RELATIONSHIP BETWEEN COLORS AND SPECTRA OF LATE MAIN-SEQUENCE STARS

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ABSTRACT

Spectrograms of 109 main-sequence stars of types G5 and later have been obtained at a dispersion of 10 A/mm and have been used to derive spectral types on the Yerkes system, based on ratios of metallic lines. A plot of the revised types against the old Mount Wilson types shows a very considerable scatter, which is believed to be due chiefly to errors in the Mount Wilson values. Nevertheless, even with the revised types, it is found that there is not a one-to-one correspondence between spectral type and photoelectric color for these field stars.

Spectral types of 69 Hyades main-sequence stars have been estimated from 38 A/mm spectrograms. For these objects the correlation of type and color is appreciably closer than for the field stars. It is suggested, following an argument based on the Vogt-Russell theorem, that these facts imply a greater degree of chemical non-uniformity in the local main sequence than in that of the Hyades. A number of instances of anomalous intensities of the hydrogen lines and of CN bands among the local main-sequence stars are indicated.

I. INTRODUCTION

In a previous paper (Wilson 1961) I called attention to the fact that when the Mount Wilson spectral types of main-sequence stars are plotted against Eggen's (1955) photoelectric colors, a rather curious distribution results. Down to type G5 the spread in color for a given type is small, but thereafter it increases, attaining a width of about 0.3 mag. in the middle K types. In order to see whether stars near the two boundaries of the distribution are spectroscopically distinguishable, 10 A/mm spectrograms of six pairs of stars were obtained. This material seemed to show conclusively that the redder stars of a given type had noticeably stronger H and K reversals and that the bluer stars had stronger hydrogen lines. Also, although the spectrograms were mostly too dense for accurate type estimates, comparison of the pairs of stars of each type seemed to show satisfactory agreement. Since these observations were most unlikely to be the result of pure chance, a report of the investigation was published.

It was realized at the time, however, that the validity of the conclusions was entirely dependent on the accuracy of the spectral types of the stars. The distribution of points in the plot mentioned above could be due entirely to errors in the spectral types, since the photoelectric colors must be considered as amply accurate, although this was not believed to be the case. Nevertheless, further spectrograms were obtained, of good density for estimation of type, and it quickly became apparent that many of the Mount Wilson types were indeed seriously inaccurate. The reasons for these inaccuracies also became obvious upon inspection of some of the old plates, most of which were obtained during the period 25–40 years ago with spectrographs and emulsions very much less efficient than those available today. Many of the spectra are extremely narrow and underexposed and are really capable of revealing only a rough indication of the true spectral type. Moreover, the Mount Wilson catalogue (Adams *et al.* 1935) contains nothing to indicate the authors' opinions as to the relative reliabilities of their results. The user, therefore, has no guidance as to the confidence he should have in any of the published types. Perhaps the only general precept is that the fainter the star, the higher the probability of an erroneous type.

At this point it was evident that the whole matter would have to be investigated *ab initio* with new spectrograms of good quality for the determination of spectral types of maximum reliability. A great deal of observing time could have been saved by using a rather small dispersion for this purpose, but for several reasons 10 A/mm was chosen. For one thing, in spectra rich in lines as these are, there is always the possibility that useful criteria might be found among lines too weak to be of value at lower dispersions. For another, it seemed likely that, for criteria depending on ratios of metallic lines, the higher dispersion would increase the accuracy of estimation. Third, it was desired to obtain as much information as possible about the H and K reversals, since these are the only spectral features which are known to vary widely among late main-sequence stars with otherwise very similar spectra. Finally, there is the more general point that these stars have never been examined in wholesale fashion with moderately high dispersion. Since this can now be done with modern equipment, it seemed desirable to do so.

II. THE VOGT-RUSSELL THEOREM

The Vogt-Russell theorem (Chandrasekhar 1939) states, subject to some quite general conditions, that the entire structure of a star is uniquely determined by its mass, m, and chemical composition. These two parameters therefore fix the radius and luminosity and consequently also the surface gravity, g, and effective temperature, Te. The chemical composition referred to here is that of the interior of the star, which we may denote simply by Xi.

In the absence of strong magnetic fields or of fairly rapid stellar rotation, the structure and physical state of the surface layers of a star must be determined by the chemical composition of these layers, Xs, and by g and Te. In fact, this is the basic assumption underlying the computation of model stellar atmospheres. It is presumably still valid even though the surface layers are not in strict hydrostatic equilibrium, since any dynamic activity in the outer stellar layers can only be caused by interaction between them and the radiant flux. Therefore, if we indicate symbolically by "L.S." a detailed description of the absorption line spectrum, we may write, in view of the Vogt-Russell theorem,

$$\text{L.S.} = \phi(Xs, g, Te) = \phi^1(Xs, Xi, m) . \tag{1}$$

The color of the star, indicated in general by C, is simply the difference in magnitudes between the emergent fluxes integrated over two wavelength bands. This difference will be a function of Te, of the general absorption coefficient, and of the differential blanketing between the two bands due to the influence of the absorption lines. Thus

$$C = \psi(Xs, g, Te, \text{L.S.}) = \psi^1(Xs, Xi, m) \tag{2}$$

by virtue of equation (1). The relationships indicated by equations (1) and (2) are, of course, quite complicated, but it seems physically reasonable to assume that, for a given choice of the independent variables, they would give results which are unique and single-valued. If so, the Vogt-Russell theorem implies that all stars of the same mass and the same values of Xi and Xs should have identical line spectra and identical colors.

Moreover, within a group of stars of constant Xi and Xs but variable m, one would expect to find a one-to-one correspondence between line spectrum and color. Another group of stars with different values of Xi and/or Xs would also yield a one-to-one correspondence between line spectrum and color, but, because of the complex way in which the independent variables are involved, the relationship between color and spectrum would in general not be the same for the two groups. Thus, if observation shows that there is not a one-to-one correspondence between spectrum and color for a group of stars, we must conclude either that Xi or Xs or both are variable within the group or else that factors not included in the derivation of the Vogt-Russell theorem, or in the simple theory of stellar atmospheres, are playing an important role.

Two possible factors of this kind—magnetic fields and rotation—were mentioned above. Both strong internal magnetic fields and rotation could introduce additional parameters into the equations of stellar structure which might limit the validity of the Vogt-Russell theorem. Strong surface fields might have an effect on the dynamical characteristics of the outer layers, and rotation would reduce g below its geometrical value and cause it to be variable over the stellar surface. Weak surface fields could produce changes in the details of the line spectrum but would probably not effect any major modification. It should be borne in mind also that some stars of high intrinsic luminosity show in their spectra effects due to macroscopic turbulence, and in these objects the effective surface gravities are presumably less than the geometrical values computed from the masses and radii. Whether these phenomena are simply dependent on the masses and chemical compositions or whether they imply some additional parameter does not seem to be known.

In any event, there is no evidence for any of the foregoing effects among the late main-sequence stars, with the possible exception of relatively weak surface magnetic fields, and there is good evidence against most of them. According to Babcock (1962), no large magnetic fields have been found among these stars, although admittedly they have not been investigated extensively. Also, as far as is known, atmospheric turbulence is always small in these objects, and rotational widening of the lines is extremely rare. At 10 A/mm some minor differences in line quality can be seen, but these are of slight degree and also infrequent and are probably to be attributed to small rotational widening. In fact, one is impressed much more by the essential uniformity of sharp lines throughout this part of the H-R diagram than by the very slight differences in this quality which occasionally appear. Therefore, it seems reasonable to assume that the implications of the Vogt-Russell theorem are valid for these stars and that, if they do not exhibit a one-to-one correspondence between color and spectrum, the most probable explanation is that there are variations in the chemical compositions. Otherwise it would be necessary to invoke some hitherto unanticipated phenomenon.

The foregoing ideas are the basis for the present investigation. Essentially the question is this: Among the later main-sequence field stars within range of observation are there, or are there not, stars of identical spectra with different colors or, conversely, stars of identical color with different spectra? The answer, as will be seen, appears to be definitely in the affirmative.

The scope of the investigation could be extended if there were available for observation a main sequence composed of stars all formed at about the same time out of portions of the same primeval mass of material. Such an opportunity—the only one at present—is offered by the Hyades. As a result of the work of many individuals, we now know with fair certainty a fairly large number of Hyades members extending down throughout the region of the main sequence with which we are concerned. Therefore, I have made spectrographic observations of a number of these stars also, covering the wavelength range 3900–4500 A. Since the apparent magnitudes of the relevant stars lie between the approximate limits 8.5 and 11.5, it was necessary to employ considerably smaller dispersion than for the field stars. In fact, for the Hyades observations I used the 8.4-inch camera of the Palomar coudé spectrograph, which yields a dispersion of 38 A/mm. The stars were trailed 12 mm on the slit, which gives a spectrum width on the plate of just under 0.25 mm. Spectra of this rather small width are not ideal for the estimation of spectral type, although they yield results of good consistency. However, since a considerable number of rather faint stars in the winter sky were to be observed, consideration of observing time requirements precluded any major increase in spectrum width.

III. STANDARD STARS AND ESTIMATION OF TYPES

The standard stars used throughout this investigation are those given by Johnson and Morgan (1953). These standards are well established and several stars are included as representative of most spectral subdivisions. Therefore, the spectral types derived by me are on the Yerkes system, although the criteria used are not those favored by the Yerkes observers. There are two reasons for this. First, the most useful criteria of spectral type in any given part of the H-R diagram are a function of the dispersion employed and must be selected by inspection of the spectra of the standards taken with that dispersion. Second, not all the Yerkes criteria are satisfactory for determining types among these late main-sequence stars. We shall return to this point later.

