# MULTICOLOR PHOTOELECTRIC PHOTOMETRY OF STARS WITH COMPOSITE SPECTRA

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ABSTRACT

Multicolor observations of stars with composite spectra have been analyzed to determine the individual characteristics of the separate components Observations of fifty normal stars representing a considerable range in spectral types and luminosity classes were used to establish a set of standard colors. For unreddened stars of population I these colors furnish definite classification criteria for the spectral type and luminosity class and thus are capable of classifying stars in two dimensions. The colors in the red region are the best temperature indicators, while the ultraviolet color is most sensitive to the luminosity effect. In the case of early-type stars the effect of interstellar reddening can be separated from temperature reddening and the luminosity effect. In the case of late-type stars, however, the separation cannot be made from the photoelectric colors alone. Observations of two population II stars—one a K giant and the other a subdwarf—confirmed the ultraviolet excess found by other investigators and indicated a temperature lower than that normally found for population I stars of the same spectral type.

Observed colors of thirty stars with known or suspected composite spectra were compared with artificial colors calculated from selected combinations of two standard stars. The selection was guided by the spectroscopic results and such other information on reddening, parallax, and the like as was available. In most cases it was found that a unique classification could be made by the present method with the information on hand. This ability to interpret the colors and spectra of unresolved binary stars indicates that the multicolor method may be useful in identifying the components of a stellar population in much more complex composite sources.

## INTRODUCTION

The present investigation deals with the multicolor photoelectric photometry of stars by wide-band transmission filters, with particular reference to the possibility of the spectral classification of stars with composite spectra. To date, the most comprehensive and perhaps the only exhaustive study on composite stars is that of Hynek (1938). Even with an advanced method such as the MK system, classification of the composite stars is still quite difficult and has not received as much attention as it deserves.

It would seem that the photoelectric colors obtained with wide-band filters would be less sensitive to the blending and veiling effects than is spectral classification involving the usual criteria based on the relative intensities of the lines and bands. The present investigation is an attempt to classify these stars according to the relative strengths of the continuum alone. It was felt that an ordinary three-color photometry, such as the ($U$, $B$, $V$) system of Johnson and Morgan (1953), did not cover a sufficient range of the spectrum to delineate the complex character of the composite stars. Hence a program was initiated to measure these stars in six wave-length regions, ranging from infrared to ultraviolet, with a new 12-inch reflector at the Washburn Observatory.

The stars to be observed were selected from two sources: the standard stars whose colors would serve the same function as the standard spectra in the *Atlas* of Morgan, Keenan, and Kellman (1943) were chosen from the list of Johnson and Harris (1954), and the composite stars were taken from the survey of Hynek (1938). Inasmuch as the present investigation was in the nature of a preliminary reconnaissance, only the brighter stars were selected. Moreover, owing to the moderate size of the telescope and the bright Madison sky, sufficiently accurate observations of the fainter stars would have been difficult.

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## OBSERVATIONS

The observing program consisted of two separate and independent systems of three-color photometry: one covering from infrared to yellow with a red-sensitive photomultiplier RCA C7160 and the other covering from green to ultraviolet with an RCA 1P21, in order to utilize the sensitivity maximum of both the cesium oxide-on-silver and antimony-cesium cathode surfaces and make the best use of the light available from a 12-inch telescope. The filter combinations and the effective wave numbers of each color in inverse micron units ($\mu^{-1}$) are given in Table 1. The filter G125 is an interference filter having a broad reflection band from λ 8200 A to about λ 12000 A. It was supplied by Dr. A. F. Turner of the Bausch and Lomb Optical Company. The ultraviolet filter 9863 was cemented with an ordinary microscope cover slide to give a better-defined cutoff in the short-wave-length side, where the variable atmospheric extinction would otherwise have introduced an uncertain factor in the total transmission. The over-all response of the cell-filter combination to a constant energy source is shown in Figure 1, where the ordinate is the response in an arbitrary unit with $i$, $r$, and $y$ in the same scale, and $g$, $b$, and $u$ in another scale. The response in Figure 1 does not include the effect of reflections from the two aluminized surfaces in the telescope optics. The amount of transmission in

TABLE 1

FILTERS AND EFFECTIVE WAVE NUMBERS

| Detector | Color | Filter | $1/\lambda$ ($\mu^{-1}$) |
|---|---|---|---|
| C7160 | Infrared | Schott RG10 (3 5 mm) | 1 14 |
| | Red | Schott RG2 (2 mm)+interference filter G125* | 1 38 |
| | Yellow | Corning 3385 (2 mm)+Corning 9788 (2 5 mm), cemented | 1 79 |
| 1P21 | Green | Corning 3384 (3 mm) | 1 85 |
| | Blue | Schott BG12 (2 mm)+Schott GG13 (2 mm), cemented | 2 39 |
| | Ultraviolet | Corning 9863 (3 mm)+clear glass (1 mm),* cemented | 2 84 |

* See text

the red of the ultraviolet filter was found by observing several stars, first, with the ultraviolet filter alone and then with this filter in combination with a Schott RG2, which transmits only the red leak of the ultraviolet filter. For stars earlier than F8 the effect of the red leak on the ultraviolet color was found to be completely negligible. For the later-type stars the observed ultraviolet colors have been corrected for the effect of red leak; for a K5 III star the correction was 0.035 mag. The procedure for reducing the observations to outside the atmosphere was essentially the same as that outlined by Stebbins (1953). Between March, 1956, and February, 1957, observations were made on 26 nights, 15 with the blue and 11 with the red photometer.

The results of the observations are given in Table 2. The first column gives the running number; an asterisk after the number refers to the note at the end of the table. The second and third give the *HD* numbers and the designations of stars, respectively. These are followed by a letter which signifies the basis of selection of each star: "s" for standard and "c" for composite or suspected composite stars. The fifth to eighth columns give the observed instrumental colors $(u - g)$, $(b - g)$, $(r - y)$, and $(i - y)$. The ninth column gives the spectral types in the MK system if such were available or in the *HD* classification otherwise. The two numbers listed in the last column refer to the number of observations with the blue photometer and with the red photometer in that order. The extinction stars are denoted by "Ext" in this column.

An estimate of the internal accuracy of each observed color was made from the deviations from the mean of the values obtained for the same star on different nights. The calculated probable errors of the observations for each color are as follows: $(i - y)$, $\pm 0^m032$; $(r - y)$, $\pm 0^m020$; $(b - g)$, $\pm 0^m010$; $(u - g)$, $\pm 0^m022$. Comparisons with other color systems, such as the $(U, B, V)$ system of Johnson and Morgan (1953) and the six-color measurements of Stebbins and Whitford (1945) and Stebbins and Kron (1956), are shown in Figure 2, where the colors in each system are referred to the average of the observed colors of 10 Lacertae and $\alpha$ Virginis. Assuming a linear relationship between the corresponding color indices, the transformation equations as derived by the

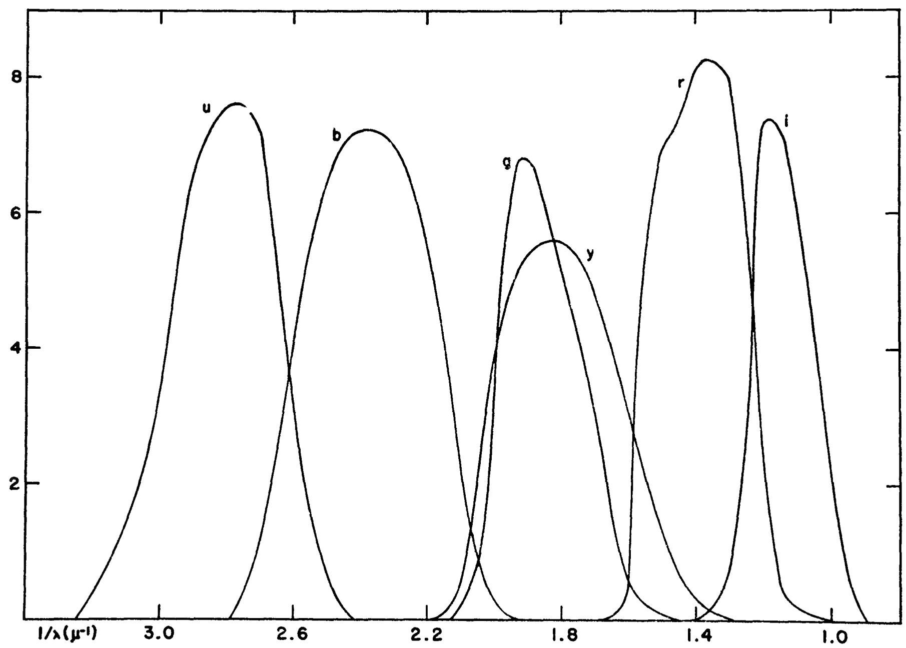


FIG 1 —Response of photometers to a constant source The abscissa is $1/\lambda$ in units of $\mu^{-1}$. The ordinate is response in arbitrary units with $i$, $r$, and $y$, in the same scale and $g$, $b$, and $u$ in another scale

least-squares solutions are given below. The color indices with a subscript $J$ are on the $(U, B, V)$ system, and those with $S$ on the six-color system.

$$(B - V)_J = \underset{\pm 0.046}{+0.834} \; (b - g) \; \underset{\pm 0.007}{+0.585} \tag{1}$$

$$(U - V)_J = \underset{\pm 0.049}{+1.028} \; (u - g) \; \underset{\pm 0.055}{-0.308} \tag{2}$$

$$(I - G)_S = \underset{\pm 0.087}{+1.107} \; (i - y) \; \underset{\pm 0.038}{-0.192} \tag{3}$$

$$(R - G)_S = \underset{\pm 0.088}{+0.856} \; (r - y) \; \underset{\pm 0.029}{+0.321} \tag{4}$$

