LUMINOSITY CRITERIA FROM OBJECTIVE-PRISM SPECTRA FOR STARS FROM F0 TO K5

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ABSTRACT

This paper presents a method for determining the luminosity of stars between F0 and K5 from objective-prism spectra made with the 24–36-inch Schmidt-type telescope of the Warner and Swasey Observatory. The spectrum region studied was from λ 3706 to $H\gamma$. The luminosity criteria are described by means of drawings showing the intensity distribution in twelve spectral classes from F0 to K5 and for approximately four luminosity classes. It is expected that accurate classification by this method is possible for stars of at least the tenth magnitude and probably fainter for many spectral classes.

INTRODUCTION

In a previous paper, J. J. Nassau and C. K. Seyfert[1] gave a general outline of the spectrum-luminosity criteria used for the classification of spectra made with the 4° objective prism attached to the Burrell Telescope of the Warner and Swasey Observatory. The first study dealt with the classification of giants and dwarfs, beginning with class G2. The present paper deals with the subdivision of stars of spectral classes F0–K5 into four luminosity groups. Criteria for this separation were derived from a study of the ultraviolet and blue regions of the spectrum.

OBSERVATIONAL MATERIAL

In order to be able to establish suitable criteria, we have studied a number of stars of known luminosity. Good spectra for these standard stars which have visual magnitudes between 4 and 6 could be photographed with very short exposures. Two different exposures were generally needed in order to secure spectra of good quality in both blue and ultraviolet regions. In addition to the standard stars, most plates showed a number of spectra of neighboring stars, for which the luminosity was sometimes known; these stars were included in the study. These secondary standards did not always have well-exposed spectra. For this reason in a number of spectra only the ultraviolet region was available and in other stars only the blue. This provided a valuable test for the classification of stars for which only a limited region of the spectrum was accessible. A list of all the stars used is given in Table 1.

All spectra were taken with the 4° objective prism mounted on the Schmidt-type telescope. The dispersion varies from 150 A/mm at λ 3700 to 280 A/mm at $H\gamma$. Our study of spectra was limited to the region from λ3700 to $H\gamma$, notwithstanding the fact that the spectra of bright stars extended to much shorter wave lengths. The far ultraviolet region is of little practical use, since it does not appear in faint spectra. The region to the red of $H\gamma$ is left for later consideration.

REPRESENTATION OF THE CRITERIA

During the progress of the investigation it became apparent that we could not give a simple scheme for luminosity classification. The general features which show distinct variation with luminosity are intermingled with changes of spectral type. In addition, the number of features useful for luminosity classification is large and the features them-

[1] *Ap. J.*, **103**, 117, 1946.

