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# THE INTRINSIC COLORS OF EARLY-TYPE STARS

Abstract

The "Q"-method of determining interstellar reddening for early-type main-sequence stars is re- examined. The curved reddening line found by Hiltner and Johnson and the change of slope of the reddening line with spectral type shown by Lindholm require minor modifications of the method. These modifications have been incorporated in a nomogram for the computation of intrinsic colors from UBV photometry.

Intrinsic colors are derived for supergiant stars of various spectral types. These colors differ somewhat from those for main-sequence stars of the same spectral type.

## I. Introduction

Recent data and analyses have shown that the "Q" -method as originally set up by Johnson and Morgan (1) must now be modified. The modifications are made necessary by the curvature of the reddening line (2) and by the change in the slope of the reddening line with spectral type (3); these effects were not recognized in the original discussion. Only relatively minor differences result from their inclusion in the method.

Published data on the UBV photometric system and the MK spectral classification system allow a determination of the intrinsic colors of the supergiants, in addition to those already known for main-sequence stars. The intrinsic B-V colors for supergiants are now redder for B-stars and bluer for A-stars compared with those for main- sequence stars.

## II. The Determination of Reddening and Intrinsic Colors.

Recent observations and analyses have shown that there is a change in the slope of the reddening line as a function of spectral type. The work of Johnson and Morgan (1) assumed that this slope is constant.

Lindholm (3) has published computations that show that we can no longer ignore this variation of the slope of the reddening line. Walker (4) has given observations in NGC 6530 which can be interpreted as a change in the slope with spectral type and I have unpublished observations in M 25 that also show this effect. The M 25 results agree with Lindholm's analysis; Walker's data agree fairly well provided my zero-point for U-B (quoted by Walker) is used instead of Walker's.

If we assume after Hiltner and Johnson (2) that

$$\frac{E_{(U-B)}}{E_{(B-V)}} = X + 0.05E_{(B-V)} \qquad (1)$$

we can plot Figure 1 from Lindholm's tables. If further, we assume that X = 0.72 for

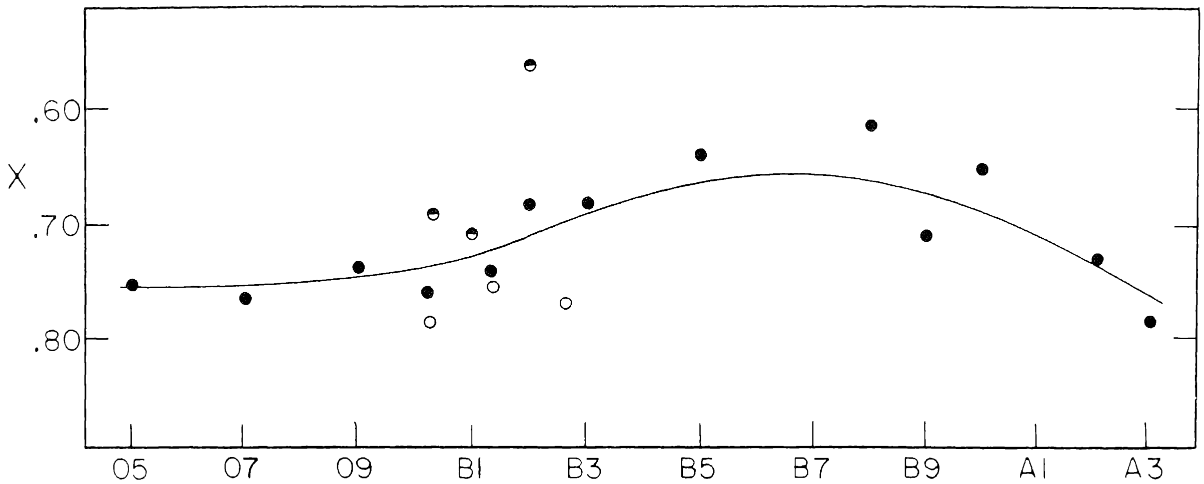



Figure 1. The slope, X, of the reddening line as a function of spectral type. The filled circles designate luminosity class V, the half-filled circles, class III, and the open circles, class I.

