THE RATIO OF TOTAL TO SELECTIVE ABSORPTION IN THE CARINA OB2 ASSOCIATION

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Abstract. Several previous studies in and around the Great Carina nebula (NGC 3372) have strongly indicated an abnormal interstellar extinction law with a high ratio of total to selective absorption R. In the present study, new *UBV* photometric data and accurate MK spectral-types of stars in the region of the Carina OB2 association are used to show that (1) Car OB2 is a genuine stellar association located at a distance of 3.2 kpc, and (2) the interstellar extinction law seems to be normal throughout most of the region. A representative value of $R = A_v/E(B - V) = 3.0$ is derived for Car OB2 from the variable extinction method.

1. Introduction

The ratio of total to selective absorption $R = A_v/E(B - V)$ is of fundamental importance in determining distances in our Galaxy. As there are no trigonometric parallaxes of reddened OB stars available yet, this ratio so far has to be determined by intrinsic methods. Among others, procedures have been used that include spectrophotometric studies (Schultz and Wiemer, 1975), kinematic studies of young objects (Bell, 1971; Bell and Fitzgerald, 1971), extinction in two colours of dark nebulae (Schalén, 1975), diameters of open clusters (Harris, 1973), and the variable extinction method (Fernie and Marlborough, 1963; Herbst, 1974, 1975, 1976; Turner, 1976; Turner and Moffat, 1980). This latter one has the advantage of being very easily applied and of providing values of R for localized regions of space.

During many years typical values have been accepted for R ranging between 3.0 (Sharpless, 1963) and 3.3 (Aanestad and Purcell, 1973). The problem of whether there exist appreciable variations of R in some regions of the sky has been largely discussed in the literature. In fact, on this problem can be consulted, among others, the studies

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carried out by Johnson (1965, 1968), Fernie and Hube (1968), Garrison (1970), Turner (1973, 1974), Moffat (1974), Feinstein *et al.* (1973), Herbst (1976), and Forte (1978).

As has been shown by Turner (1976), R does not vary systematically with the galactic longitude or, if these variations exist, they are very small. On the other hand, there are various localized regions including OB stars, generally associated with high-darkening and marked ionization, where observations suggest an abnormal extinction law ($R \geq 4$). These results are apparently compatible with the assumption that in the neighbourhood of very bright OB stars the interstellar extinction law could be peculiar due to the influence of the strong radiation field on the grains (Johnson and Borgman, 1963).

The nature of the interstellar extinction in the Carina complex has been examined by several authors. Rodgers and Searle (1967), Feinstein *et al.* (1973), Turner (1974), and Herbst (1976) have shown that near the center of Carina nebula (Tr 14–16, Cr 228), R has a significantly higher value than normal. An exhaustive study made by Turner and Moffat (1980), however, seems to show that R cannot be very far from 3.2 in this region.

On the other hand, from the studies of Herbst (1975) and Forte (1978) follows that in the central regions of the Car R1 and Car OB1 associations, the ratio of total to selective absorption is indeed abnormal ($R \geq 3.4$). A similar result was obtained by Turner (1973) when applying the variable extinction method in the region of the cluster IC 2581. Five years later, however, Turner (1978) derived a normal law for this cluster.

The present investigation is aimed at determining whether or not the extinction law in the region of the Car OB2 association is anomalous. This is specially important for two reasons: (1) To prove if the optical properties of the interstellar matter in this region differ or not from the general tendency recognized in the Galaxy. (2) To determine correctly the distance of Car OB2 and to discuss its relation with the clusters and H II regions of the area.

2. The Carina Complex and the Car OB2 Association

One of the most conspicuous features in the Carina region is the nebula NGC 3372 which surrounds the irregular variable η Carinae. This nebula is perhaps the most extensively studied H II region of the southern hemisphere. Radio observations of the ionized hydrogen have been carried out by Gardner *et al.* (1970) and Hutchmeier and Day (1975), among others. Molecular clouds of OH and H_2CO have been reported by Gardner *et al.* (1973) and Dickel and Wall (1974). Dickel (1974) estimated at $\sim 10^5\ M_{\odot}$ the total mass of this gas and dust complex.