TABLE 1

Star	Qual. U	Qual. B	Class	HD	M_v
α Lep	4	6	F0 *Ib*	F0	−2.1
BD+68°1082	6	6	F0 III	F0	+0.9
89 Her	6	8	F2 *Ib*	F5p	−2.1
41 Cyg	7	6	F2 *Ib*	F5p	−1.4
ν Her	7	5	F2 III	F0	−0.7:
22 And	8	8	F2 III	F0	+0.7
13 Peg	4	2	F2 III	F2	+1.3
BD+45°2949	8	8	F2 III	F2	+1.5
BD+74°1033	1	3	F2 IV	F2	+2.4
BD+60°143	6	6	F2 V	F5	+2.4
BD+47°2937	7	6	F2 V	F0	+2.8
BD+53°2876	4	5	F2 V	F5	+3.3
BD+60°2414	7	9	F2 V	F2	+3.4
ε Aur	8	9	F5 *Ia*	F5p	−2.7
α Per	10	10	F5 *Ib*	F5	−2.7
T Vul	8	5	F5 *Ib*	F8p	−1.6
5 And	7	8	F5 V	F0	+2.6
BD+71°964	7	7	F5 V	F2	+3.0
BD+31°3026	6	6	F5 V	F8	+3.2
BD+76°934	7	7	F5 V	F5	+3.6
BD+30°3113	0	2	F5 V	F5	+3.7
α U Mi	10	10	F8 *Ib*	F8	−3.5
BD+54°535	0	5	F8 *Ib*	G0p	−2.0
45 Dra	9	9	F8 *Ib*	F8p	−1.5
BD+62°130	7	7	F8 III	F5	+1.6
BD+56°2727	9	9	F8 IV	F8	+2.4
BD+55°2099	6	6	F8 IV	F8	+2.8
ι Psc	7	4	F8 IV	F8	+3.4
BD+44°4549	0	4	F8 V	F8	+3.0
BD+3°93	5	7	F8 V	F8	+3.3
ξ Cap	7	4	F8 V	F5	+3.7
T Vul	5	5	G0 *Ib*	F8p	−0.7
π Cep	9	7	G0 III	G5	−0.2
υ Peg	6	5	G0 III	G0	+1.4
BD+45°3245	0	2	G0 IV	G0	+2.4:
BD+57°2240	8	7	G0 IV	G0	+2.9
χ Her	9	5	G0 IV	G0	+3.5
BD+60°124	8	0	G0 IV	F8	+3.9
β C Vn	6	6	G0 V	G0	+4.5
BD+56°2923	9	9	G2 *Ia*	G0p	−3.0
α Aqr	8	5	G2 *Ib*	G0	−2.6
β Dra	7	7	G2 *Ib*	G0	−2.2
BD+58°101	7	4	G2 *Ib*	G5	−2.0
η Peg	1	7	G2 III	G0	−1.2:
BD+60°170	5	4	G2 IV	G0	+3.4
BD+3°4896	0	2	G2 IV	G0	+3.9
BD+1°4820	3	3	G2 IV	G0	+4.1
72 Her	8	8	G2 V	G0	+4.8
$α^1$ Cap	8	8	G5 *Ib*	G0p	−3.0
ε Leo	7	7	G5 *Ib*	G0p	−1.9
ε Dra	6	1	G5 III	K0	−0.4
BD+34°86	7	3	G5 III	G5	+0.6
γ Psc	10	1	G5 III	K0	+0.9
$α^2$ Cap	9	4	G5 III	G5	+1.0
31 Vul	8	8	G5 III	G5	+1.1:
BD+36°66	7	4	G5 III	G5	+1.6
μ Her	9	6	G5 IV	G5	+3.7
BD+64°1427	1	4	G5 IV	G5	+3.8
BD+43°3759	0	2	G5 IV	G5	+4.2
51 Peg	8	2	G5 V	G0	+4.8
BD+66°1281	10	5	G5 V	F8	+5.3
BD+2°4723	0	3	G5 V	G5	+5.4
BD+46°4214	0	5	G8 *Ib*	K0	−1.5
9 Peg	8	2	G8 *Ib*	G5	−1.3
BD+49°3954	3	7	G8 *Ib*	K0	−1.2
BD+44°3617	2	6	G8 III	K0	−0.2
BD+60°21	5	4	G8 III	G5	0.0
BD+59°161	6	5	G8 III	G5	+0.2
BD+56°2746	6	5	G8 III	K0	+0.2
60 Psc	8	5	G8 III	G5	+0.4
7 Per	0	5	G8 III	K0	+0.4
BD+31°3047	9	5	G8 III	K0	+0.6
λ Peg	8	7	G8 III	K0	+0.8
62 Psc	7	6	G8 III	K0	+0.9
BD+56°767	9	9	G8 III	K0	+1.2
BD+43°3777	2	6	G8 III	K0	+1.2
BD+33°47	0	3	G8 IV	G5	+1.0
μ Peg	7	2	G8 IV	K0	+1.1
BD+33°39	0	1	G8 IV	G5	+1.3
5 Psc	5	5	G8 IV	G5	+2.1
BD+63°1882	0	4	G8 V	G0	+5.7
30 Vul	7	7	K0 III	K2	−0.1
α Boo	10	0	K0 III	K0	−0.1
δ Cnc	0	10	K0 III	K0	+0.1
3 And	9	8	K0 III	K0	+0.3
1 Cap	0	5	K0 III	K0	+0.3
ξ Her	8	2	K0 III	K0	+0.3
BD+2°118	1	6	K0 III	G5	+0.4
BD+53°2874	0	3	K0 III	K2	+0.4
BD+39°4964	0	5	K0 III	K2	+0.7
BD+55°2769	8	6	K0 III	K0	+0.8
β Lac	8	6	K0 III	K0	+1.0
BD+45°2940	3	6	K0 III	G5	+1.1
BD+68°1129	4	6	K0 III	G5	+1.1
BD+59°199	0	4	K0 IV	K0	+1.4
BD+44°3185	9	8	K0 IV	G5	+1.6
BD+59°1899	0	5	K0 IV	K0	+1.7
60 Peg	8	5	K0 IV	K0	+2.3
γ Cep	9	5	K0 IV	K0	+2.6
σ Dra	9	7	K0 V	K0	+6.1
56 Peg	8	8	K1 *Ib*	K0	−2.0
ζ Cep	8	8	K1 *Ib*	K0	−0.5
BD+52°92	0	3	K1 III	K0	−0.4
25 Cep	3	6	K1 III	K5	+0.2
BD+29°3126	0	6	K1 III	K0	+0.4
BD+60°2358	4	7	K1 III	K0	+0.5
BD+55°2820	8	7	K1 III	K0	+0.6
BD+58°2393	1	4	K1 III	G5	+0.8
BD+40°4885	0	4	K1 III	K0	+0.9
BD+25°3368	0	2	K1 V	K0	+3.7:
BD+26°3151	0	6	K1 V	K0	+5.6
BD+29°4121	0	3	K2 III	K0	+0.4
87 Her	7	6	K2 III	K0	+0.9
BD+4°123	9	8	K2 V	G5	+6.7
BD+61°178	5	4	K3 *Ia*	K2	−3.6
22 Psc	5	5	K3 *Ib*	K2	−0.7
39 Cyg	0	7	K3 III	K2	−0.1
BD+74°1047	0	6	K3 V	K2	+6.4
BD+56°2966	8	7	K3 V	K2	+6.5
BD+48°3887	1	10	K5 *Ib*	K0	−2.5
ξ Cyg	1	10	K5 *Ib*	K5	−2.2
BD+38°4855	0	4	K5 III	K5	−0.9
BD+47°3188	0	6	K5 III	K0	−0.5
20 Cep	5	7	K5 III	K5	−0.4
32 Vul	9	8	K5 III	K5	−0.3
δ Psc	8	10	K5 III	K5	+0.3

selves vary with the spectral class. For these reasons we have considered two possible visual descriptions of the classification criteria.

