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SPECTRAL CLASSIFICATION OF THE HIGH-VELOCITY STARS*

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ABSTRACT

Spectral types and absolute magnitudes are determined for 108 suspected high-velocity stars; 83 of these are accepted as probable members of the high-velocity group defined by a minimum space motion of 85 km/sec.

In their distribution over the spectrum-luminosity diagram, these stars appear to be intermediate between normal low-velocity stars and the stars which are members of globular clusters.

For stars of types G and K the spectral peculiarities associated with high velocity are termed the "cyanogen discrepancy" for convenience and are evaluated by several criteria, of which the most sensitive is the line ratio 4172/4216 in the range from G6 to K4. Stars of a given type and luminosity show a considerable range of values of the cyanogen discrepancy, which accordingly appears as an additional variable of classification.

I. THE PROBLEM OF CLASSIFICATION

The construction of a spectrum-luminosity diagram for the stars with high space velocities involves difficulties peculiar to these objects. In the first place, the course of the giant branch cannot be directly established by trigonometric parallaxes, for in the entire northern sky there are only about five giants and subgiants which have both accurately known parallaxes and large space velocities. At the same time, the very definition of the high-velocity group rules out most of the usual statistical methods of finding mean distances by the use of radial or tangential velocities. Such methods assume that the peculiar motions have small dispersion and (usually) random distribution—conditions which are known to be violated when the stars are selected by their high speeds.

For these reasons the present investigation attacks the problem by direct spectroscopic estimates of the luminosities of stars belonging to the group. This method is also open to objection, for the spectra of the high-velocity stars are known to exhibit peculiarities in the strengths of some of the features which are normally used as criteria of classification. The more serious effects are the general weakening of the lines of hydrogen and the metals in spectra of types F5–G5,[1] and the marked weakening of the bands of

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[1] N. G. Roman, *Ap. J.*, **112**, 554, 1950.

CN in types G8–K3.[2] The change in absorption within the λ 4216 band affects the intensities of most of the metallic lines between 4143 A and 4216 A.

The essential question is whether criteria can be found in which the effects of the high-velocity peculiarities are either very slight or tend to counterbalance one another. Examination of the spectra of the near-by standard stars of high velocity (listed in Table 1) showed that these requirements are met by the following spectral features:

1. Ratios *Hδ/Ca* 4226, *Hγ*/4325, and strength of the G band. Useful for assigning types in the range F5–K0. In stars later than G5 some weight is given also to the absolute intensities of the metallic lines.
2. Ratios *Cr* 4254/*Fe* 4250 and *Fe* 4260. Useful for assigning types in the range G8–K5.
3. Absolute intensities of the *TiO* bands. Define subdivisions of type M.
4. Ratios *Sr* II 4077/*Fe* 4045, *Fe* 4063, and *Fe* 4071. Useful for estimating luminosities in the range F5–M5.

TABLE 1

HIGH-VELOCITY STARS AT KNOWN DISTANCES

Star	m_v	Parallax (p)	Source of Parallax	M_v	Type	Space Velocity (Km/Sec)
μ Cas	5.26	0″136	Trig.	+5.9	G5 V+	145
γ Leo A	2.61	.017	Trig.+dyn.	−1.2	K0 III−	113
γ Leo B	3.80	.017	Trig.+dyn.	0.0	G7 III+	113
HR 4550	6.46	.116	Trig.	+6.8	G7 V+	290
α Boo	0.24	.090	Trig.	0.0	K1 III	103
HD 135204	7.5	.056	Trig.	+6.2	G8 V	108
31 Aql	5.23	.059	Trig.	+4.1	G8 IV	120
η Cep	3.59	.071	Trig.	+2.7	K0 IV	87
61 Cyg A	5.57	0.292	Trig.	+7.9	K5 V	88

5. Ratio 4172/4185. Each of these two absorption features is a blend of several atomic lines and lies within the area affected by the 4216 *CN* bands. Nevertheless, their ratio remains a useful criterion of luminosity in the range G5–K2. In using this criterion, correction must be made for the slightly enhanced intensity of 4172 in the high-velocity stars.

The first four of the above criteria are well known and are generally employed in the classification of normal stars. It should always be remembered that all these criteria were chosen for their applicability to spectrograms with scales ≈ 100 A/mm. If one wishes to classify high-velocity stars on plates differing greatly from this moderately low dispersion, the criteria must be re-examined.

II. OBSERVATIONAL MATERIAL

The spectrograms employed in this investigation were taken with the two-prism spectrograph on the 69-inch reflector during the period July, 1948, to August, 1952. About 25 per cent of the spectrograms were made with the Pβ camera, which gives a scale of 54 A/mm at *Hγ*; but, after it was found that the images obtained with the new PGγ camera (scale 104 A/mm at *Hγ*) were very satisfactory for classification, the remainder of the program was carried out with this camera. For the great majority of the suspected high-velocity stars on the program, at least two good spectrograms of each were obtained. Altogether, more than 240 spectrograms of the program stars were judged

[2] Morgan, Keenan, and Kellman, *An Atlas of Stellar Spectra* (Chicago: University of Chicago Press, 1943), Pl. 45.

satisfactory for classification and were compared with several hundred comparison spectrograms of standard stars with either MKK types from the *Atlas of Stellar Spectra* or additional types on the same system.

The observing list for the high-velocity group was made up chiefly of stars with estimated space motions in Miczaika's catalogue[3] exceeding 80 km/sec, or with radial velocities exceeding 60 km/sec if the space velocity had not previously been estimated. The published radial velocities of Moore's catalogue,[4] Redman,[5] Shajn and Albitzky,[6] Joy and Wilson,[7] and Moore and Paddock[8] were drawn upon. The stars chosen were mostly brighter than the eighth visual magnitude and north of $-20°$ declination. Stars earlier than F0, variable stars, and *CH* stars, for all of which the spectroscopic criteria of luminosity are of doubtful validity, were excluded. Although no claim of completeness even within these limits is made, the group chosen appears to be representative of the brighter nonvariable stars with relatively large space motions.

Of this group, the spectra of 108 stars proved suitable for classification, and spectral types and luminosity classes were assigned. The quality of the plates permitted interpolation to about a third of a subdivision in both co-ordinates. The luminosity classes were then converted to visual absolute magnitudes by means of the reduction table given by Keenan and Morgan.[9] This table was constructed chiefly from data for stars having normally low velocities, and its application to the luminosity classes defined by the slightly different criteria of the high-velocity stars might be expected to lead to some systematic errors in the derived absolute magnitudes. For this reason it is important to take into account every bit of evidence which might give clues to the detection of such systematic effects.