TABLE 2

COLORS OF 83 STARS

| No | Star | Name | | (u−g) | (b−g) | (r−y) | (i−y) | Sp Type | n |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 432 | β Cas | s | +0 69 | −0 29 | −0 11 | +0 61 | F2 IV | 2, 2 |
| 2 | 2905 | κ Cas | s | −0 34 | −0 52 | +0 07 | +0 88 | B1 Ia | 2, 2 |
| 3 | 4727 | ν And | s | −0 42 | −0 87 | +0 35 | +1 28 | B5 V | 1, 2 |
| 4 | 4775-6 | | c | +0 94 | −0 10 | −0 29 | +0 25 | A+F | 2, 2 |
| 5 | 8538 | δ Cas | s | +0 51 | −0 55 | +0 12 | +0 90 | A5 V | 2, 2 |
| 6 | 9270 | η Psc | s | +1 92 | +0 45 | −0 50 | +0 00 | G8 III | 2, 2 |
| 7 | 10516 | φ Per | c | −0 63 | −0 77 | +0 03 | +0 94 | B0 ne | 2, 2 |
| 8 | 11636 | β Ari | s | +0 52 | −0 51 | +0 15 | +0 97 | A5 V | Ext |
| 9 | 12447 | α Psc | c | +0 25 | −0 60 | +0 18 | +1 00 | A2 np | 3, 2 |
| 10 | 12929 | α Ari | s | +2 49 | +0 70 | −0 67 | −0 23 | K2 III | Ext |
| 11 | 17878-9 | τ Per | c | +1 41 | +0 18 | −0 41 | +0 10 | G1 | 2, 3 |
| 12 | 18925-6 | γ Per | c | +1 34 | +0 11 | −0 41 | +0 12 | G8 III: +A3 | 2, 3 |
| 13 | 20630 | κ Cet | s | +1 15 | +0 10 | −0 34 | +0 24 | G5 V | 2, 2 |
| 12 | 20902 | α Per | s | +0 99 | −0 16 | −0 22 | +0 39 | F5 Ib | 2, 3 |
| 15 | 23089-90 | | c | +1 27 | +0 21 | −0 52 | −0 08 | cF5 | 2, 3 |
| 16 | 25555-6 | 36 Tau | c | +1 41 | +0 30 | −0 66 | −0 34 | F4 | 3, 3 |
| 17 | 26673-4 | 52 Per | c | +1 87 | +0 46 | −0 56 | −0 11 | cG3 | 2, 3 |
| 18 | 27697 | δ Tau | s | +2 01 | +0 46 | −0 51 | −0 02 | K0 III | 2, 3 |
| 19 | 28305 | ε Tau | s | +2 10 | +0 51 | −0 52 | −0 03 | K0 III | 2, 3 |
| 20 | 29094-5 | 58 Per | c | +2 26 | +0 75 | −0 73 | −0 40 | cG2 | 2, 3 |
| 21 | 29139 | α Tau | s | +3 64 | +1 16 | −1 08 | −0 93 | K5 III | 2, 3 |
| 22 | 30652 | $\pi^3$ Ori | s | +0 67 | −0 19 | −0 21 | +0 48 | F5 V | 3, 3 |
| 23 | 32068-9 | ζ Aur | c | +1 95 | +0 75 | −0 95 | −0 74 | K4 II+B | 3, 3 |
| 24 | 32630 | η Aur | s | −0 51 | −0 89 | +0 39 | +1 37 | B3 V | 2, 3 |
| 25 | 34029 | α Aur | c | +1 46 | +0 24 | −0 44 | +0 11 | G8 III: +F | 3, 3 |
| 26 | 34085 | β Ori | s | −0 41 | −0 73 | +0 18 | +1 10 | B8 Ia | 2, 2 |
| 27 | 37128 | ε Ori | s | −0 86 | −0 90 | +0 34 | +1 35 | B0 Ia | 2, 2 |
| 28 | 37202 | ζ Tau | c | −0 65 | −0 94 | +0 27 | +1 17 | B4 ne | 2, 2 |
| 29 | 39801 | α Ori | s | +3 98 | +1 49 | −1 60 | −1 60 | M2 Ia | 2, 2 |
| 30 | 40369-70 | | c | +1 77 | +0 35 | −0 58 | −0 15 | G4 | 1, 2 |
| 31 | 48737 | ξ Gem | c | +0 71 | −0 20 | −0 16 | +0 55 | F3 | 2, 3 |
| 32 | 49618-9 | 14 Lyn | c | +1 30 | +0 07 | −0 36 | +0 16 | A+F | 3, 2 |
| 33 | 56537 | λ Gem | s | +0 41 | −0 58 | +0 17 | +1 01 | A3 V | Ext |
| 34 | 58946 | ρ Gem | s | +0 53 | −0 35 | −0 09 | +0 59 | F0 V | 2, 3 |
| 35 | 60178 | α Gem | c | +0 24 | −0 68 | +0 20 | +1 03 | A0+F5 | 2, 3 |
| 36 | 62345 | κ Gem | s | +1 87 | +0 43 | −0 48 | +0 02 | G8 III | Ext |
| 37 | 63208-9 | 82 Gem | c | +1 06 | −0 05 | −0 37 | +0 16 | F2+A | 2, 2 |
| 38 | 78362-3 | τ UMa | c | +0 76 | −0 26 | −0 05 | +0 65 | cF6 | 3, 3 |
| 39 | 74874 | ε Hya | s | +1 26 | +0 09 | −0 41 | +0 15 | G0 III | 2, 2 |
| 40 | 83808-9 | ο Leo | c | +0 92 | −0 14 | −0 20 | +0 45 | cF5 | 2, 2 |
| 41 | 102870 | β Vir | s | +0 90 | −0 06 | −0 29 | +0 34 | F8 V | 3, 2 |
| 42* | 103095 | | s | +1 19 | +0 20 | −0 54 | −0 09 | G8 Vp | 2, 3 |
| 43 | 103287 | γ UMa | s | +0 30 | −0 64 | +0 21 | +1 03 | A0 V | 3, 2 |
| 44 | 109358 | β CVn | c | +0 97 | +0 05 | −0 33 | +0 26 | G0 V | 3, 1 |
| 45 | 111812 | 31 Com | s | +1 13 | +0 11 | −0 35 | +0 22 | G0 III | 3, 3 |
| 46 | 113139 | 78 UMa | s | +0 68 | −0 22 | −0 14 | +0 55 | F2 V | 3, 1 |
| 47 | 114710 | β Com | s | +0 96 | +0 02 | −0 30 | +0 29 | G0 V | 3, 3 |
| 48 | 116658 | α Vir | s | −0 82 | −0 95 | +0 40 | +1 44 | B1 V | 3, 3 |
| 49 | 118022 | 78 Vir | c | +0 28 | −0 63 | +0 19 | +1 03 | A3 ns | 3, 2 |
| 50 | 120315 | η UMa | s | −0 55 | −0 90 | +0 36 | +1 33 | B3 V | 3, 1 |

TABLE 2—*Continued*

| No | Star | Name | | $(u-g)$ | $(b-g)$ | $(r-y)$ | $(i-y)$ | Sp Type | $n$ |
|---|---|---|---|---|---|---|---|---|---|
| 51 | 124897 | $\alpha$ Boo | s | +2 73 | +0 86 | −0 78 | −0 45 | K2 IIIp | 3, 2 |
| 52 | 128167 | $\sigma$ Boo | s | +0 64 | −0 22 | −0 14 | +0 54 | F2 V | 2, 1 |
| 53 | 141004 | $\lambda$ Ser | s | +1 02 | +0 06 | −0 36 | +0 25 | G0 V | 2, 1 |
| 54 | 142860 | $\gamma$ Ser | s | +0 75 | −0 12 | −0 23 | +0 40 | F6 V | 2, 1 |
| 55 | 143107 | $\epsilon$ CrB | s | +2 78 | +0 83 | −0 71 | −0 36 | K3 III | Ext |
| 56 | 147394 | $\tau$ Her | s | −0 38 | −0 86 | +0 35 | +1 32 | B5 IV | Ext |
| 57 | 150997 | $\eta$ Her | s | +1 80 | +0 41 | −0 50 | −0 02 | G4 III | 5, 2 |
| 58 | 164058 | $\gamma$ Dra | s | +3 65 | +1 18 | −1 00 | −0 78 | K5 III | 2, 3 |
| 59 | 169985-6 | 59 Ser | c | +1 01 | −0 12 | −0 33 | +0 21 | A0+F2 | 3, 1 |
| 60 | 172167 | $\alpha$ Lyr | s | +0 29 | −0 68 | +0 24 | +1 07 | A0 V | 4, 3 |
| 61. | 175492-3 | 113 Her | c | +1 54 | +0 25 | −0 45 | +0 03 | G0 | 4, 3 |
| 62* | 183912 | $\beta^1$ Cyg | c | +2 04 | +0 65 | −0 68 | −0 39 | K0 | 2, 2 |
| 63 | 186882 | $\delta$ Cyg | s | +0 16 | −0 71 | +0 24 | +1 06 | B9 5 III | 3, 3 |
| 64 | 187076-7 | $\delta$ Sge | c | +2 70 | +1 00 | −1 46 | −1 58 | G+M | 4, 3 |
| 65 | 187642 | $\alpha$ Aql | s | +0 57 | −0 43 | +0 00 | +0 77 | A7 IV–V | 5, 3 |
| 66 | 188512 | $\beta$ Aql | s | +1 64 | +0 34 | −0 48 | +0 01 | G8 IV | Ext |
| 67 | 193237 | P Cyg | s | +0.12 | −0 25 | −0 24 | +0 36 | B1 p | 3, 3 |
| 68 | 194093 | $\gamma$ Cyg | s | +1 41 | +0 13 | −0 31 | +0 26 | F8 I*b* | 2, 3 |
| 69 | 196093-4 | 47 Cyg | c | +2 60 | +1 18 | −1 13 | −1 04 | cK4 | 1, 2 |
| 70 | 196867 | $\alpha$ Del | s | +0 02 | −0 74 | +0 26 | +1 12 | B9 V | Ext |
| 71 | 197345 | $\alpha$ Cyg | s | +0 18 | −0 53 | +0 09 | +0 82 | A2 I*a* | 2, 2 |
| 72. | 198478 | 55 Cyg | s | +0 28 | −0 21 | −0 20 | +0 39 | B3 I*a* | 3, 2 |
| 73* | 201091 | 61 Cyg A | s | +2 45 | +0 69 | −0 77 | −0 41 | K5 V | 1, 2 |
| 74* | 201092 | 61 Cyg B | s | +2 59 | +0 88 | −0 96 | −0 73 | K7 V | 1, 2 |
| 75* | 201091-2 | 61 Cyg | c | +2 46 | +0 75 | −0 85 | −0 55 | K5 V+K7 V | 1, 2 |
| 76 | 202447-8 | $\alpha$ Equ | c | +1 09 | −0 07 | −0 29 | +0 28 | F5 | 4, 3 |
| 77 | 203280 | $\alpha$ Cep | s | +0 62 | −0 39 | +0 04 | +0 81 | A7 V–IV | 3, 2 |
| 78 | 206778 | $\epsilon$ Peg | s | +3 50 | +1 20 | −0 88 | −0 59 | K2 I*b* | 1, 3 |
| 79 .. | 209790-1 | 17 Cep | c | +0 73 | −0 24 | −0 06 | +0 68 | A3+F7 | 3, 2 |
| 80 | 213310-1 | 5 Lac | c | +2 99 | +1 28 | −1 21 | −1 16 | K6 | 2, 2 |
| 81 | 214680 | 10 Lac | s | −0 88 | −0 92 | +0 38 | +1 38 | O9V | 4, 3 |
| 82 | 217014 | 51 Peg | s | +1 20 | +0 12 | −0 32 | +0 25 | G4V | 3, 2 |
| 83 | 219134 | | s | +2 14 | +0 48 | −0 59 | −0 13 | K3 V | 2, 2 |