In Table 1 are listed the standard stars for which plates were obtained at the two dispersions used. In order to get a close match in density with the stars whose types are to be estimated, several spectra of different exposure times were made on most plates of the standard stars.

By intercomparison of spectrograms of the standard stars, one must determine which spectral features provide the most useful criteria of type. At 10 A/mm it is found that the weak lines, with one exception noted below, are not of value for this purpose. From G5

TABLE 1

STANDARD STARS (YERKES CLASS V)

Star	Type	10 A/mm	38 A/mm
HD 115043	G1		x
20630	G5	x	x
186427f	G5	x	.
101501	G8	x	x
131156A	G8	x	x
3651	K0	x	x
124752	K0	...	x
185144	K0	x	
165341A	K0	x	x
22049	K2	x	x
109011	K2	x	x
110463	K3	x	x
128165	K3	...	x
219134	K3	x	
201091	K5	x	x
201092	K7	x	x

to K3 the ratios 4254/4250 and 4274/4271 and the strength of the blend at 4290 all increase monotonically with type. At this dispersion the Fe lines at 4250.13 and 4250.80 are well separated, and the most valuable type indicator appears to be the ratio of λ 4254.35 Cr I to the Fe I line λ 4250.80. At G5, 4254.35 is slightly weaker than 4250.80; at G8, the two are about equal; and, at K0, 4254.35 is slightly stronger. The ratio 4274/4271, the 4290 feature, and λ 4226 Ca I all increase uniformly also, but they are somewhat less precise for type estimation, and I have regarded them as constituting secondary or confirmatory criteria.

Later than K3 the Fe I lines weaken, and the Cr I lines develop marked wings. Between K5 and K7 the weakening of the Fe I lines is quite pronounced, and the strength of λ 4260 seems to be the best criterion for separating these types. Stars between K3 and K5 are characterized by moderate weakening of Fe I and strengthening of Cr I and also by the rather sudden increase in a pair of weak features near λ 4242. These have been identified as band heads of Al H (Davis 1947), and, after increasing in strength at type K4, they do not change much more through K7.

The foregoing are the criteria employed in estimating spectral types from the 10 A/mm spectrograms. Standard stars which have been given the same spectral types by the Yerkes observers agree according to the above criteria as closely as one can estimate. As to interpolations between the standard subtypes, it is my feeling that attempts to do this between G5 and G8 or between G8 and K0 are futile. G5, G8, and K0 are certainly distinguishable, but the differences between successive types here are so small as to render accurate interpolations unlikely. Therefore, I have not attempted any. In this part of the sequence one may wonder why the hydrogen lines have not been used to improve matters, especially since these lines can be well seen at 10 A/mm. The reason is that the hydrogen lines are fairly frequently erratic in behavior and have intensities which would indicate a spectral type somewhat different from that derived from the metallic lines. This effect is present even among the Yerkes standards of the same types, and examples will be illustrated later in this paper.

Interpolation at the late end of the sequence is almost entirely restricted to the stars between K3 and K5. It is a curious fact that only a single field star has been classified as K5. All other stars in this region appear either slightly earlier than 61 Cyg A and have been called K4, or they agree more closely with 61 Cyg B and have been put at K7 except for one star, which has been placed at K6.

At 38 A/mm the classification is based entirely on the relative intensities of the whole group of lines $\lambda\lambda$ 4250, 4254, 4260, 4271, 4274, with λ 4290 and λ 4226 as secondary criteria. The $\lambda\lambda$ 4250–4274 group presents an intensity pattern which is quite characteristic for each type, and there is little difficulty in assigning each star to its appropriate place. Since the spectra are narrow, grain irregularities and clumping still produce noticeable effects, however. Thus the spectral types are based on essentially the same criteria for both the high and the low dispersions, although the details differ for the two groups. It is my opinion, based on a great deal of work with all the spectrograms, that the accuracy of classification is appreciably higher for the spectrograms of higher dispersion.

IV. RESULTS

The field stars observed are listed in Table 2, where they are grouped according to the spectral types which I have derived. The first six columns are self-explanatory except to note that, for a few stars not included in Eggen's (1955) list, $B - V$ values found in the literature were transformed to $P - V$ by use of the appropriate equations given by Eggen (1955). In the seventh and eighth columns are, respectively, the trigonometric parallaxes, probable errors, and number of measures taken from the Yale catalogue (Jenkins 1952) and the absolute visual magnitudes and probable errors computed from these parallaxes and Eggen's V's. Estimated intensities of the H and K reversals are given in column 9.

It is important to make sure as far as possible that the stars under consideration are really main-sequence objects, and to this end the absolute magnitudes and $P - V$ values from Table 2 are plotted in Figure 1. Stars with trigonometric parallaxes less than $0\overset{''}{.}030$ have been omitted and the remainder divided somewhat arbitrarily into groups with $0\overset{''}{.}030 \leq \pi < 0\overset{''}{.}060$, $0\overset{''}{.}060 \leq \pi < 0\overset{''}{.}090$, and $\pi \geq 0\overset{''}{.}090$, as indicated in the figure. It is necessary to appeal to the trigonometric parallaxes in this way because, as will be seen later, spectroscopic discrimination between luminosity classes IV and V is highly uncertain in this part of the H-R diagram.[1]

In any event, all but a few of the stars of the smallest parallax group lie within the indicated region having a vertical width of about 1.5 mag., which is defined by the stars of larger parallax. A good part of this apparent dispersion in luminosity is undoubtedly due to error in the parallaxes, and, though some of it is also probably intrinsic, we shall not attempt to discuss this point. Fourteen of the stars in Table 2 have trigonometric parallaxes less than $0\overset{''}{.}030$, or no parallax. Six of these, however, have H and K reversals whose widths clearly indicate that they are main-sequence objects. Of the remaining eight, one, HD 104556, is almost certainly a subgiant, since its parallax, although small,

[1] In Fig. 1, HD 82885 and 190007 have been inadvertently omitted, and HD 37065 and 74377 have been plotted one magnitude too high.