The first check on the luminosities of the giant branch was furnished by the 21 high velocity giants and subgiants with apparent magnitudes between 3.5 and 5.5 and types later than G0. The trigonometric parallaxes of these stars are not large enough to define their individual distances precisely, but the group mean should be significant. The mean trigonometric parallax of the group, reduced to the fourth magnitude, is $0\overset{''}{.}031$. The mean spectroscopic reduced parallax is $0\overset{''}{.}027$, giving a difference $\bar{P}_s - \bar{P}_t = -0\overset{''}{.}004$ with a mean error of $\pm 0\overset{''}{.}0031$. The difference implies that our spectroscopic estimates make the luminosity too bright by 0.3 mag. Since, however, the difference is comparable to its error and nearly all the negative excess comes from the two stars η Sct and 31 Aql, we do not feel justified in applying any systematic correction. Rather, the comparison suggests that the spectroscopic absolute magnitudes of the high-velocity stars are comparable in accuracy to those of normal low-velocity stars. We shall, therefore, assume a probable error of 0.8 mag. in discussing the observations.

This comparison with the trigonometric data serves to confirm the luminosity scale for absolute magnitudes up to $M_v \approx 0$, but says very little about any stars which may lie above the middle of the usual giant branch. The possible existence of such objects among the high-velocity stars bears upon the question of their relationship to the members of globular clusters. Both groups have been generally considered as belonging to population type II, as defined by Baade,[10] particularly since Popper[11] noted some similarities in their spectral peculiarities on his low-dispersion plates.

[3] *A.N.*, **270**, 249, 1940.
[4] *Pub. Lick Obs.*, Vol. **18**, 1932.
[5] *Pub. Dom. Ap. Obs. Victoria*, **6**, 27, 1931.
[6] *M.N.*, **92**, 771, 1932.
[7] *Ap. J.*, **111**, 221, 1950.
[8] *Ap. J.*, **112**, 48, 1950.
[9] *Astrophysics: A Topical Symposium* (New York: McGraw-Hill Book Co., 1950), chap. ii.
[10] *Ap. J.*, **100**, 137, 1944; *Mt. W. Contr.*, No. 696.
[11] *Ap. J.*, **105**, 204, 1947.

Spectrograms of several of the brightest stars in M3 and M92, taken on a scale of 38 A/mm, have been discussed by Baum,[12] and these plates were made available to us for comparison with the material on the high-velocity stars.[13] The cluster spectra showed peculiarities, such as the weakening of *CN* and metallic lines, developed to a much greater degree than in the spectra of high-velocity stars. Judged by the distance moduli given by Baum, the values of M_v for these most luminous cluster members must be close to -3.

The comparison of the plates established the fact that no stars very similar to these are included among the high-velocity objects studied here. The two stars from the Perkins list which were assigned the highest luminosity are HR 965 ($M_v = -1.5$:) and HR 1908 ($M_v = -2.5$); and each of these has much closer spectroscopic resemblance to ordinary supergiants of low velocity than to the bright cluster stars. Thus the classification of even the brightest high-velocity stars should not be greatly in error, though additional comparisons with somewhat fainter cluster stars should be made whenever spectrograms of the latter can be obtained.[14] One modification in the criteria of luminosity has already been indicated by the cluster spectra, which show that in such objects the intensity of *Sr* II 4077 does not continue to increase with luminosity as rapidly as in standard supergiants. At least an incipient effect of this sort might be looked for in those high-velocity stars which show the characteristic peculiarities most strongly. Accordingly, we have taken into account other criteria, such as the intensity of the G band and the ratio 4376/4383, which begin to become sensitive at the higher luminosities, in classifying any high-velocity stars which are suspected of being brighter than an average giant. The resulting changes in assigned luminosities never amounted to more than a few tenths of a magnitude.

The spectroscopic absolute magnitudes of the high-velocity stars, given in column 6 of Tables 2 and 3, are the spectroscopic values except for the near-by stars. Trigonometric parallaxes (designated by "t") are given when they exceed 0".060 and for a few F- and G-type dwarfs in which the weakening of the metallic lines is so pronounced that no reliable spectroscopic estimates of luminosity could be made. If the mean of the spectroscopic and trigonometric parallaxes lay in the range between 0".020 and 0".059, this mean is given in the tables, followed by the symbol "s, t." Thus the adopted parallaxes and absolute magnitudes in Tables 2 and 3 differ in a few cases from the trigonometric values of the calibration stars in Table 1.

There is also the possibility of errors in the assignment of types. For the stars later than G5 there is no reason to expect appreciable errors, for the relative intensities of lines of the several metals give consistent results. For the earlier stars there is a more serious possibility of systematic effects, since there is evidence that the hydrogen lines are enhanced relative to the metallic lines.[14a] When the Balmer lines are used for classification, the resulting type is too early as compared to the type obtained from relative intensities of metallic lines or from color temperatures. The effect is greatest in the small group of high-velocity dwarfs which have sometimes been assigned to type A, but for which later types are indicated by their colors and by analyses of their atmospheres.[15] Of these stars only HD 140283 is included in Table 2, since the luminosities of the others are uncertain. For HD 140283 the trigonometric parallax of 0".03 has been used, together with the type A8.[16]

[12] *A.J.*, **57**, 222, 1952.

[13] We are greatly indebted to Dr. Baum and to Dr. O. C. Wilson for sending these plates for examination.

[14] The importance of such comparisons has been particularly emphasized by Dr. Baade in discussions with the authors.

[14a] M. and B. Schwarzschild, *Ap. J.*, **112**, 248, 1950; cf. also the notes to Table 2 following.

[15] Chamberlain and Aller, *Ap. J.*, **114**, 52, 1951.

[16] Dr. J. L. Greenstein has kindly made available his unpublished estimate that the relative intensities of lines on coudé spectrograms of this star indicate a type within the range A6–F0.