* The starred numbers are as follows:
42 HD 103095; Groombridge 1830
62 HD 183912; colors of a brighter component, $\beta^1$ Cygni
73 HD 201091; colors of a brighter component, 61 Cygni A, alone
74 HD 201092; colors of a fainter component, 61 Cygni B, alone
75 HD 201091-2; combined colors of both components

$$(V-G)_S = \underset{\pm 0.075}{+1.086}\ (b-g)\ \underset{\pm 0.006}{-0.122} \tag{5}$$

$$(U-G)_S = \underset{\pm 0.148}{+1.046}\ (u-g)\ \underset{\pm 0.114}{-1.159} \tag{6}$$

STANDARD COLORS FOR MK TYPES

The standard stars are grouped together according to their spectral types. The mean of individual colors then defines the standard colors for a given spectral type and luminosity class. In forming the standard colors, the average of the observed colors of 10 Lacertae

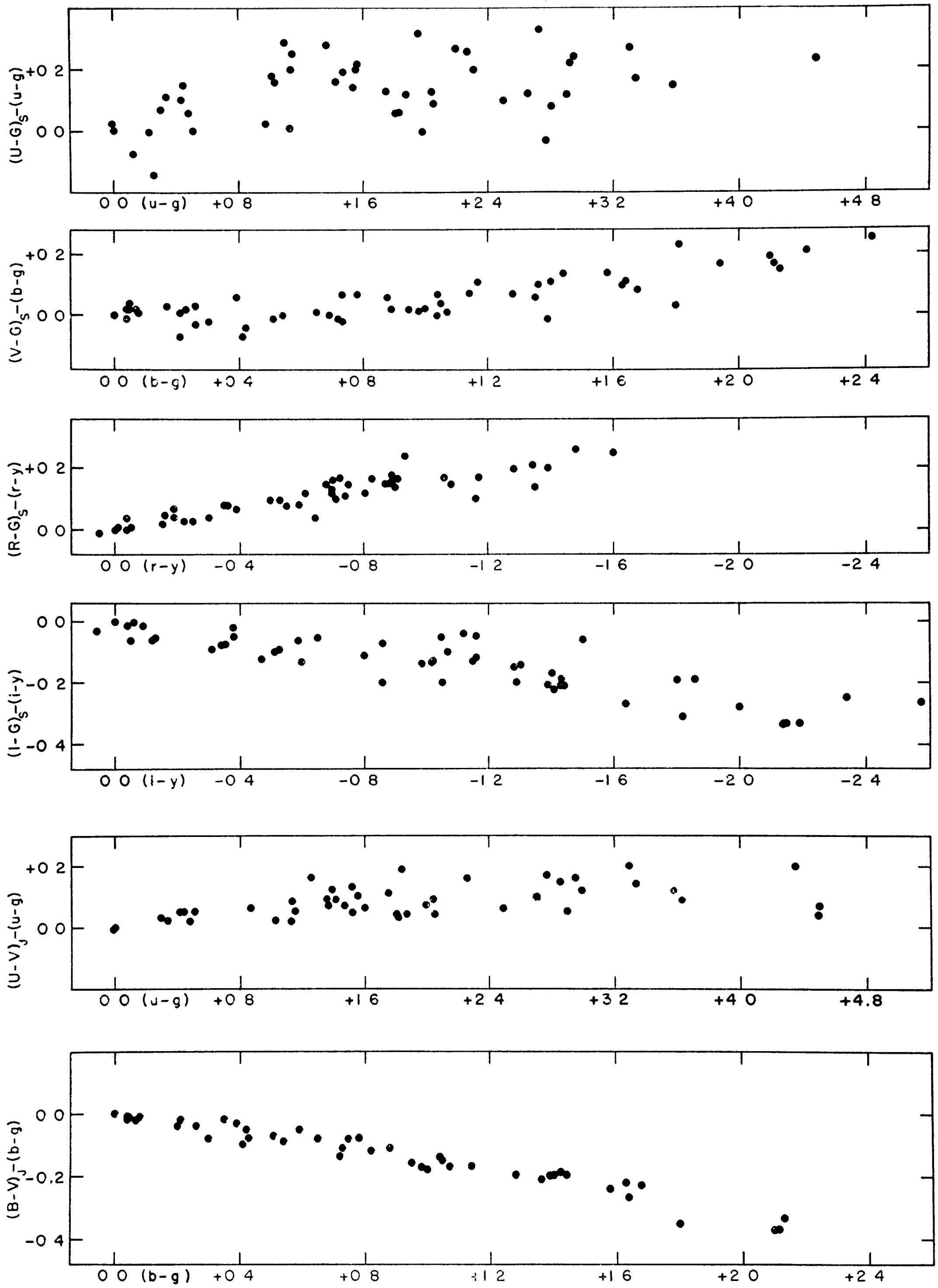


FIG 2.—Comparisons with other color systems. Subscript $J$ refers to the $(U, B, V)$ system, and subscript $S$ to the six-color system.

(O9 V) and $\alpha$ Virginis (B1 V) are taken as the reference. The colors defined in this way are denoted by $U$, $B$, $R$, and $I$. It has not been possible to choose two filters such that $g$ and $y$ would have the same effective wave number. Instead of determining a precise tie-in relation between them, the two color systems are left separate and independent in the following discussion. In graphical representation, however, a hypothetical color $Y$ is used as a common zero point; the effective wave number of $Y$ is taken to be 1.82, the mean of the effective wave numbers of $g$ and $y$. In order to transform the observed colors on the

TABLE 3

STANDARD COLORS FOR MK TYPES

| MK | $U$ | $B$ | $R$ | $I$ | $M_v$ | $n$ |
|---|---|---|---|---|---|---|
| B0 V | 0 000 | 0 000 | 0 000 | 0 000 | −3 9 | 2 |
| B3 V | +0 321 | +0 042 | −0 003 | −0 045 | −2 0 | 2 |
| B5 V | +0 453 | +0 072 | −0 039 | −0 112 | −1 3 | 2 |
| B9 V | +0 874 | +0 195 | −0 134 | −0 290 | 0 0 | 1 |
| A0 V | +1 145 | +0 277 | −0 171 | −0 361 | +0 3 | 2 |
| A3 V | +1 260 | +0 353 | −0 221 | −0 402 | +1 8 | 1 |
| A5 V | +1 365 | +0 409 | −0 260 | −0 471 | +2 2 | 2 |
| A7 V | +1 444 | +0 527 | −0 369 | −0 625 | +2 6 | 2 |
| F0 V | +1 464 | +0 618 | −0 491 | −0 809 | +3 0 | 2 |
| F2 V | +1 510 | +0 721 | −0 529 | −0 868 | +3 2 | 2 |
| F5 V | +1 523 | +0 751 | −0 599 | −0 935 | +3 4 | 1 |
| F7 V | +1 677 | +0 850 | −0 648 | −1 042 | +4 0 | 2 |
| G0 V | +1 840 | +0 975 | −0 721 | −1 139 | +4 4 | 2 |
| G5 V | +2 026 | +1 045 | −0 723 | −1 165 | +5 1 | 2 |
| G8 V | +2 486 | +1 275 | −0 875 | −1 398 | +5 6 | 1 |
| K3 V | +2 990 | +1 418 | −0 979 | −1 540 | +6 9 | 1 |
| K5 V | +3 297 | +1 629 | −1 158 | −1 823 | +7 8 | 1 |
| K7 V.. | +3 439 | +1 814 | −1 350 | −2 135 | +8 5 | 1 |
| B9 5 III | +1 007 | +0 228 | −0 149 | −0 351 | −1 5 | 1 |
| G0 III | +2 042 | +1 032 | −0 772 | −1 227 | +0 7 | 2 |
| G4 III | +2 649 | +1 349 | −0 887 | −1 429 | +0 3 | 1 |
| G8 III | +2 747 | +1 376 | −0 884 | −1 398 | +0 4 | 2 |
| K0 III | +2 906 | +1 420 | −0 904 | −1 434 | +0 2 | 2 |
| K2 III | +3 338 | +1 637 | −1 062 | −1 637 | 0 0 | 1 |
| K3 III | +3 631 | +1 677 | −1 103 | −1 766 | −0 1 | 1 |
| K5 III | +4 494 | +2 104 | −1 431 | −2 260 | −0 3 | 2 |
| F5 I*b* | +1 839 | +0 780 | −0 608 | −1 032 | −4 5 | 1 |
| F8 I*b* | +2 256 | +1 065 | −0 698 | −1 151 | −4 5 | 1 |
| K2 I*b* | +4 351 | +2 134 | −1 275 | −2 002 | −4 5 | 1 |
| M2 I*a* | +4 835 | +2 422 | −1 995 | −3 007 | −7 0 | 1 |

instrumental system into the $U$, $B$, $R$, $I$ system, the following constants were added to the colors of Table 2: $(u - g)$, $+0^{\mathrm{m}}.85$; $(b - g)$, $+0^{\mathrm{m}}.94$; $(r - y)$, $-0^{\mathrm{m}}.39$; $(i - y)$, $-1^{\mathrm{m}}.41$.

The mean colors for the various MK types are given in Table 3. The first column gives the MK types. The second through the fifth give the standard colors $U$, $B$, $R$, and $I$, respectively. The sixth column lists the absolute visual magnitude as given by Keenan and Morgan (1951). The last column gives the number of stars from which the mean is obtained. In the table the main-sequence stars are well represented from B to K. The lack of M dwarfs is due to the absence of these stars brighter than 6.5 mag., which was the limiting magnitude of the present study. The intermediate-type giants are actually scarce. It is assumed that the colors listed in Table 3 are the normal unreddened colors for their respective classes. The average distance (the geometric mean) of all standard stars is 44 parsecs. If the supergiants are excluded, the average distance is 29 parsecs. The trigonometric parallaxes are known for forty-two stars (Jenkins 1952). For the remaining stars the photometric distances without regard to interstellar absorption are used in calculating the average distance. As a whole, the effect of interstellar reddening can be neglected. The same, however, cannot be assumed for the early-type supergiants, and hence they are not included in Table 3.

The classification of stars from the analysis of their radiation depends upon three distinct classification criteria: temperature, luminosity, and chemical composition. Hereafter, these will be designated by "*T*-, *L*-, and *C*-criterion," respectively. In some cases the modification of the stellar radiation due to the space absorption, designated as "*S*-criterion," must be taken into account. A very brief review and summary of the role of each criterion on the classification of stars by the photoelectric method will be considered next.

In wide-band photoelectric photometry, the *T*-criterion depends, for the most part, on the relative strengths of the continuum rather than on the relative intensities of lines and bands used in the usual spectral classification. In dealing with a black body, it is well known (e.g., see Russell, Dugan, and Stewart 1938, p. 732) that measurements at two wave lengths in the continuum are sufficient for a temperature determination, provided that these two wave lengths are chosen strategically. In stellar photometry, even though the stars do not radiate like black bodies, Stebbins and Whitford (1945) found that a simple color index gave a definite differential temperature. In general, the red region of the spectrum is simpler than the photographic region, where the lines are more numerous. For this reason, the colors $R$ and $I$ are probably the best *T*-criterion to be used for the present purpose.