The study of the cluster NGC 3372, as well as of the clusters and regions related to it or located in its neighbourhood, is doubtless of great interest for the analysis of various astrophysical problems. The astronomical literature is abundant in studies related to the Carina complex and the stellar aggregates of the region as well. Among many others, we can mention the studies of Bok (1970, and numerous quotations indicated here), Feinstein *et al.* (1973, 1976), Walborn (1973), Clariá (1976), Forte (1978), Thé *et al.* (1980), and Turner and Moffat (1980).

In particular, the Carina region between the absolute equatorial coordinates 11^h02^m

and 11^h04^m and $-59°10'$ and $-59°42'$ (1950.0), has been observed relatively little so far. This region contains a large number of very bright early-type stars, spread out apparently over a nearly elliptical ring whose major and minor axes are 30 and 23 min of arc, respectively. This region, located half a degree above the galactic plane, is known as Car OB2 (see *Trans. IAU*, Vol. XIIB, 1964).

Seggewiss (1970) determined *UBV* photographic magnitudes and colours of 480 stars in the mentioned area. Although the lack of precision in the photographic photometry of Seggewiss is relatively large, the *UBV* diagrams seem to suggest that, if Car OB2 really exists, it would be probably formed not only by O and early B stars, but also by intermediate and late-type B stars and even by early-type A stars. From his photographic data, Seggewiss (1970) estimated at $0^m.38$ the mean $E(B-V)$ colour excess and at 2.04 kpc the distance of the group.

On the other hand, from a photometric study of several clusters in the region around Car OB2, Clariá (1976) proposed the idea that the open cluster Cr 240 is an OB association, perhaps an extension of Car OB2, whose nucleus would be NGC 3572. According to Clariá's study, the open clusters NGC 3590, Hogg 11, and some of the brightest stars of the cluster Tr 18, as well as the H II regions G37 (Gum, 1955), An 2, and An 3 (Georgelin and Georgelin, 1970), would also form part of this complex for which the mentioned author calculated a distance of 2.42 kpc.

After Seggewiss, no other detailed study of Car OB2 has been carried out which would allow us to draw definite conclusions about its existence and possible relation with the open clusters of the region (NGC 3572, Hogg 11, Tr 18, etc.). For that reason, four years ago we began the photometric and spectroscopic observation of the stars Seggewiss measured photographically. All these observations were carried out by one of us (BG) at various observing runs at the Cerro Tololo Inter-American Observatory (CTIO) during 1983 and 1985. An analysis of all the spectrophotometric material collected up to date has enabled us basically: (1) To demonstrate the genuine existence of the Car OB2 association. (2) To determine its approximate dimensions, stellar content, distance from the Sun, age, luminosity function, and other relevant astrophysical properties. (3) To analyze the spatial distribution of the observed stars and that of the absorbing matter at different distances from the Sun. (4) To discuss the possible physical relation of Car OB2 with various clusters and H II regions of the area. (5) To determine radial velocities and axial rotation of an appreciable number of members. (6) To show up new variable stars, binaries, and anomalous objects in general. The analysis and detailed discussion of these results, together with all the observational material gathered, will be published in a future paper.

3. The Variable Extinction Method: Fundamental Principles

The variable exitnction method for determining R is usually applied to a cluster or association situated in or behind clouds of interstellar matter whose extinction varies from place to place (Johnson, 1968). The fundamental principle this method is based upon is that for a group of stars located at the same distance r from the Sun and affected by different amounts of interstellar reddening, there should exist a linear correlation between the $V - M_v$ apparent distance moduli and $E(B - V)$ colour excesses, of the form

$$V - M_v = 5 \log r/10 + RE(B - V). \tag{1}$$

The slope of this correlation is precisely R. The great advantage this method presents is the simplicity with which it can be applied to open clusters and associations. However, in order to get reliable results it is necessary to satisfy the two basic hypotheses on which this method is based, namely: (1) That the stars of the aggregate in question are actually physical members of it; the inclusion of field stars can spuriously raise the value of R (Becker, 1966; Moffat, 1974). (2) That the objects in consideration are actually located at the same distance from the Sun. Car OB2 is well suited to this method since a large amount of differential reddening is clearly present. Furthermore, the separation between members and field stars can be established with fair certainty from the photometric and spectroscopic data of high quality obtained. Finally, the association is situated at an appreciable distance (3.1 kpc) so that small differences in the individual distances of the members do not affect noticeably the variable extinction analysis.