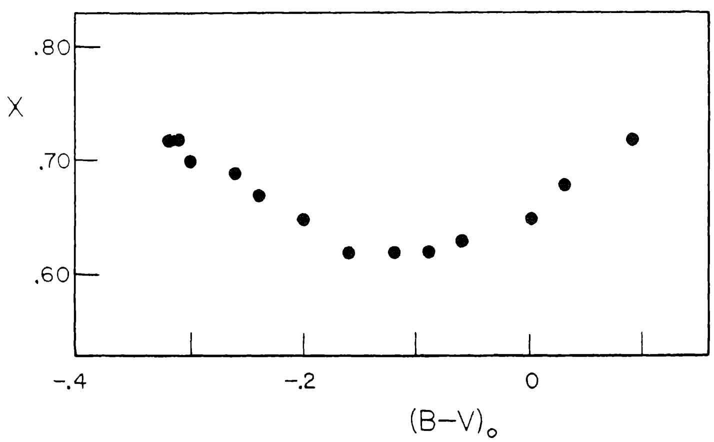



Figure 2. The slope of the reddening line, X, as a function of the intrinsic color, $(B-V)_o$.

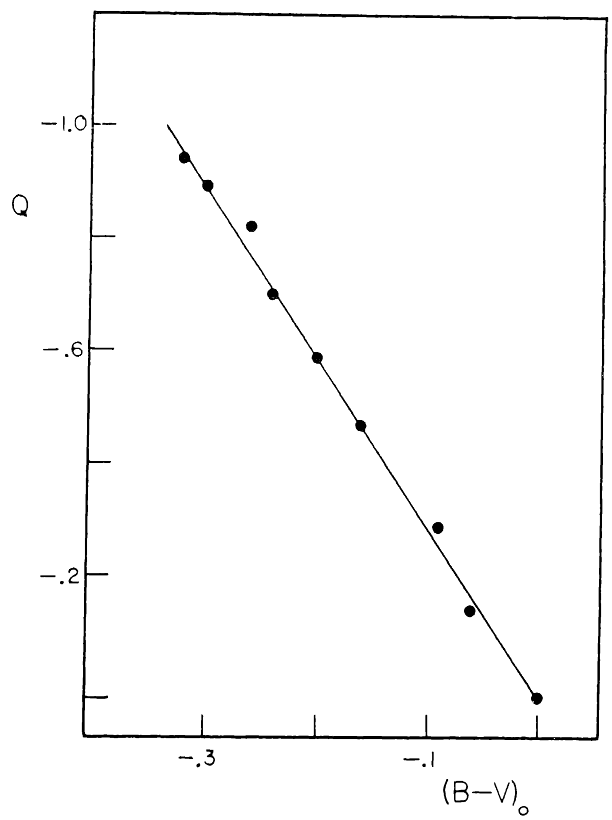



Figure 3. The relation between Q and $(B-V)_o$.

O-stars (2) and the change of X with spectral type shown in Figure 1, the relation between X and spectral type given in Table I follows.

Table I.

The Relation between X and Spectral Type for Luminosity Class V.

| Sp. T. | X |
|---|---|
| 05-09 | 0.72 |
| B0 | 0.70 |
| B1 | 0.69 |
| B2 | 0.67 |
| B3 | 0.65 |
| B5 | 0.62 |
| B7 | 0.62 |
| B8 | 0.62 |
| B9 | 0.63 |
| A0 | 0.65 |
| A1 | 0.68 |
| A3 | 0.72 |

This relation is valid only for main-sequence stars (luminosity class V). The known relation between intrinsic color and spectral type (5) allows us to transform to the relation between intrinsic color and X; this relation is given in Figure 2 and Table II. We shall adopt this relation, based upon Lindholm's analysis, for the following discussion.

From the relation between intrinsic color and spectral type given by Morgan, Harris and Johnson and the values of a given in Lindholm's tables, we compute the relation between $(U-B)_o$ and $(B-V)_o$. From this relation and the values given in Table II, we compute the relation between $(B-V)_o$ and Q, which is shown in Figure 3.

Table II.

The Relation between X and Intrinsic Color for Luminosity Class V.

| $(B-V)_o$ | X |
|---|---|
| -0.32 | 0.72 |
| -0.30 | 0.71 |
| -0.28 | 0.695 |
| -0.26 | 0.685 |
| -0.24 | 0.67 |
| -0.22 | 0.66 |
| -0.20 | 0.645 |
| -0.16 | 0.625 |
| -0.12 | 0.62 |
| -0.08 | 0.62 |
| -0.04 | 0.635 |
| 0.00 | 0.655 |

The straight line in Figure 3 has the equation,

$$(B-V)_o = 0.332\ Q. \qquad (2)$$

This equation differs very little from that derived by Johnson and Morgan (1, Eq. 6).

The straight line seems to be a satisfactory representation of the data.