An attempt to use colors to find an *L*-criterion, which will be an analogue of the luminosity-sensitive lines in ordinary spectral classification, must first take account of the well-known temperature differences between giants and dwarfs of the same spectral type. This effect, which appeared early in the International Color Index system (Seares 1918), shows up clearly in the colors of the standard stars in the present study, as it did also in the first six-color discussion by Stebbins and Whitford (1945). After removing the temperature difference by using the colors $R$ and $I$, which are least affected by lines and bands, there remain large differences in the ultraviolet that are particularly interesting as a luminosity indicator.

Figure 3 shows typical examples for the early-type stars. It shows that the high-luminosity stars of these types are much stronger in the ultraviolet, because of the smaller Balmer discontinuity and the narrower, less intense hydrogen lines near the series limit. Günther (1950) noted this difference in Stebbins and Whitford's (1945) six-color data; it forms the principal basis of the luminosity classification system of Chalonge and Divan (1952). Before it can be used reliably, doubts about space reddening, which also shows an upward curvature on magnitude plots like Figure 3 (Stebbins and Whitford 1945; Whitford 1958), must be considered. In the present case the main-sequence stars $\alpha$ Delphini (B9 V) and $\lambda$ Geminorum (A3 V) both have the $(B - V)$ colors (Johnson and Harris 1954) of normal unreddened stars of their respective spectral type (Morgan, Harris, and Johnson 1953). The high-luminosity star in Figure 3, *a*, $\beta$ Orionis (B8 I*a*), was found to be very little reddened (Sharpless 1952); that in Figure 3, *b*, $\alpha$ Cygni (A2 I*a*), is a doubtful one, although the $C_1$ color is nearly normal (Stebbins, Huffer, and Whitford 1940). The latter star is discussed more fully in connection with the *S*-criterion. The colors of $\delta$ Cygni (B9.5 III) show that the same effect is detectable in stars of intermediate luminosity; in $\delta$ Cygni the ultraviolet excess is about one-third that of $\beta$ Orionis.

The luminosity effect for late-type stars is shown in Figure 4. Because of the previously mentioned difference in the temperature between the giants and dwarfs of the same spectral type, comparisons are made of the stars with nearly the same $R$ and $I$. The colors of the main-sequence stars are derived from the observed colors of three stars, HD 219314 (K3 V), 61 Cygni A (K5 V), and 61 Cygni B (K7 V), which are known from good trigonometric parallaxes (Jenkins 1952) to be so near the sun that space absorption is negligible. For the giant stars $\alpha$ Arietis (K2 III) and $\epsilon$ Pegasi (K2 I*b*), no definite information is available, but at galactic latitudes of $-35°$ and $-32°$, respectively, little reddening would be expected. From Figure 4 it appears that the useful *L*-criterion is again the ultraviolet; the effect here is the reverse of that found for the early-type stars. The weak

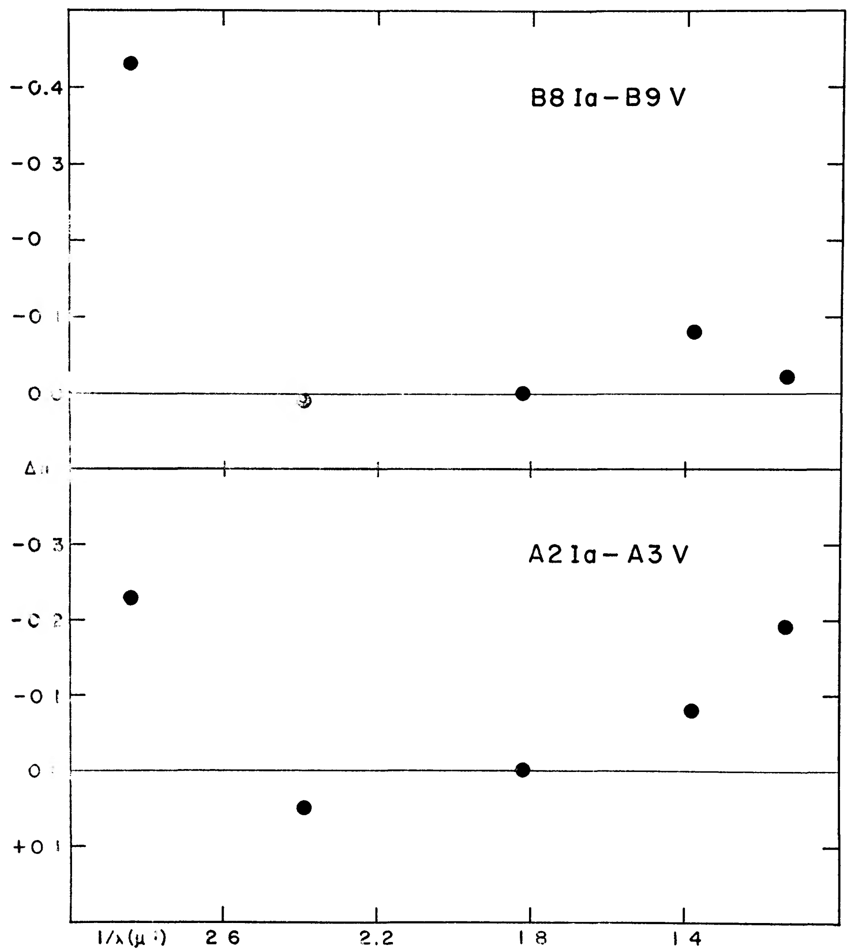


FIG. 3 —Luminosity effect in early-type stars

ultraviolet in late-type stars of high luminosity must be due in part to the strong cyanogen band at λ 3883 A. The number and strengths of metallic lines may also play a role. It appears that the color *B* is also sensitive to the luminosity, though the effect is much smaller than in the ultraviolet.

W stars, carbon stars, and perhaps other peculiar stars which show anomalous abundances of certain elements would be expected to show abnormal colors that could serve as a *C*-criterion. In addition, the low metal abundance in type II stars should likewise leave a mark in the colors which would separate these stars from "normal" stars of the type I population. Sandage and Walker (1955) observed the ultraviolet excess amounting to almost 0.5 mag. in giant stars of a globular cluster NGC 4147 from a plot of $(U - B)$ against $(B - V)$.

In the present investigation the stars known to have anomalous abundances have not been systematically observed. However, the observing list includes two stars, HD 124897 ($\alpha$ Bootis) and HD 103095 (Groombridge 1830), which are of interest here. The MK classification of $\alpha$ Bootis is K2 IIIp, but from the present $T$-criterion it is about a K3 or K4 giant. Figure 5 shows the deviations of the observed colors from those of a normal K3 III star. It is seen that $\alpha$ Bootis has a stronger ultraviolet radiation than a star of the same spectral type, as inferred from the colors in the red region.

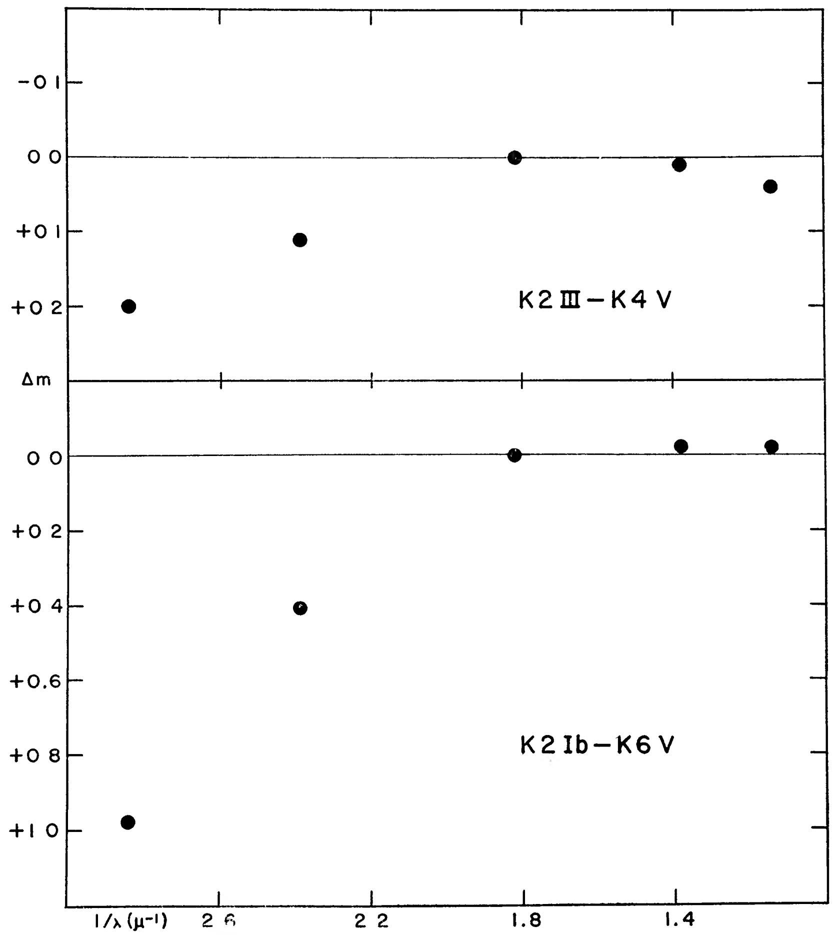


FIG 4 —Luminosity effect in late-type stars

The MK classification of HD 103095 is G8 Vp. That this well-known high-velocity star lies about 1 mag. below the main sequence and is a subdwarf rather than a normal G8 dwarf is firmly established by its parallax, 0".116 ± 0".005 (Jenkins 1952). The strong ultraviolet, which led Stebbins and Kron (1956) to suspect that the star was composite, agrees with Miss Roman's finding (1954). The color excess over a normal G8 V color found by her seems to continue into the red and infrared and indicates that the star is intrinsically cooler than an equivalent main-sequence star. From the colors $R$ and $I$, the temperature of this star is estimated to be slightly higher than in a normal K3 V star. Figure 6 shows the difference of the colors from those of a normal K3 V star. It appears that the effect of a smaller blanketing in the atmosphere of HD 103095 already begins to show in the blue. It would seem that the ultraviolet color could be used as a population indicator; however, observations of many more population II objects are needed before classification from colors alone could be attempted.

