STELLAR ULTRAVIOLET COLORS AND INTERSTELLAR EXTINCTION

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ABSTRACT

In this paper, we study a sample of Celescope results. Most of the sample stars belong to the Orion and Vela regions. We first compare measurements by Celescope filter U3 with the m_{1500} of Weber et al. (1971). (The U3 filter has an average wavelength of about 1600 Å.) Second, we select stars with visual excess E(B-V) less than 0.05 in order to derive relationships of intrinsic color index versus spectral type. We compare the resulting intrinsic color-color relations with existing blanketed and unblanketed model calculations. Finally, we utilize the preceding intrinsic relations to derive some results on interstellar extinction. Owing to the rather large scatter in the Celescope data (0.2-mag standard deviation for multiply observed stars), the Vela stars give the more significant results because their visible excess E(B-V) is, in general, larger than that for the Orion stars. We find somewhat less ultraviolet extinction than do other authors, although their results lie within 1 standard deviation of our values.

I. INTRODUCTION

In this paper, we study a sample of results from The Celescope Catalog of Ultraviolet Observations (Davis 1972). In addition to the results for the Vela region already published in the preliminary catalog, we have used data for several hundred stars in the Orion and southern Scorpio regions.

For this preliminary interpretation of these Celescope results, we have selected only those stars for which we know the photoelectric V magnitude and B-V color index, the spectral type, and at least one Celescope ultraviolet magnitude. There are 166 stars in the resulting sample; most of them are B and early A-type stars.

In addition to the derivation of some specific relationships from our sample data (e.g., intrinsic color versus spectral type, or ultraviolet color excesses versus visible-light color excesses), one purpose of this work is to show what sort of properties we can deduce from a broad survey such as the Celescope Catalog. We restrict ourselves to those properties that show a significant effect on ultraviolet broad-band colors. To do this, we must compare the expected size of these effects to the size of the observational errors. Because the Celescope Catalog contains a very large number of observed stars, we can determine statistical properties with considerably more accuracy than we can determine the properties of individual stars. A study of our observational errors, based on repeated observations of individual stars, indicates a standard deviation of slightly less than 0.2 mag for an individual observation of normal weight. The scatter in our color-spectrum relationships (§ III) is compatible with a standard deviation of such a size. The scatter in our comparison with the results of Weber, Henry and Carruthers (1971) (§ II) can most easily be attributed to a standard deviation exceeding that amount for their observations.

We shall divide the rest of this paper into three parts. The first compares Celescope results with those of Weber et al. (1971) and discusses the accuracy of the Celescope results. In the second, we derive intrinsic relationships (i.e., no interstellar extinction) of color versus spectral type and of different colors against each other. And in the third, we derive ultraviolet color excesses arising from interstellar extinction.

Here we summarize the basic features of the Celescope broad-band measurements. One of us (Davis 1968) has described the observational system. A shorter description, which also includes a brief account of our data-analysis procedure, appears elsewhere in these proceedings (Davis, Deutschman, Lundquist, Nozawa and Bass 1972).

The Celescope photometric system consists of four band passes, designated by U1, U2, U3 and U4. (Only the results for the U1, U2 and U3 filters will be considered here.) The corresponding magnitudes are also designated by the same symbols or, more generally, by U_i ($i = 1,2,3,4$). The mean wavelengths λ_{0i} of each filter i are defined by

$$\lambda_{0i} = [\int_0^\infty S_i(\lambda)\lambda \, d\lambda]/[\int_0^\infty S_i(\lambda) \, d\lambda], \quad i = 1,2,3,4 \; ,$$

where $S_i(\lambda)$ are the sensitivity functions of the system as a function of the wavelength λ.

Table 1 lists average wavelengths, λ_{0i}, and the total bandwidths, $\Delta\lambda_i$, at half the maximum sensitivity ($\Delta\lambda_i = \max\{S_i(\lambda)\}/2$).

Table 1. Average wavelengths λ_{0i} and total bandwidths $\Delta\lambda_i$ for the Celescope filters.

