to Morgan (1943).

192. α Equ: Composite spectrum. A + G5 giant, according to Morgan (1943). Deutsch (1954) has made a study of this system and arrives at a similar classification.

199. ξ Cep(br): Metallic-line star: A2 K-line and F2 metallic spectrum.

203. ζ Aqr (A+B): The rotational velocity given is an upper limit for the more rapidly rotating component. Herbig and Spalding (1955) find the two components to be rotating at the same speed: each with a v sin i = 75 Km/sec.

208. π Cep: The present rotational velocity (25 Km/sec) is considerably smaller than that of 70 Km/sec originally announced for this star (Slettebak 1953), but still somewhat larger than that of $\leq$ 15 Km/sec, given by Herbig and Spalding (1955).

214. ρ Cas: According to P.C. Keenan (private conversation) the type of this irregular variable star at the time of writing (September, 1954) is approximately G0Iap.

tors are possible. Figure 2 illustrates a comparison of the present data with that of Miss Westgate (1933*b*) for 53 A-type stars in common. As in similar comparisons with Miss Westgate for the B2–B5 and B8–A2 stars, a scale difference is present, in the sense that the present values run somewhat higher than those of Miss Westgate.

A comparison with the values of Huang (1953) for 104 stars in common is shown in Figure 3, where Huang's parameter γ is set equal to 2 in converting his line widths to rotational velocities. A scale difference is also evident in this comparison, in the sense that the present values run somewhat lower than those of Huang for small and intermediate values of $v \sin i$, while the agreement is better for large values. A similar tendency was found in comparing the values of Slettebak and Howard (1955) with those of Huang

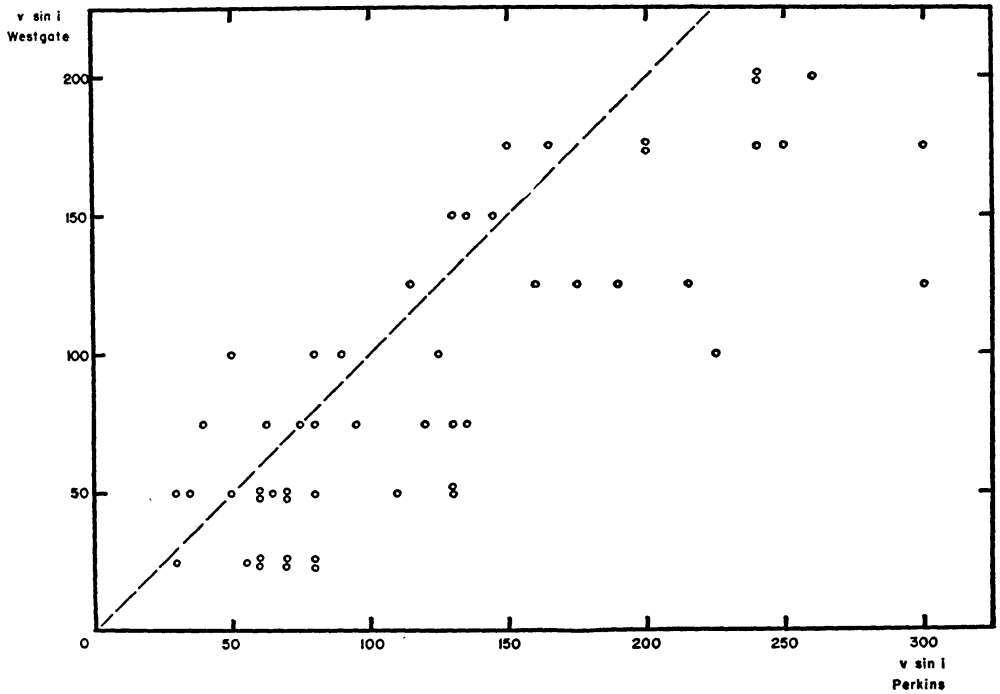

FIG. 2.—A comparison of rotational velocities measured at Perkins with those measured by Miss Westgate for 53 A-type stars in common.

(1953) for the B2–B5 stars. Also, in a comparison of their values with those of Huang for the F0–K5 stars, Herbig and Spalding (1955) find a similar scale difference and conclude that Huang's rotational velocities can be reduced to the scale of their paper by using $\gamma \simeq 1.4$. In a recent conversation, Dr. Huang informed the writer that his parameter γ should probably be given the value 1.25 for small velocities and 2 for large velocities in reducing his line widths to values of $v \sin i$.