4. Photometric and Spectroscopic Observations

A total of 478 stars brighter than $V = 14.5$ were observed photoelectrically in the *UBV* system with the 61-cm Lowell and 91-cm telescope at CTIO. The measurements, carried out between 1983 and 1985, have typical errors ranging between $0\overset{m}{.}01$ and $0\overset{m}{.}93$, depending slightly on the magnitude. From this sample, 110 objects brighter than $V = 12.6$ were also observed spectroscopically between 1984 and 1985. In general, between 2 and 4 spectrograms at a dispersion of 42 Å mm^{-1} were obtained for each star using the grating spectrograph and RCA image-tube at the Cassegrain focus of the 1.0-m Yale telescope at CTIO. The slit width and widening for these observations were 2 arc sec and 1.0 mm, and the spectra were recorded on IIIa–J plates developed in D-19. The spectrograms were classified in the frame of the revised MK system of Morgan *et al.* (1978) by comparison with a set of standards observed with the same instruments under identical conditions. The resultant MK classifications for the O and B members of Car OB2 are listed in Table I. The spectroscopic material was also used to determine radial velocities and to measure projected axial rotational velocities. These results will be fully discussed in a future paper.

5. Analysis and Discussion of the Data

5.1. Association Membership

Basically, we suppose that each member of Car OB2 must verify two conditions: (1) Its location in the observed $V/(B - V)$, $V/(U - B)$, *and* $(B - V)/(U - B)$ diagrams must

TABLE I

Colour excesses, absolute magnitudes, and apparent distance moduli for stars in Car OB2

No.	MK	$E(B-V)$	M_v	$V-M_v$
1	B1Ib	0.44	−5.70	13.43
2	B1.5Ve	0.49	−4.05	13.74
4	B4V	0.42	−1.45	13.78
5	B2.5V	0.36	−2.43	13.16
8	B1V	0.39	−3.25	13.75
10	–	0.37	−0.80	14.00
15	B3V	0.41	−1.85	13.57
21	B1V	0.38	−3.38	12.86
28	–	0.34	−0.24	14.01
29	B5V	0.42	−1.23	13.57
30	–	0.41	−0.80	14.31
32	B3V	0.44	−1.98	13.53
35	–	0.46	−1.08	13.73
36	–	0.43	−0.38	14.33
37	B3V	0.43	−1.60	13.73
38	B3V	0.40	−2.10	13.74
39	–	0.46	−1.08	14.34
51	B2V	0.46	−2.38	13.63
53	B2V	0.38	−2.75	12.93
57	–	0.36	−0.52	13.57
58	–	0.37	−1.08	14.12
61	B2V	0.34	−2.25	12.99
67	–	0.44	−0.52	14.26
73	B2.5IV–V	0.36	−2.14	14.12
89	B0V	0.36	−3.68	12.98
91	B4V	0.36	−1.58	13.65
103	B2V	0.41	−2.63	13.32
110	–	0.50	−0.66	14.33
111	–	0.50	−0.80	14.77
112	–	0.43	−1.08	14.02
115	B2.5IV	0.42	−2.45	13.93
117	B3V	0.37	−1.85	13.72
129	B3V	0.39	−1.53	13.92
139	–	0.40	−1.75	14.40
180	O9.5V	0.48	−3.98	12.92
184	–	0.45	−1.08	14.00
193	O7V((f))n	0.47	−5.20	12.65
194	–	0.55	−1.08	14.48
196	B2V	0.45	−2.13	14.25
199	B3V	0.44	−1.85	13.96
202	–	0.45	−1.08	13.94
214	–	0.37	−1.08	14.22
227	B1V	0.44	−3.25	13.32
228	–	0.43	−0.94	13.58
229	–	0.49	−1.75	14.73
2330	–	0.48	−0.52	14.38
231	–	0.76	−3.75	14.96
234	–	0.55	−1.50	14.61
235	B2Vn	0.61	−2.50	13.44