Celescope filter designation U_i	Average wavelength λ_{0i} (Å)	Total bandwidth $\Delta\lambda_i$ (Å)
U1	2582	550
U2	2308	850
U3	1621	325
U4	1537	450

II. COMPARISON WITH OTHER OBSERVATIONS

Weber et al. (1971) have measured a number of ultraviolet electronographic magnitudes. Their effective wavelength is about 1500 Å, and their band pass covers the wavelength range 1230-2100 Å. These heterochromatic magnitudes are therefore very similar to Celescope's U3 magnitudes. This means that if we compare the magnitudes of stars measured in both systems, they should be identical, provided that both magnitude scales have been given the same zero point. In all, 51 resolved stars have been measured by both experiments; the comparison of both sets of results is displayed in Figure 1, with Weber's m(1500) magnitudes plotted against Celescope's U3 magnitudes. (Weber's m(1500) magnitude was computed by adding his tabulated V magnitude to his tabulated m(1500)-V color.) Also shown on Figure 1 are three reference lines for comparing the calibrations: (1) the solid line, of slope 45°, corresponds to no scale error in either magnitude system; (2) the dashed line, departing from the solid line at m(1500) = 1.8, corresponds to the dashed line in Weber's Figure 12 and indicates a possible correction to his magnitude scale for magnitudes brighter than that; and (3) the dotted line corresponds to the best least-squares fit between the two magnitude systems. The dotted line corresponds to the situation where one or both of the magnitude systems may have a zero point error and a scale

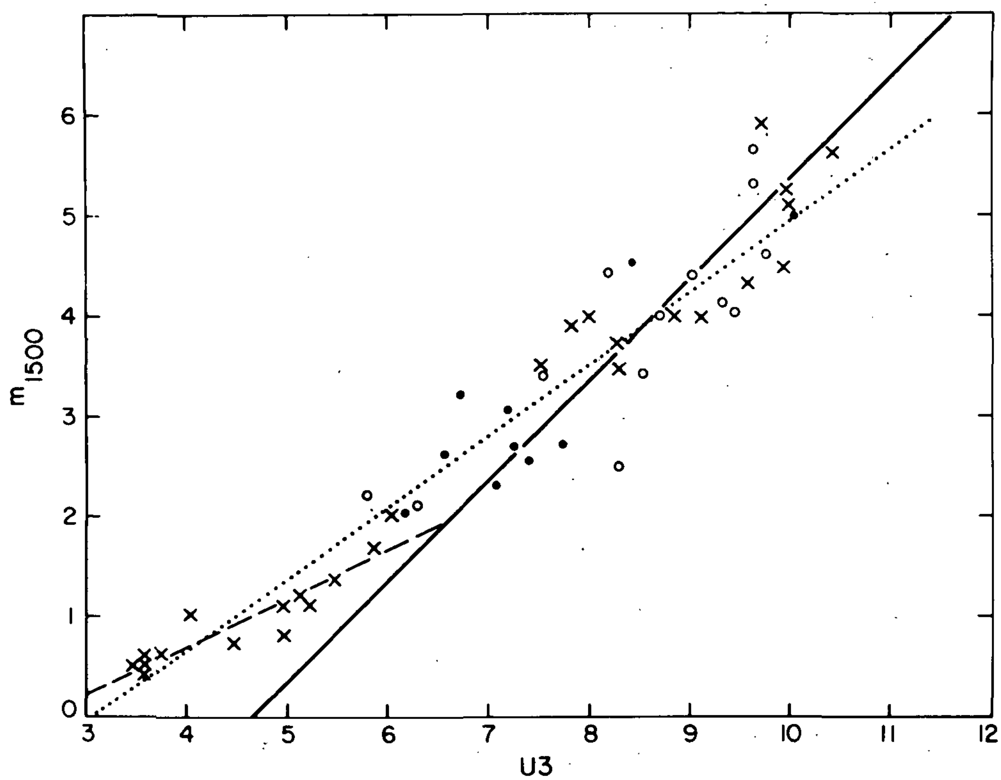

Figure 1.—Comparison of the ultraviolet magnitudes m_{1500}-V by Weber et al. (1971) with the U3-V magnitudes of the Celescope Catalog. Open circles (O), dots (●), and crosses (×) represent, respectively, B3 V stars, B1 V stars, and other spectral types. The solid line (——) indicates the relationship the two systems would have if there were no scale error. The dashed line (---) indicates Weber's suggested revision of his magnitude scale for bright stars. The dotted line (···) indicates the best least-squares linear fit between the two systems.

error.