TABLE 2

NON-VARIABLE HIGH-VELOCITY STARS

Star	α(1950)	δ(1950)	m_v	Type	M_v	p	$\mathring{V}$	W_o	W_o-r_w
HD 26	$0^h02^m.8$	+ 8°30'	8.2	G4p ?			-213		
HD 2901	0 30.0	+53 51	7.10	K2 III	+0.3	*.0044 s	-107	131	129
ε And	0 35.9	+29 02	4.52	G5 III+	+1.6	.026 s,t	- 84	103	88
HD 5780	0 56.8	+ 0 31	7.78	K5 II-III	-1.4	.0015 s	-103	348	290
HR 316	1 04.0	+56 40	6.58	K2 III+	+0.8	.0069 s	- 94	133	106
μ Cas	1 04.9	+54 41	5.26	G5 V+	+5.5	.136 t	- 97	145	141
HD 6755	1 06.5	+61 17	7.8	F8 V	+4.1:	.018 s	-325	352	329
HD 6833	1 07.2	+54 28	7.10	G8 III	+0.3	.0043 s	-257	259	257
HR 375	1 16.1	+77 18	6.38	G5 III+	+1.1	.0087 s	- 73	90	74
HR 452	1 32.9	+40 49	6.39	K1 III	+0.6	.0069 s	+ 66	105	82
56 And	1 53.2	+37 00	5.82	G8 III+	+0.9	.0105 s	+ 59	91	72
HR 645	2 10.3	+50 50	5.40	G8 III:	+0.3	.0095 s	+ 28	176	113
27 Ari	2 28.1	+17 29	6.41	G5 III-IV	+1.8	.012 s	-117	126	123
HD 16397	2 35.5	+30 36	7.21	G0 V	+4.6	.030 s,t	-100	145	119
HR 965	3 20.1	+84 44	5.78	G3p:II	-1.5:	.0035 s	+ 33	188:	122
HD 21910	3 32.7	+74 36	7.60	G8 III+	+1.0	.0048 s	-104		
14 Tau	3 40.9	+19 31	6.34	G8 III	+0.3	.0063 s	+ 78	110	85
HD 23841	3 45.8	+ 9 30	6.95	K1 III	+0.1	.0043 s	- 80	119	101
HD 28424	4 26.7	+13 47	7.76	K1 III+	+0.4:	.0033 s	+ 94	236	
40 φ² Ori	5 34.2	+ 9 16	4.39	G6 III-IV	+1.6	.027 s,t	+ 99	94	87
HR 1908	5 34.3	+11 00	6.10	K4 II	-2.5	.0019 s	-112	173	141
δ Lep	5 49.2	-20 53	3.90	G8+ III	+0.3	.019 s	+ 99	185	128
HR 2065	5 52.4	-11 47	5.81	K3+ III-	-1.0:	.0043 s	+ 87	110	102
HR 2153	6 04.9	+41 04	6.42	G9 III+	+0.9	.0080 s	- 86	94	80
θ CMa	6 51.9	-11 58	4.25	K3+ III	+0.6	.018 s,t	+ 97	85	81
32 υ² Cnc	8 30.0	+24 15	6.41	K0 III	0.0	.0052 s	+ 75	90	74
HR 3578	8 56.4	-15 56	5.92	F6 V	+3.2	.029 s,t	+122	126	118
HD 77236	8 58.7	- 2 22	7.87	K0 III	+0.2	.0029 s	+142	130	129
HD 77408	9 00.2	+33 05	7.08	F6 IV	+2.9	.0144 s	+ 70	139	99
HD 81192	9 21.9	+20 00	6.67	G7 III+	+0.6	.0061 s	+136	161	140
γ Leo A	10 17.2	+20 06	2.61	K0 III-	-1.2	.017 t,d	- 37	113	77
γ Leo B	10 17.2	+20 06	3.80	G7 III+	0.0	.017 t,d	- 37	113	77
HD 94028	10 48.8	+20 33	8.1	F4 V+:	+3.8:	.014: s	+ 62	180	175
HD 94190	10 51.3	+77 21	7.04	M3 III-	-1.0	.0025 s	- 90	87	80
75 Leo	11 14.7	+ 2 17	5.44	M0 III+	+0.4	.0098 s	- 59	96	76
HD 100041	11 28.3	+28 44	7.00	M3 III+	0.0	.0040 s	+ 85	121	99
HR 4550	11 50.1	+38 05	6.46	G7 V+	+6.8	.116 t	- 98	290	286
HR 4609	12 02.7	+77 11	5.96	G9 III	+0.2	.0070 s	- 19	131	83
HR 4657	12 12.6	-10 01	6.12	F5 V	+3.4	.029 s,t	+ 6	165	104
16 Vir	12 17.8	+ 3 35	5.10	K1 III+	+0.5	.012 s	+ 36	106	72
HD 107760	12 20.1	+73 31	8.2	G7 V	+5.7	.032 s,t	- 98	92	89
HD 108910	12 28.1	- 3 47	7.06	K3+ III	0.0	.0039 s	+ 84	111	95
33 Vir	12 43.3	+ 9 53	5.86	K1 III-IV	+1.9	.0159 s	+ 51	169	114
HR 5102	13 30.4	+24 36	6.18	G8 III	+0.5	.0073 s	+ 7	141	90
87 Vir	13 44.2	-17 34	5.79	M2+ III-	-0.9	.0046 s	+ 63	105	82
α Boo	14 13.4	+19 27	0.24	K1 III	0.0	.090 t	- 5	103	97
HR 5455	14 34.3	-12 06	6.24	F5 V	+3.5	.032 s,t	- 70	146	101
HR 5464	14 36.3	+43 51	5.92	K2 III	0.0	.0065 s	- 48	118	78
11 Lib	14 48.2	- 2 05	5.05	G8+ III-	-0.5	.0077 s	+ 83	149	116
HD 134063	15 05.1	+22 45	7.7	G5 III+	+1.2	.0050 s	-108		
HD 134088	15 05.5	- 7 43	8.1	G0 V:	+4.4	.018 s	- 59	123	119
HD 135204	15 11.4	- 1 09	6.7:	G8 V	+5.5	.058 s,t	- 70	114	108
5 Ser	15 16.7	+ 1 57	5.18	F8 III-IV	+2.6	.030 s,t	+ 54	122	91
HD 140283	15 40.4	-10 46	7.26	A8 V	+4.7	.031 t	-170	231	203
HR 6014	16 06.7	+ 6 31	6.02	K1+ III-IV	+2.6	.021 s,t	- 3	163	103
HR 6128	16 25.0	- 7 29	5.45	M2+ III:	-1.0	.0051 s	+100	180	152
HD 148816	16 28.0	+ 4 18	7.45	F8 V+	+4.5	.026 s,t	- 52	256	161
48 Her	16 47.3	+30 02	6.68	K1 II-III	-1.5	.0023 s	- 43	205	131
HR 6286	16 51.9	+47 30	6.30	K2 III	0.0	.0055 s	- 62	96	70
HR 6364	17 04.2	+22 09	5.72	K3+ III	-0.2	.0066 s	- 96	107	88