TABLE 2

FIELD STARS

Star	α(1960) h m	δ(1960) ° '	V	P−V	Mt. W. Type	π ± p.e. (0.001")	M_V ± p.e.	H−K	Rem.
					G5				
HD 186427f	19 40.8	+50 25	6.2	0.56	G2	34 ± 5 (4)	+3.9 ± 0.32	0	1
20630	3 17.3	+ 3 13	4.8	0.57	G5	105 ± 6 (3)	+4.9 ± 0.12	3	1
51219	6 54.5	+ 1 13	7.4	0.60	G5	26 ± 4 (4)		0	
					G8				
HD 196761	20 37.8	−23 55	6.4	0.60	G7	65 ± 7 (3)	+5.5 ± 0.23	0	
106116	12 10.5	− 2 52	7.4	0.60	G6	42 ± 6 (3)	+5.5 ± 0.31	0	
3443	0 35.3	−24 59	5.6	0.61	G7	70 ± 7 (3)	+4.8 ± 0.22	0	
14412	2 17.2	−26 08	6.3	0.61	K0	93 ± 8 (2)	+6.1 ± 0.19	0	
20794	3 18.3	−43 13	4.2	0.61	G7	156 ± 8 (2)	+5.2 ± 0.11	0	9
HD 158614	17 28.3	− 1 02	5.3	0.62	G6	50 ± 4 (6)	+3.8 ± 0.17	0	
116878	13 24.1	+44 42	8.3	0.62	-	-	-	0	
10700	1 42.2	−16 09	3.5	0.62	G4	275 ± 5 (4)	+5.7 ± 0.04	0	
101501	11 39.0	+34 26	5.3	0.62	G6	110 ± 8 (1)	+5.5 ± 0.16	2	1
154345	17 01.5	+47 08	6.8	0.62	K0	65 ± 7 (2)	+5.9 ± 0.23	0	
HD 145958A−B	16 11.4	+13 38	7.4	0.63	K0	50 ± 5 (3)	+5.9 ± 0.22	0−1	4
31501	4 55.3	+34 13	8.1	0.64	G8	18 ± 7 (3)		0	
190067	20 00.7	+15 29	7.1	0.65	G7	48 ± 7 (2)	+5.5 ± 0.32	0	
131156A	14 49.6	+19 16	4.5	0.65	G5	145 ± 4 (4)	+5.3 ± 0.06	3	1
152391	16 50.9	+ 0 03	6.6	0.65	G9	65 ± 5 (4)	+5.7 ± 0.17	3	
HD 190360	20 02.0	+29 47	5.7	0.66	G8	46 ± 6 (2)	+4.0 ± 0.28	0	
158633	17 25.1	+67 20	6.5	0.66	K1	75 ± 5 (4)	+5.9 ± 0.14	0	9
161198	17 41.6	+21 38	7.5	0.66	G8	47 ± 6 (2)	+5.9 ± 0.28	0	
82885	9 33.3	+36 00	5.4	0.68	K0	107 ± 5 (4)	+5.7 ± 0.10	1	3
164922	18 00.9	+26 19	7.0	0.71	K0	48 ± 7 (2)	+5.4 ± 0.32	0	
HD 182488	19 22.1	+33 08	6.4	0.72	K1	57 ± 5 (1)	+5.2 ± 0.19	0	2:, 3
104556	12 00.4	+43 19	6.6	0.77	G9	10 ± 5 (3)		0	
9540	1 31.4	−24 23	6.9	0.77	G8	64 ± 8 (2)	+5.9 ± 0.27	2	
175541	18 53.7	+ 4 13	8.0	0.82	K0	65 ± 13 (1)	+7.1 ± 0.43	0	3
					K0				
HD 100623	11 32.5	−32 37	6.0	0.68	K2	99 ± 7 (2)	+6.0 ± 0.15	1	
10780	1 44.8	+63 39	5.6	0.68	K0	111 ± 6 (3)	+5.8 ± 0.12	2	
HD 185144	19 32.4	+69 35	4.7	0.69	G8	179 ± 5 (3)	+6.0 ± 0.06	0	1
+41° 3306	19 17.7	+41 34	8.9	0.70	K1	27 ± 6 (2)		0	2:
HD 112758	12 57.0	− 9 37	7.5	0.70	K1	61 ± 8 (2)	+6.4 ± 0.28	0	
HD 149661	16 34.2	− 2 12	5.8	0.73	K0	87 ± 5 (4)	+5.5 ± 0.12	3	
26965	4 13.4	− 7 43	4.4	0.73	K0	200 ± 4 (5)	+5.9 ± 0.04	1	
221354	23 29.4	+58 57	6.8	0.73	K2	23 ± 11 (1)		0	2:, 3
37008	5 35.1	+51 25	7.7	0.74	K2	34 ± 6 (2)	+5.4 ± 0.38	0	
191785	20 09.3	+16 04	7.3	0.75	K2	36 ± 6 (2)	+5.1 ± 0.36	0	
HD 2880	0 30.1	− 5 24	8.5	0.76	G8	35 ± 11 (1)	+6.2 ± 0.68	1	
10476	1 40.3	+20 04	5.2	0.76	G9	133 ± 6 (2)	+5.8 ± 0.10	0	
165341br	18 03.4	+ 2 30	4.0	0.77	K1	188 ± 4 (5)	+5.5 ± 0.05	2	1, 9
4747	0 47.5	−23 26	7.1	0.77	G7	58 ± 8 (2)	+5.9 ± 0.30	1	
3651	0 37.3	+21 02	5.9	0.78	K1	100 ± 6 (2)	+5.9 ± 0.13	1	1, 2, 3
HD 20781	3 18.3	−28 55	8.4	0.80	K0			0	3:
145675	16 09.1	+43 56	6.6	0.80	K1	63 ± 7 (1)	+5.6 ± 0.24	1	2:, 3
					K2				
HD 87884	10 06.1	+12 12	8.1	0.71	K1	39 ± 7 (2)	+6.0 ± 0.39	5	
151877	16 47.2	+37 05	8.4	0.73	K0	50 ± 5 (2)	+6.9 ± 0.22	0	
190404	20 02.2	+23 14	7.3	0.74	K3	50 ± 6 (2)	+5.8 ± 0.26	0	4
37394	5 38.1	+53 28	6.2	0.75	K2	91 ± 6 (2)	+6.0 ± 0.14	3	
155885−6	17 12.9	−26 33	5.0	0.76	K1 − K3	183 ± 9 (1)	+6.3 ± 0.11	2−2	4, 5
HD 191408	20 08.6	−36 12	5.3	0.76	K4	174 ± 10 (1)	+6.5 ± 0.12	1	4
155456	17 09.0	+24 35	8.3	0.77	K0	51 ± 13 (1)	+6.8 ± 0.55	0	2:, 3
184467	19 30.5	+58 30	6.6	0.78	K5	38 ± 5 (4)	+4.5 ± 0.29	1	
130669	14 47.3	+10 23	8.4	0.78	G9			0	3:
17925	2 50.6	−12 55	6.0	0.78	K0	127 ± 6 (3)	+6.5 ± 0.10	4	
HD 166620	18 08.3	+38 27	6.4	0.78	K2	100 ± 7 (2)	+6.4 ± 0.15	1	
4628	0 46.3	+ 5 05	5.7	0.80	K4	145 ± 5 (2)	+6.5 ± 0.07	1	2, 4
192310	20 12.8	−27 09	5.8	0.80	K5	116 ± 7 (3)	+6.1 ± 0.13	1	3, 9
74576	8 41.8	−38 44	6.5	0.80	K5	91 ± 7 (2)	+6.3 ± 0.17	3	
22049	3 31.1	− 9 36	3.7	0.81	K2	303 ± 4 (5)	+6.1 ± 0.03	4	1
HD 139341	15 34.6	+39 56	7.6	0.81	K4	48 ± 15 (1)	+6.0 ± 0.68	1	2, 3, 5
115404	13 14.9	+17 14	6.5	0.82	K3	67 ± 8 (2)	+5.6 ± 0.26	4	
C 891	7 26.5	+32 05	7.6	0.83	K0	40 ± 11 (1)	+5.6 ± 0.60	4	2:
HD 109011	12 29.3	+55 20	8.1	0.83				4	1
196794	20 37.4	+ 9 56	8.5	0.83	K1	13 ± 10 (2)		2	3:

TABLE 2 (Cont'd)

Star	α(1960) h m	δ(1960) ° '	V	P−V	Mt. W. Type	π ± p.e. (0.001")	M_V ± p.e.	H−K	Rem.
					K3				
HD 5133	0 51.1	−30 34	7.1	0.82	K5	103 ± 11(1)	+7.2 ± 0.23	2	9
37065	5 33.1	−23 29	8.8	0.82	K4	42 ± 7 (2)	+6.9 ± 0.36	0	
183255	19 25.3	+49 22	8.0	0.83	K1	41 ± 4 (3)	+6.1 ± 0.21	1	2,7
74377	8 42.6	+41 50	8.5	0.83	K5	59 ± 5 (4)	+7.3 ± 0.18	0	2
127871	14 31.6	+ 9 31	8.8	0.83	K6	19 ± 5 (4)		1	3
+31° 3330	18 39.4	+31 32	8.5	0.84	K4	31 ± 7 (2)	+6.0 ± 0.49	1	
HD 116012	13 18.7	+ 4 20	8.6	0.84	K5	25 ± 7 (2)		1	2,3
110833	12 42.5	+51 59	7.0	0.84	K0	63 ± 6 (1)	+6.0 ± 0.21	2	3
223778	23 50.4	+75 19	6.3	0.85	K5	90 ± 4 (6)	+6.1 ± 0.10	5	6,9
110463	12 39.9	+55 57	8.3	0.86				4	1
HD 139323	15 34 5	+39 57	7.6	0 86	K5	48 ± 15(1)	+6 0 ± 0.68	1	3
144872	16 05.0	+38 44	8.6	0.87	K5	56 ± 7 (2)	+7.3 ± 0.27	3	
16160	2 33 9	+ 6 42	5.8	0.88	K4	147 ± 5 (3)	+6.6 ± 0.07	1	2
160346	17 37.3	+ 3 34	6.5	0 88	K3	80 ± 6 (2)	+6.0 ± 0 16	1	2:,3:
79969	9 15 5	+28 44	7.2	0 90	K4	59 ± 9 (2)	+6.1 ± 0 33	4	2:
HD 219134	23 11.4	+56 57	5.6	0 90	K5	152 ± 5 (3)	+6.5 ± 0.07	2	1,2,3
130992	14 49.4	−24 08	7.9	0.90	K5	64 ± 6 (3)	+6.9 ± 0.20	2	2
186858A−B	19 44.0	+33 31	8.3	0.91	K5	45 ± 5 (3)	+6.6 ± 0.24	2	5
136834	15 20.7	+ 1 34	8.3	0.91	K5	31 ± 14(1)	+5.8 ± 0.98	2	2,3
39715	5 52.3	+ 2 10	8.8	0.93	K4	62 ± 9 (1)	+7.8 ± 0.32	2	2:
HD 156384br	17 16.2	−34 57	5.9	0.93	K5	137 ± 5 (3)	+6.6 ± 0.08	5	2,9?
34673	5 17.2	− 3 07	7.8	0.94	K5	71 ± 5 (4)	+7.1 ± 0.15	2	2
+12° 4499	20 53.2	+13 01	8.8	0.94	K5			4	2
127506	14 29.1	+35 38	8.7	0.95	K5	52 ± 13(1)	+7.3 ± 0.54	3	2
32147	4 58.8	− 5 48	6.2	0.97	K5	104 ± 4 (7)	+6.3 ± 0.08	3	2,9
HD 216803	22 54.2	−31 47	6.5	0.99	K4	123 ± 8 (2)	+7.0 ± 0 14	5	2,9?
29697	4 39.0	+20 50	8.0	1.00	K4	79 ± 10(2)	+7.5 ± 0.27	5	2
51866	6 58.6	+48 26	8.0	1.00	K5	32 ± 6 (3)	+5.5 ± 0.41	3	2:
					K4				
HD 120476A	13 47.3	+27 11	7.0	1.00	K6	56 ± 8 (2)	+6.4 ± 0.31	5	
171314	18 31.6	+22 18	8.9	1.00	M1	70 ± 8 (2)	+8.1 ± 0.25	1	
36003	5 26.5	− 3 31	7.6	1.00	K6	71 ± 6 (4)	+6.9 ± 0.18	2	
190007	20 00.8	+ 3 13	7.4	1.02	K4	70 ± 10(1)	+8.2 ± 0.31	5	
24916	3 55.5	− 1 16	8.0	1.02	K5	97 ± 12(1)	+7.9 ± 0.27	5	
HD 156026	17 13.8	−26 29	6.3	1.02	K5	172 ± 7 (2)	+7.5 ± 0.09	5	
+31° 1781	8 15.7	+30 45	8.8	1.04	K4	46 ± 5 (2)	+7.1 ± 0.24	3	
HD 103932	11 56.0	−27 28	7 2	1.04	K6	96 ± 8 (2)	+7.1 ± 0.18	5	9
21197	3 23.0	− 5 30	7.8	1.06	K6	61 ± 7 (3)	+6.7 ± 0.25	4	
					K5				
+30° 2512	14 20.2	+29 49	8.6	1.15	-	71 ± 11(1)	+7.9 ± 0.34	5	
					K6				
HD 154363	17 03.0	− 4 58	7.8	1.04	M0	83 ± 4 (5)	+7.4 ± 0.10	4	
					K7				
HD 28343	4 26.6	+21 48	8.4	1.04	M1	76 ± 10(1)	+7.8 ± 0.29	5	
157881	17 23.8	+ 2 10	7.6	1.22	K6	125 ± 6 (4)	+8.1 ± 0.10	5	
151288	16 43.6	+33 34	8.1	1.25	M0	118 ± 7 (3)	+8.5 ± 0.13	5	
88230	10 08.9	+49 39	6.6	1.25	M0	222 ± 5 (3)	+8.3 ± 0.05	5	
79210−11	9 11.7	+52 52	7.7	1.28	M0	163 ± 5 (6)	+8.8 ± 0.07	5	5
HD 111631	12 48.7	− 0 33	8.4	1.30	M0	90 ± 6 (3)	+8.2 ± 0.14	5	