The first consists in showing a number of spectra arranged in order of spectral type and of luminosity, similar to the reproductions given in this paper. This method has been followed with great success in the *Atlas of Stellar Spectra*.[2] But the problem in our case is a little different. On account of the low dispersion of our spectra, the method of photographic reproduction will never show all detail visible in the plates (Figs. 1 and 2). In addition, in the process of classification of a great number of stars it is desirable to have some means of illustration which will more rapidly draw attention to the luminosity criteria.

The second method consists in showing drawings which reproduce the intensity distribution in the spectrum. This method has been adopted, as it provides a clear representation of all significant features. The drawings of Figures 3–6 illustrate the method, and it must be stated that they are not microphotometric tracings. They have been drawn by hand and represent estimated, rather than measured, intensities.

Although this way of producing the tracings introduces some subjective factors, this procedure has some advantages in our case. Since the luminosity classification is made by visual estimate, the personal factor is already introduced into the classification process. This circumstance destroys the advantage of objectivity which true microphotometer tracings might otherwise have had. The method has the further advantage that exposure effects may be eliminated more readily in the drawings, as the appearance of the microphotometer tracings does not correspond to the visual estimate.

The drawings have been made with great care. The positions of the lines in the spectra were measured, and a first set of drawings was made by sketching the profiles with respect to the measured lines. These sketches were independently checked by both authors. Since the varying definition of the spectra sometimes caused irregular variations in some features as represented in the drawings, a second tracing was derived for each class from that of a neighboring spectral type by changing only those features which showed a clear variation. Later the entire new set of tracings was compared with the first set in order to check on the differences between them. The evolution of the different features with spectral type and luminosity was considered carefully, and in every doubtful case new comparisons on the plates were made. Finally, the tracings were used in a reclassification of all first- and second-class standard stars. The resulting classes are given in Table 1.

Our experience shows that the tracings furnish a very useful guide in the process of actual classification. However, they have to be used with caution. Even with the careful intercomparison of spectra and tracings, there always remain minor differences which cannot be removed. Minor observable features depend too much on the definition of the spectrum, and, at the same time, spectra of two different stars of the same type are not always identical. The drawings for stars of different luminosities in one spectral class may show slight variations due to small differences in temperature. Finally, a general resemblance of the spectrum to a particular tracing should not be considered sufficient evidence of the temperature and luminosity class of a given star. One should consider also the tracings for neighboring luminosity classes and spectral types, for many times a slight change in temperature classification will necessitate a change in luminosity classification and vice versa.

For the purpose of actual classification we produced a set of tracings which includes most luminosity classes in spectra from F0 to K5. Part of these tracings are shown in Figures 3, 4, 5, and 6. In all spectral classes we can readily distinguish between luminosity classes V, III, and I*b*,[3] corresponding to main-sequence stars, ordinary giants, and

[2] W. W. Morgan, P. C. Keenan, and E. Kellman, *An Atlas of Stellar Spectra* (1943).

[3] We are using the notation adopted by Morgan, Keenan, and Kellman (*ibid*).