TABLE 2 - Continued

NON-VARIABLE HIGH-VELOCITY STARS

Star	α(1950)	δ(1950)	m_v	Type	M_v	p	V	W_o	W_o-r_w
HD 157089	$17^h18^m.6$	+ 1°29'	6.96	F9 V	+4.5	.032 s,t	-162	152	146
HD 162756	17 50.3	- 7 54	7.60	G0 IV-V	+3.8	.018 s	-125	140	121
HD 165401	18 03.2	+ 4 39	6.83	G0 V	+4.8	.040 s,t	-124	109	106
HR 6840	18 14.2	- 3 01	6.11	G3 III-	-0.3:	.0053 s	+ 1	240	152
HR 6853	18 15.5	+40 54	6.10	G8 III	+0.5	.0076 s	- 74	125	88
35 ν² Sgr	18 52.0	-22 44	5.04	K3+p		.037 t	-110		
31 Aql	19 22.5	+11 50	5.23	G8 IV	+3.8	.052 s,t	-100	120	96
α Vul	19 26.7	+24 34	4.63	M0+ III	-0.4	.010 s	- 86	106	82
HD 184499	19 31.6	+33 05	6.61	G0 V	+4.3	.035 s,t	-162	161	155
HR 7523	19 43.1	+40 36	6.44	M3 III	-0.5	.0041 s	- 96	101	85
HR 7680	20 03.0	+15 21	6.56	M2+ III-	-0.9	.0032 s	-110:	103	94
HD 191046	20 03.6	+36 05	7.17	G9 III+	+0.6	.0048 s	-100		
HD 195019	20 26.0	+18 36	6.85	G3 IV-V	+4.2	.0295 s	- 93	89	81
HR 7841	20 28.3	+45 45	6.59	K2+ III:	0.0:	.0048:s	- 31	158	100
η Cep	20 44.3	+61 39	3.59	K0 IV	+2.8	.071 t	- 87	87	85
HD 199191	20 51.9	+54 20	7.16	G8 III+	+0.9	.0055 s	-195	233	195
61 Cyg A	21 04.7	+38 30	5.57	K5 V	+7.9	.292 t	- 65	89	88
61 Cyg B	21 04.7	+38 30	6.28	K6 V	+8.6	.292 t	- 63	88	87
HR 8165	21 18.8	+23 38	5.82	K1 III	+0.1	.0071 s	- 89	180	125
HR 8325	21 44.1	+25 19	6.48	K3- III-III+	+0.4	.0061 s	- 45	123	81
HD 213893	22 32.0	+ 0 20	7.02	K5+ III	-0.3	.0034 s	- 89	136	104
γ Psc	23 14.6	+ 3 01	3.85	G5 III	+0.7	.023 s,t	- 13	140	89
HR 8875	23 17.3	+48 05	6.35	K1 III+	+0.5	.0068 s	+ 23	133	86
14 And	23 28.8	+38 58	5.34	K0 III+	+0.7	.012 s	- 59	111	79
HD 221830	23 33.0	+30 44	6.72	F9 V	+4.4	.035 s	-103	119	103

Remarks on the Spectra

HD 26	Very peculiar; similar to CH stars.
HD 2901	CN weak; H_δ, H_γ, 4172 slightly strong.
ε And	Most lines weak; CN weak; 4172 and CH strong.
HD 5780	CN slightly weak; 4143 strong.
HR 316	Normal except 4172 slightly strong; 4352 strong.
HD 6755	Atomic lines very weak; CH strong. Classified from Mt. Wilson spectrograms.
HD 6833	CN quite weak; 4172 strong.
HR 375	CN slightly weak; 4172 and CH strong.
HR 452	H_δ slightly strong.
56 And	CN slightly weak? 4172 slightly strong.
HR 645	CN strong.
27 Ari	4172 slightly strong.
HR 965	CH strong; CN and 4077 consistent in indicating luminosity class II.
HD 21910	4172 slightly strong. No proper motion published.
14 Tau	4172 strong.
40 φ² Ori	Atomic lines and CN weak.
HR 1908	CN slightly weak: 4172 strong.
δ Lep	CN weak; 4172 slightly strong.
HR 2065	CN slightly weak.
θ CMa	CN weak; 4172 slightly strong?
32 ν² Cnc	CN strong.
HR 3578	Weak lines.
HD 77236	CN weak; H_δ, 4172, 4143 strong.
HD 81192	PGC 2527. CN and metallic lines weak; 4172 slightly strong.
γ Leo A	CN slightly weak; 4143 strong.
γ Leo B	CN slightly weak; 4172 slightly strong.
HR 4550	Groombridge 1830. Normal dwarf spectrum except that CH may be slightly weak.
HR 4609	CN slightly weak; 4172, H_δ slightly strong; 4143 strong.
16 Vir	CN slightly weak; 4172 strong.
HD 108910	CN weak.

TABLE 2 - Continued

Remarks on the Spectra

33 Vir	CN weak.
HR 5102	CN slightly weak.
87 Vir	Ca 4226 weak; 4172 slightly strong? H_δ strong.
α Boo	CN slightly weak; 4172 strong.
HR 5464	CN weak; H_δ,H_γ, 4172, 4143, 4025 strong.
11 Lib	CN slightly weak; 4172 strong; H_δ slightly strong.
HD 134063	Metallic lines weak; CH and 4016 strong.
5 Ser	4172 slightly strong?
HD 140283	Metallic lines very weak.
HR 6014	CN weak; 4172 strong.
HR 6128	CN weak; H_γ slightly strong.
HD 148816	Lines slightly weak.
48 Her	CN weak! 4172, 4025 strong.
HR 6286	H_δ slightly strong; 4172 slightly strong?
HD 157089	CH slightly strong?
HD 162756	CH slightly strong?
HD 165401	All lines except 4172, 4187 slightly weak.
HR 6840	Lines slightly weak; CH strong.
HR 6853	CN weak! Atomic lines slightly weak? CH slightly strong.
35 ν^2 Sgr	Very peculiar. CH and CN very strong. CH star? 4143 strong. Luminosity uncertain; H_δ, H_γ too weak for a supergiant spectrum.
31 Aql	H_δ, H_γ, Mg4167 strong. 4172 slightly strong?
HD 184499	All lines weak; 4077 narrow.
HD 191046	CN weak; 4172, 4143 strong; H_δ slightly strong. No proper motion in G.C.
HR 7841	H_δ, 4172 slightly strong.
η Cep	4172 slightly strong.
HD 199191	CN weak! Other lines slightly weak? 4172 strong; 4143 slightly strong. Color may be abnormally red for type.
HR 8165	H_δ, H_γ slightly strong?
γ Psc	CN slightly weak.
14 And	CN slightly weak; 4172 strong.
HD 221830	CH slightly strong.