Figure 4 illustrates a final comparison: between the present rotational velocities and those of Herbig and Spalding (1955) for 30 stars in common (stars with rotational velocities expressed as upper limits by either investigator were not plotted). The scatter is rather small, but a scale difference may be present in the sense that the present values run lower than those of Herbig and Spalding for $v \sin i$'s up to about 110 km/sec and somewhat higher for values in excess of this. The latter conclusion is quite uncertain, however, in view of the small number of stars in common.

NOTE ADDED FEBRUARY 12, 1955.—At the time this manuscript was submitted, the writer was not aware of the work of J. B. Oke and Jesse L. Greenstein on the rotational velocities of A-, F-, and G-type giant stars (*Ap. J.*, **120**, 384, 1954), which was then in press. I am indebted to Dr. Greenstein for sending me a copy of this paper in advance of publication. A comparison between $v \sin i$'s as determined from high-dispersion plates by Oke and Greenstein with those of the present paper for 19 stars in common shows excellent agreement. The only two stars for which any discrepancy exists are γ Herculis and β Coronae Borealis, for which Oke and Greenstein obtained 171 and 43 km/sec, respectively, while the writer found 140 and <25 km/sec.

2. THE SPECTRAL TYPES

A comparison between the writer's spectral types and luminosity classes and those of Miss Roman is possible for 25 common F- and G-type stars. Of these, 3 were classified by Miss Roman (1952) on the MK system, while the others were classified by her (1950) on the MKK system. The latter have been converted to the MK system by changing luminosity class III to IV and IV to IV–V for the F2–F8 stars (see Johnson and Morgan 1953; Roman 1952). The results of the comparison are shown in Figure 5. The agreement