FOOTNOTES

1. Yerkes Standard Star.
2. Hydrogen lines weaker than standard.
3. CN stronger than standard.
4. CN weaker than standard.
5. Magnitudes for one star.
6. Lines broadened by rotation.
7. Weak lines appear somewhat weakened. Sub dwarf?
8. $H\epsilon$ in emission. $H\gamma$ absorption line probably filled by emission.
9. Spectroscopic binary.

is well determined. HD 221354 is another possible subgiant, although less certain. Six stars remain uncertain as to luminosity, but, since none of them are critical for the purposes of this paper, they have been retained. As judged by their parallaxes, HD 158614, 190360, and 184467 could also be subgiants, but the appearance of the H and K reversals in the latter star show it to belong to the main sequence. Hence, with the elimination of HD 104556, 158614, 190360, and 221354, we seem to be reasonably safe in assuming that the remainder of the observed field stars constitute a sample of the main sequence in the solar neighborhood. It is understood that some of these objects might be what are sometimes referred to as "mild subdwarfs," but it seems to me to be more realistic to consider them all as members of the main sequence and to suppose, if need be, that the latter is to some degree non-homogeneous in character.

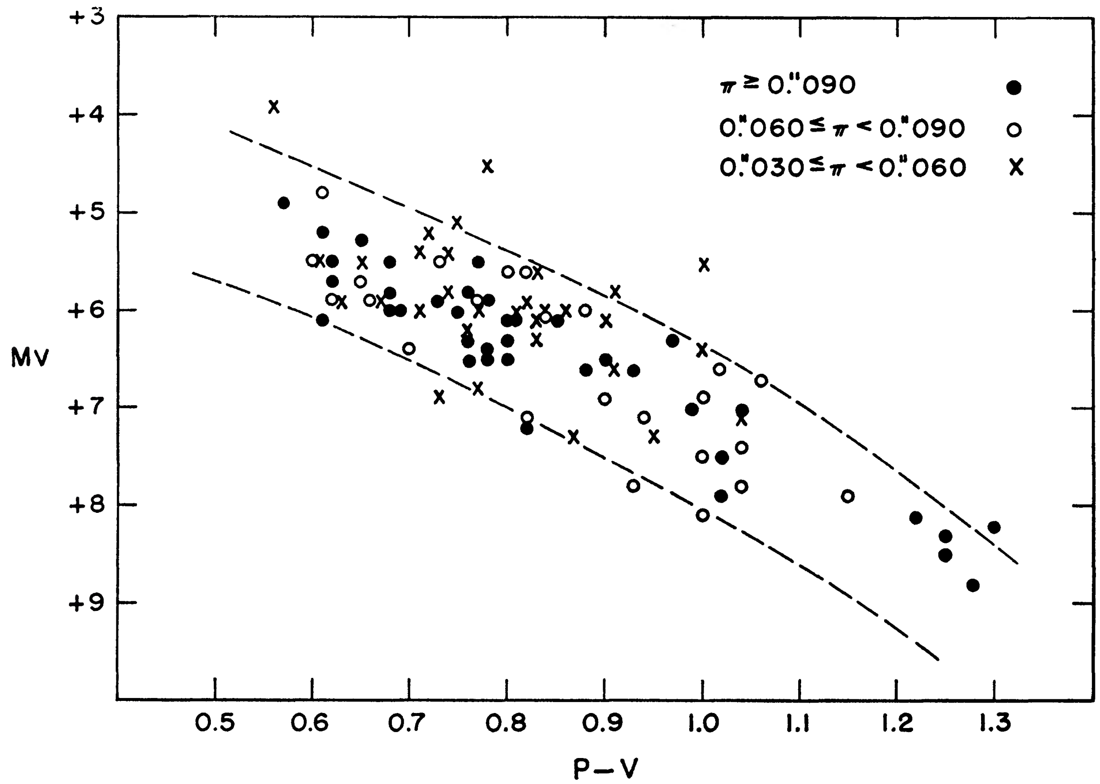

FIG. 1.—Absolute magnitude from trigonometric parallaxes versus $P - V$ for field stars

Spectral types for the field stars are plotted in Figure 2 against those from the Mount Wilson catalogue (Adams *et al.* 1935). Nearly all the scatter in this diagram must be due to the old Mount Wilson results, since I feel certain that the high quality of the 10 A/mm spectrograms insures an accuracy of classification within one subtype.

Spectral types and colors for the Hyades stars are given in Table 3. The values of $B - V$ are from Johnson and Mitchell (1962). Most of the spectral types depend on a single 38 A/mm plate of good quality, the majority of which have not been measured for radial velocity. Stars were selected for observation on the grounds that they lie within about 0.5 mag. of the mean Hyades main sequence as defined by the photometry of Johnson and Mitchell. A few stars could be seen by inspection of the plates to have radial velocities clearly differing from that of the cluster. These could be either spectroscopic binaries or non-members; in any event, they have been excluded. It is still possible, of course, that a few field stars have been included in Table 3. However, it should be noted that, of 36 stars observed between spectral types G5 and K3 inclusive, only 3 do not show H and K emission components, even at 38 A/mm. This fact is good evidence that most of the stars are cluster members, although the general question of the occurrence of H and K reversals in main-sequence stars will be taken up in a subsequent paper.

The spectral types are plotted against colors in Figures 3 and 4 for field stars and Hyades stars, respectively. It is evident that there is a tighter correlation between the two quantities for the Hyades than for the field stars, even though the spectral types of the latter are probably more precise. This is the result to be expected if our deductions from the Vogt-Russell theorem are correct and if the Hyades main sequence is more uniform in chemical composition than that represented by the field stars.

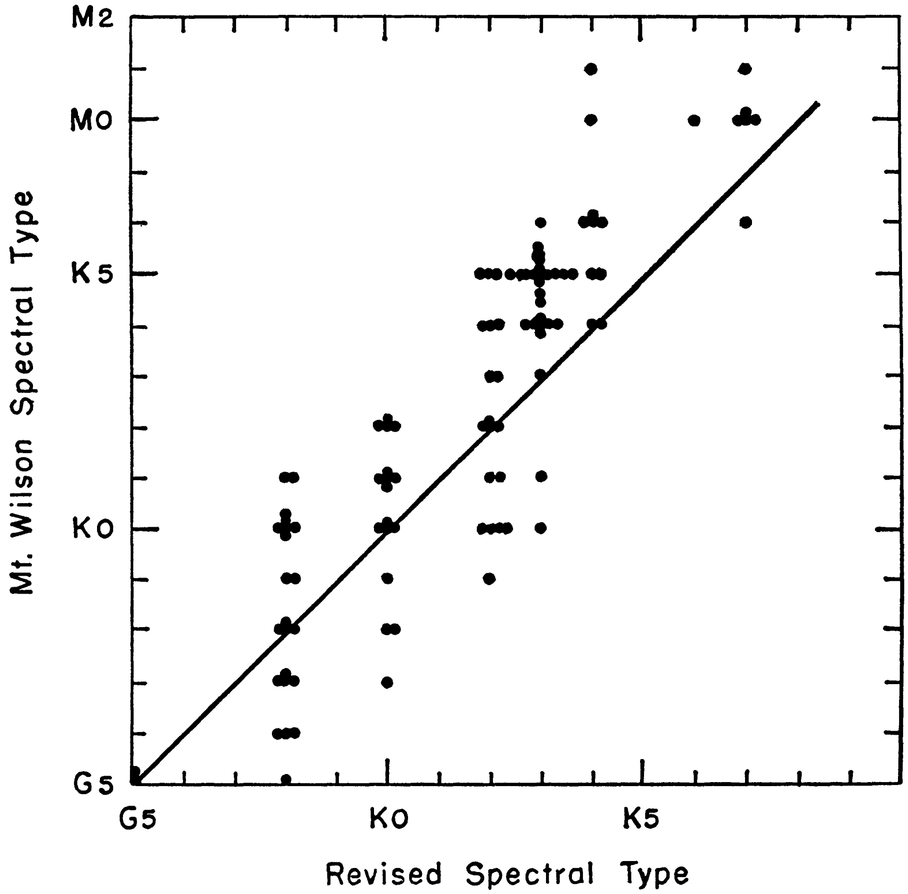

FIG. 2.—Mount Wilson versus revised spectral types

In Figure 5 the two groups are shown together after transformation of the Hyades $B - V$ values to $P - V$. It appears that the two main sequences agree well, on the average, but there are some spectral types in which the local main sequence seems to contain stars both bluer and redder than its Hyades counterparts.