The standard deviation of the scatter between the two magnitude systems is about the same, 0.5 mag, whether we use the dotted line or the combination of dashed line and solid line in making the comparison. If the errors in both systems are the same size, this comparison would indicate standard deviations of about 0.35 mag for each system. We ran an independent check on the standard deviation of magnitudes in our system. Based on about 1500 observations in each color band, of the 500 stars we observed more than once, our standard deviation is slightly less than 0.2 mag. For the purposes of this paper, it does not matter whether we take our standard deviation to be 0.2 or 0.35 mag, since our sample is sufficiently large to enable us to derive average properties quite accurately in either case. We therefore postpone a more detailed discussion of our observational errors to a later paper.

The results presented in the next two sections have thus been obtained from data whose analysis had revealed scatters on the order of 0.3 to 0.4 mag in the color-color, or color-spectrum, diagrams. We could have attempted to explain these scatters in terms of properties of the stars or the interstellar medium. However, the comparison we have made in this section tells us that it is probably not justified to interpret observed effects in terms of peculiarities of individual stars unless these effects are larger than, say, 0.5 mag; we have confined this paper to a discussion of the statistical properties of our observed stars and of the interstellar medium.

III. INTRINSIC COLOR-SPECTRUM RELATIONSHIPS

In what follows, we shall call "intrinsic" all those properties that are proper to the observed stars before encountering the interstellar medium. To derive these intrinsic properties, we selected stars whose color excess E(B-V) due to interstellar extinction is less than 0.05. The intrinsic $(B-V)_0$ indices have been taken from Schmidt-Kaler (1965). This limit was chosen as a compromise between (1) as little interstellar reddening as possible and (2) the need for a rather large sample of stars. The underlying assumption is that there is no unknown extinction component in the ultraviolet or, in other words, that E(B-V) near zero implies that the ultraviolet interstellar extinction is also approximately zero.

For each spectral class, we then computed the average ultraviolet colors U_i-V (V being the photoelectric magnitude in the UBV system). Stars of various luminosity classes within the same spectral class were lumped together. The results for the colors U1-V, U2-V and U3-V are plotted in Figures 2, 3 and 4, respectively. The dots and crosses represent averages for Orion stars and Vela stars, respectively. The number of stars in each spectral class ranges from 1 (B0, A7, A8, F0, F2) to 14 (B8) and 16 (B9). We do not indicate the standard deviations for each color and each spectral class. In general, for a given number of stars, the standard deviation is smallest for the U3 color and largest for the U1 color. As can be seen from Figures 2, 3 and 4, the scatter between adjacent spectral classes gives a fair idea of the internal errors or of the individual peculiarities or of both, because we do not expect such drastic and random changes between plus or minus one spectral class, as they appear on the various graphs. On the basis of what we have seen in § II, it could well be that much