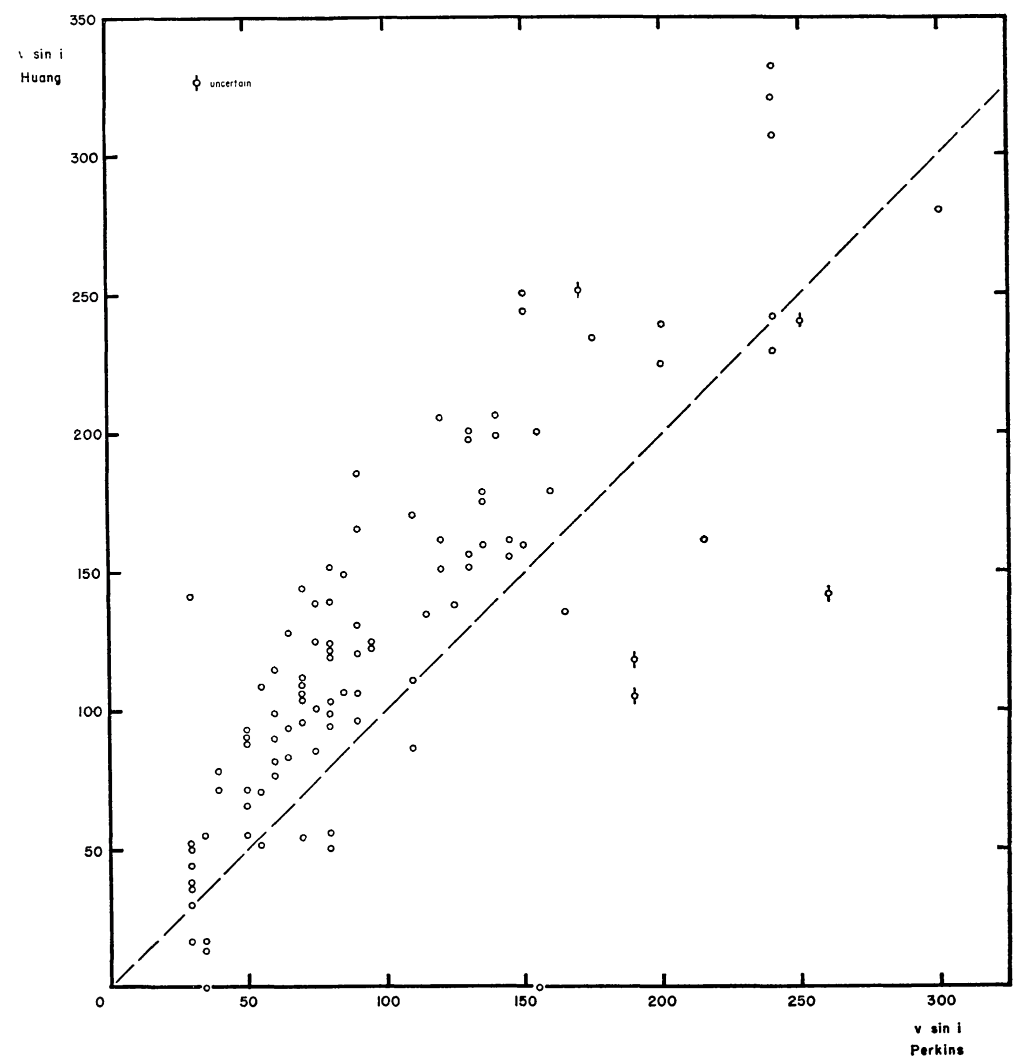

FIG. 3.—A comparison of rotational velocities measured at Perkins with those measured by Huang for 104 stars in common.

is quite satisfactory, although there may be a tendency for the writer's types to run somewhat earlier than Miss Roman's for spectral type F5 and earlier.

Unfortunately, no comparison is possible between the writer's spectral types and luminosity classes and those of other investigators for the A3–A7 stars. These were by far the most difficult to classify among the A3–G0 stars, particularly with regard to

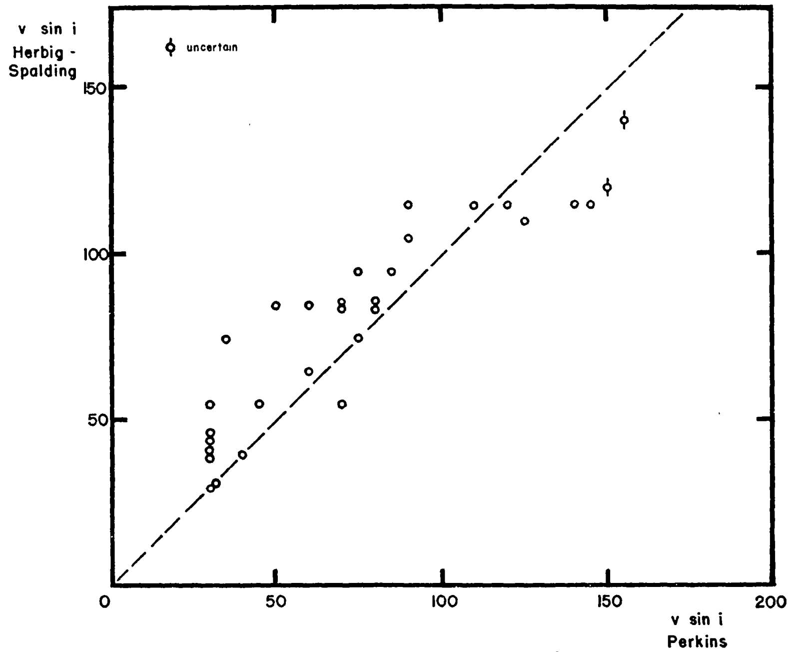

FIG. 4.—A comparison of rotational velocities measured at Perkins with those measured by Herbig and Spalding for 30 stars in common.