We turn now to illustration of some of the results and begin with groups of stars which have the same spectral types but different colors. This effect is best shown at G8, K3, and K7. Spectra of four G8 stars representing nearly the extreme range in color for this type are given in Figure 6, *a*. The trigonometric parallaxes of these four stars all appear to be reliable, with the possible exception of HD 175541, where the parallax depends on one determination and yields an absolute magnitude of $+7.1$. This value suggests that the star may be a subdwarf similar to Groombridge 1830. However, the spectrum of HD 175541 is quite unlike that of Gr 1830 in at least two important respects. First, there is no indication of the weakening and disappearance of weak lines which characterizes Gr 1830, and, second, although the CN bands are completely missing in the spectrum of Gr 1830, they are rather stronger than normal for type G8 in HD 175541. Therefore, I think it can safely be concluded that this star is certainly not a pronounced subdwarf. The only evidence that HD 175541 is not a subgiant is provided by the parallax itself. In order that this star be a subgiant, its true parallax would have to be about one-fourth the value given in the Yale catalogue, and an error of this size seems rather improbable. Additional evidence that HD 9540 is a main-sequence object is provided by the widths of the H and K reversals in its spectrum.

TABLE 3

SPECTRAL TYPES AND COLORS OF HYADES STARS

Star	$B-V$	Star	$B-V$	Star	$B-V$
G0:		*K0:*		*K4:*	
2	0 62	276	0 84	117	1.07
G5:		4	0 85	275	1 07
15	66	46	0 87	222	1 07
17	70	*K2:*		289	1.09
9	.71	79	0 83	312	1 09
G8:		99	0 85	273	1.10
114	.72	91	0 88	330	1 11
27	72	93	0 88	253	1 11
26	74	135	0.89	318	1 12
87	74	228	0 89	337	1 14
92	74	7	0 90	211	1 16
127	74	43	0 91	*K5:*	
69	.75	5	0 92	344	1.17
3	75	206	0 92	259	1 18
42	.76	274	0 93	291	1 19
76	76	*K3:*		288	1 22
140	.76	152	0 94	251	1 23
22	77	151	0 95	*K6:*	
351	77	285	0 97	262	1.30
145	.78	328	0 97	*K7:*	
K0:		240	0 98	226	1 34
109	.82	25	0 99	286	1 36
21	.82	229	0 99	332	1 36
116	.82	319	1 00	245	1 38
96	84	271	1 03	207	1 39
115	0 84			202	1 42

A similar group of four K3 stars extending over the color range for these objects is shown in Figure 6. Here two of the trigonometric parallaxes are rather small, but in three of the four stars the H and K reversals confirm their main-sequence nature. In fact, there is no evidence for subdwarf characteristics in any of the four spectra, and at this type we can rule out the possibility of subgiants.

Figure 6, *c*, shows the extremes in color for type K7. Here there can be no question that all three stars are certainly close to the main sequence in luminosity. It is also evident that their spectra are indistinguishable.

Two groups of stars with only a slight range in color but a distinct and relatively large range of spectral type are illustrated in Figure 7, *a* and *b*. Some stars necessarily appear in more than one of the illustrations, since in Figure 6, *a*, *b*, and *c* represent vertical sections through the distribution of Figure 3, while in Figure 7, *a* and *b* are horizontal sections, and these sections have been made where the vertical and horizontal widths of the distribution are largest.

To summarize, we may say that among the late-type main-sequence field stars near the sun there is not a one-to-one correspondence between spectrum and color and that, if the same spread of type for a given color, or of color for a given type, existed in the Hyades main sequence, we should be able to see it. In the Hyades main sequence I suspect that the correlation between color and spectrum is really quite close and that the

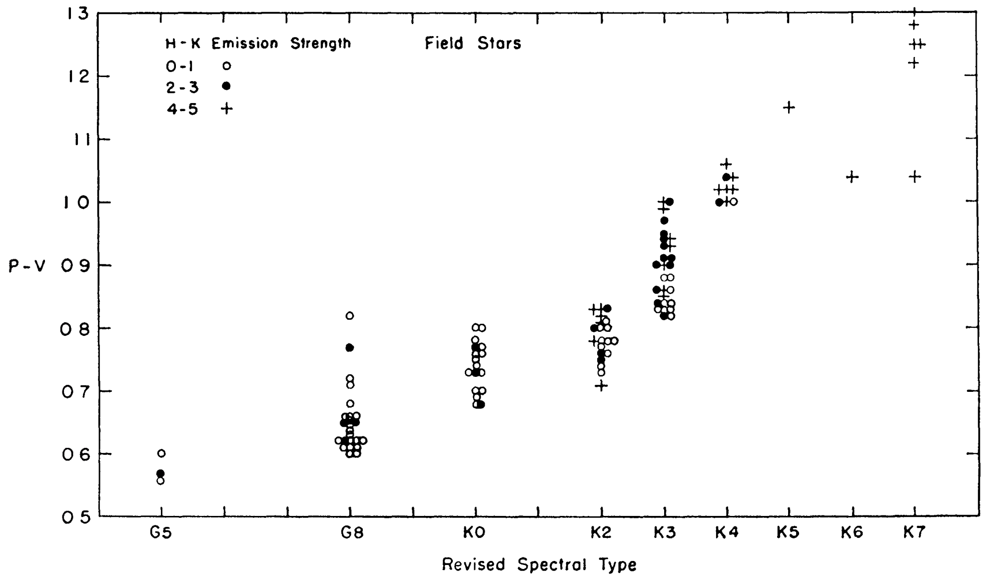

FIG. 3.—Spectral types versus color for field stars

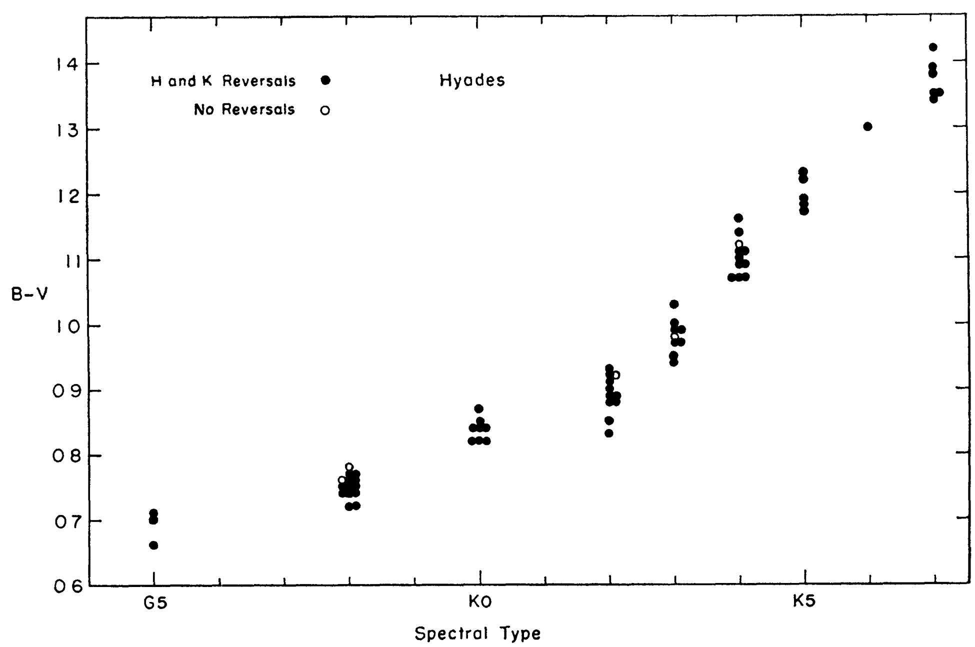

FIG. 4.—Spectral types versus color for Hyades

dispersion exhibited in Figure 4 is due largely to the inadequacies of spectral-type determination which require that we represent a continuous distribution of spectral characteristics by a series of discrete steps.