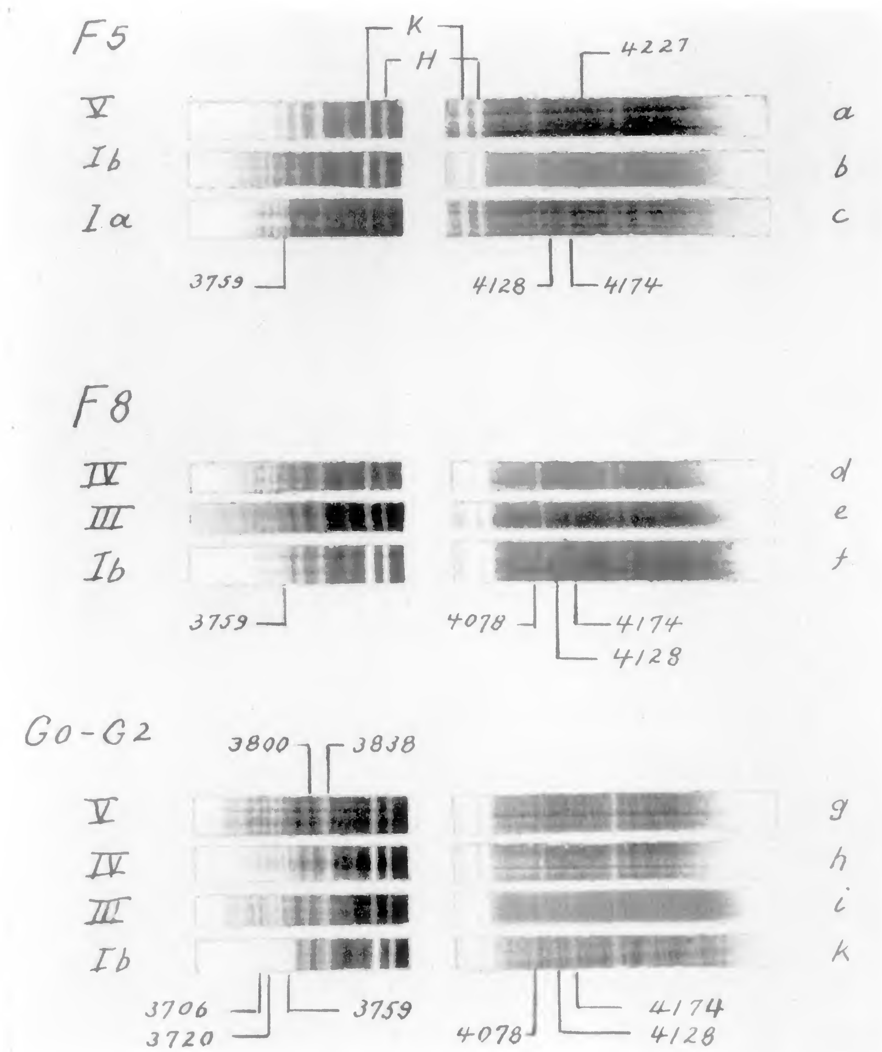


FIG. 1.—Objective-prism spectra of (*a*). 5 And F5 V; (*b*) T Vul F5 I*b;* (*c*) ϵ Aur F5 I*a;* (*d*) ι Psc F8 IV; (*e*) BD+62°130 F8 III; (*f*) 45 Dra F8 I*b;* (*g*) 72 Her G2 V; (*h*) χ Her G0 IV; (*i*) π Cep G0 III; (*k*) BD+56°2923 G2 I*a*.