Let us now write

$$\frac{E_{(U-B)}}{E_{(B-V)}} = 0.72 + 0.05E_{(B-V)} - \Delta X.F, \tag{3}$$

$$F = \begin{cases} 1; & E_{(B-V)} = 0 \\ 0; & E_{(B-V)} = \infty \end{cases} \tag{4}$$

The reason for the first limiting value for F is obvious; the second is required by the fact that for highly reddened stars the amount of radiation short of 3600A (the source of the change of slope of the reddening line with spectral type)has very little effect. We shall approximate F by the equation

$$F = 1 - 0.5E_{(B-V)}; \quad E_{(B-V)} \leq 2.0 \tag{5}$$

This equation has been chosen to facilitate construction of a nomogram. Its use restricts us to color-excesses less than about 2.0 mag.

Since $Q = (U-B) - \left[E_{(U-B)}/E_{(B-V)}\right] \quad (B-V)$

we can write

$$Q = (U-B) -0.72(B-V)-0.05(B-V)E_{(B-V)} + \Delta X\left[1-0.5E_{(B-V)}\right] \quad (B-V); \tag{6}$$

and since $(B-V)_o = 0.332Q$ (see Figure 3 ) $= (B-V) -E_{(B-V)}$

$$E_{(B-V)} = (1.2393 + 0.332\Delta X)(B-V) + (0.0166 - 0.1662\Delta X)E_{(B-V)} \; (B-V) -0.332(U-B); \tag{7}$$

or $\left[(0.2393 + 0.332\Delta X) + (0.1662\Delta X - 0.0166)(B-V)_o\right] \; (B-V)$

$$-0.332(U-B) + (B-V)_o + (0.0166 - 0.1662\Delta X)(B-V)^2 = 0. \tag{8}$$

Equation (8) can be written, approximately,

$$(0.2584 - 0.1658\Delta X)(B-V) - 0.332(U-B) +(B-V)_o \cong 0. \tag{9}$$

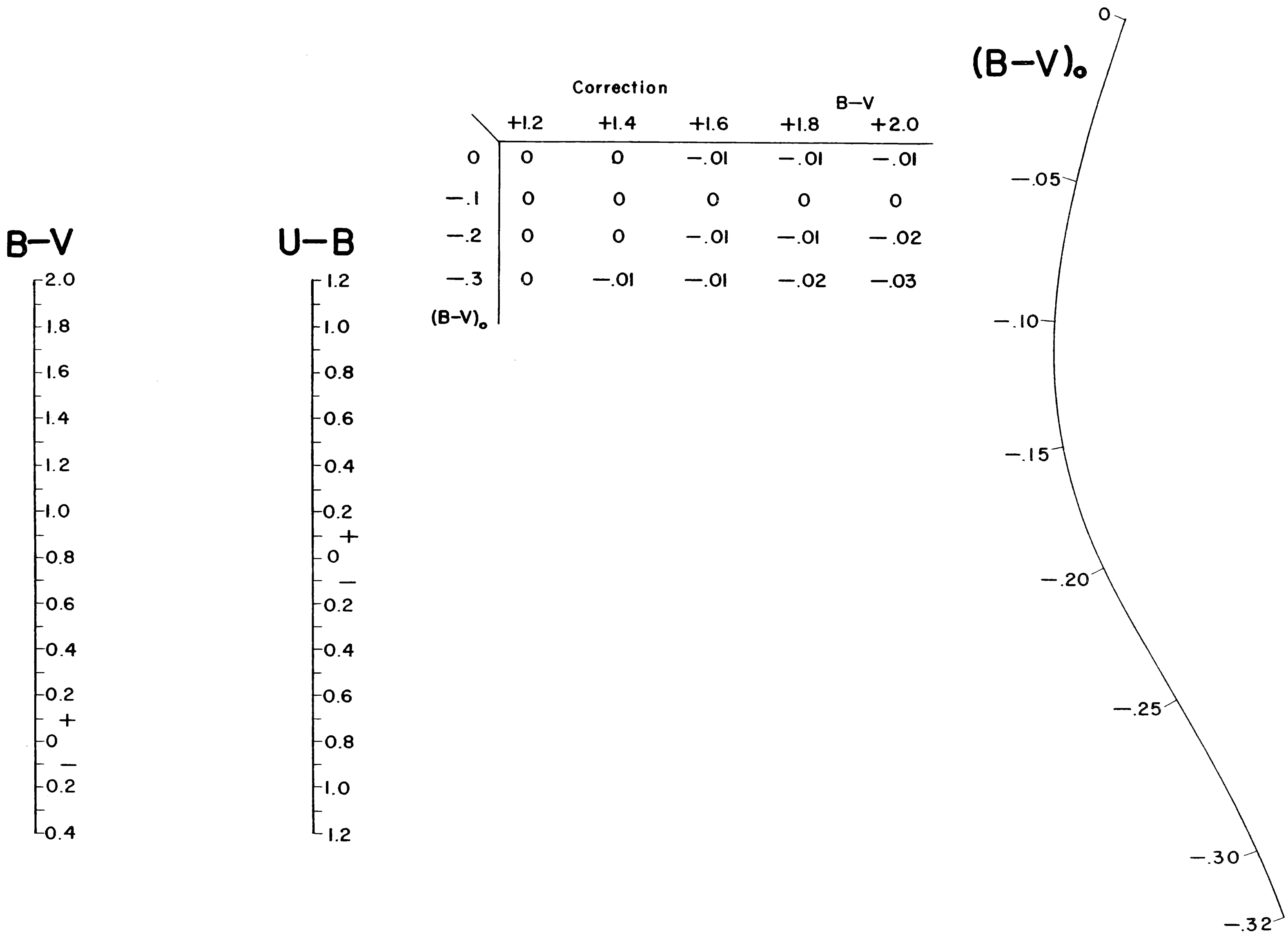
The difference between equations (8) and (9) is less than 0.01 mag., for $E_{(B-V)} < +1.25$.