V. COMPARISON WITH PREVIOUS RESULTS

In the interest of clarification it is necessary to see what becomes of the earlier conclusions (Wilson 1961). The intensities of the H and K reversals on the field-star spectrograms were estimated on a scale of 0–5, which, while rather rough, is adequate to discriminate weak, medium, and strong emissions. In Figure 3 three symbols have been used

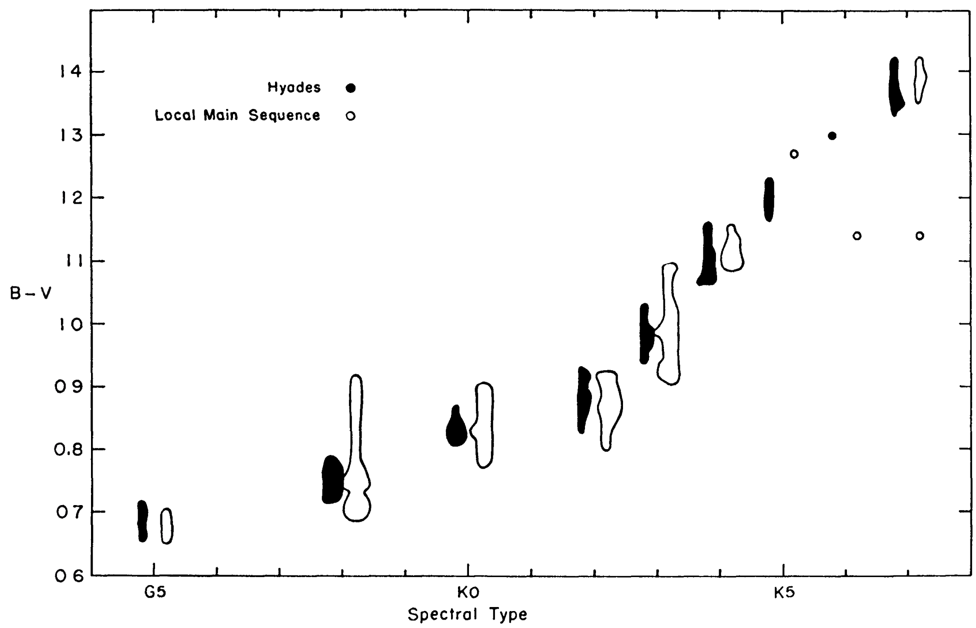

FIG. 5.—Spectral types versus color for field stars and Hyades

to indicate these three gradations of emission intensity. One sees that, while there is some tendency for the redder stars of a given type to exhibit stronger emissions than the bluer ones, this tendency is not very pronounced, and there are many exceptions. The excellent correlation in this sense found previously is therefore only partially verified, and one of the reasons for it is to be found in the old Mount Wilson spectral types. In Table 4 are listed the stars previously observed, with their Mount Wilson types, colors, and revised types, and one sees that, except for one pair, the comparison was really between a bluer, earlier-type star and a redder, later-type one. Since Figure 3 clearly shows the well-known increase in emission intensity with increasing type, we must regard this systematic deviation of spectral types as at least partially responsible for the erroneous conclusion noted above. Chance also probably played a role here, since HD 171314, for example, has unusually weak emissions even for its revised type.

Inspection of Table 2 does not lend much support to the previous conclusion that the hydrogen lines are weaker in the redder stars of a given type, except possibly at K3. The fact that these lines decrease in strength down the main sequence, together with the systematic errors in spectral type shown in Table 4, is adequate to account for the erroneous result.

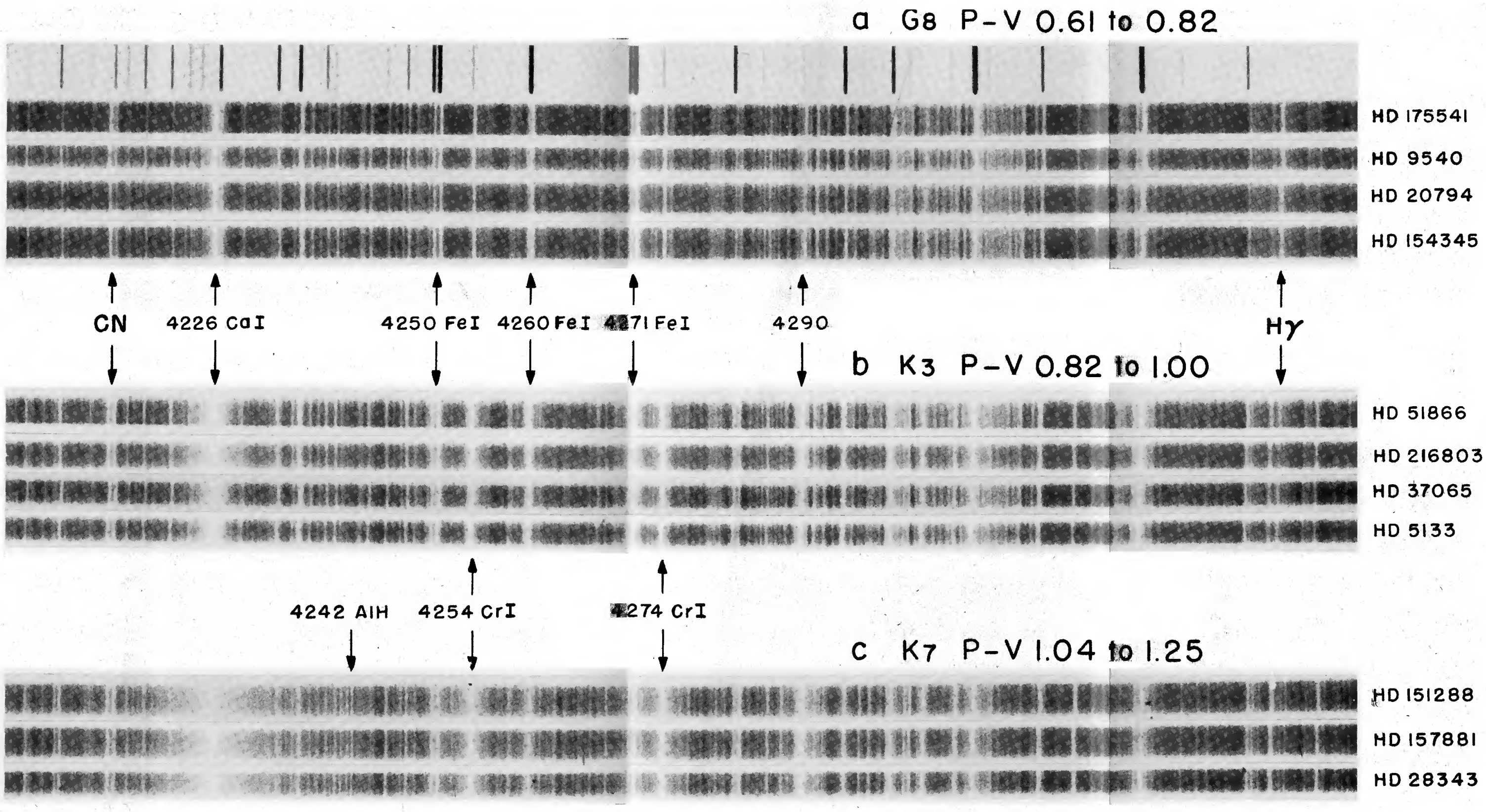

FIG. 6.—Stars of same types with different colors. $P - V$ from top to bottom: (*a*) 0.82, 0.77, 0.61, 0.62; (*b*) 1.00, 0.99, 0.82, 0.82; (*c*) 1.25, 1.22, 1.04