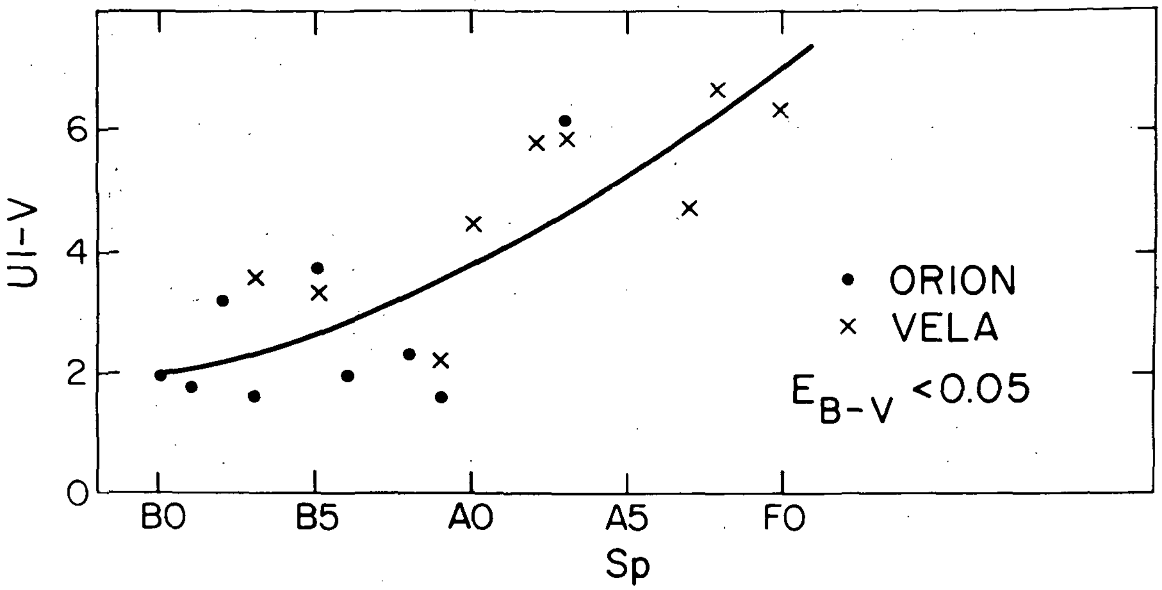

Figure 2.—Ultraviolet color index U1-V versus spectral type. The dots (●) (Orion) or crosses (×) (Vela) are average colors for each spectral type. Only stars with visual color excess $E(B-V) < 0.05$ have been selected. The solid line represents a tentative relation between intrinsic color index and spectral type.

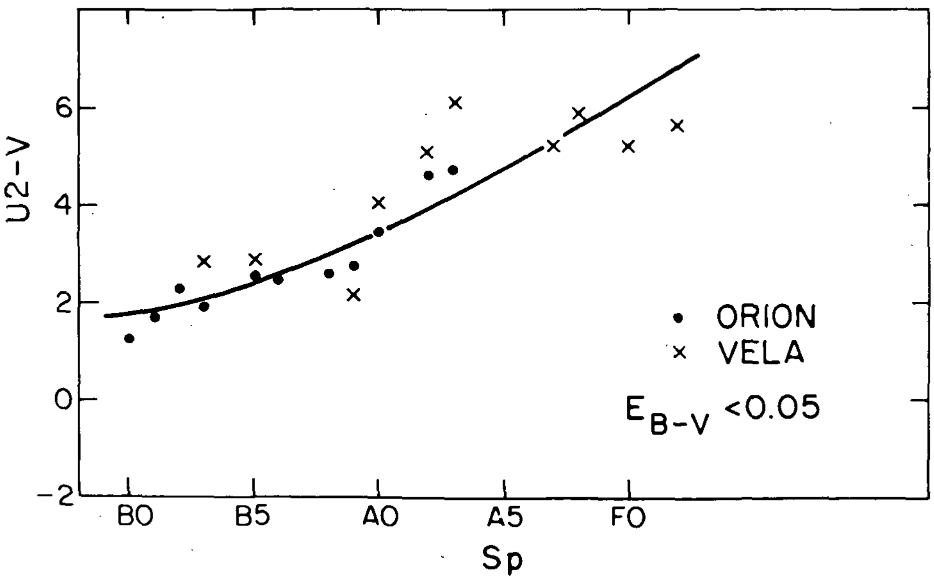

Figure 3.—Same as Figure 2, for color U2-V.

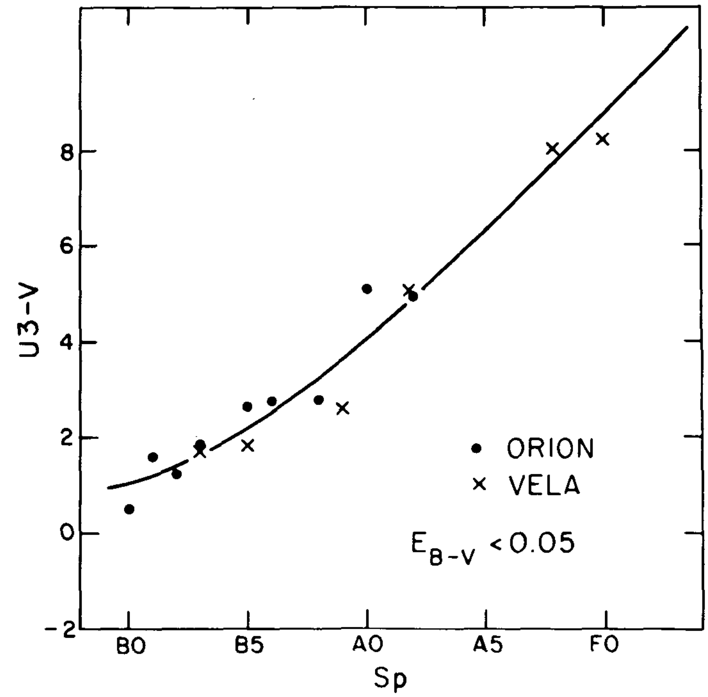

Figure 4.—Same as Figure 2, for color U3-V.

of this scatter is due to observational errors. Some is also most certainly due to our use of Henry Draper spectral types for stars having no MK classification; as shown by Schild and Chaffee (1971), significant differences exist between the HD and the MK classifications for stars having HD spectral types of B8 and B9. Nevertheless, we can try to derive average relations between the observed colors (U_i-V) and the spectral types. These relations are shown by solid lines. It is questionable whether the curvature of our fitted curves corresponds to reality. The fitting is best for the U3-V color; it is not so good for U1-V and U2-V.