The error of Equation (9) is given by

$$\Delta(B-V)_o = (0.0166 - 0.1662\Delta X)(B-V)^2 - (0.0166 - 0.1662\Delta X)(B-V). \tag{10}$$

The nomogram for the solution of Equation (9) is given in Figure 4. The correction according to Equation (10) is given in the small table on the figure. The approximation involved in writing Equation (9) makes it possible to construct the nomogram. This nomogram, which is valid for B-V $\leq$ +2.0, yields $(B-V)_o$, from which the reddening may be computed.

We must emphasize that the "Q"-method is valid only for main-sequence stars earlier than spectral type AO. Appreciable systematic errors will result from the use of Figure 4 for stars other than main- sequence stars unless the proper corrections are made.




Correction

| $(B-V)_0$ \ B−V | +1.2 | +1.4 | +1.6 | +1.8 | +2.0 |
|---|---|---|---|---|---|
| 0 | 0 | 0 | −.01 | −.01 | −.01 |
| −.1 | 0 | 0 | 0 | 0 | 0 |
| −.2 | 0 | 0 | −.01 | −.01 | −.02 |
| −.3 | 0 | −.01 | −.01 | −.02 | −.03 |

Figure 4. The nomogram for intrinsic colors of main-sequence early-type stars.

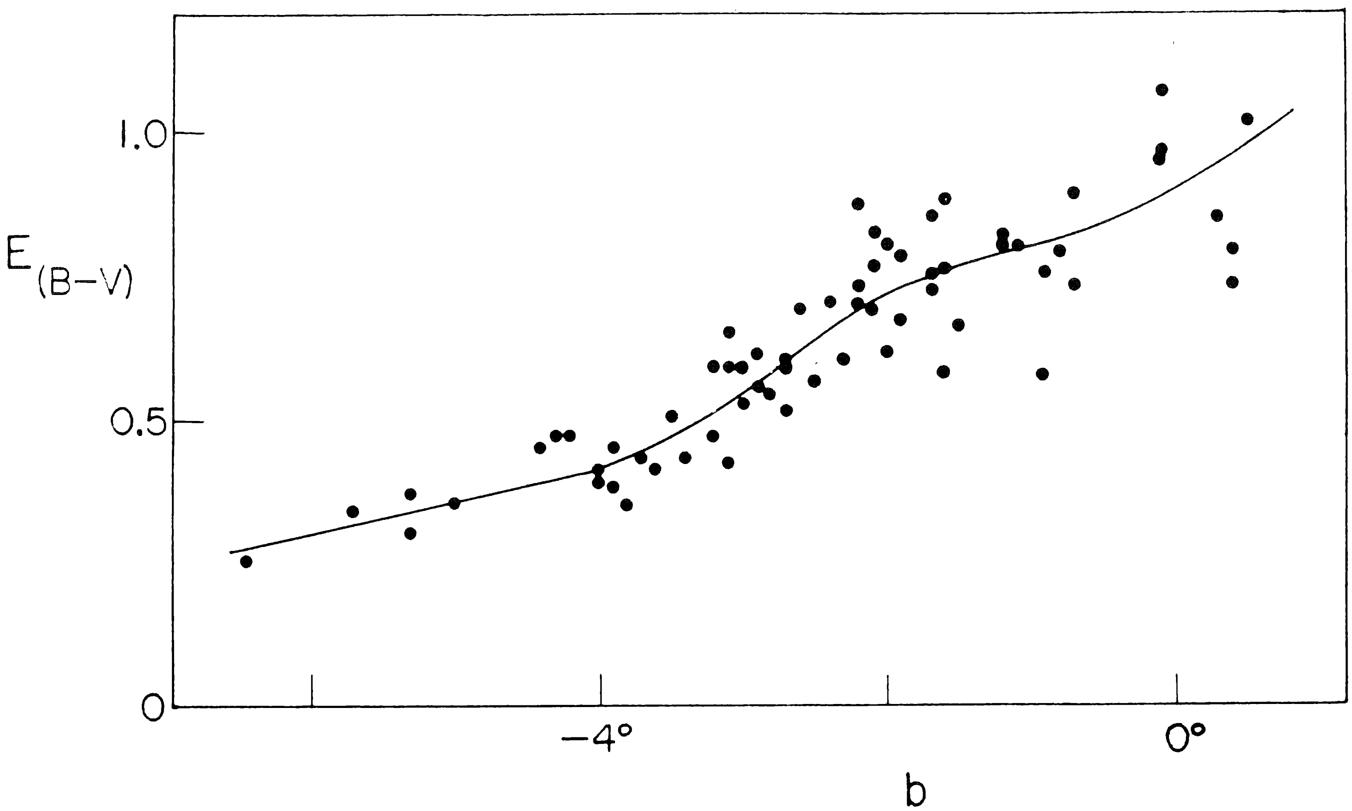



Figure 5. Color-excess, $E_{(B-V)}$, versus galactic latitude, b, for the region of the double cluster in Perseus.

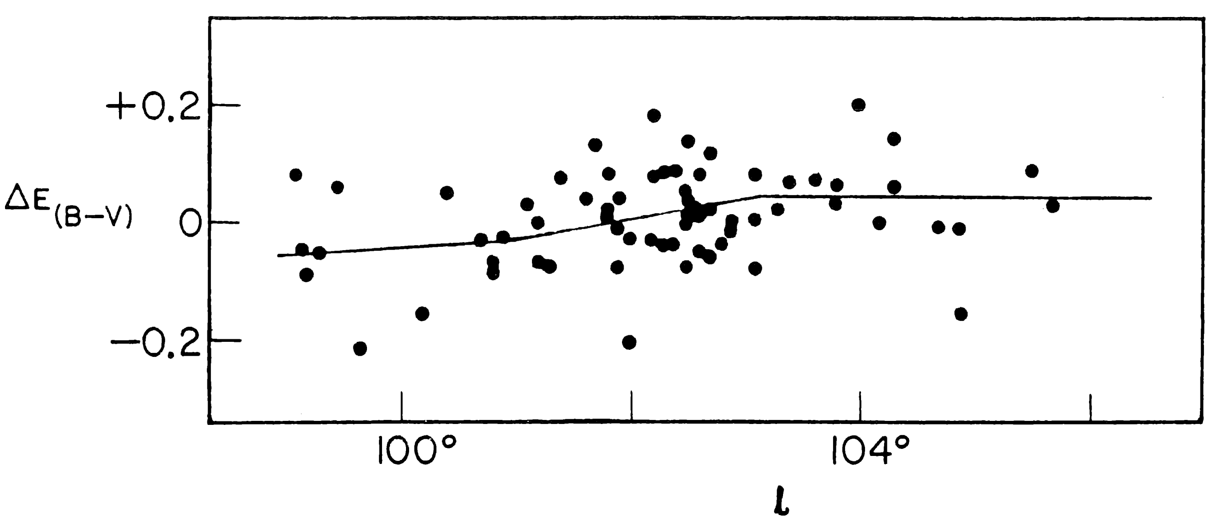



Figure 6. Color-excess, $\Delta E_{(B-V)}$, versus galactic longitude, l, for the region of the double cluster in Perseus.

## III. The Intrinsic Colors of the Supergiants

It has long been assumed, because of the lack of data bearing on the problem, that the intrinsic colors of the early- type supergiants are the same as those of main-sequence stars of the same spectral types. The intrinsic colors of main- sequence stars on the UBV system are now firmly established (5), but we are only now able to determine tentatively the intrinsic colors of the higher luminosity stars.