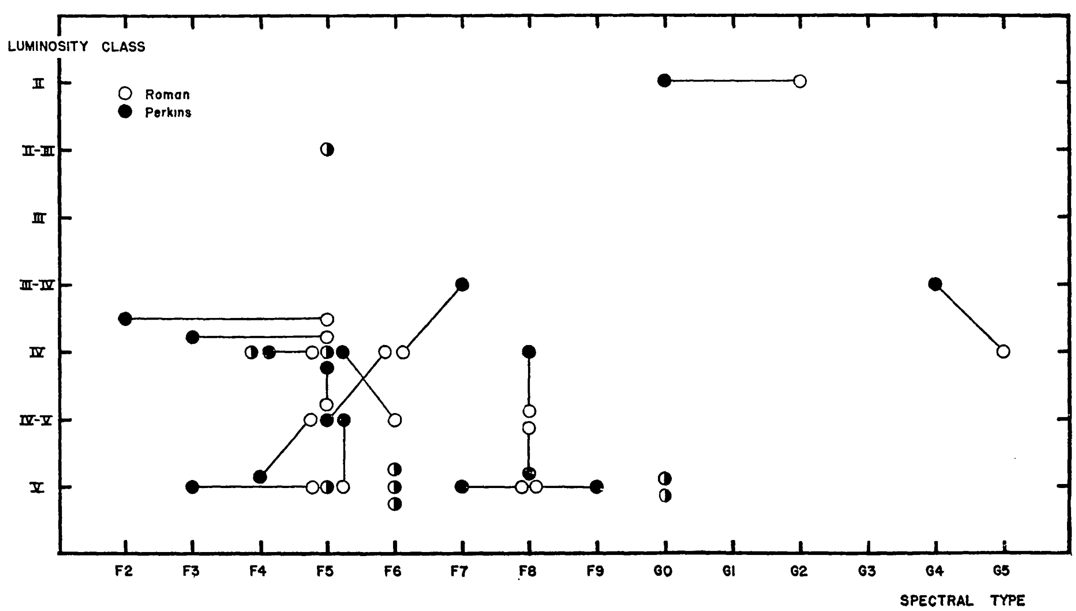

FIG. 5.—A comparison of spectral types and luminosity classes estimated at Perkins with those of Miss Roman for 25 F- and G-type stars in common.

luminosity class. As has been pointed out by Morgan (Johnson and Morgan 1953), an indeterminateness exists between luminosity classes IV and V at type A7 for stars with very broad lines, and the writer feels that the same holds true for the A3–A5 stars.

V. DISCUSSION

1. THE MAIN-SEQUENCE STARS

Seventy-four of the 215 stars considered were judged to be normal main-sequence stars in the range A3–G0. In addition, 13 normal main-sequence stars of types A3 and A5 as classified in the writer's B8–A2 rotation paper (1954) were included in the following discussion, making a total of 87.

The sample is not overwhelmingly large, and it was therefore not possible to group them by individual spectral types in order to study the variation of axial rotation along the main sequence with the maximum resolution. The stars have, instead, been grouped to give an indication of axial rotation along the main sequence for the middle A types, the early F types, the middle F types, and the late F types. The results are tabulated in Table 3, where the mean true rotational velocity, $\bar{v}$, is $4/\pi$ times the mean observed

TABLE 3

AXIAL ROTATION IN THE NORMAL A3–G0 STARS

Spectral Types	Luminosity Class V		Luminosity Classes III, IV		Spectral Types	Luminosity Class V		Luminosity Classes III, IV	
	$\bar{v}$ (Km/Sec)	N	$\bar{v}$ (Km/Sec)	N		$\bar{v}$ (Km/Sec)	N	$\bar{v}$ (Km/Sec)	N
A3–A7......	173	37	202	24	F3–F6.......	31	14	67	14
A9–F2.......	87	15	125	26	F7–G0......	<25	21	34	8

rotational velocity, $\overline{v \sin i}$, allowing for the effect of the random distribution of rotational axes (Chandrasekhar and Münch 1950). Those stars which are designated as having rotational velocities <25 km/sec in Table 2 have been arbitrarily assigned a $v \sin i$ of 10 km/sec in forming the means in Table 3, as well as elsewhere in this paper.

Despite the rather small number of stars used in forming the means, there is no doubt that axial rotation decreases along the main sequence from the middle A-type stars to the late F-type and early G-type stars, as is generally known. The writer found no main-sequence star with a $v \sin i$ greater than 35 km/sec later than F4. The main-sequence star of latest spectral type which still showed a measurable $v \sin i$ was the F7 star θ Bootis (30 km/sec). Herbig and Spalding (1953, 1955) have considered stars as late as K5 and have reached substantially the same conclusion (the main-sequence star of latest spectral type for which they find measurable axial rotation is the F8 star, 111 Tauri, with $v \sin i = 25$ km/sec).

2. THE STARS OF INTERMEDIATE LUMINOSITY

Sixty-four stars in Table 2 were classified as being of intermediate luminosity in the range A3–G0. In addition, 8 A3 stars of intermediate luminosity from the writer's B8–A2 rotation paper (1954) are included in the following discussion, making a total of 72 stars. Stars of intermediate luminosity refer to those having luminosity classes II–III, III, III–IV, and IV. This grouping is necessitated by the small number of stars available. The stars of luminosity class II are considered separately with the supergiants in the following section. The stars of luminosity class IV–V are not included in the statistical discussion at all, nor are those four A-type stars with such pronounced line broadening that their luminosity classes are indeterminate.