The $S$-criterion can be unambiguously determined if the other three physical variables are known from considerations independent of the colors. The law of interstellar reddening shows a sufficient departure from temperature reddening in the ultraviolet, however, for the colors alone to give a useful indication of space reddening in early-type stars. The deviation of the reddening law in the ultraviolet is in the sense that the reddening predicted from a simple $1/\lambda$ law would be too great (Whitford 1958). The bright ultraviolet is the basis of the "reddening line" in plots of $(U - B)$ versus $(B - V)$ (Morgan, Harris, and Johnson 1953). For late-type stars, in which the luminosity effect in the ultraviolet has the opposite sense, interstellar reddening cannot be separated from

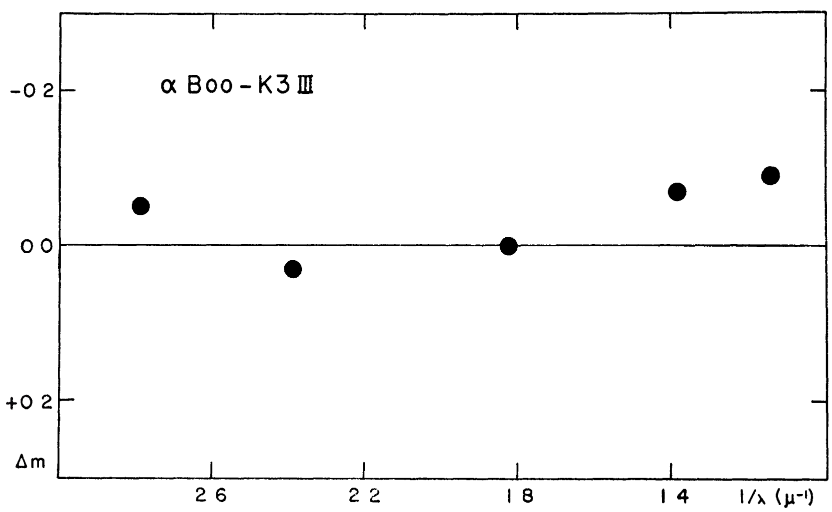


FIG 5—Colors of α Bootis referred to a normal K3 III star

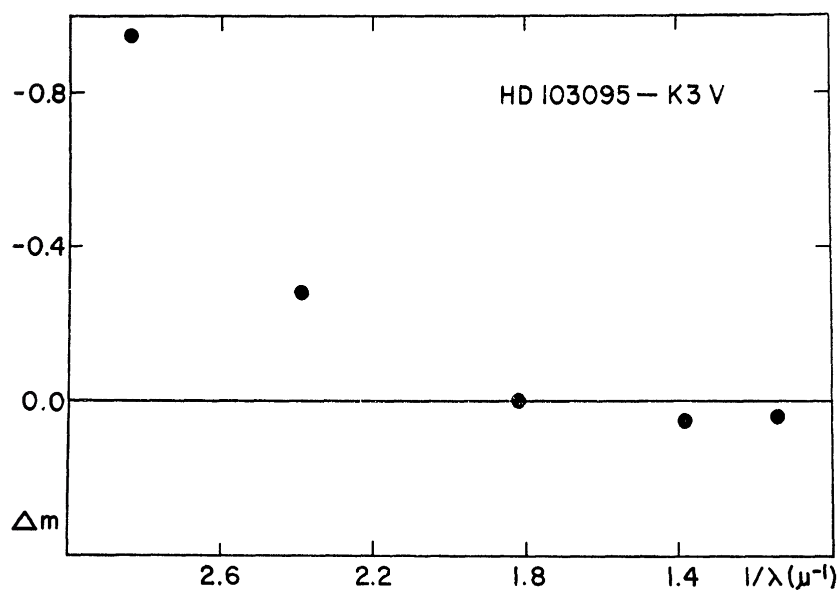


FIG 6.—Colors of HD 103095 referred to a normal K3 V star

temperature and luminosity effects, and additional information from the spectral classification is necessary to decide whether the star is normal or reddened.

In the discussion of the $L$-criterion for the early-type stars, the colors of $\alpha$ Cygni in the long-wave-length region were found to be redder than those of an A3 V star. In order to estimate the departures more accurately, the results of six-color measurements of Stebbins and Whitford (1945) are used, since the colors of both $\alpha$ Cygni and an A2 V star ($\beta$ Aurigae) are available in their system. A comparison of these two stars shows that the $(V - G)$ indices are about the same, while $\alpha$ Cygni is redder in the $(G - I)$ index by 0.23 mag., in approximate agreement with the color difference shown in Figure 3, *b*. The color of $\alpha$ Cygni in the $C_1$ system of Stebbins, Huffer, and Whitford (1940) is $-0.10$ mag., while that of an unreddened A2 star is $-0.08$ mag. (Morgan, Harris, and Johnson 1953); hence the color of $\alpha$ Cygni is actually bluer than that of an unreddened A2 star. It is clear, however, that the color of a supergiant star should not be compared to that of a main-sequence star without taking into account the possible luminosity effect. In order to isolate the effect of space reddening, $\alpha$ Cygni should be compared with an unreddened A2 I*a* star. Inasmuch as we know of no such star, the only way in which the effect can be estimated seems to be to study the amount of reddening for stars located very near $\alpha$ Cygni. A star, HD 197036, lies less than $0\overset{\circ}{.}5$ from it; the next nearest B star for which the photometric information is known is about $1\overset{\circ}{.}5$ away. The MK classification of HD 197036 is not available, but the Victoria classification is B3n. If it is a normal B3 star, the color excess in the $C_1$ system is 0.08 mag., corresponding to a reddening of about 0.2 mag. in the six-color system $(G - I)$. It is quite reasonable to assume that $\alpha$ Cygni is reddened at least as much. It appears, therefore, that the deviation in the red region can be entirely explained as a result of space reddening. The inference from the foregoing discussion is that the effect of reddening in the $C_1$ color is compensated for by the luminosity effect. Effective wave lengths of two filters defining the $C_1$ system are $\lambda$ 4190 A and $\lambda$ 4760 A (Stebbins and Huffer 1934). While the latter filter transmits only H$\beta$, the former has half its maximum transmission at about $\lambda$ 4000 A and includes a good portion of the ultraviolet. The influence of the Balmer lines on blue and ultraviolet colors in wide-band photometry can be seen clearly from the results of narrow-band spectrophotometry (Code 1953).

In the actual comparison of composite stars with the standards, there were no cases of early-type supergiants where reddening could have been detected directly from the observed colors, and reddening, therefore, had to be estimated from other information. In cases where an allowance for reddening was made, the amount of reddening in each observed color was derived by referring to the standard law as given by Whitford (1958). The following values, adjusted to a standard color excess $(b - i) = 1.00$ mag., are obtained: $u$, $1\overset{m}{.}20$; $b$, $1\overset{m}{.}00$; $g$, $0\overset{m}{.}61$; $y$, $0\overset{m}{.}56$; $r$, $0\overset{m}{.}24$; $i$, $0\overset{m}{.}00$.

There are three stars which are omitted from Table 3 because of their spectral peculiarities. Two of these—$\alpha$ Bootis and HD 103095—have been discussed in connection with the $C$-criterion. The third is HD 193237 (P Cygni). The spectrum of this star is characterized by the numerous emission lines of hydrogen. The importance of the hydrogen absorption lines in influencing the observed colors has been noted in the discussion of the $L$-criterion for the early-type stars. In emission stars, if the higher members of the Balmer series are in emission, the ultraviolet will be considerably stronger. The spectroscopic studies show both the Balmer and the Paschen lines in emission (Merrill and Burwell 1933; Hiltner 1947). This will explain the observed excesses in the ultraviolet and in the infrared. It is quite clear that anomalous colors must be expected in emission stars, and hence the usual criteria cannot be applied.

## CLASSIFICATION OF COMPOSITE STARS

From Table 3 the colors of a composite star can be constructed by a combination of any two spectral types. The combined colors are obtained with due allowance for the difference in luminosities of the two types. In classifying the normal stars from the photoelectric colors, the criteria outlined in the previous section can be used. In the case of composite stars, however, some modification is needed in applying these criteria. No general systematic principle can be laid down, but, as a rule, the $T$-criterion is the dominant one and must be applied first, for it has been shown in the preceding section that both $L$- and $C$-criteria are ordinarily connected with only one color, the ultraviolet. In the actual classification of composite stars, some information about the approximate spectral types is available from the spectroscopic studies. Such information is extremely valuable and must be used as a guide, with other criteria serving as the check on the correctness of the classification.

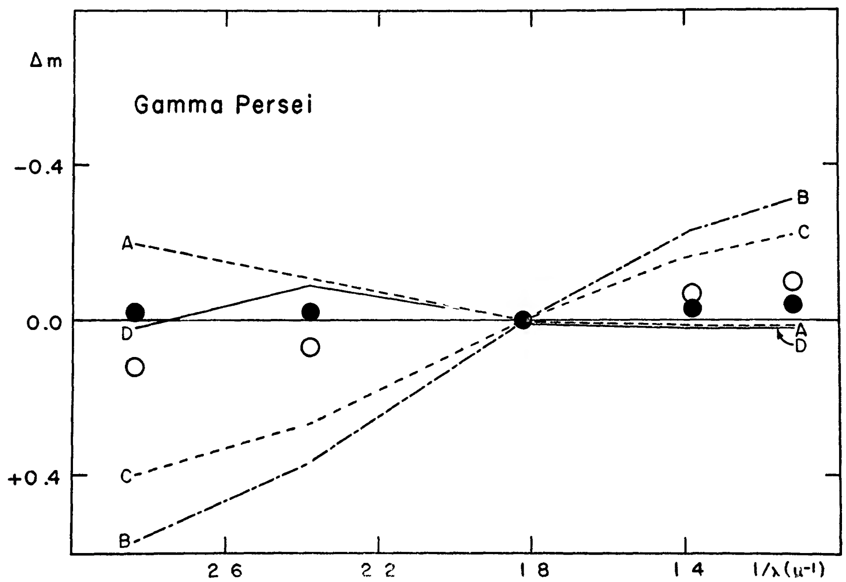


FIG 7 —Classification of a composite star, $\gamma$ Persei *Solid circles:* G8 III + A3 V with $\Delta M_v = 1\,4$; *open circles:* G8 III + A3 V with $\Delta M_v = 0\,9$; line *A:* G8 III + A5 V; line *B:* G8 III + A0 V; line *C:* G4 III + A3 V; line *D:* K0 III + A3 V.

As an example of the classification method, we may take $\gamma$ Persei. The *HD* classification is F5 + A3, while Hynek (1938) gives A + cF7. The MK classification (Morgan, as quoted by Stebbins and Kron 1956) is G8 III: + A3. It is apparent from the composite colors $R$ and $I$ that only a late G giant can be considered for the redder component. It must be a giant in order for a combination with an A star to have a small enough luminosity difference to show both spectra in the violet region. The veiling effect of the light of early-type stars must be blamed for the earlier type assigned to the giant star in the *HD* and Hynek's classification. If the MK classification is adopted and the standard MK luminosities for G8 III and A3 V are used, the resulting computed colors come out as shown by the solid circles in Figure 7; the horizontal line at $\Delta m = 0.0$ represents the observed colors. Lines $A$ and $B$ show the computed colors for the combinations G8 III + A5 V and G8 III + A0 V, respectively. The original choice is seen to have the best over-all agreement, though alternative $A$ is slightly better in the red and infrared. Lines $C$ and $D$ show the combinations G4 III + A3 V and K0 III + A3 V. It is seen that the agreement is not satisfactory.

Variation in the luminosity parameter may also be considered. The open circles show the result of reducing the $\Delta M_v$ of 1.4 given by the MK luminosity table for G8 III + A3 V to 0.9 mag. This change would make $\Delta M_p$ (Johnson and Morgan 1953) 0.1 mag., as opposed to 0.6 mag. in the original choice; in both cases G8 III is the brighter of the two.