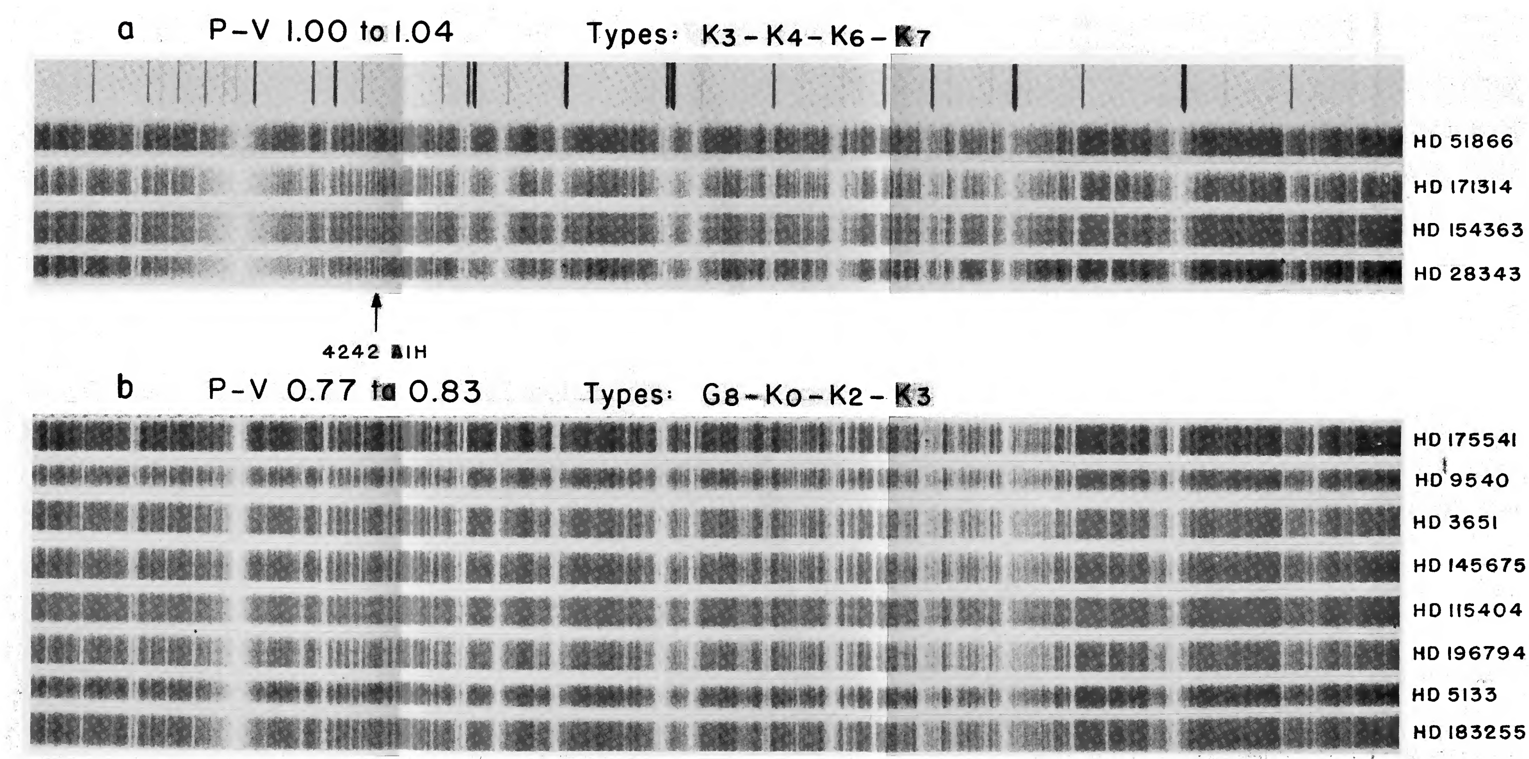

FIG. 7.—Stars of different types, nearly same colors. $P - V$ from top to bottom: (*a*) 1.00, 1.00, 1.04, 1.04; (*b*) 0.82, 0.77, 0.78, 0.80, 0.82, 0.83, 0.82, 0.83

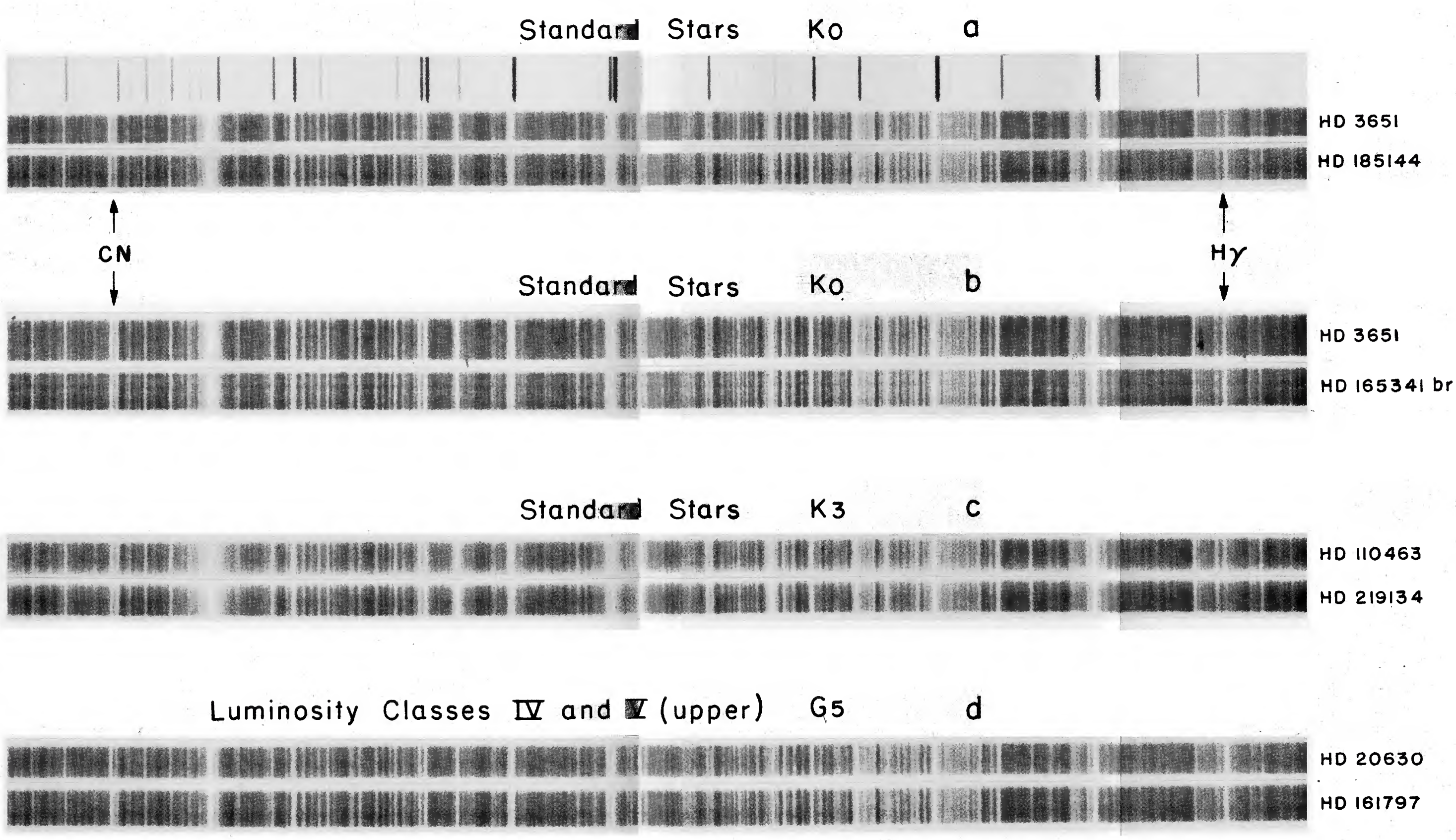

FIG. 8.—*a, b, c:* Comparison of Yerkes standard class V stars; (*d*) Yerkes standards of classes IV and V at G5

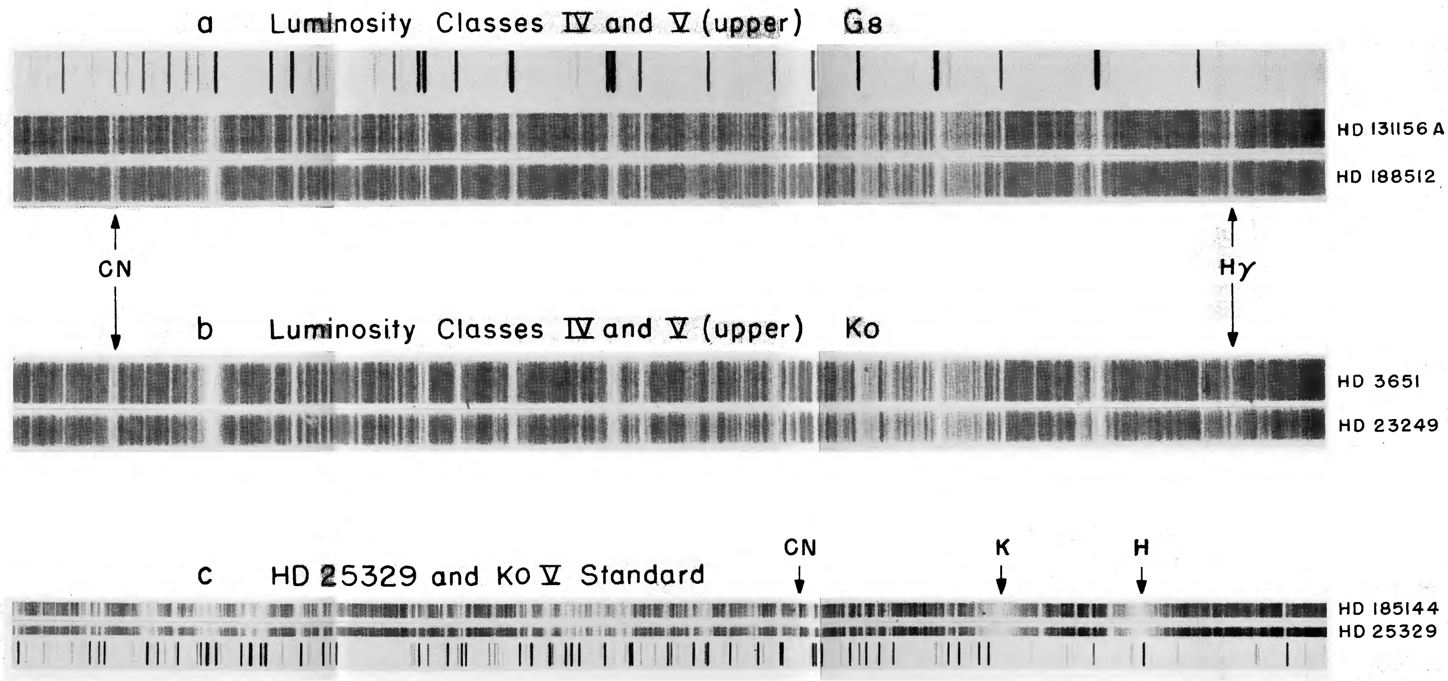

Fig. 9.—*a, b:* Comparison of Yerkes standards of classes IV and V at G8 and K0; (*c*) HD 25329 and Yerkes standard K0 V, shortward of λ 4000

VI. SPECTRAL ANOMALIES

Two features which occasionally differ noticeably from the norm for stars of a given type have been noted in the course of the visual intercomparisons of the 10 A/mm plates. One of these features is the hydrogen lines, which are sometimes seen to be abnormally weak for the spectral type derived from the metallic lines. The other anomaly is to be found in the CN bands, which sometimes are stronger or weaker than normal. These two anomalies may or may not occur in the same spectrum. Thus far I have not been able to find any correlation between them and the other parameters which describe a spectrum, such as color or strength of H and K reversals. In Table 2, I have indicated in the notes those stars in which I believe either of the anomalies to be present. For estimating intensities of hydrogen lines and CN bands, these stars were used as standards: G8, HD 101501; K0, HD 185144; K2, HD 22049 and 109011; K3, HD 110463 and 5133.