Table 3 lists the mean true rotational velocities for the A3–G0 stars of intermediate luminosity, grouped by spectral types in the same manner as was done for the main-sequence stars. Two conclusions can be drawn:

a) Axial rotation decreases from the middle A-type to the late F-type stars of intermediate luminosity, just as it does for the main-sequence stars, but it appears to persist to later spectral types for the former. Extreme examples are the F8 IV star, υ Pegasi (85 km/sec), and the G0 III star, 31 Comae (70 km/sec); and, with less certainty, the G2 III star, π Cephei (25 km/sec). This effect was pointed out earlier by Herbig and Spalding (1955) and by Slettebak (1953; 1954, n. 14).

b) The stars of intermediate luminosity have generally greater axial rotation than the corresponding main-sequence stars among the F-type stars. This was pointed out earlier by Herbig and Spalding (1953, 1955) and by Slettebak (1953; 1954, n. 14). Still earlier, Greenstein (1953) noted that broad lines are very common among A5 III–F5 III stars, and Herbig and Miss Turner (1953) pointed out that only a minority of giant stars in the interval F5–G2 have sharp lines.

Among the middle A-type stars, the dependence of axial rotation on luminosity is less clear. Table 3 shows that the stars of intermediate luminosity have somewhat greater axial rotation than the main-sequence stars; but this must be viewed with caution, in view of the difficulty of luminosity classification in the middle A-type stars. It is probably safe to say that the main-sequence stars and the stars of intermediate luminosity have about the same axial rotation in the middle A-type stars.

3. THE LUMINOUS GIANT AND SUPERGIANT STARS

Twenty-seven stars in Table 2 are of luminosity classes I*a*, I*b*, and II. Of these, it can only be said that none have very large line broadening; a complete study of these stars requires higher dispersion than that used in this investigation (see Herbig and Spalding 1955).

Line broadening was noted in a few luminous giant and supergiant stars, however. Among the luminosity class II stars, the F2 star, 22 Andromedae, and the F5 star, ν Persei, have broadened lines corresponding to rotational velocities of 40 and 30 km/sec, respectively. The F0 I*a* stars, ϵ Aurigae and ϕ Cas, have broadened lines corresponding to $v \sin i$'s of 30 and ≤ 25 km/sec, respectively. The determinations for the latter two stars were based on weak lines, since the strong lines appear to be largely turbulence-broadened. Incidentally, it should be pointed out that the assignment of $v \sin i$'s to all stars of these luminosity classes is only to indicate the degree of line broadening; the extent of line broadening by axial rotation as against other broadening agents is uncertain.

4. THE METALLIC-LINE STARS

Fourteen metallic-line stars are included among the 215 stars listed in Table 2. The mean true rotational velocity, $\bar{v}$, of the group is 57 km/sec. This is in good agreement with the corresponding value for the 6 metallic-line stars included in the writer's B8–A2 rotation paper (1954): 51 km/sec. The conclusion reached earlier that the metallic-line stars as a group are characterized by rather small axial rotation still stands.

5. THE PECULIAR A STARS

Only three peculiar A stars are included in the present sample, and, of these, only ι Cassiopeiae has a measurable rotational velocity: 55 km/sec. When these 3 peculiar A stars are added to the 16 studied in the writer's B8–A2 rotation investigation (1954), a value of 48 km/sec for $\bar{v}$ is found for the group. The conclusion remains that the peculiar A-type stars have small axial rotation as a group, although values of $v \sin i$ up to 100 km/sec have been measured for individual stars.

6. THE STARS WITH COMPOSITE SPECTRA

Twelve stars in Table 2 have composite spectra, showing an A-type plus a late-type component. Of these, 11 were known previously, and 1, 93 Leonis, was found on Perkins plates.

The rotational velocities listed for these stars in Table 2 refer in all cases to the late-type component. It can be said quite generally that no significant line broadening was visible for the late-type components of any of these composite systems. The A-type components were detectable in general by a weakening of the broad K line of the late-type component and a strengthening of the Balmer lines in the composite spectrum. In some cases the A-type component showed a sharp K line superimposed on the broad K line of the late-type component, which made possible a rough classification of the A-type star. A determination of the rotational velocities of the A-type components for these systems was not possible with the present observational material.