Such a variation appears to be equivalent to a change of only one- to two-tenths of a spectral class in the temperature classification. The "fit," therefore, is insensitive to variations from the mean luminosity of a given class by about the amount of mean error as that generally assigned to such a luminosity classification. Variations much larger than 0.5 mag. would frequently run into difficulties with the threshold visibility of the fainter spectrum. It seems that, of the two variables at our disposal—temperature class and luminosity class—the latter has a much less important effect on the composite color. Because of this insensitivity and the fact that $\Delta M$ cannot be made arbitrarily large on account of the threshold visibility of the fainter spectrum, in most cases the MK absolute magnitudes as given by Keenan and Morgan (1951) are used. Furthermore, any large departures from the average place of the selected types on the H-R diagram, for which the MK values would apply, should be detectable in the luminosity-sensitive lines of the spectrum and in the colors.

If the assignment G8 III + A3 V is adopted with the MK luminosities, the absolute visual magnitude is +0.1, and the spectroscopic parallax is $0\overset{''}{.}025$. Miss Jenkins (1952) gives a trigonometric parallax $0\overset{''}{.}011 \pm 0\overset{''}{.}006$. To make the former agree with the latter, the luminosity of each component would have to be raised by 1.8 mag. The resulting combination G8 II + A3 III would be quite implausible, since, in all open clusters where the "break-off" comes as late as A3, there are no yellow or red stars more luminous than luminosity class III (Johnson and Sandage 1955). The alternative of accepting a spectroscopic parallax differing from the trigonometric parallax by more than twice the probable error of the latter seems to be the more likely one. The assumption that there is some interstellar absorption could only worsen the discrepancy.

The results of the classification are listed in Table 4, where the observed colors of thirty composite and suspected composite stars are given in the fourth through the seventh columns. The eighth column gives the spectral types in the *HD* classification, and the ninth column gives the classification based on the photoelectric colors. Descriptions and discussions on each star are given in the next section.

### DISCUSSION OF INDIVIDUAL STARS

In the following detailed discussion of the basis of the classification of each composite star, the spectroscopic features reported fully in Hynek's (1938) survey are not in general repeated; hereafter this survey is referred to simply as "Hynek." Unless otherwise stated, the trigonometric parallaxes quoted here are taken from the *General Catalogue of Trigonometric Stellar Parallaxes* (Jenkins 1952). The following abbreviations are used: "MW" for the study of the spectroscopic absolute magnitudes and parallaxes by Adams, Joy, Humason, and Brayton (1935), and "ADS" for the *General Catalogue of Double Stars* by Aitken (1932).

1. *HD 4775–6*.—From the photoelectric colors the composite nature of this star is not so apparent; the colors are quite similar to those of a late F star except that the ultraviolet and infrared colors tend to give a slightly later type. The combination G0 III + A3 V reproduces the observed colors in the blue region very well, but not so well in the red region. On the other hand, the combination G0 III + A5 V agrees well in the red region but is somewhat discordant in the blue. On the basis of this, the star is classified as G0 III + A4 V. Hynek states that the combined color is that of an A6 star, and he gives a classification similar to that in *HD*, F2 + A2. This combination does yield the International Color Index, $C = +0.04$, listed by Hynek. However, the colors observed by the writer are definitely redder than this. The present classification will give $\Delta M_p = 0.5$, the G component being the brighter of the two. Hence the composite character of this star should be clearly visible in an ordinary spectrogram. The combined $M_v$ is +0.4, while MW gives +3.2 for the brighter component. The latter value would imply a main-sequence F2 star, which is already bluer than the observed composite colors. A G subgiant could be combined with it to give the observed colors, but the strong hydrogen

lines, which led the spectroscopic observers to ascribe one component to an A2 star, would not be accounted for. Since there is no trigonometric parallax for this star, the question of its luminosity cannot be settled. The combination assigned here gives a photometric distance of 100 parsecs, at which distance there can be little reddening.

2. *HD 10516* (*$\phi$ Persei*).—Stebbins and Kron (1956) made an attempt to reproduce the observed colors from their six-color measurements. A combination of B0 + gK0 with some absorption gave a satisfactory agreement in all but the red. In the present study a combination B0 V + K0 II with a color excess of $E_{(b-i)} = 0^{m}.15$ gave an agreement with the observed colors within 0.02 mag. in all but the red. In both cases the discrepancy in the red is in the sense that the observed color is brighter than in the trial combination. In addition to this departure in the red, certain difficulties are encountered if the above combination is assumed. Since the B-type component is at least 3 mag. brighter in the photographic region than the K-type companion, the latter cannot be responsible for the observed composite spectrum. On the other hand, the features belonging to the K-type component should be visible in an infrared spectrum. Hiltner's (1947) study of an in-

TABLE 4

CLASSIFICATION OF COMPOSITE STARS

| No | Star | Name | *U* | *B* | *R* | *I* | Spectral Type | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | *HD* | Photoelectric |
| 1 | 4775-6 | | +1 79 | +0 84 | −0 69 | −1 16 | F2 A2 | G0 III+A4 V |
| 2 | 10516 | $\phi$ Per | +0 23 | +0 17 | −0 36 | −0 47 | B0p | . |
| 3 | 12447 | $\alpha$ Psc | +1 10 | +0 34 | −0 21 | −0 41 | A2p | A2 V |
| 4 | 17878-9 | $\tau$ Per | +2 26 | +1 11 | −0 80 | −1 31 | G0 A5 | G4 III+A4 V |
| 5 | 18925-6 | $\gamma$ Per | +2 19 | +1 04 | −0 80 | −1 29 | F5 A3 | G8 III+A3 V |
| 6 | 23089-90 | . . | +2 12 | +1 14 | −0 91 | −1 49 | F5 A | G0 III+A3 V |
| 7 | 25555-6 | 36 Tau | +2.26 | +1 24 | −1 05 | −1 75 | F5 A | G0 III+A4 V |
| 8 | 26673-4 | 52 Per | +2 72 | +1 39 | −0 95 | −1 52 | G0 A5 | K2 III+A6 V |
| 9 | 29094-5 | 58 Per | +3 11 | +1 68 | −1 12 | −1 81 | K0 A3 | K4 III+A3 V |
| 10 | 32068-9 | $\zeta$ Aur | +2 80 | +1 68 | −1 34 | −2 15 | K0 B1 | K4 II+B8 V |
| 11 | 34029 | $\alpha$ Aur | +2 31 | +1 17 | −0 83 | −1 30 | G0 | G4 III+G0 III |
| 12 | 37202 | $\zeta$ Tau | +0 20 | 0 00 | −0 12 | −0 24 | B3p | . . . . . |
| 13 | 40369-70 | . | +2 62 | +1 29 | −0 97 | −1 56 | G5 A5 | K2 III+A5 V |
| 14 | 48737 | $\xi$ Gem | +1 56 | +0 73 | −0 55 | −0 86 | F5 | F3 IV |
| 15 | 49618-9 | 14 Lyn | +2 15 | +1 00 | −0 75 | −1 25 | F5 A2 | G4 III+A2 V |
| 16 | 60178 | $\alpha$ Gem | +1 09 | +0 26 | −0 19 | −0 38 | A0 | A0 V+A5 V |
| 17 | 63208-9 | 82 Gem | +1 91 | +0 88 | −0 76 | −1 25 | F2 A0 | G2 III+A4 V |
| 18 | 78362-3 | $\tau$ UMa | +1 62 | +0 68 | −0 44 | −0 76 | F5 A5 | G2 III+A0 V |
| 19 | 83808-9 | $o$ Leo | +1 77 | +0 80 | −0 59 | −0 96 | F5 A3 | F8 III+A5 V |
| 20 | 109358 | $\beta$ CVn | +1 82 | +0 98 | −0 72 | −1 15 | G0 | G0 V |
| 21 | 118022 | 78 Vir | +1 13 | +0 31 | −0 20 | −0 38 | A2p | A2 V |
| 22 | 169985-6 | 59 Ser | +1 86 | +0 82 | −0 73 | −1 21 | A0 G | G0 III+A6 V |
| 23 | 175492-3 | 113 Her | +2 39 | +1 18 | −0 84 | −1 38 | G0 A3 | G4 III+A6 V |
| 24 | 183912 | $\beta$ Cyg | +2 90 | +1 58 | −1 08 | −1 80 | K0 A0 | K0 II+B9 V |
| 25 | 187076-7 | $\delta$ Sge | +3 55 | +1 94 | −1 85 | −2 99 | Ma A0 | M2 II+A0 V |
| 26 | 196093-4 | 47 Cyg | +3 45 | +2 12 | −1 52 | −2 45 | K5 A3 | K2 I*b*+B5 V |
| 27 | 201091-2 | 61 Cyg | +3 32 | +1 68 | −1 24 | −1 96 | K5 | K5 V+K7 V |
| 28 | 202447-8 | $\alpha$ Equ | +1 94 | +0 87 | −0 68 | −1 14 | F8 A3 | G0 III+A5 V |
| 29 | 209790-1 | 17 Cep | +1 59 | +0 70 | −0 45 | −0 73 | A3 G | A7 V+F5 V |
| 30 | 213310-1 | 5 Lac | +3 84 | +2 21 | −1 60 | −2 57 | K0 A0 | K5 I*b*+B7 V |

frared spectrum of this star did not show such features. Moreover, an extensive spectroscopic study made by Hynek (1940) indicated that both the components were B stars. The observed colors could not be represented by a combination of two B stars in the present study. Evidently, anomalies such as the shell structure (Struve 1950) and emission lines in the Balmer series (Hynek 1940) and in the Paschen series (Hiltner 1947) are responsible for the peculiar run of the colors in this star. It seems, therefore, that no classification can be made from the present study.

3. *HD 12447* (*α Piscium*).—The observed colors include both components of a visual binary, separation 3″. According to ADS, both components are spectroscopic binaries. The spectral types of the components must be very similar, for the colors can be fitted to either a normal A2 V or a combination A2 V + A3 V. In both cases, however, the observed colors show a small ultraviolet excess. The spectrum has an appearance of a "metallic-line" star—weak K line and strong Sr II lines (Hynek). It has been shown (Roman, Morgan, and Eggen 1948) that the "metallic-line" stars have colors corresponding more nearly to class F. The observed colors are very close to those of an early A star. The observed ultraviolet excess cannot be reproduced from a combination of main-sequence stars in or near the type A. Because of the multiplicity of this system and the spectral peculiarities, a tentative classification of A2 V is given.

4. *HD 17878–9* (*τ Persei*).—Spectroscopic binary. As in the case of HD 4775–6 (No. 1), the final classification G4 III + A4 V was obtained from the agreement with the two combinations G4 III + A3 V and G4 III + A5 V. In all cases considered here, the red and infrared colors remain about the same, but the A-type component has a strong influence on the blue region. The present classification gives $\Delta M_p = 0.7$. The spectroscopic parallax based on the present classification is 0″.016, consistent with the value of the trigonometric parallax, 0″.012 ± 0″.005.