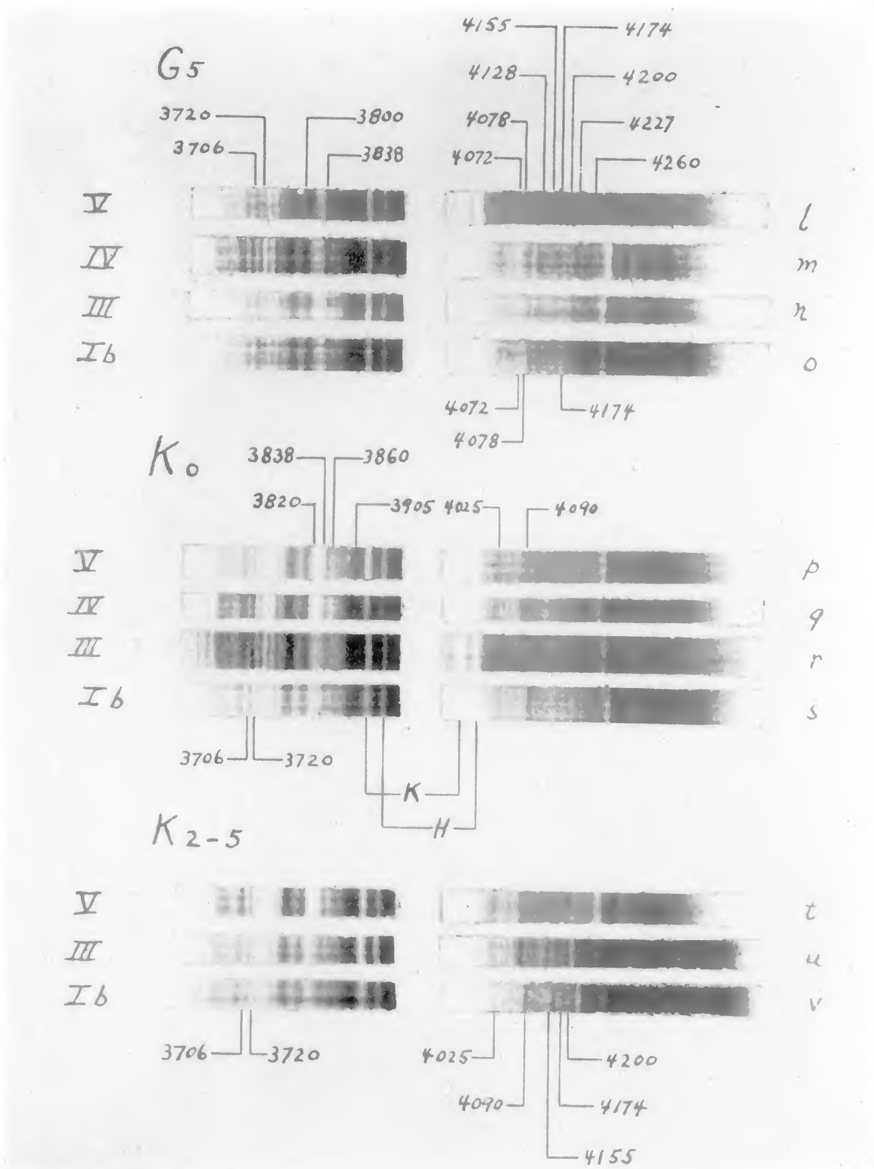
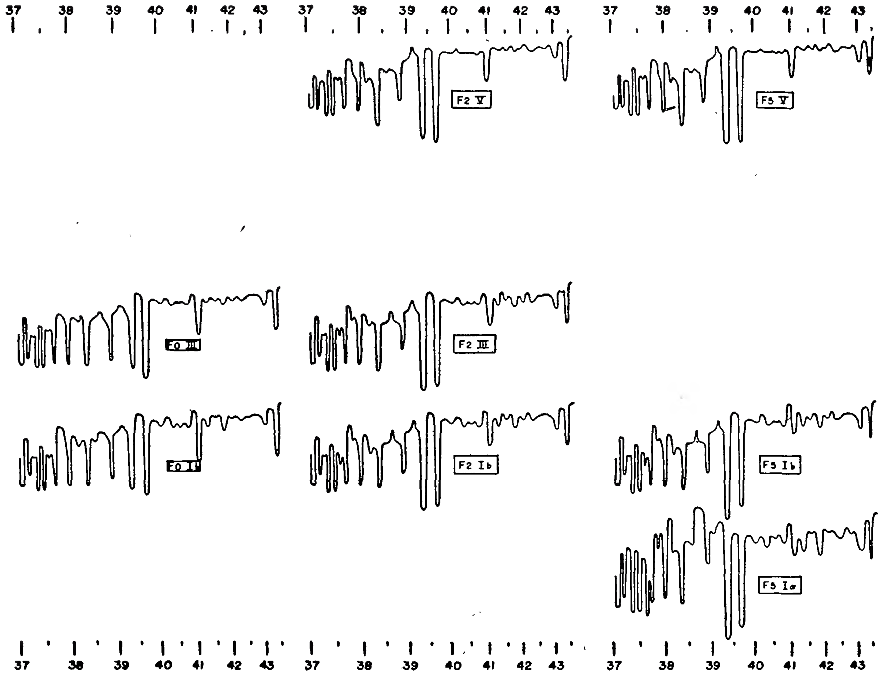
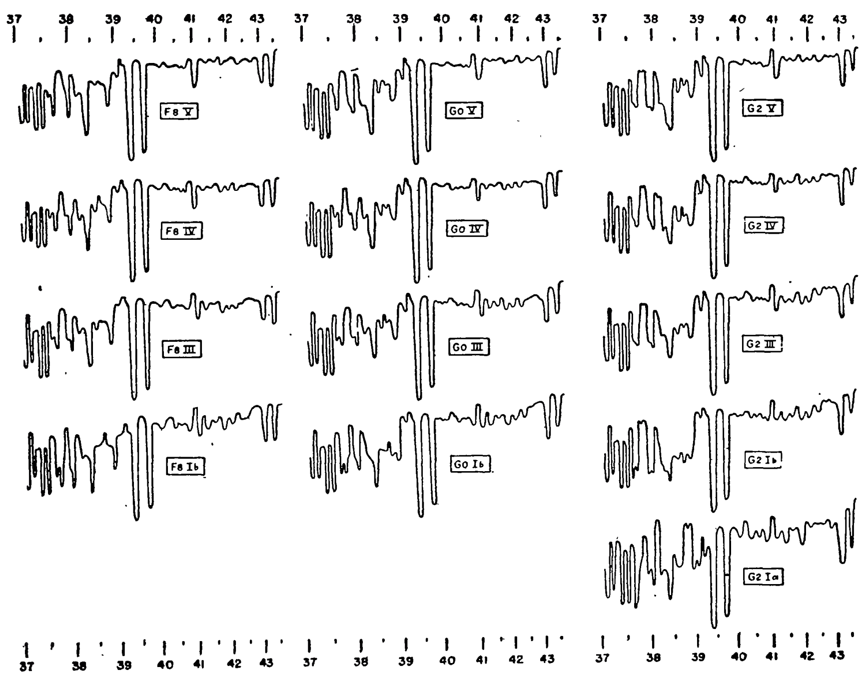


FIG. 2.—Objective-prism spectra of (*l*) BD+66°1281 G5 V; (*m*) μ Her G5 IV; (*n*) 31 Vul G5 III; (*o*) α^1 Cap G5 I*b;* (*p*) σ Dra K0 V; (*q*) γ Cep K0 IV; (*r*) 3 And K0 III; (*s*) 56 Peg K1 I*b;* (*t*) BD+4°123 K2 V; (*u*) δ Psc K5 III; (*v*) BD+48°3887 K5 I*b*.