7. THE STRONG- AND WEAK-LINE STARS

Miss Roman (1950, 1952) has distinguished spectroscopically two groups of stars in the spectral range F5–G5, the strong- and weak-line stars, and has pointed out that these differ in their space-velocity characteristics. Sixty-two stars in Table 2 have been classified by Miss Roman as belonging to one of these two groups: 33 weak-line stars and 29 strong-line stars. All degrees of line broadening are found in both groups, although the strong-line stars have a few more rapidly rotating stars. A value of $\bar{v} = 37$ km/sec was obtained for the strong-line stars, as compared with 24 km/sec for the weak-line stars; but this difference is not significant, since no attempt was made to divide the stars into spectral types and luminosity classes, because of the small sample available. The conclusion that there is no significant difference in axial rotation between the strong- and weak-line stars had also been reached earlier by Herbig and Spalding (1953, 1955) and by Slettebak (1953). The limitations of the relatively low dispersion used in this paper should be kept in mind, however, in evaluating this conclusion.

VI. SUMMARY AND CONCLUDING REMARKS

Including the 215 A3–G0 stars considered in this investigation, a total of 579 stars in the range of *Henry Draper* spectral types B2–G0 have been studied with respect to axial rotation and spectral type by the writer. Of these, 427 were treated in statistical discussions of the relation between axial rotation and spectral type and luminosity class. The latter stars were all judged to be normal in the sense that they could be located uniquely on the H-R diagram. Figure 6 summarizes these results: values of the mean true rotational velocity, $\bar{v}$, are listed for the various groups of stars considered, on a diagram in which bolometric absolute magnitude is plotted against the logarithm of the effective temperature. The following conclusions can be drawn:

1. On the main sequence, axial rotation appears to reach a maximum for the middle B-type stars, decreasing gradually through the middle A-type stars. Near F0, the rotational velocities drop rather sharply and are very small for the middle F-type stars. The main-sequence stars of late F type and later have little or no axial rotation.
2. The variation of axial rotation with luminosity class is a function of spectral type. In the B1–A2 range, the main-sequence stars have greater axial rotation than the stars of intermediate luminosity. Among the A3–A7 stars, the two groups probably have about the same axial rotation. In the range F0–G0, the stars of intermediate luminosity are characterized by greater axial rotation than the corresponding main-sequence stars.
3. There is a tendency for axial rotation to persist to later spectral types for the stars of intermediate luminosity, as compared with the main-sequence stars.

It is the hope of the writer that the results presented in Figure 6 may be of interest to workers in the field of stellar evolution. With regard to the numbers listed there, however, the following should be remembered:

1. The samples considered for some of the groups of stars are small. Later investigations with more stars may change some of the $\bar{v}$'s considerably.

2. Figure 6 is the result of three separate investigations. Although the writer checked various groups of stars against one another, the possibility remains of systematic differences in the rotational velocities of the groups considered.

3. The accuracy of spectral type and luminosity classifications varies across the H-R diagram. In the opinion of the writer, the most accurate classifications are those for the B1–B6 and F0–G0 stars. Without question, the B8–A7 stars are the most difficult to classify, particularly for luminosity class. The values of $\bar{v}$ for the latter range should therefore be considered the most uncertain and subject to change.

A few remarks concerning further observational work on stellar axial rotation might be appropriate. In the range of spectral types considered by the writer, larger samples