The computation of the intrinsic colors of the supergiants can be made from the published data in the region of the double cluster in Perseus. For this purpose we select all of the stars in the lists of Johnson and Morgan (6) and Hiltner (7) that have galactic longitude between 99°.1 and 106°.2, and galactic latitude between +0°.5 and -6°.5. Stars of all luminosity classes are present in this selected list.

First, we determine the reddening in the region from the stars of luminosity classes III to V, inclusive. We use the nomogram of Figure 4, and the three-color photometry; however, the same result would be obtained from the use of the spectral types and the intrinsic colors of Morgan, Harris and Johnson. Figure 5 shows the relation between galactic latitude and color-excess in the region of the double cluster, while Figure 6 shows the relation between galactic longitude and color- excess after correction for Figure 5. If we assume that the supergiants are affected by the reddening material in the same amount as the stars of lower luminosity, we can compute the "color- excesses" of supergiants compared with main-sequence stars. This comparison is shown in Figure 7 (filled circles). A mean "color- excess" of +0.09 mag. is shown in this figure for B-stars, while the A-stars show a similar, but negative, "color-excess". A mean line has been drawn in to represent the data.

It is possible to argue that the "color-excesses" shown in Figure 7 are merely the result of different amounts of reddening material between the supergiants and the main-sequence stars. We can, however, check the excesses of Figure 7 against the colors obtained for supergiants in other regions of the sky. For this purpose, we use the data for M29 given by Morgan and Harris (8) and for the $\alpha$ and $\zeta$ Persei clusters by Harris (9). In all cases, the observed colors of the supergiants are corrected by the reddening of the clusters determined from the main- sequence stars. In addition, we asume that a number of bright, nearby supergiants are unreddened. These stars, and the sources of spectral types and colors, are as follows: $\alpha$ Cyg and $\beta$ Ori (1); $\alpha$ Car (10); $\ell$ Pup, 48G e Vel, $\iota$ Car, $\phi$ Vel, and s Car (11). Figure 7 (open circles) shows that these stars, not in the region of the double cluster, fit the mean line and, furthermore, allow us to extend the relationship to stars as late as F5. We can now compute the intrinsic B-V colors for supergiants. There is no systematic difference between luminosity classes Ia and Ib in Figure 7.

We wish next to determine the intrinsic U-B colors for these stars. For this purpose, we select from Hiltner's (7) table all of the stars of luminosity classes Ia, Ib and II which are little or moderately reddened. A total of 106 stars (including those in the region of the double cluster) are selected. We next determine $E_{U-B}$ from the curved reddening line of Hiltner and Johnson (2) and the intrinsic B-V colors obtained through the adopted relationship shown in Figure 7. We now compute $(U-B)_0$.

These intrinsic colors, $(B-V)_0$ and $(U-B)_0$, permit us to derive the mean relationships for each luminosity class shown in Figure 8. The mean intrinsic colors are listed in Table III, which also lists the values of Q for these spectral types and luminosity classes. The values for luminosity classes II and III were obtained in the same manner as for the higher luminosity classes; class III differs very little from Class V.

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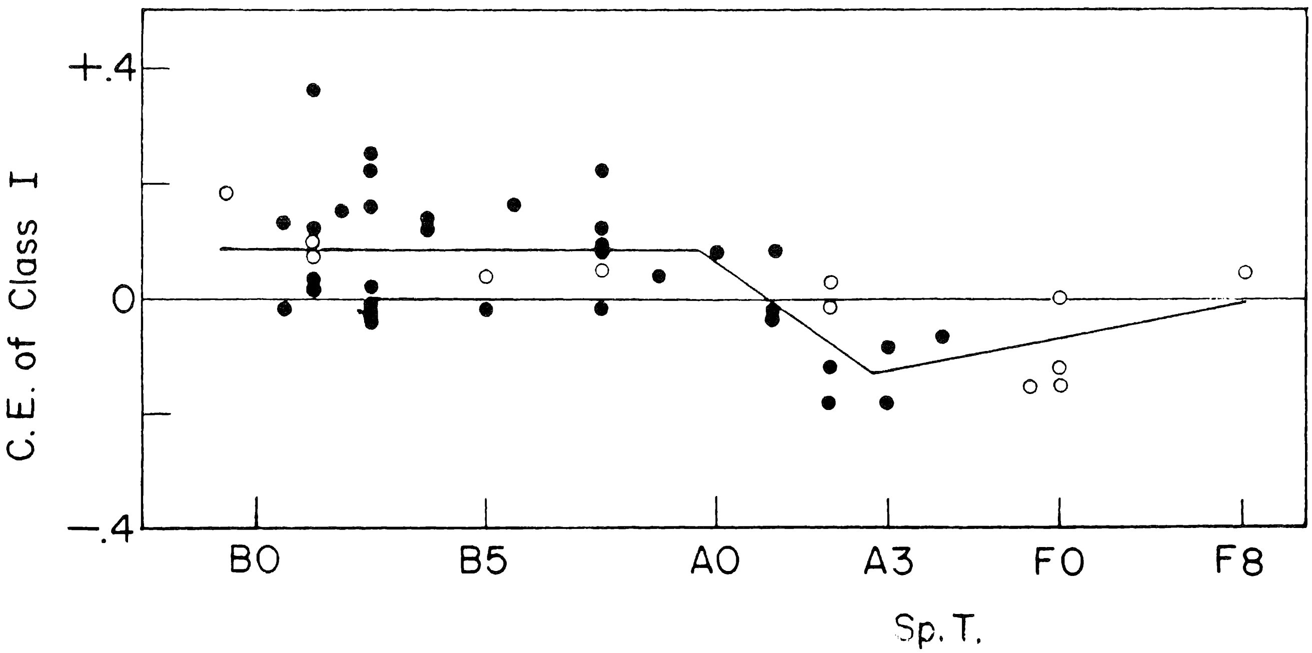