From the set of relations (U_i-V) = f(Sp), where Sp stands for the spectral type, we can now derive a set of color-color relations

$$U_i - V = g_{Sp}(U_j - V) \ , \qquad j,i = 1,2,3;\ i \neq j \ ,$$

with the spectral type Sp as a parameter. The relations U3-V versus U1-V and U3-V versus U2-V are represented by solid lines in Figures 5 and 6, respectively. These lines are broken for spectral types later than about A3, because the scarcity of the data gives them less reliability for those later

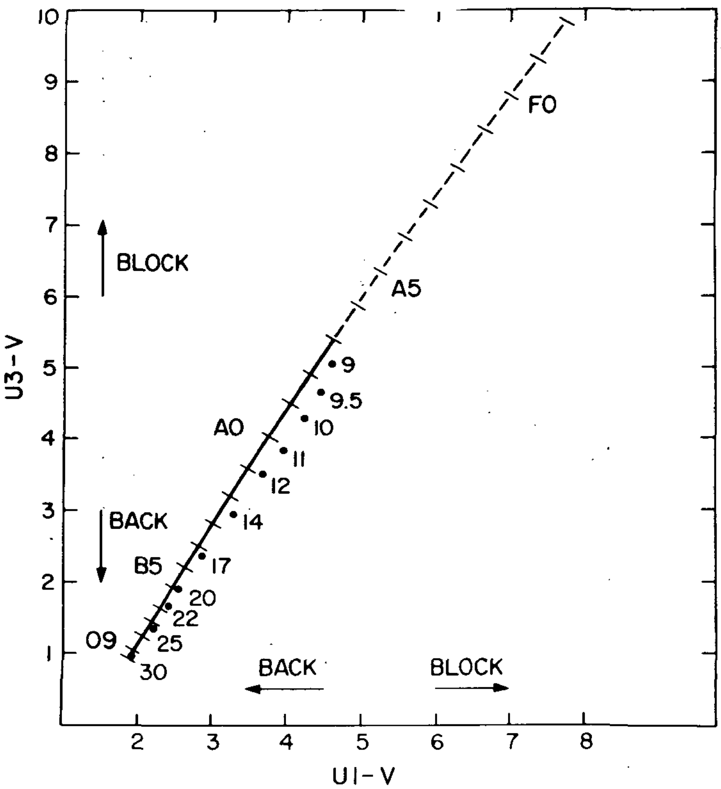

Figure 5.—Intrinsic color indices U3-V versus U1-V. The line labeled with spectral types is deduced from observations. The dots, labeled with $T_{eff} \times 10^{-3}$, represent colors computed from model atmospheres. Arrows show in which direction pure backwarming or pure blocking would displace the theoretical colors.

types. We can see that within a given spectral type range, the change in ultraviolet color is larger for the U3-V color than for U2-V or U1-V. Also, the change in color index per unit spectral type is smaller for early spectral types than for later spectral types. This is a direct consequence of the curvature of the lines in Figures 2, 3 and 4 and could therefore be modified, although we do not believe that straight lines would be a good fit for the $(U_i-V) = f(Sp)$ relations. It is interesting to note that the observed color-color relations

$$(U_i-V) = g_{Sp}(U_j-V)$$

can be represented by straight lines (there is only a very slight curvature).