TABLE 3

DOUBTFUL HIGH-VELOCITY STARS (W_o-r_w 70 km/sec)

Star	α1950	δ1950	m_v	Type	M_v	p		V	W_o	W_o-r_w
μ Psc	$1^h27^m.6$	+ 5°53'	5.12	K3+ III+	+1.4	.018	s,t	+ 35	67	47
25 Eri	3 42.4	- 0 27	5.84	K4 III+	+0.6	.0091	s	+ 70	60	56
λ Aur	5 15.6	+40 03	4.85	G0 IV-V	+4.0	.067	s,t	+ 66	74	72
51 Ori	5 39.9	+ 1 27	5.24	K1- III+	+0.9	.014	s	+ 88	74	72
55 ψ^4 Aur	6 39.4	+44 34	5.17	K5 III+	+0.5	.0115	s	- 75	83	81
20 Mon	7 07.7	- 4 09	5.02	K0- III-IV	+1.7	.022	s,t	+ 79	83	75
81 Gem	7 43.2	+18 38	5.02	K3+ III+	+1.0	.016	s	+ 82	72	70
θ UMa	9 29.5	+51 54	3.26	F6 III-IV	+1.9	.052	t	+ 15	83	74
HR 4092	10 23.1	- 6 48	5.85	M0+ III+	+0.4:	.0081	s	+ 32	106	69
71 Leo	11 19.5	+17 42	7.04	K1 III-IV	+1.7	.0088	s	+ 6	70	44
HR 4586	11 57.7	+81 08	6.44	M3 III	-0.5	.0041	s	+ 31	83	59
9 Dra	12 58.2	+66 51	5.50	K0 III	+0.4	.010	s	- 31	53	36
HD 114960	13 11.3	+ 1 43	6.76	K4 III+	+0.6	.0058	s	+ 10	46	30
84 Vir	13 40.6	+ 3 47	5.7	K1+ III-IV	+1.9	.017	s	- 42	74	52
HR 5541	14 48.5	+37 28	5.50	K0+ III-IV	+2.3	.023	s,t	- 66	62	55
HR 5924	15 52.3	+20 27	5.76	M0 III-	-0.9	.0045	s	- 60	99	69
φ Ser	15 54.9	+14 33	5.66	K2 III+	+1.2	.0126	s	- 68	81	63
HR 6820	18 11.1	+21 51	6.25	K4 III	0.0	.0057	s	- 66	78	58
η Sct	18 54.4	- 5 54	5.04	K1 III+	+2.0	.025	s,t	- 93	78	76
69 Dra	20 01.0	+76 20	6.43	M3: III	-0.4	.0043	s	- 68	101	75
HR 7810	20 23.3	+09 54	6.46	K5: III+	+0.2	.0056	s	- 75	63	59
30 Vul	20 42.7	+25 05	5.13	K2- III+	+0.5	.012	s	+ 31	86	65
HD 211076	22 11.9	+16 56	6.59	K4 III+	+0.6:	.0063:	s	- 35	104	67

Remarks on the Spectra

μ Psc	CN very slightly weak?
25 Eri	CN very slightly weak?
λ Aur	Nearly normal; H_δ, H_γ slightly strong.
51 Ori	CN weak; H_δ, H_γ slightly strong?
20 Mon	CN slightly weak; 4172 slightly strong; 4143 strong.
81 Gem	CN weak; 4172 strong.
θ UMa	Lines slightly weak.
71 Leo	4172 slightly strong.
HR 4586	H_δ slightly strong.
9 Dra	CN weak; 4172, 4143 slightly strong.
84 Vir	4172 slightly strong.
HR 5924	H_δ, H_γ slightly strong.
HR 7810	CN slightly weak?
HD 211076	H_δ slightly weak?

The remaining stars in Table 2 are all of type F5 or later, and these F- and G-type stars all show the G band. Since, as will be shown below, the *CH* bands tend to be enhanced in the high-velocity stars, the strength of the G band through the range F5–G4 of their spectra corresponds to a later type than would be assigned from the ratios of hydrogen to metal lines. Thus the systematic effects in *H* and *CH* tend to cancel one another in classification, and it can be hoped that the types of these stars in Table 2 are at least reasonably consistent. Eventually it should be possible to use accurate colors and excitation temperatures to make any necessary systematic corrections.

There remains the question of which stars to accept as forming the high-velocity group. A limiting space motion (W_0) in the vicinity of 60–70 km/sec has been commonly used,[17] though the frequency curves of stellar motions do not serve to define any velocity sharply separating the stars into distinct groups. On the other hand, the spectroscopic data indicate that the peculiarities characteristic of the spectra of the most rapidly moving stars become noticeable in a majority of the stars having velocities greater than about 80–85 km/sec (see Fig. 4 and the notes to Tables 2 and 3), while, of the more slowly moving objects, only a few show any evidence of these peculiarities. On physical grounds, therefore, it is useful to make a separation near this velocity; and we shall somewhat arbitrarily set the limit at $W_0 \geqslant 85$ km/sec.

For our purpose of investigating the physical properties of the high-velocity group, it is not satisfactory to accept every star for which the estimated space motion exceeds this limit. It is important to select the sample so that it will not be contaminated by any considerable number of stars for which the true value of W_0 is less than 85 km/sec, but for which the measured motion appears to exceed this amount because of the errors of observation. The individual errors in W_0 will differ greatly from star to star. The radial velocities are usually known with probable errors not exceeding 2 km/sec; and any star with a measured radial velocity, corrected for the solar motion, of 87 km/sec or more has a high probability of actually belonging to the high-velocity group as defined here. On the other hand, if almost all the motion of a star is tangential to its direction from the sun, the measured value is affected not only by the error in the proper motion but even more seriously by the uncertainty in the parallax. Thus an error of 1 mag. in M_v, which is not unlikely, changes the computed tangential motion by 60 per cent. It is chiefly for this reason that many of the space velocities in Table 2 differ greatly from those found by other investigators. For example, the space motion of μ Psc was given by Miczaika as 114 km/sec, on the basis of a parallax of $0\overset{''}{.}011$. We estimate the luminosity of this K3 star as slightly, but definitely, below that of an average giant, and therefore assign it an absolute magnitude of $+0.8$. The corresponding spectroscopic parallax is $0\overset{''}{.}014$. The trigonometric parallax is $0\overset{''}{.}021 \pm 0.006$, large enough to deserve consideration. We therefore take a mean parallax of $0\overset{''}{.}018$ and find a corresponding space velocity of 67 km/sec, which necessarily removes the star from the high-velocity group.

Since many stars could similarly be shifted in or out of the group by quite reasonable adjustments in their measured distances, the aim of finding the properties of the real high-velocity stars can be attained best by rejecting those stars for which the probability of chance inclusion is greatest. Consequently, we shall require not only that $W_0 \geqslant 85$ km/sec but also that $W_0 - r_w \geqslant 70$ km/sec, where r_w is the probable error of the space velocity of that star. From the expression for the probable error of a function of observables, we have

$$r_w = \frac{1}{W_0}\left[V^2 r_v^2 + T^2\left(\frac{4.74}{p}\right)^2 r_\mu^2 + \frac{T^4}{p^2}\, r_p^2\right]^{1/2},$$

where T is the tangential velocity; r_v is the probable error of radial velocity; r_μ is the probable error of proper motion; and r_p is the probable error of parallax.