Figure 7. Color-excess of luminosity class I stars, relative to class V.

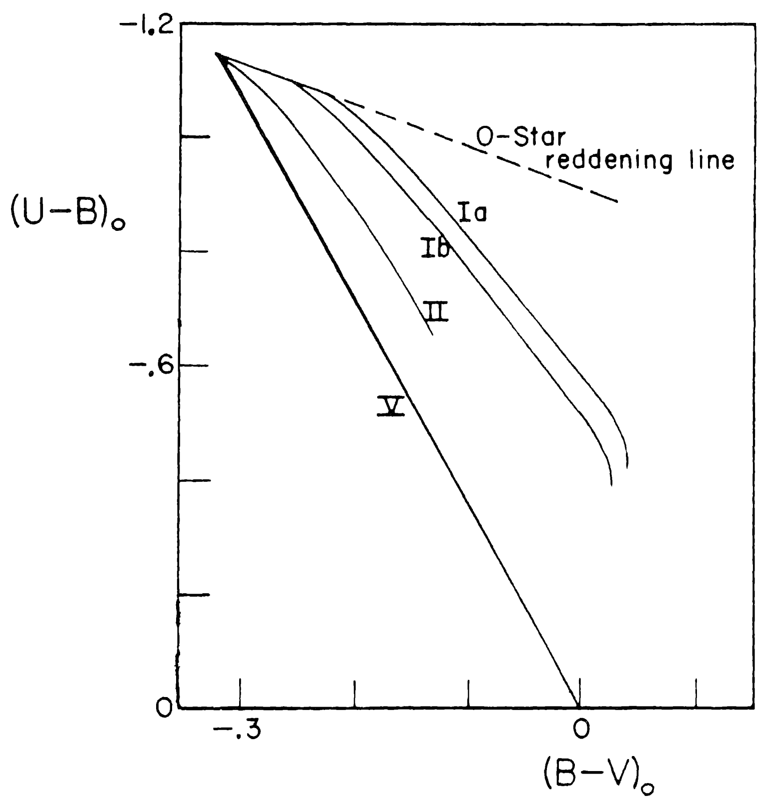


Figure 8. The intrinsic colors of early-type stars.