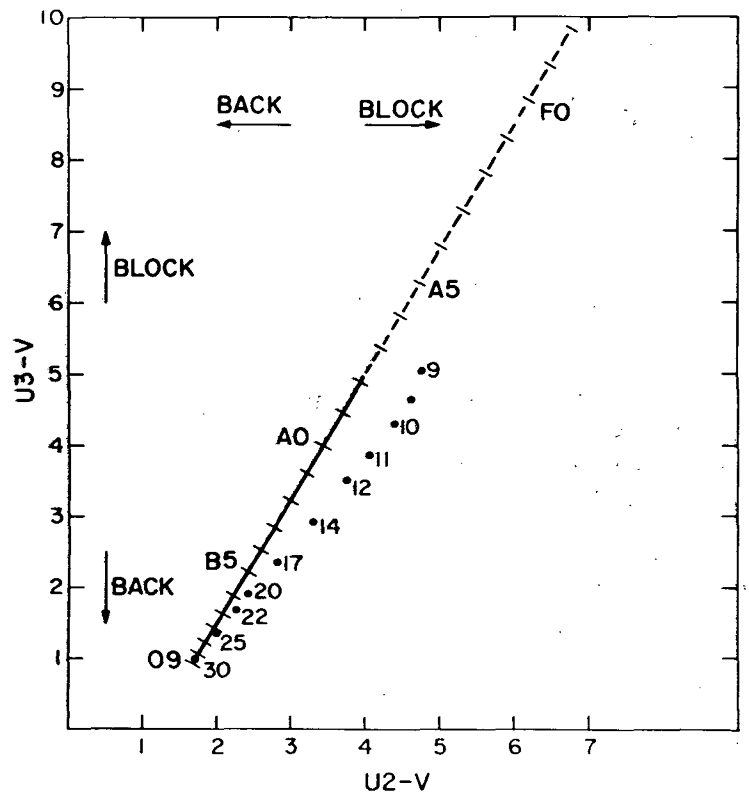

Figure 6.—Same as Figure 5, but U3-V versus U2-V.

To this point, we have derived all our intrinsic relationships from observed quantities only, without the aid of any theoretical models. This allows us now to make an independent comparison of the observed intrinsic relationships with the same relationships derived from model calculations. Weber et al. (1971) could not do so, because they used the theoretical colors to establish their calibration.

The theoretical colors $m_i - m_j$ ($i \neq j$) are calculated quite generally (for spherically symmetric stars) according to the formula

$$m_i = -2.5 \log(E_i/\phi_i) + C_i + C \quad , \qquad (1)$$

where i stands for a given band pass, C_i are constants that should be equal to zero if the sensitivity functions $S_i(\lambda)$ had been calibrated absolutely; C is a constant that stands for all quantities independent of the wavelength λ, such as the radius or the distance of the star. If the C_i's were equal to zero, the theoretical color indices $m_i - m_j$ would be directly comparable to the observed indices as defined in the Celescope experiment. However, as we shall see, these constants C_i have to be adjusted, as is generally the case for photometric systems. Next, we define E_i and ϕ_i:

$$E_i = \int_{\lambda_{ai}}^{\lambda_{bi}} F_\lambda(\lambda) \cdot A(\lambda) \cdot S_i(\lambda) \cdot d\lambda \ , \qquad (2)$$

$$\phi_i = \int_{\lambda_{ai}}^{\lambda_{bi}} S_i(\lambda) \ d\lambda \ , \qquad (3)$$

where λ_{ai} and λ_{bi} are the shortest and longest wavelengths of filter i; $S_i(\lambda)$ are again the sensitivity functions; and $A(\lambda)$ represents the monochromatic interstellar extinction at wavelength λ, with $0 \leq A(\lambda) \leq 1$. In this section, we deal only with stars for which the interstellar extinction is negligible; hence, $A(\lambda) = 1$. Finally, $F_\lambda(\lambda)$ is the stellar monochromatic flux per unit wavelength interval at wavelength λ.

The sensitivity function of the filter V has been taken from Azusienis and Straizys (1969). The Celescope sensitivity functions were taken from Davis (1968); see also § I, above.

The theoretical fluxes $F_\lambda(\lambda)$ have been computed by means of the program ATLAS (Kurucz 1969) with hydrogen line-blanketed model atmospheres also calculated by ATLAS. The resulting color indices U_i-V (defined by (1), (2) and (3)) are represented by dots in Figures 5 and 6. The parameter of the theoretical color-color relations is the effective temperature T_{eff} of the models. The representative points are labeled with T_{eff} in thousands of degrees Kelvin. The gravity of the models is equal to log g = 4. Some calculations with models having log g = 3 did not show any significant differences on the U1, U2 and U3 colors. Also, we compare the theoretical indices with average results derived mostly from class V stars, and therefore a gravity log g = 4 seems to be appropriate.