F2 V
F5 V
F0 III
F2 III
F0 Ib
F2 Ib
F5 Ib
F5 Ia
37 38 39 40 41 42 43

FIG. 3



F8 V
G0 V
G2 V
F8 IV
G0 IV
G2 IV
F8 III
G0 III
G2 III
F8 Ib
G0 Ib
G2 Ib
G2 Ia
37 38 39 40 41 42 43

FIG. 4

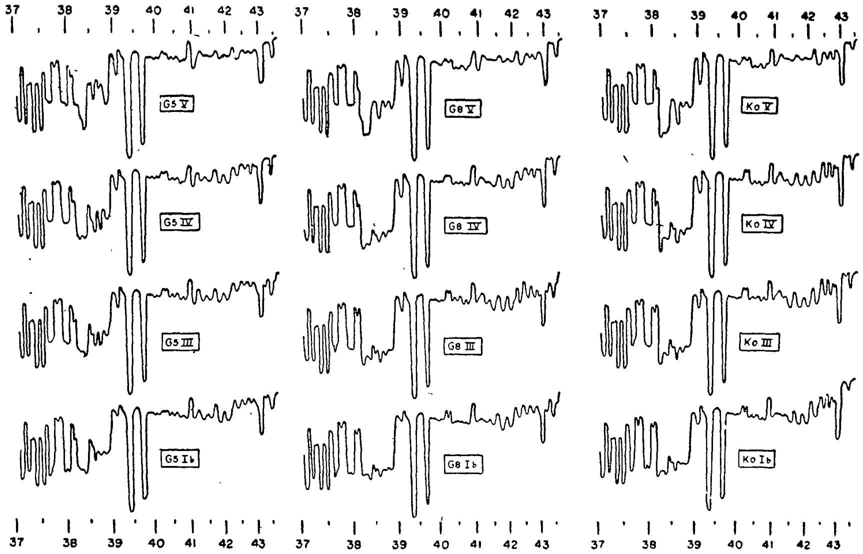

37 38 39 40 41 42 43
G5 V
G5 IV
G5 III
G5 Ib
G8 V
G8 IV
G8 III
G8 Ib
K0 V
K0 IV
K0 III
K0 Ib

FIG. 5

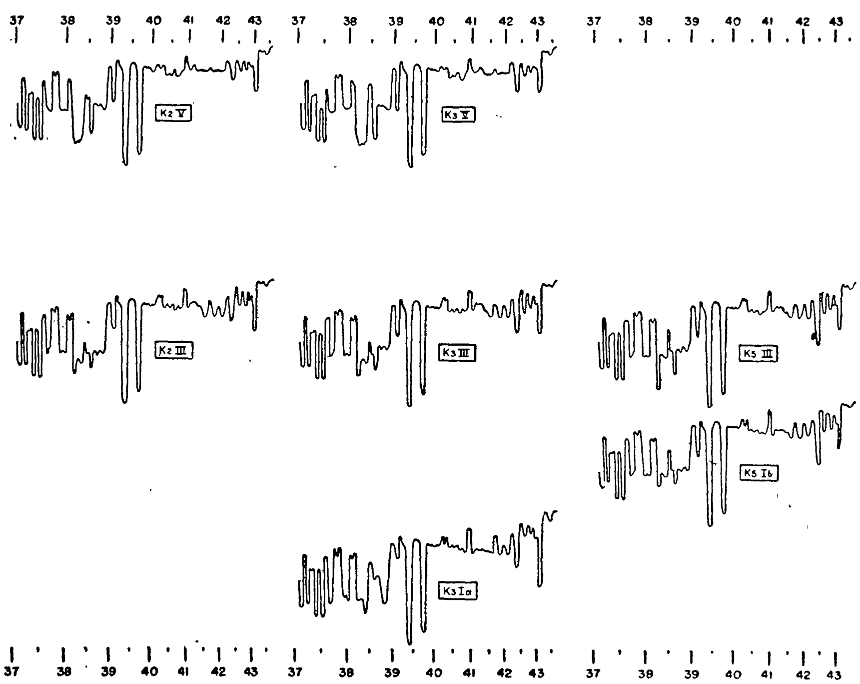

37 38 39 40 41 42 43
K2 V
K3 V
K2 III
K3 III
K5 III
K5 Ib
K3 Ia

FIG. 6

supergiants. In addition, in classes F8–K0 the luminosity class IV can be determined. From F8 to G5 the stars in class IV appear to be luminous dwarfs; in G8 and K0 they appear to be subgiants. Our limited data show a discontinuity in this class between G5 and G8.

PRINCIPAL FEATURES IN THE DIFFERENT SPECTRAL REGIONS

The spectrum can be divided into a number of regions, some of which are more sensitive to spectral-type changes, others to luminosity. Regions primarily sensitive to spectral-type variation are λ 3860 to the K line and λ 4227 to $H\gamma$. Sensitive for luminosity differences are the regions $\lambda\lambda$ 3700–3838, H–$H\delta$, and $H\delta$–λ 4227. This separation into regions is only approximate, but it is useful in the discussion.