Table I (continued)

No.	MK	$E(B-V)$	M_v	$V-M_v$
238	B1V	0.68	-3.38	14.00
240	–	0.63	-2.00	15.08
243	B2IV	0.67	-3.11	14.59
244	B1.5V	0.64	-2.88	14.57
245	B1V	0.74	-3.13	14.18
246	B0.5IV	0.76	-4.19	15.01
248	O8V	0.59	-4.32	12.91
249	–	0.51	-1.75	14.61
252	B2.5V	0.51	-2.30	13.15
253	–	0.52	-1.08	14.51
256	–	0.48	-1.08	14.19
274	–	0.41	-1.36	14.07
275	B1II–III	0.49	-4.75	13.33
276	B1IV	0.61	-3.08	14.76
284	B1.5Iab	0.42	-6.25	12.80
288	B4V	0.36	-1.70	13.03
290	B2.5IV	0.35	-2.33	13.60
297	B1II–III	0.38	-4.75	13.16
309	B1V	0.38	-3.13	13.84
312	–	0.45	-0.66	13.93
314	B1II–III	0.44	-4.75	12.54
319	–	0.39	-0.59	14.23
326	B2IV–V	0.36	-1.33	13.68
331	B2IV–B	0.38	-2.85	12.96
333	–	0.44	-0.94	14.46
334	B2II–III	0.44	-4.00	12.62
342	–	0.42	-0.80	14.21
351	B3IV	0.36	-3.12	13.04
355	–	0.50	-0.94	14.00
356	B1V	0.47	-2.88	13.62
364	–	0.53	-1.22	14.31
370	B4V	0.56	-1.83	13.78
396	–	0.35	-0.38	13.76
398	–	0.35	-1.22	13.74
399	–	0.39	-1.08	13.69
400	B2III	0.37	-3.83	12.92
401	B3V	0.38	-1.60	13.89
403	–	0.34	-0.80	14.08
405	–	0.39	-0.80	13.77
409	B7Vp	0.32	-1.11	12.92
473	B1V	0.49	-3.13	14.35

correspond to the same evolutionary stage in the association. (2) This stage must be compatible with the assigned MK-type.

Since many factors such as duplicity, rotation, and others contribute to increase the dispersion in the *UBV* diagrams, a star located just or at most 0.75 mag above the association Main Sequence in the two colour-magnitude diagrams is considered to belong to it. A total of 90 O and B stars were retained as members of Car OB2, while

62 stars were considered to be probable members. It is important to note that, with the exception of three stars, all the members with $V \leq 12.6$ have MK spectral types assigned in this study.

5.2. Colour excesses and absolute magnitudes

In addition to the measured V magnitudes, the data necessary to apply the variable extinction method are the colour excesses and absolute magnitudes for member stars. The first ones were calculated from the photoelectric data using the expression

$$E(B-V) = \frac{4.551(B-V) - (U-B) + 0.226}{3.831 - 0.05(B-V)}, \tag{2}$$

whose justification is presented in the Appendix. Although this method is strictly valid for Main-Sequence stars earlier than about A2, its application to other stars close to the Main Sequence does not introduce major errors, provided supergiants are excluded. Furthermore, due to the fact that a large percentage of members have been classified in the MK system, it was possible to use these data to derive $E(B-V)$ from Schmidt-Kaler's (1982) calibration.

A comparison between the colour excesses determined by both procedures is illustrated in Figure 1. Since the average difference $|E(B-V)_{UBV} - E(B-V)_{\mathrm{MK}}|$ is $0\overset{m}{.}02$, the agreement can be considered satisfactory. Therefore, for those stars with known $E(B-V)_{UBV}$ and $E(B-V)_{\mathrm{MK}}$, the mean value of both determinations was finally adopted.