[17] J. H. Oort, *Groningen Pub.*, No. 40, 1926; Miczaika, *op. cit.*

If the parallax is derived from a spectroscopic absolute magnitude, the last term under the root sign becomes

$$\frac{T^4 r_M^2}{25\,(\text{Mod.})^2} = \frac{T^4 r_M^2}{4.70},$$

where r_M is the probable error of absolute magnitude.

In computing the probable errors in the final columns of Tables 2 and 3, a value of 0.8 mag. was assumed for r_M if the parallax of column 7 was obtained from our spectroscopic absolute magnitude, as indicated by the symbol "s." The same error was accepted for the means of trigonometric and spectroscopic parallaxes, except for a few cases where both values were rather large and agreed closely enough to justify adoption of the trigonometric error. All trigonometric parallaxes were taken from the Yale *General Catalogue of Trigonometric Stellar Parallaxes*.

In Table 3 are listed the stars which were observed but which failed to satisfy the velocity criteria for inclusion in the high-velocity group. These stars are excluded from the discussion of the following section.

III. THE LUMINOSITY-SPECTRUM DIAGRAM

Table 2 contains both luminosities and types for all the adopted high-velocity stars with the exception of HD 26 and 35 ν^2 Sgr. These two stars are notably peculiar for the strengths of the bands of the carbon compounds in their spectra and show similarities to the *Ba* II and *CH* stars.[18] The peculiarities preclude any significant spectroscopic estimate of their luminosities.

The luminosity-spectrum diagram for the remaining 83 stars of Table 2 is shown in Figure 1. Since the observing list contained relatively few stars with apparent magnitudes fainter than 7.5, the cooler and fainter part of the main sequence is only sparsely represented. For the purpose of giving a better picture of the location of the main sequence, four dwarf stars, for which radial velocities exceeding 100 km/sec were measured at Mount Wilson,[19] have been added. The trigonometric absolute magnitudes and the Mount Wilson types of these four stars are plotted as crosses.

The first question to be asked about the diagram is the extent to which it is distorted by "spurious" high-velocity stars—either those which have slipped in because of errors of observation or stars which have the physical properties of "low-velocity stars" (population type I?) but happen to lie on the upper tail of whatever velocity-frequency-curve these objects may have. The observations of the spectral peculiarities again furnish the most direct evidence; for giants in the range G5–K2, about one-third of those with $85 \leqslant W_0 < 100$ show no clear peculiarities and are, therefore, suspicious cases. In Table 2 there are 13 stars of all types in this velocity range, and accordingly we might expect four or five points in Figure 1 which do not correspond to real "high-velocity stars." Actually two such objects, HR 645 and 32 ν^2 Cnc, can be singled out as probably spurious just because they are G8–K0 giants, which should show the peculiarities but definitely do not. Among the giants later than K2 and the dwarfs of types G and K, which make up about one-quarter of the stars in Figure 1, there could easily be a couple of spurious cases, though we have found no spectroscopic means of detecting them.

Further evidence that few of the large space velocities of Table 2 are the result of chance errors is furnished by Figure 2, which shows the distribution in longitude of the projections of the velocity vectors on the galactic plane. The components from low-velocity stars are known to lie in all longitudes and would continue to do so if magnified by errors of observation. In Figure 2, however, no components exceeding 60 km/sec

[18] The peculiarities in the spectrum of 35 ν^2 Sgr were noticed by Morgan and Bidelman on Yerkes plates.

[19] A. H. Joy, *Ap. J.*, **105**, 96, 1947.

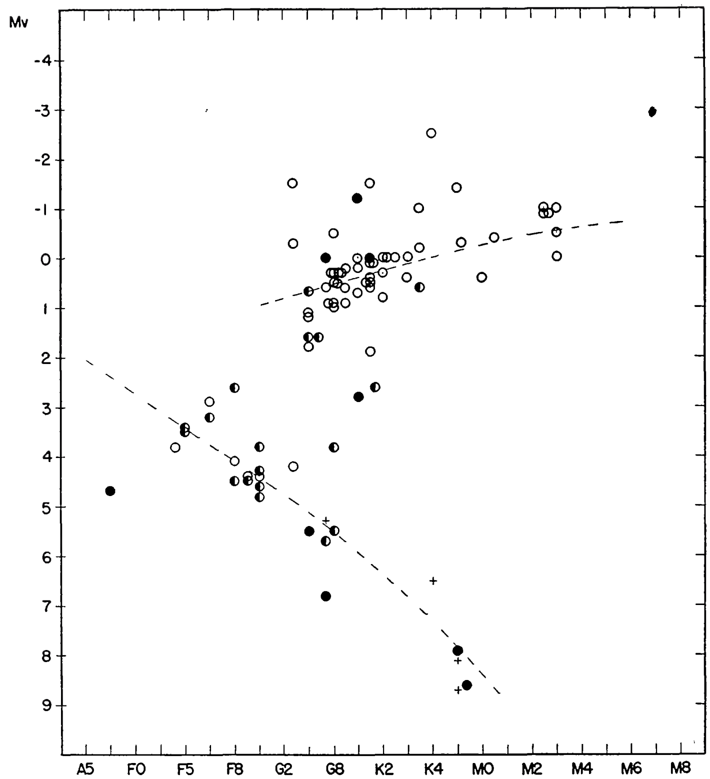

FIG. 1.—Luminosity-spectrum diagram for the high-velocity stars. Spectroscopic absolute magnitudes are plotted as open circles, trigonometric (and dynamical) as filled circles, and means of both as half-filled circles. The four dwarf stars classified at Mount Wilson are shown as crosses.