The procedure in classification begins with an approximate determination of spectral type for which well-known criteria are used. In the F stars the relative strength of the H and K lines and of the G band as compared to $H\gamma$ gives the first approximation. The latter criterion may be used up to G5, where the break at the G band becomes apparent. The prominence of $H\delta$ is another indication of spectral class. From G8 onward the relative intensity of the calcium line λ 4227 compared to the G band becomes the chief class criterion. In addition to these well-known criteria, the region λ 3860 to the K line gives material help. The appearance of the line at λ 3860 in late F stars and early G's, the general absorption in this region in spectral types G2–K0, and the greater strength of λ 3860 in late K spectra may be used for spectral classification. None of the above criteria will give an accurate temperature as long as the luminosity of the star has not been determined.

The first important luminosity criterion is furnished by the relative intensities of the lines in the ultraviolet around λ 3706 and λ 3720. The line λ 3720 appears to be much weakened in supergiants. Since the blend at λ 3706 is much broader than λ 3720, a very accurate intensity estimate is not possible, and the minor intensity changes indicated in the drawings between classes III, IV, and V are of little use. Supergiants, however, may be recognized at first sight if this region of the spectrum is accessible.

A second important feature is the Ti^{+} line at λ 3759, which is much strengthened in supergiants of types F2–G5.

A comparison of the broad blend at $\lambda\lambda$ 3820–3838 with that at λ 3800 is very useful. Generally, the intensity ratio of these two features varies markedly with luminosity, the blend near $\lambda\lambda$ 3820–3838 increasing in relative strength when the luminosity of the star diminishes. The actual variations of this region are involved, and they should be studied from the tracings.

In the region between the H line and $H\delta$ there are some faint lines which show luminosity changes in the F stars. The intensity ratio of λ 4078 to the line on the violet side of it furnishes a useful luminosity criterion throughout almost the entire spectral range. However, this feature is at the limit of visibility in many of our spectra.

In the region to the green of $H\delta$ the relative intensity of λ 4174 furnishes a very sensitive luminosity criterion. In the F stars this blend is most readily compared to the blend at λ 4227 or to the G band. In stars of later types, λ 4174 is compared with the blends on either side of it (λ 4155 and λ 4200) as well as with $H\delta$. The blend at λ 4128 increases in strength with increasing luminosity but is very sensitive to spectral type and disappears around K0.

In the classes F0–K0 the features mentioned above make a distinction between luminosity classes V, III, and I*b* relatively easy. Distinction between V and IV in types F8–G5 and between IV and III and in G8 and K0 is more difficult. In the K stars the distinction between classes V and III is easily observed. In the K dwarfs the blend at the position of $H\delta$ is still strong. This might be the reason why some of the K dwarfs among our standards have been classified as G stars in the *Henry Draper Catalogue*.

The differentiation between classes III and I*b* is difficult in the K stars, since the ultraviolet is usually invisible. The blue is of little help except for the inconspicuous feature near λ 4078. The filling-up of the region near λ 4025 and especially the change of the background level in the region from $H\delta$ to λ 4155 are useful in distinguishing between classes III and I*b* in these spectra.

In making the drawings we have been careful to represent the level of the different spectral regions (ultraviolet and blue separately) as accurately as possible. This was found desirable, particularly, in the classification of faint spectra.

The few stars of class I*a* have exceptional spectra. They deviate in many respects fundamentally even from class I*b* stars. The spectrum of BD + 61°178 in the ultraviolet looks more like an early-type star. The strongest lines in this spectrum appear at the places of the hydrogen lines. The strengthening of the hydrogen lines, if there is not an accidental coincidence of wave length, appears also in the blue. However, the star may be composite. The star BD +56°2923 also shows exceptionally strong hydrogen and may be of earlier type than G2. More detailed study of these spectra seems highly desirable.

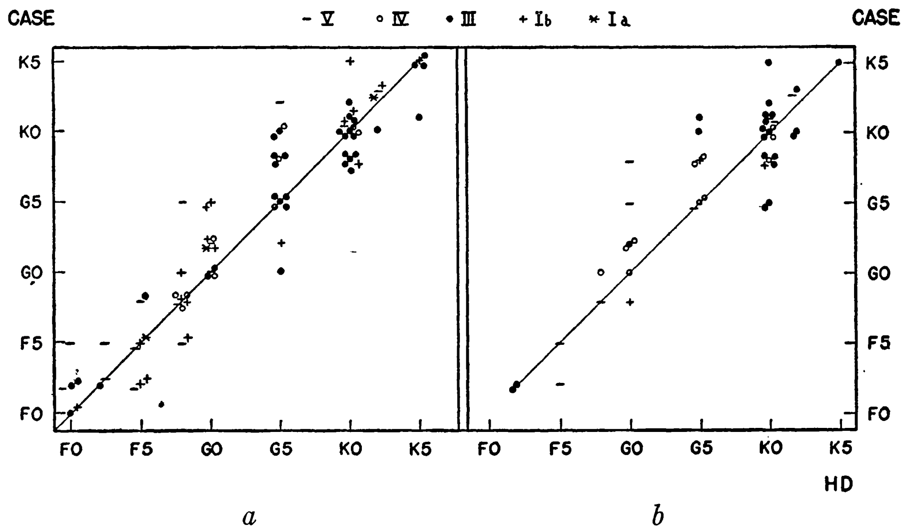


FIG. 7.—*a*, Correlation diagram of 81 stars having spectra of good quality; *b*, Correlation diagram of 45 stars having spectra of inferior quality.