Table III

Intrinsic Colors

| Sp. T. | B-V V | B-V III | B-V II | B-V $I_b$ | B-V $I_a$ |
|---|---|---|---|---|---|
| O5 | -.32 | -.32 | -.32 | -.32 | -.32 |
| O6 | -.32 | -.32 | -.32 | -.32 | -.32 |
| O7 | -.32 | -.32 | -.32 | -.31 | -.31 |
| O8 | -.31 | -.31 | -.31 | -.29 | -.29 |
| O9 | -.31 | -.31 | -.31 | -.28 | -.28 |
| O9.5 | -.30 | -.30 | -.30 | -.25 | -.25 |
| B0 | -.30 | -.30 | -.29 | -.22 | -.22 |
| B0.5 | -.28 | -.28 | -.26 | -.20 | -.20 |
| B1 | -.26 | -.26 | -.24 | -.18 | -.18 |
| B2 | -.24 | -.24 | -.22 | -.16 | -.16 |
| B3 | -.20 | -.20 | -.18 | -.12 | -.12 |
| B5 | -.16 | -.16 | -.14 | -.08 | -.08 |
| B6 | -.14 | -.14 | -.12 | -.06 | -.06 |
| B7 | -.12 | -.12 | -.10 | -.04 | -.04 |
| B8 | -.09 | -.09 | -.07 | -.01 | -.01 |
| B9 | -.06 | -.06 | -.04 | +.02 | +.02 |
| B9.5 | -.03 | -.03 | -.01 | +.03 | +.03 |
| A0 | .00 | .00 | +.01 | +.04 | +.04 |
| A1 | +.03 | +.03 | --- | +.04 | +.04 |
| A2 | +.06 | +.06 | --- | .00 | .00 |
| A3 | +.09 | --- | --- | -.03 | -.03 |
| A5 | +.15 | +.15 | --- | +.05 | +.05 |
| A7 | +.20 | --- | --- | +.12 | +.12 |
| F0 | +.30 | --- | --- | +.23 | +.23 |
| F2 | +.38 | --- | --- | +.34 | +.34 |
| F5 | +.45 | --- | --- | +.45 | +.45 |

| Sp. T. | U-B V | U-B III | U-B II | U-B $I_b$ | U-B $I_a$ |
|---|---|---|---|---|---|
| O5 | -1.15 | -1.15 | -1.15 | -1.15 | -1.15 |
| O6 | -1.14 | -1.14 | -1.14 | -1.14 | -1.14 |
| O7 | -1.14 | -1.14 | -1.14 | -1.14 | -1.14 |
| O8 | -1.13 | -1.13 | -1.13 | -1.13 | -1.13 |
| O9 | -1.12 | -1.12 | -1.12 | -1.12 | -1.12 |
| O9.5 | -1.10 | -1.11 | -1.12 | -1.09 | -1.10 |
| B0 | -1.08 | -1.09 | -1.10 | -1.05 | -1.07 |
| B0.5 | -1.01 | -1.03 | -1.05 | -1.01 | -1.04 |
| B1 | - .93 | - .96 | -1.00 | - .96 | -1.00 |
| B2 | - .86 | - .89 | - .95 | - .91 | - .96 |
| B3 | - .71 | - .74 | - .83 | - .82 | - .87 |
| B5 | - .56 | (- .59) | - .69 | - .72 | - .78 |
| B6 | - .49 | (- .51) | - .62 | - .67 | - .73 |
| B7 | - .42 | (- .44) | (- .55) | - .62 | - .68 |
| B8 | - .30 | (- .32) | (- .41) | - .53 | - .60 |
| B9 | - .19 | (- .20) | (- .25) | - .48 | - .56 |
| B9.5 | - .10 | (- .11) | (- .14) | ---- | ---- |
| A0 | .00 | (- .01) | (- .06) | ---- | ---- |

Table III cont'd.

Intrinsic Colors

| Sp. T. | Q V | Q III | Q II | Q $I_b$ | Q $I_a$ |
|---|---|---|---|---|---|
| O5 | - .92 | - .92 | - .92 | - .92 | - .92 |
| O6 | - .91 | - .91 | - .91 | - .92 | - .92 |
| O7 | - .91 | - .91 | - .91 | - .92 | - .92 |
| O8 | - .91 | - .91 | - .91 | - .92 | - .92 |
| O9 | - .90 | - .90 | - .90 | - .92 | - .92 |
| O9.5 | - .88 | - .89 | - .90 | - .91 | - .92 |
| B0 | - .86 | - .88 | - .89 | - .89 | - .91 |
| B0.5 | - .81 | - .83 | - .86 | - .87 | - .90 |
| B1 | - .74 | - .77 | - .83 | - .83 | - .87 |
| B2 | - .69 | - .72 | - .79 | - .79 | - .84 |
| B3 | - .57 | - .60 | - .70 | - .73 | - .78 |
| B5 | - .44 | (- .47) | - .59 | - .66 | - .72 |
| B6 | - .39 | (- .41) | - .53 | - .63 | - .69 |
| B7 | - .33 | (- .35) | (- .48) | - .59 | - .65 |
| B8 | - .24 | (- .26) | (- .36) | - .52 | - .59 |
| B9 | - .15 | (- .16) | (- .23) | - .49 | - .57 |
| B9.5 | - .08 | (- .09) | (- .13) | ---- | ---- |
| A0 | .00 | (- .01) | (- .07) | ---- | ---- |


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