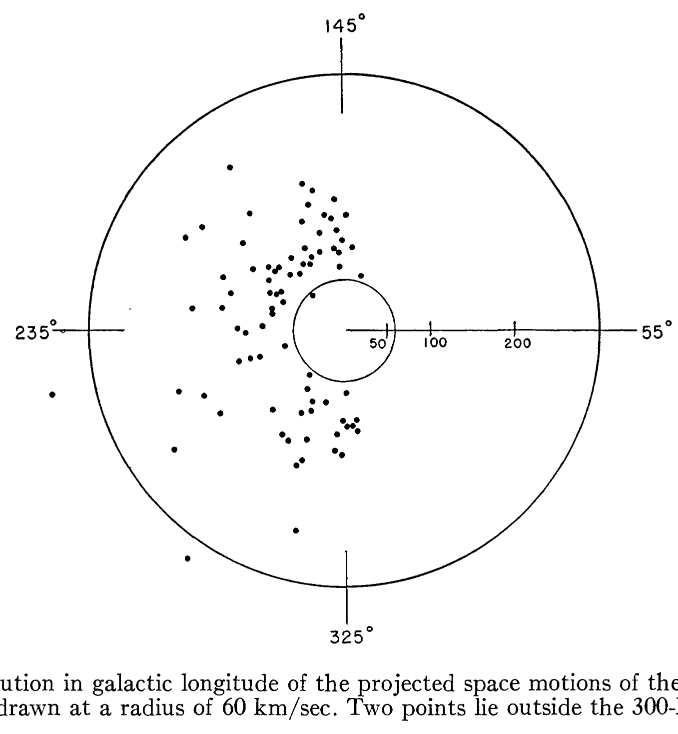

FIG. 2.—Distribution in galactic longitude of the projected space motions of the high-velocity stars. The small circle is drawn at a radius of 60 km/sec. Two points lie outside the 300-km/sec circle.

occur in the range from 340° to 120°. This zone of avoidance agrees well with that found originally for the high-velocity stars by Oort.[20]

On the whole, then, Figure 1 should give a reasonably good picture of at least the upper part of the spectrum-luminosity distribution of the high-velocity stars.

Inspection of the figure shows at once several already well-known features of the high-velocity group: the relative scarcity of both early-type stars and very bright supergiants, and the apparent tendency of large velocities to occur often among stars at the lower edge of the main sequence. This last point is not certain, for observations of many more faint dwarfs are needed properly to define the main sequence for the group.

The dashed lines in Figure 1 mark the approximate centers of the giant and main-sequence branches for normal stars of low velocity. The positions of these lines were estimated from the calibration of MKK luminosity classes against absolute magnitude for standard stars,[9] with some correction for the apparent centroid of the giant branch determined from the distribution of Mount Wilson[21] and Victoria[22] absolute magnitudes. The giant branch for high-velocity stars is also fairly well represented by the upper dashed line, though the real dispersion is large, as usual. When comparison is made with the steeply slanted giant branches for the stars in globular clusters,[11, 12] the *distribution of the high-velocity stars* could be described as *intermediate* between those of *cluster stars* and those of *low-velocity stars* in the vicinity of the sun. The major difference is the red giant branch extending well into type M for the high-velocity stars. It is worth noting that if the diagram is replotted to include only stars with space motions exceeding some larger amount, say 120 km/sec, the distribution of the remaining stars is not much different from that of Figure 1.

IV. SPECTRAL CHARACTERISTICS

The notes at the end of Table 2 summarize the spectroscopic differences remarked between the individual high-velocity stars and standard stars of the same type and luminosity. For *main-sequence stars later than G5* and for *M-type giants no consistent peculiarities are observed* on the low-dispersion spectrograms. Among the remaining stars the following characteristics tend to accompany large space velocities:

1. *General weakening of atomic lines.*—This characteristic of both giants and dwarfs in the range F5–G5 has been studied by Miss Roman,[1] who found a correlation with space motion in the sense that, while stars with low velocities might have either normal or weak absorption lines, "the conventional 'high-velocity' stars occur only in the weak-line group."

Among the giants (F5–G6) in Table 2, the general weakening of lines is noted in more than half (five out of nine). The effect is less striking among the main-sequence stars, where it is noted in only four out of fourteen dwarfs. These results do not mean that line weakening is definitely absent for the negative cases but merely that in such stars any such effect was not conspicuous enough to be noticed in the process of classification.

Among the giants of later type, general weakening of lines was observed in only three stars, all near type G8.

2. *Strengthening of the G band of CH.*—In Table 2, six out of the nine giants (F5–G6) are noted as having the G band unusually strong. In two of the stars (HD 6755 and 35 ν^2 Sgr) the enhancement is so pronounced that it is possible that these stars should be grouped with HD 26[23] as marginal members of the *CH* group of the carbon stars.

[20] J. H. Oort, *B.A.N.*, **4**, 273, 1928.

[21] W. S. Adams *et al.*, *Ap. J.*, **81**, 187, 1935; *Mt. W. Contr.*, No. 511.

[22] Young and Harper, *Pub. Dom. Ap. Obs. Victoria*, Vol. **3**, No. 1, 1924.

[23] Keenan and Keller, *Ap. J.*, **113**, 700, 1951.

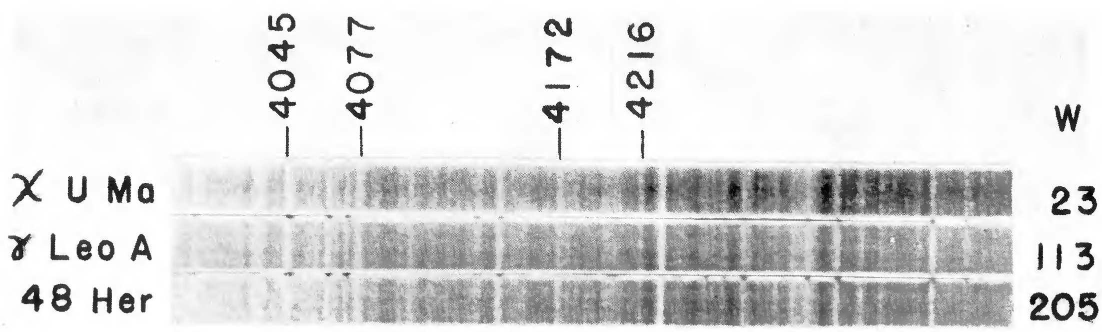

FIG. 3.—Spectra of three giants (K0–K1) of differing space motions. The two lower spectra represent stars in the high-velocity group.

Among the dwarfs, however, marked strengthening of *CH* is noted for only four out of the fourteen stars.

It appears that an abnormally strong G band or abnormally weak metallic lines are about equally good spectroscopic indicators of the high-velocity character among late F-type or early G-type stars.

3. *Weakening of the CN bands.*—On spectrograms with a scale ≈ 100 A/mm, none of the individual *CN* bands is resolved; but, since the strong head at 4216 A degrades to the violet, the ratio of intensities of the continuum just to the red and to the violet of λ 4216 is a fairly good measure of the strength of *CN* (see Fig. 3).[24]

It is helpful also to use the strength of the λ 4216 line itself, for the apparent line observed on low-dispersion spectrograms is a blend of the *Sr* II atomic line at 4215.5 A and the *CN* head at 4216.0 A. Since the λ 4216 blend is not used in classifying the high-velocity stars, the difference between its intensity in one of their spectra and in that of a standard star of the same luminosity and spectral type is another measure of abnormality of the *CN* absorption in the high-velocity star.