In addition to the ATLAS results, we also calculated a number of color indices with fluxes taken from Van Citters and Morton (1970). It turns out that these models do not show any significant line-blocking effect on the magnitudes U1, U2 and U3. These blanketed models bring about a backwarming effect on these three filters, and hence the net change between these blanketed models and the ATLAS models consists essentially of a shift in effective temperature along the sequence of theoretical colors. However, the theoretical color sequence had to be translated anyway, because the zero point of the theoretical magnitudes was ill defined (constants C_i in (1) not equal to zero). We adjusted the zero point of the theoretical colors so that the model at T_{eff} = 30,000°K has the same colors as do stars of spectral class between O9 and B0. Once this arbitrary adjustment of the theoretical curve has been made, it is possible to discuss only relative differences between models and observations.

We then notice that the theoretical color-color relations in Figures 5 and 6 are not parallel to the observed relations and that this effect is more pronounced in the U3-V versus U2-V relation. We also see that the cooler models have colors that make them look like stars with spectral types that are too late. For example, the models at 10000°K look like A1 or A2 stars, which, according to Morton and Adams (1968), are too late by about 2 classes for this temperature.

In view of the rather poor fit of the relations of the intrinsic color versus spectral type (Figures 2, 3 and 4), it is difficult to decide whether these differences between models and observations are real. It should first be noted that our models do not include significant line blocking in any of the U1, U2 or U3 magnitudes. Models with a significant number of lines in these filters could modify the actual color-color relationships by a combination of backwarming and blocking effects. We have not yet studied the modified theoretical relations.

On the other hand, if we assume that the models give a good picture of real stars, the differences between models and observations could be explained in the following terms. The change in color per unit spectral class is essentially a function of the slope of the relations of color versus spectral type. A curvature change of these relations would expand or contract the spectral type scale in the color-color relations. The poor fit in Figures 2, 3 and 4 shows that such a change in curvature could explain quite well a difference of 2 to 3 spectral classes in the range 10,000 to 30,000°K.

The second difference between models and observations (i.e. the observed and theoretical color-color relations are not parallel) can be explained as follows. The curvature of the color-color observed relations is essentially due to different curvatures in the relations of color versus spectral type.

By changing any one of these curvatures, one could easily fill the gap between observations and theory in the color-color relations. As stated before, owing to the large scatter in our data, we cannot ignore the possibility of such changes in the fittings of Figures 2, 3 and 4.

Further discussions should be based on the analysis of much larger samples of the Celescope Catalog and on the use of models that include the best possible treatment of line blocking (i.e. very extensive tables of oscillator strengths).

IV. INTERSTELLAR EXTINCTION

In this section, we attempt to derive some results on interstellar extinction. Because our data are broad-band heterochromatic magnitudes, we are not able to present our results in terms of a monochromatic extinction law. Instead, we estimate color excesses in the usual way:

$$E_{i-V} = (U_i - V) - (U_i - V)_0 \ , \qquad (4)$$

where i stands for any one of the Celescope filters, and $(U_i-V)_0$ and (U_i-V) are, respectively, the intrinsic and observed color indices. In addition, we normalize the excesses E_{i-V} so that $E(B-V) = 1$. This requires that for the stars used to calculate the excesses E_{i-V}, we know the spectral type (necessary to define the star's intrinsic color indices), the B-V index, and at least one of the ultraviolet color indices. Furthermore, we need to select stars with an excess E(B-V) as large as possible, for the following reasons: a) because we normalize with respect to E(B-V), E(B-V) must be much larger than its possible errors $\delta E(B-V)$; b) the excesses E_{i-V}, as given by (4), must be larger than the typical standard deviations of the U_i-V indices. As seen previously, these deviations are on the order of 0.3 mag. So we require that

$$E_{i-V} >> 0.3 \quad . \qquad (5)$$

With our normalization, the normalized excess E^*_{i-V} is

$$E^*_{i-V} = \frac{E_{i-V}}{E_{B-V}}$$

which, together with (5), gives the condition

$$E_{B-V} >> \frac{1}{E^*_{i-V}} \quad .$$

As we shall see later, our results, as well as those of others, indicate that for our filters, $E^*_{i-V} \gtrsim 3$, so that we should like to select stars with

$$E_{B-V} >> 0.1 \quad .$$

But only five of our sample stars have E(B-V) > 0.6. Of the three in Orion having E(B-V) > 0.15, two are supergiants, and the third (HD 37903) has an abnormal spectral energy distribution, as indicated by its U-B color, by our observations in U2 and U3, and by Weber's observations at 1500 Å.