After the luminosity of the star has been decided upon, the accurate temperature class can be determined. All features mentioned above may be used for this purpose. In addition, many other features may be used now, e.g., the intensity ratio λλ 4128–4155, or even the two lines between λ 4227 and the G band. Many of the features in the region between H and $H\gamma$, described above, correspond to features shown in the *Atlas of Stellar Spectra* and have been described by Morgan, Keenan, and Kellman. Since we deal with more blended lines, the criteria had to be studied independently for use in objective-prism spectra of low dispersion.

APPLICATION OF LUMINOSITY CRITERIA TO THE STANDARD STARS

After the tracings for the different luminosity classes had been made, the final check consisted in a reclassification of the first- and second-class standards in our plates. The results of this classification are given in Table 1. The first column gives the name of the star, the second column gives the quality of the ultraviolet and the blue regions, respectively, on a scale from 0 to 10. The third column gives our classification. The fourth column gives the *Henry Draper* class, and the fifth column the absolute visual magnitude taken from the Schlesinger parallax catalogue.[4] Where both spectroscopic and trigonometric parallaxes were given, the weighted mean taken from the *Bright Star Catalogue*[5] has been adopted. A few cases, in which the data were conflicting or where only a very inaccurate trigonometric parallax was available, have been marked by colons.

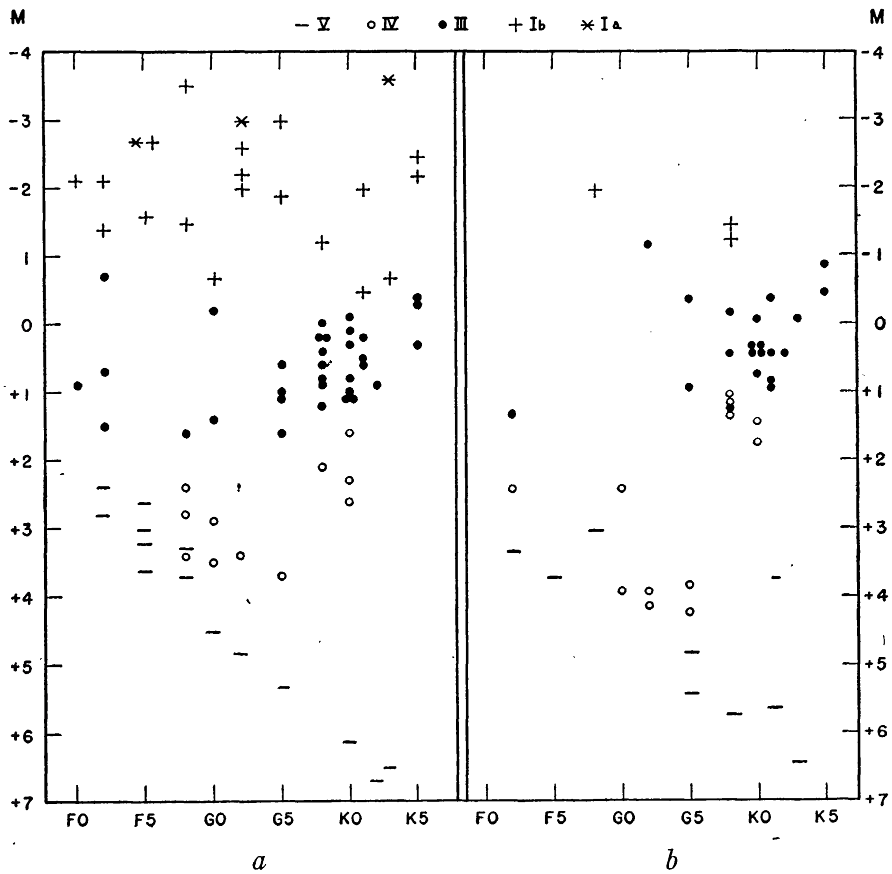


FIG. 8.—*a*, Spectrum-luminosity relation of 81 stars having spectra of good quality; *b*, Spectrum-luminosity relation of 45 stars having spectra of inferior quality.

The table contains 126 spectra, of which 81 have been considered of good quality and 45 inferior. Figures 7 and 8 show, respectively, the comparison with the *Henry Draper* classification and a Russell diagram for these two groups of stars. The star T Vul is listed twice, since its spectrum was taken once near maximum light and once near minimum. It appears from these two figures that the method can be used with success on relatively poor spectra.

[4] *General Catalogue of Stellar Parallaxes Compiled at Yale University Observatory* (1935).

[5] *Yale University Observatory Catalogue of Bright Stars* (1940).