TABLE 4

SPECTRAL TYPES AND COLORS FOR STARS PREVIOUSLY OBSERVED

Star	$P-V$	Mount Wilson Type	Rev. Type
HD 190360	656	G8	G8
9540	769	G8	G8
+41°3306	699	K1	K0
HD 196794	833	K1	K2
190404	743	K3	K2
219134	901	K3	K3
191408	756	K4	K2
190007	1 017	K4	K4
216803	990	K4	K3
184467	776	K5	K2
+12°4499	942	K5	K3
HD 171314	1 001	M1	K4
202560	1 274	M1	*

* Not reobserved Color would indicate type at least as late as K7

It happens that both effects are represented among the Yerkes standards, which can therefore be used for purposes of illustration. Figure 8, *a*, is a comparison of HD 3651 with HD 185144, both standard K0 V stars. It is evident that the hydrogen lines are weaker and that the CN band at λ 4215 is stronger in HD 3651. The latter is compared with another standard K0 V star, HD 165341br, in Figure 8, *b*. Here, while the hydrogen lines are weaker in HD 3651, the CN band in this star is only slightly stronger. Figure 8, *c*, compares two standard K3 V stars, HD 110463 and HD 219134. Hydrogen is weaker and CN somewhat stronger in the latter.

Before terminating this section, mention should be made of HD 25329, a star which is very deficient in metals (Heiser 1960) and of somewhat later type than Gr 1830. In Gr 1830 the CN bands are missing, and, according to Greenstein (1962), this is a characteristic of the extreme metal-poor subdwarfs. In HD 25329, however, this rule is violated, since the CN bands appear in quite normal strength for its type, as may be seen in Figure 9, *c*, where the star is compared with the K0 V standard HD 185144. It would seem, therefore, that the CN anomaly is not restricted to the more or less normal main-sequence stars but extends also into the region of extreme metal deficiency.

VII. REMARKS ON LUMINOSITY CLASS IV

In a study such as this one, it is, of course, quite important to eliminate subgiants and to insure that only main-sequence stars are included. This question arises only around spectral types G8–K0, since for later types the gap between the main sequence and the subgiants in the color-magnitude plane widens rapidly and confusion between the two becomes improbable. It was supposed that luminosity classes IV and V would be readily distinguishable spectroscopically, but, to make sure of this, 10 A/mm spectrograms of the Yerkes standard class IV stars of types G5, G8, and K0 were obtained for comparison with the corresponding class V standards. When this comparison was made, it was disconcerting to find that the two luminosity classes were not distinguishable. The usual luminosity criteria—the strengths of the Sr II lines at λ 4215, λ 4077—are apparently not sufficiently sensitive in these stars to enable them to be separated, and no other distinguishing features could be found in the spectra. This question was pursued farther by also observing several stars whose luminosities, determined by the widths of their H and K reversals, placed them in the general class IV region. All such stars for which spectrograms were obtained are listed in Table 5 with other relevant data. The result of these efforts was to confirm the statement made above.

TABLE 5

STARS ABOVE MAIN SEQUENCE

Star	Type	I_{CN}	M_v(K)
HD 161797	G5*	2 08	
188512	G8*	2 05	.
23249	K0*	. . .	. . .
5286	K1†	2 26	+3 8
22072	G7†	2 07	+4 1
47205	K1†	.	+2 6
67767	G6†	. . .	+3 4
81192	G5†	2 01	+2 5
111028	K1†	2 13:	+3 5

* Yerkes Standards, class IV.
† Mount Wilson spectral types.

The class IV stars do have one spectroscopic feature in common however: compared with the average class V stars of the same type, the CN bands are usually stronger in the spectra of the class IV stars. This appears, therefore, to be a necessary, but not a sufficient, condition for inclusion in class IV, since some of the class V stars—HD 3651, for example—have CN bands of similar strength. In any event, it is for the reasons given here that the trigonometric parallaxes have been considered decisive in eliminating class IV stars from the main-sequence objects. The foregoing remarks are illustrated by the comparisons between Yerkes standard class IV and class V stars in Figures 8, *d*, and 9, *a* and *b*.

VIII. COMPARISON WITH RESULTS OF GRIFFIN AND REDMAN

In the two preceding sections estimated intensities of the λ 4215 CN band play a prominent role. Therefore, after all the work on the spectrograms was completed, a comparison was made with the photoelectric measures of this band by Griffin and Redman (1960), in order to check on the reliability of the eye-estimates. These authors give a CN intensity for thirty-three of the stars of Table 2. Their results, together with my estimates of anomalous CN strengths from Table 2, are shown in Table 6.

For nineteen of the stars, both methods agree in indicating no CN anomalies. If it be assumed that a photoelectric measure in excess of 2.05 represents a real strengthening of the CN band, there are nine such stars in Table 6, of which seven were picked up by spectroscopic examination and two were missed. On the other hand, excess CN intensity was attributed to two stars which do not have it and deficient CN to three others which are normal according to the photoelectric data. There are thus a total of seven errors out of thirty-three attempts, which would indicate that the CN estimates of Table 2 are of the order of 80 per cent correct.

TABLE 6

STARS IN COMMON WITH GRIFFIN AND REDMAN

Type	Star	I_{CN}	Remarks (Table 2)
G5	HD 20630	1 99	
G8	101501	2 01	
	154345	2 02	
	145958A-B	2 02	CN weak
	131156A	2 03	
	152391	2 00	
	HD 190360	2 10	
	158633	2 00	
	161198	2 02	
	82885	2 09	CN strong
	164922	2 04	
	HD 182488	2 09	CN strong
	104556	1 98	
K0	HD 10780	2 03	
	185144	2 02	
	221354	2 10	CN strong
	191785	2 04	
	10476	2 07	
	HD 165341br	2 05	
	3651	2 11	CN strong
	145675	2 16	CN strong
K2	HD 190404	1 99	CN weak
	37394	2 00	
	184467	2 01	
	166620	2 02	
	4628	2 01	CN weak
	HD 139341	2 15	CN strong
	115404	2 02	
K3	HD 110833	2 03	CN strong
	16160	2 00	
	160346	2 00	CN strong(?)
	79969	1 97	
	219134	2 08	CN strong

Undoubtedly the reason why the eye-estimates do as well as this is the following: Griffin and Redman use an instrument of high intrinsic precision but are forced to dilute the information they seek (the true intensity of the CN band) with a great deal of unwanted "noise." The visual observer, however, while using much less accurate equipment, can concentrate on the band head which lies within the little stretch of spectrum bounded by the 4215 A line of Sr II and the 4216 A line of Fe I and thus make use of the maximum effect of changes in the amount of CN.

In Table 5 for stars above the main sequence I have entered the CN measures of Griffin and Redman. These results confirm the statements made about these objects in Section VII.

IX. CONCLUSION

It is hoped that this paper has succeeded in (1) setting the record straight on the true relationship between spectrum and color among the late main-sequence field stars; (2) providing evidence pointing toward chemical non-uniformity among these stars, and no corresponding evidence for the Hyades main sequence; and (3) indicating some of the interesting problems presented by these late main-sequence stars and providing initial guidance for any who might be inclined to pursue these problems further.

That the local main sequence should show evidence of non-uniform composition is certainly not surprising in the present state of our knowledge; for among these stars we would expect to find objects of a variety of ages and of points of origin within the Galaxy. Thus, depending on the ages and evolutionary rates of the stars, there is the possibility not only of a range in the original chemical compositions but of evolutionary modification of them.

If we are dealing with a relatively young star or with an old one in which there is thorough mixing between the interior and the surface, then in equations (1) and (2) $Xi = Xs$, and we may speak of "the" chemical composition of the star. In the first instance this composition is the original one, whereas in the second it need not be if the time since formation of the star is sufficiently long. On the other hand, if there were not such mixing in an old star, Xi and Xs could differ, although Xs would then be representative of the original mixture of which the star was formed. At least this would be true unless there existed the possibility of contamination of the surface layers from outside, a contingency which would obviously increase the difficulties of the whole problem.

Finally, it does not seem wholly unreasonable to ask this question: If there have been successive generations of stars formed within the Galaxy, can we hope to find and identify any of the original stellar inhabitants? Clearly, the only sensible place to look for them must be well down on the main sequence, since all other stars of that generation will have evolved away and disappeared into the white dwarf graveyard or become otherwise unidentifiable. According to present ideas, these aboriginal stars should be objects of very low metal content and, necessarily, small mass, in order that they still be near the main sequence. If a careful search fails to reveal stars of this kind, some good reason will have to be found to account for their absence.

I wish to express my thanks to H. L. Johnson and R. I. Mitchell for the use of their finding charts and positions of the Hyades stars and for sending me a copy of their complete photometric results prior to publication. I also wish to thank G. Pels, of the Leiden Observatory, for additional Hyades charts and positions.

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