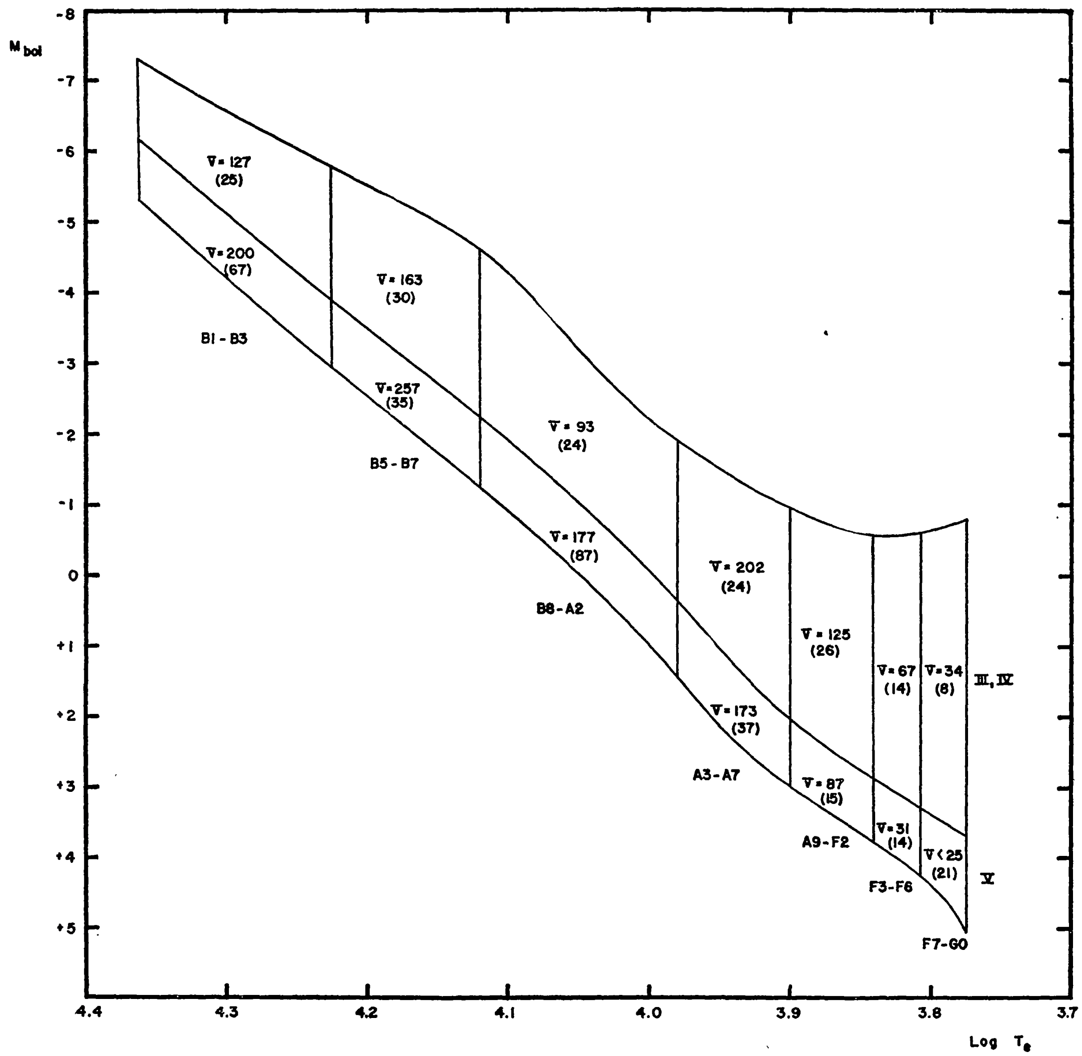

FIG. 6.—The variation of stellar axial rotation across the M_{bol} versus log T_e diagram, as determined from measured rotational velocities of 427 normal B1–G0 stars. The values of the mean true rotational velocities, $\bar{v}$, are listed for each group of stars, and the numbers of stars discussed in each group are given in parentheses.

and a finer resolution into spectral types and luminosity classes would be very desirable. The major observational problem is not so much the rotational velocities (which can be estimated rather rapidly, as well as accurately, by visual means) as it is the accurate classification into spectral types and luminosity classes, as Herbig and Spalding (1955) have pointed out. Outside the range of spectral types considered by the writer, the late-type stars to spectral class K5 have been investigated by Herbig and Spalding (1955), but more work is necessary for the O-type and early B-type stars. Although line broadening is observed for stars of all luminosity classes in this region, the role of axial rotation as a broadening agent is still uncertain. Until it can be distinguished from large-scale turbulence and any other broadening agents which may play a role, it will be difficult to arrive at any statistical analysis of axial rotation in these stars.

I am extremely grateful to Dr. W. W. Morgan for valuable information regarding problems of spectral classification encountered in this investigation and, in general, for his continued interest and encouragement while this work was going on. Thanks are also due Dr. P. C. Keenan, for his help in the classification of the G-type and composite spectra, and Dr. George H. Herbig, for very kindly sending a copy of his and Mr. J. F. Spalding's paper in advance of publication. All the microphotometer tracings and a large part of the reductions were carried out by Mr. Robert F. Howard, whose help I gratefully acknowledge.

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