5. *HD 18925–6* (*γ Persei*).—Discussed in previous section as selected example.

6. *HD 23089–90*.—Hynek states: "Color of gG4. . . . Trace of G band is present and class is probably somewhat later than F5, the veiling effect tending to make the spectrum appear earlier than it is." It is highly questionable whether a combination of a star which is earlier than a G4 and an A star could produce a combined color of gG4, unless there is some interstellar reddening. There are three B stars within 5° of this star, the nearest one being the star MWC 71 about 2° away. The colors of these stars show that there is some space reddening in this region (Stebbins, Huffer, and Whitford 1940). MWC 71 is reddened by the amount $E_1 = 0^m.24$. A combination of G0 III + A3 V with a color excess of $E_{(b-i)} = 0^m.7$ reproduces the observed colors very well. The spectroscopic parallax corrected for the reddening is 0″.016, while the trigonometric parallax is −0″.002 ± 0″.007. The latter value and the MW classification of cF5 suggest that the star may have supergiant components. The lack of G-type supergiants in the present list of standard stars prevents testing colors of such a combination.

7. *HD 2555–6* (*36 Tauri*).—The observed colors are very similar to those of HD 23089–90 (No. 6). The star is only about 5° from the Pleiades, and the Palomar Sky Survey photograph of the region clearly shows the presence of several obscuring clouds. A combination of G0 III + A4 V with a color excess of $E_{(b-i)} = 0^m.7$ reproduces the observed colors very well. In this combination the two stars are about equally bright in the photographic region. A combined $M_v = +0.4$ gives a spectroscopic parallax of 0″.014 after correction for absorption. This agrees well with the trigonometric parallax of 0″.011 ± 0″.011. In the case of this star as well as the previous one (No. 6), the observed colors alone are not sufficient to determine the spectral types with certainty.

8. *HD 26673–4* (*52 Persei*).—The red region can be reproduced equally well from either a combination K2 III + A5 V or K2 III + A7 V. In the blue region the observed colors lie between the colors given by these combinations, slightly favoring the latter. On the basis of this, the adopted classification is K2 III + A6 V. In this combination $\Delta M_p = 1.0$, and this is probably close to the limit of detectability of a composite spec-

trum such as this. The spectroscopic descriptions of the composite nature of this star are almost entirely limited to the ultraviolet region around the H and K lines and the higher members of the Balmer series. The trigonometric parallax is 0".002 ± 0".007, while the assigned type gives a spectroscopic parallax of 0".006.

9. *HD 29094–5* (*58 Persei*).—The red region shows a good agreement with K5 III + A0 V, while the blue region agrees well with K5 III + A3 V. Unlike HD 26673–4 (No. 8), the observed colors do not lie between the two combinations. The indication is that the K-type component is responsible for the discordance. The colors of a K4 III star are obtained by means of interpolation from those of a K3 III and a K5 III. A combination of K4 III + A3 V gives a very good agreement with the observed colors, except in the ultraviolet, where the observed color is about 0.1 mag. fainter. A simple interpolation may not be accurate enough. This combination gives $\Delta M_p = 0.6$, and a combined $M_v$ of $-0.4$. The resulting spectroscopic parallax of 0".011 is in only fair agreement with the trigonometric parallax, 0".020 ± 0".005. A combination of K2 II + A0 V does represent the observation rather well. In this case the colors of the K star were taken from those of a K2 I*b* star, and $M_v = -2.3$ was assumed. It is not certain whether these actually represent the colors of a K2 II star. Moreover, the combined $M_v$ gives a distance in serious disagreement with the value of the trigonometric parallax. Because of this difficulty, the apparent ultraviolet deficiency in comparing with a combination K4 III + A3 V cannot be ascribed to the luminosity effect. Because of the lack of better information, the star is classified as K4 III + A3 V.

10. *HD 32068–9* (*ζ Aurigae*).—The MK classification is K4 II + B, which Dr. W. W. Morgan has kindly communicated to the author. From the detailed analysis of the spectrum taken during the eclipse, Wellmann (1951) found the primary to be K4 II. The basis of this classification seems to be quite reliable. Moreover, from the value of the trigonometric parallax, 0".002 ± 0".006, and the diameter of the K component, which is of the order of 200 ⊙ (Kopal 1946; Wellmann 1951), it is obvious that the star must be a supergiant. The classification of the companion is more difficult, but Wellmann assigned B7 V. From the present study, a combination K4 II + B8 V with $E_{(b-i)} = 0^{m}.34$ gives a good agreement with the observed colors, except in the blue, where the observed color is 0.06 mag. redder. Since the colors of stars making up this combination were derived by interpolation, this can be considered a good agreement. In the present classification, $\Delta M_v = 1.9$, and a combined $M_v = -2.6$ will give a spectroscopic parallax of 0".006, which is not inconsistent with the value of the trigonometric parallax. Since this observing program did not start until March, 1956, the last favorable eclipse (December, 1955—January, 1956) could not be observed. Multicolor observations of this star during the eclipse phase will be extremely valuable in determining the precise classification.

11. *HD 34029* (*α Aurigae*).—This star is not listed in Hynek's survey. The *HD* classification is G0, while the MK gives G8 III: + F (Morgan, as quoted by Stebbins and Kron 1956). From the spectroscopic evidence and the results of interferometer observations by Merrill (1922), Struve (1951) concludes that the two components must be nearly the same in luminosity and spectral type. A recent study by Wright (1954) gives a combination G5 III + G0 III, with a luminosity ratio of 1.26. This means that both the components are normal giants. A combination of G4 III + G0 III from the present observations with the above-mentioned luminosity ratio gives the observed colors within the errors of measurements. As was mentioned in the discussion of HD 12447 (No. 3), the observed colors are not very sensitive to the composite nature of a star with components as nearly alike as G4 III and G0 III. The observed colors could also be represented within the errors of measurements by combinations between G8 III + F5 III and G8 III + F8 III. The colors of F giants are found by interpolation. From this a classification of G8 III + F6 III can be given. The classification of Wright gives a spectroscopic parallax of 0".077, while G8 III + F6 III will give a value of 0".083. The trigonometric parallax is 0".073 ± 0".004. It is apparent that multicolor photometry cannot give

an unambiguous determination of the types of the components. Struve (1951) concluded from spectroscopic studies, which have the advantage of separating the lines of the two components at certain phases, that the fainter component is not a normal star. In the present study a tentative classification G4 III + G0 III is given.

12. *HD 37202* (*ζ Tauri*).—This is a well-known single-line spectroscopic binary with numerous emission lines. The star is listed by Merrill and Burwell (1933) in their catalogue of emission stars. Apparently, the star is an anomalous one, for it has not been possible to obtain a combination which will reproduce the observed colors. According to Struve (1950), this is a shell star quite similar to HD 10516 (No. 2). As in the case of the latter star, the shell features apparently add so much confusion to the basic energy-curve of the primary that the light of the secondary component cannot be derived from the colors.

13. *HD 40369–70*.—This star is clearly a case of a late giant with an early-type companion. The observed colors are best represented by K2 III + A5 V. The star is a visual binary with a secondary of 7.8 mag., separation 0".5 (ADS). The composite spectrum of this star is almost certainly due to this visual companion. The observed $\Delta M_v = 2.0$ is in agreement with the classification found here. The absolute magnitude difference between the two components is somewhat less than 1 mag. in the photographic region. No trigonometric parallax is available, but a spectroscopic parallax derived from the present assignment, 0".007, agrees well with the MW value of 0".006.

14. *HD 48737* (*ξ Geminorum*).—The spectrum appears perfectly normal, though the lines are somewhat rotationally broadened (Hynek). The observed colors appear to be those of a normal F star, most probably of F3. The trigonometric parallax of 0".051 ± 0".006 gives a fairly reliable distance and makes this star somewhat brighter than a normal main-sequence star, but not bright enough to make it a giant. The star is probably a subgiant of luminosity class IV. The lack of standard colors in the luminosity class makes it difficult to determine the spectral type accurately. For the present, the star is classified as F3 IV.

15 *HD 49618–9* (*14 Lyncis*).—As in the case of HD 40369–70 (No. 13), a composite spectrum of this star is probably due to a visual companion, seventh magnitude, with a separation 0".4 (ADS). The observed colors are matched fairly well by a combination G4 III + A3 V, but there is an indication that the bluer star is actually slightly earlier. The classification G4 III + A2 V seems to be the best. The observed visual magnitude of the primary is 5.9, giving $\Delta M_v = 1.1$, with the G component the brighter. The calculated $\Delta M_p = 0.3$, agreeing with the clearly seen composite spectrum. Hynek places the primary component slightly later than G0 from the strength of the CH band.

16. *HD 60178* (*α Geminorum*).—The observed colors do not include YY Geminorum (Castor C). They are very similar to those of an early A star. It is clear that the two components must be of about the same spectral type. There are a few combinations which give a satisfactory reproduction of the observed colors. These are: A0 V + A5 V, A0 V + A3 V, and A0 V + A7 V. Here again the resolving power is not high, but, of these, the best one seems to be A0 V + A5 V. It should be remembered that both Castor A and Castor B are known to be single-line spectroscopic binaries. Hence we are dealing with the light from four stars. Some of these stars may be too faint to influence the spectrum or colors. A tentative classification of A0 V + A5 V is given here.

17. *HD 63208–9* (*82 Geminorum*).—This is an interferometer double of separation 0".18 (Wilson 1937). The observed colors lie between the two combinations G2 III + A3 V and G2 III + A5 V. The colors of a G2 III star are found from interpolation. A classification of G2 III + A4 V gives $\Delta M_p = 0.8$ and a combined $M_v = +0.1$. The trigonometric parallax is not available, but MW assigns F3 to the primary with $M_v = +3.2$. The implausibility of the latter classification is based on the same type of argument as that used in the case of HD 4775–6 (No. 1).

18. *HD 78362–3* (*τ Ursae Majoris*).—The observed colors are similar to HD 48737

(No. 14) but much weaker in the ultraviolet. The star can be represented very well by a combination G2 III + A0 V. Hynek states: "... The composite spectrum may arise from a single star, for (1) the H and K lines do not appear to be like those resulting from a superposition of an F5 and A5 spectrum ... and (2) the velocity of the K line is the same as that of other lines. A variable radial velocity, range 9 km., has been found but no orbit is available. Until definite evidence of true binary nature is given, this star must be included in class VI." Class VI is defined as the one in which the composite nature of the spectrum arises from a single star. From the photoelectric colors this star is definitely composite, for in the red it is near A7, while in the blue it is near F5. A combined $M_v = -0.4$ gives a spectroscopic parallax of 0".010, agreeing well with the MW value of 0".008.

19. *HD 83808–9* (*o Leonis*).—The observed colors are somewhat earlier than G0 III + A3 V. They are such that the change in the secondary component does not improve the result. It is clear that the primary must be slightly earlier than G0 III. The combination of two main-sequence stars cannot be made to reproduce the observed colors. A combination F8 III + A5 V represents the observations very well. The F8 III colors used in the calculation were interpolated as for Capella (No. 11). The combined $M_v = +0.7$ gives a spectroscopic parallax of 0".024, agreeing well with the trigonometric parallax 0".028 ± 0".007.