To derive average ultraviolet excesses for a reasonably sized sample, we adopted the compromise limit of E(B-V) > 0.4. This leaves us with samples of 10, 12 and 8 stars for the filters U1, U2 and U3, respectively. The normalized average color excesses are plotted in Figure 7 against $1/\lambda(\mu^{-1})$. In the case of heterochromatic excesses, λ stands for the average wavelength of the band passes. The Celescope results are represented by large dots. The associated scatter bars represent the standard deviations within each of our three samples.

We compare the Celescope results with those of Weber et al. (1971), Smith (1967), Sivan and Viton (1971), Stecher (1965) and Bless and Savage (1972).

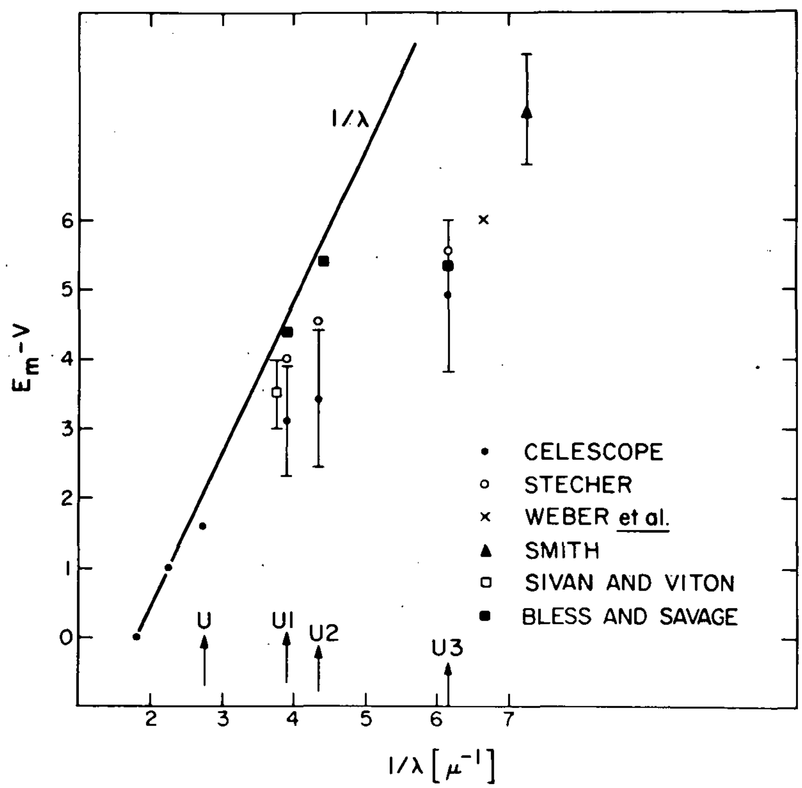

Figure 7.—Heterochromatic color excesses E_{m-V} normalized to E(B-V) = 1. The solid line represents a $1/\lambda$ extinction law (λ is the wavelength in μ^{-1}). The vertical arrows show the mean wavelengths of filters U, U1, U2, and U3. Filled circles (●) show Celescope results. Stecher's (O) and Bless and Savage's (■) extinction values have been folded with the Celescope filter response curves. The results by Weber et al. (×), Smith (▲), and Sivan (◘) are from broad-band observations.

In the case of monochromatic-extinction curves (Stecher's results and theoretical curves), we calculated heterochromatic excesses according to relations (1), (2), (3) and (4) for filters U1, U2 and U3. The only change with respect to the calculations of § III is that now $A(\lambda) \neq 1$.

Figure 7 shows that the Celescope excesses are smaller than those found by other authors, although those of Sivan and Viton, Weber et al., and Stecher lie within our scatter bars, or very close to them. One cannot exclude the possibility that the interstellar extinction in Vela is not the same as that in other regions of the sky.

Finally, it should be noted that reddening lines in the color-color diagrams (Figures 5 and 6) would be nearly parallel to the intrinsic effective temperature sequence. This means that with our ultraviolet broad-band colors, we are unable to analyze independently the interstellar extinction and the effective temperature. On the other hand, the advantage is that all effects perpendicular to the temperature sequence will be fairly independent of interstellar extinction. In other words, the properties responsible for these effects could be analyzed even if one does not know the exact amount of interstellar extinction.

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