These two differential estimates define what can conveniently be termed the "cyanogen discrepancy" of any star. Photometric measurements to set up a scale for expressing the magnitude of this discrepancy are under way, but for the purposes of this paper it is sufficient to use the qualitative estimates given in the notes to Table 2. The peculiarities noted range from slightly greater than normal strength in the two stars, HR 645 and 32 v^2 Cnc, already mentioned, through slightly weak *CN* (γ Leo A), weak *CN* (δ Lep), to very weak *CN* (48 Her and HD 199191; see Fig. 3). Table 4 summarizes the

TABLE 4

RELATIVE INTENSITY OF *CN* IN HIGH-VELOCITY STARS

CN Intensity	No. of Stars	*CN* Intensity	No. of Stars
Strong	2	Weak	13
Normal	15	Very weak	3
Slightly weak	12		

estimates for giants in the range G5–K3+ and shows that, on the average, there is a *deficiency of CN* in the high-velocity group. Not included in this tabulation is the peculiar star 35 ν^2 Sgr, in which the absolute strength of *CN* is great, but its intensity relative to *CH* is low.

In this same group of giants the blended line at approximately 4172 A is noted as strengthened relative to near-by metallic lines in twenty-six out of the forty-five stars. This may be partly an absolute effect[25] and partly a relative enhancement due to the weakening of the partially overlying *CN* bands. It seems improbable that the latter effect can fully explain the behavior of λ 4172, for in passing from standard giants to subgiants we find that the reduced *CN* absorption is accompanied by weakening rather than strengthening of λ 4172.

From these observations we should expect that the *ratio* 4172/4216 would be a useful *spectroscopic criterion for the recognition of stars of high velocity*, and it has proved the most sensitive criterion on the spectrograms used in this investigation. A plot of the

[24] The relative intensities in the continuum on either side of λ 4216 were first used as a measure of *CN* strength by B. Lindblad, *Ap. J.*, **55**, 85, 1922.

[25] M. Schwarzschild and B. Schwarzschild have kindly informed us that their examination of λ 4172 on Mount Wilson coudé spectrograms permitted the identification of a number of metallic contributors, including several lines of iron, but that no one component was definitely enhanced in the high-velocity stars. Tracings of Perkins spectrograms of various dispersions indicate that in these stars the blending on the red side of the line causes an apparent widening which makes the line appear stronger on small-scale plates.

difference in the visual estimates of the two lines, against space velocity, is shown in Figure 4. The points for velocities below 60 km/sec were taken chiefly from standard stars. This selection may contribute to the absence of any ordinates above −2 among the low-velocity group, for the stars chosen as spectroscopic standards tend to be more homogeneous than stars selected at random. Nevertheless, the correlation of the 4172–4216 intensity difference with velocity appears definite. An intensity difference of −2 is ambiguous, but any star with a difference in the range −1.5 to +1.5 has a high probability of being a physical member of the high-velocity group.

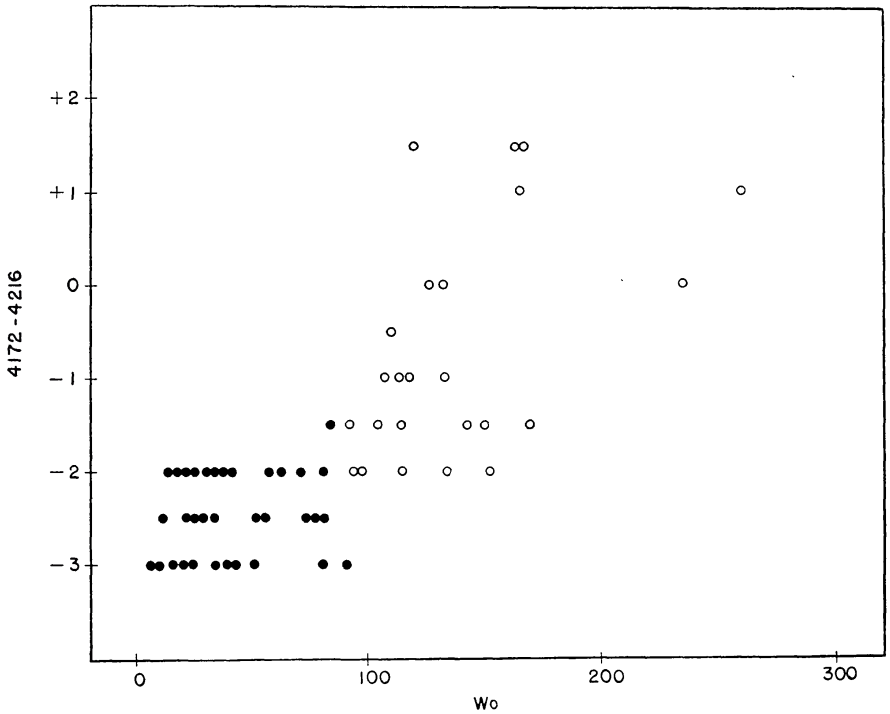

FIG. 4.—Plot of estimated differences in intensity of the lines 4172–4216 against space velocity (km/sec). Stars in the high-velocity group are shown as open circles.

This question may be raised: Does the diagram represent two slightly overlapping groups of stars which are homogeneous in the physical property measured by this line difference, or does it evidence a considerable range of values of a variable? The fact that the dispersion in the values of 4172–4216 is real, at least among the high-velocity stars, shows that the second alternative is true. The line difference clearly changes sign between such stars as γ Leo A and 48 Her (see Fig. 3), and it is unlikely that the points in the diagram are uncertain by more than half a step. For the three stars in the reproduction the values of the difference are: χ UMa, −2.5; γ Leo A, −1.5; and 48 Her, +1.5. These three stars are all bright giants, though 48 Her is probably somewhat more luminous than the other two and would, therefore, be expected to have *stronger CN* bands if the peculiarity were not present.

The general conclusions from the spectroscopic evidence are:

1. The spectra of the high-velocity giants and subgiants (G6–K4) show a *cyanogen deficiency* which can be measured either by the *break in the continuum at* λ *4216*, or by the *difference between the estimates of intensity of the lines* 4172 and 4216.

2. For stars in the range F5–G5, the corresponding characteristics are the general *weakening of atomic lines* (as discussed by N. G. Roman) and the *strengthening of the G band of CH*.

3. In stars of the same type and luminosity, a considerable range in the *cyanogen discrepancy* is observed. This quantity appears to represent another dimension in spectral classification, in addition to *temperature* and *luminosity*. Schwarzschild, Spitzer, and Wildt[26] have suggested that *chemical composition* is the variable involved.

It is a pleasure to thank Mrs. Mary Fenwick for her help in the computations and the preparation of the drawings.

[26] *Ap. J.*, **114**, 398, 1951.