20. *HD 109358* (*β Canum Venaticorum*).—The MK classification is G0 V, and the colors are identical with those of a normal star of this class. Hynek remarks that there is nothing abnormal about the spectrum. There is, therefore, no reason to believe that it is composite.

21. *HD 118022* (*78 Virginis*).—Hynek's class VI, a composite spectrum being due to peculiarities in a single star. The colors appear to be those of a normal A2 V star. No fewer than four different combinations reproduced the observed colors. These are: A0 V + A7 V, A0 V + F0 V, A0 V + A5 V, and A0 V + A3 V. If the star is a binary, the spectral types of the two components must be very similar. It appears that the star has been classified as composite mainly on the basis of unusually strong lines of certain elements in the spectrum, for it is listed as a "strontium and silicon" star by Hynek. However, if it is a "metallic-line" star, it should have a color of an F-type star (Roman, Morgan, and Eggen 1948). Since the colors appear to be normal and because of the ambiguity of the possible compositeness, the star is classified here as A2 V. In this case a spectroscopic parallax of 0".018 agrees well with the trigonometric parallax of 0".016 ± 0".005.

22. *HD 169985–6* (*59 Serpentis*).—The star is a visual double, separation 4", but the primary itself is found to be composite (Hynek). Because of the large size of the photometer diaphragm (46".9), the observed colors are due to both the components. However, the influence of the secondary component is probably very small because it is about 3 mag. fainter than the primary. The observed colors are best represented by a combination G0 III + A6 V. This assignment has been obtained from the comparison of the observed colors with the two combinations, G0 III + A5 V and G0 III + A7 V; the observed colors lie between these two combinations. The present classification give $\Delta M_p = 0.7$ and a spectroscopic parallax of 0".012, agreeing well with the trigonometric parallax, 0".013 ± 0".005.

23. *HD 175492–3* (*113 Herculis*).—The star is a visual and spectroscopic binary, period 245 days, but the composite spectrum is not due to a visual companion, which is too faint and too distant, 12.5 mag. at 40" (ADS). The observed colors do not include this companion. As in the case of the star 59 Serpentis (No. 22), the classification of G4 III + A6 V was obtained from the comparison of the observed colors with the two combinations G4 III + A5 V and G4 III + A7 V. The present classification gives $\Delta M_p = 1.0$ and a spectroscopic parallax of 0".012, agreeing very well with the trigonometric parallax, 0".011 ± 0".007.

24. *HD 183912* (*β Cygni*).—The observed colors do not include a visual companion,

which is 35″ away. The star is almost certain to be reddened. Using the interpolated colors for a K0 II star, a combination K0 II + B9 V with a color excess of $E_{(b-i)} = 0^{m}.5$ gives a satisfactory result. This classification gives $\Delta M_p = 0.7$, the K component being the brighter of the two. But in the ultraviolet the B component is brighter and hence should show its features very well. From the present result a spectroscopic parallax corrected for the assumed absorption is 0″.008, agreeing well enough with the trigonometric parallax of 0″.004 ± 0″.005.

25. *HD 187076–7* (*δ Sagittae*).—In the present study the only M star observed is *α* Orionis (M2 I*a*). It is doubtful whether the late component of *δ* Sagittae is as luminous as *α* Orionis. A combination of M2 I*a* + A0 V with $M_v = -3.0$ for the M component gives a satisfactory agreement with the observed colors. This absolute magnitude will make it a star of luminosity class I*b* or II. For this reason the star is classified as M2 II + A0 V. In this case there is a wide difference in the absolute magnitudes of the two components. However, this is a favorable case in which the early-type companion will show its presence in the blue and in the ultraviolet. If $\Delta M_v = 3.0$, it is quite likely that in the photographic region this difference would be reduced to not much more than 1 mag. The resulting combined $M_v$ gives a spectroscopic parallax of 0″.004, which is not inconsistent with the trigonometric parallax of −0″.003 ± 0″.006. The most uncertain part of the present procedure is using the colors of an M2 I*a* star for M2 II without taking into account the luminosity effect. Spectroscopic evidences are: "No star later than A2 could produce the observed blended K line, while the late star shows fairly strong TiO bands and is therefore M" (Hynek).

26. *HD 196093–4* (*47 Cygni*).—From the trigonometric parallax of 0″.001 ± 0″.006 and the MW classification of cK4, the star is certain to be a supergiant. A combination K2 I*b* + B5 V with a color excess of $E_{(b-i)} = 0^{m}.85$ gives a very good agreement with the observed colors. This combination gives a spectroscopic parallax of 0″.002, agreeing well enough with the trigonometric parallax. The K component is brighter by 1.1 mag. in the photographic region, but in the ultraviolet the B star is brighter.

27. *HD 201091* (*61 Cygni*).—A visual binary of separation 23″. Because of the wide separation of the two components, it was possible to observe the colors of each star separately. With the large aperture of the photometer diaphragm employed (46″.9), it was also possible to observe the combined colors. A combination of 61 Cygni A + 61 Cygni B with $\Delta M_v = 0.7$ was compared with the observed combined colors. This procedure indicates the degree of tolerance to be expected in comparing the observed and the artificial colors. The differences, observed minus computed, are as follows: $U$, $-0^{m}.02$; $B$, $-0^{m}.01$; $R$, $0^{m}.00$; $I$, $-0^{m}.02$.

28. *HD 202447–8* (*α Equulei*).—The observed colors are best reproduced by G0 III + A5 V. Hynek gives G0 for the primary on the basis of a faint G band and, from the K line, A4 for the secondary. The earlier classification of *HD*, F8 + A3, is probably due to the veiling effects. The present classification gives a spectroscopic parallax 0″.016, agreeing well with the trigonometric parallax of 0″.013 ± 0″.005. There seems to be little doubt about the present result.

29. *HD 209790–1* (*17 Cephei*).—The observed colors show a composite nature very well. In the red region the star has an appearance of a late A star, while in the blue region it is about an F3 star. The best result is obtained by a combination A7 V + F5 V. In this case, even though the spectral types of the two components are not too widely separated, the classification seems to be unique; other combinations do not reproduce the observed colors as well. This star probably represents the near-limiting case for this particular combination, for $\Delta M_p = 1.0$. The combined $M_v$ of 2.2 gives a spectroscopic parallax of 0″.035, while the trigonometric parallax is 0″.029 ± 0″.005.

30. *HD 213310–1* (*5 Lacertae*).—The observed colors are very similar to those of 47 Cygni (No. 26) but slightly earlier. As in the case of the latter star, it is almost certain to be a supergiant, for the trigonometric parallax is 0″.002 ± 0″.007 and the MW absolute

magnitude of −2.3 gives the same indication. The observations are best represented by a combination K5 I*b* + B7 V with a color excess of $E_{(b-i)} = 0^{m}60$. In the ultraviolet both components are about equally bright, thus still capable of producing an observable composite spectrum. A spectroscopic parallax from the present classification is 0″002, agreeing with the trigonometric parallax. The colors of a K5 I*b* star have been found by interpolation.

## CONCLUSIONS

Comparison of the last two columns in Table 4 shows that in about 50 per cent of the cases the photoelectric method gives somewhat later spectral types than those given by the spectroscopic classification. The reason for such a discrepancy may be twofold. In the first place, the blending of lines and veiling effects tend to give an earlier classification in the ordinary method. In the photoelectric method these effects will not influence the classification criteria. The second factor which may contribute to the discrepancy is the effect of interstellar reddening. In the spectroscopic analysis the presence of interstellar reddening will have little effect, as long as the classification is based on the relative intensities of neighboring lines. On the other hand, if the effect of interstellar reddening is neglected, the photoelectric classification will give a somewhat later spectral type. However, for the stars investigated here this effect is probably not important.

A question of particular interest is the uniqueness of the spectral classification derived from the photoelectric method. With the classification criteria discussed above, the method is usually capable of giving a unique solution for a single normal star. In the case of composite stars, however, it is not at once apparent that both the colors of each component and the luminosity ratio can be derived uniquely from the observed composite colors. On the other hand, any combination which can reproduce the observed composite colors must satisfy the physical condition that the luminosity ratio be reasonable to produce an observable composite spectrum. With this condition and the absolute magnitude differences derived from the MK system being assumed, the photoelectric method generally gives a unique solution when the two components are separated by one or more spectral classes. For a few cases in which the spectral types of the two components are not widely separated, the resulting composite colors are not sensitive enough to allow a unique solution. With improved measurements, such an ambiguity may be narrowed. For some stars on the present list, the classification could not be made definitively because of insufficient data on the standard colors. Improvement of the present study in obtaining more and better standard colors would undoubtedly give more definite results for these stars.

At present, the photoelectric method is not completely independent of the traditional spectral classification. In fact, to obtain the most accurate classification it seems that the two methods must supplement each other; they offer two methods whose classification criteria are independent of each other. It must be emphasized that the present method and that used by Sharpless (1954) are quite different from the photoelectric spectral classification developed by Strömgren (1956) and Strömgren and Gyldenkerne (1955). The latter method is, in essence, the same as an ordinary classification from the spectrograms, since it is based on the intensities of certain lines and bands, while the wide-band photometry bases its criterion on the relative intensities of the continuum.

The blue filter of the present study, which is nearly the same as that of the $(U, B, V)$ system (Johnson and Morgan 1953), shows a slight luminosity dependence; the $(B - V)$ index must therefore be regarded as a less accurate temperature indicator than a color index involving a red or infrared filter, which does seem to provide the purest temperature criterion. Hence more observations in the red and infrared seem to be desirable. In any event, the inclusion of the ultraviolet in a color system appears to be essential for a good classification, for this seems to be the most sensitive luminosity criterion available at present. Moreover, it has been confirmed in the present study that this color provides a good population indicator.

In recent years the color-magnitude diagrams of stars in globular clusters have supplied much valuable information (Arp, Baum, and Sandage 1953; Baum 1956). Morgan's (1956) study revealed that, even though the dwarfs are more numerous in a globular cluster (Sandage 1954), the spectrum of an integrated light was influenced mainly by the giants. Photoelectric observations in many wave lengths will no doubt furnish some valuable information on the understanding of globular clusters. Considerably more work on examples of nearby type II giants will be needed first, however.

Extragalactic systems furnish fine examples of composite sources. As in globular clusters, the integrated light of elliptical galaxies seems to be influenced mostly by the giants (Morgan and Mayall 1957). A problem of considerable interest is the possible explanation for the differences which are found between globular clusters and elliptical galaxies in color and mass-luminosity ratio. Roberts (1955) has proposed that the differences are due to two different luminosity functions in these objects. Unlike globular clusters, the color-magntude diagrams of elliptical galaxies are for the most part beyond the reach of present-day telescopes. It seems that the photometry of these objects in many wave lengths can be useful in studying the stellar contents in these systems.

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