Absolute magnitudes were also derived using both the UBV and spectral classification

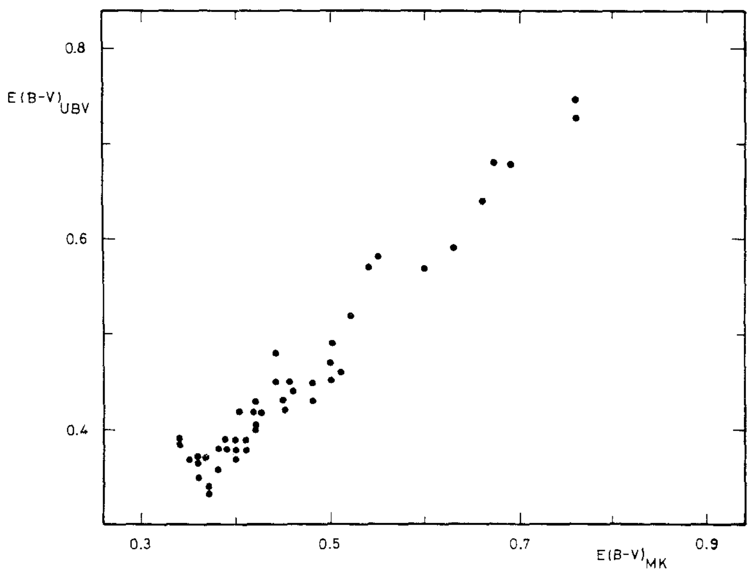

Fig. 1. Comparison between colour excesses determined from photometric and spectroscopic data.

data. In the first case, $M_v(UBV)$ was determined from the photoelectrically determined UBV intrinsic colours and the known luminosity class using the calibration of Schmidt-Kaler (1982). In those cases where the luminosity class could not be assigned, the star was assumed to belong to the Main Sequence. In the second case, Schmidt-Kaler's calibration of absolute magnitude as a function of spectral type was used to derive M_v(MK). Since the mean difference $|M_v(\text{MK}) - M_v(UBV)|$ obtained from 43 association stars (giants and supergiants omitted) turned out to be $0\overset{m}{.}35$, the mean of the two M_v estimates were adopted, or, for lack of M_v(MK), $M_v(UBV)$ was adopted.

The stars HD 96248 and HD 96261, which we have classified as B1.5Iab and B1Ib, most probably are the only supergiants of Car OB2. The colour excesses and absolute magnitudes of these stars were inferred directly from their MK-types. Table I gives the reddening, absolute magnitudes, and apparent distance moduli adopted for the Car OB2 members.

5.3. The distance to Car OB2

The distance to Car OB2 was calculated from the individual distance moduli $V_o - M_v$, where V_o is the observed V magnitude corrected for interstellar extinction. These calculations were done assuming that the interstellar extinction law is normal in the region ($R = 3.0$). The mean distance modulus of the 90 members recognized in this study turned out to be $\langle V_o - M_v \rangle = 12.48 \pm 0.51$ (s.d.), equivalent to a distance $r = (3100 \pm 740)$ pc. This value is practically not modified if the 62 probable members are included in the mean.

5.4. The ratio of total to selective absorption R

As can be seen in Table I, the differential reddening present in the region of Car OB2 is high [$\Delta E(B-V) = 0\overset{m}{.}42$], which makes the application of the variable extinction method even more interesting. The mean colour excess is $\langle E(B-V) \rangle = 0\overset{m}{.}46 \pm 0\overset{m}{.}10$ and, the same as with the distance, this value practically does not change if the probable members are included.

Especially noteworthy is a small group of 11 highly reddened early-type stars, located in the southern part of Car OB2. This group, which Seggewiss (1970) called 'group c', consists of stars 231, 235, 238, 240, 243, 244, 245, 246, 249, 276, and 370, according to Seggewiss' designation. The mean excess for these objects is $\langle E(B-V) \rangle = 066 \pm 07$. In spite of this high reddening, these stars do not seem to form a separate group farther away from Car OB2, as Seggewiss has suggested. In fact, the true distance modulus for this group is $\langle V_o - M_v \rangle = 12.46 \pm 0.48$ (s.d.), equivalent to a distance of $r = (3100 \pm 690)$ pc, identical to the one calculated for the association.

A plot of apparent distance modulus versus colour excess for the association stars is given in Figure 2. A least-squares fit to the data of Table I yields values of $R = 3.0$ and $r = 3.1$ kpc. Thus, on the basis of the present photometric and spectroscopic observations, there is no evidence for the existence of anomalous extinction in the region of Car OB2.

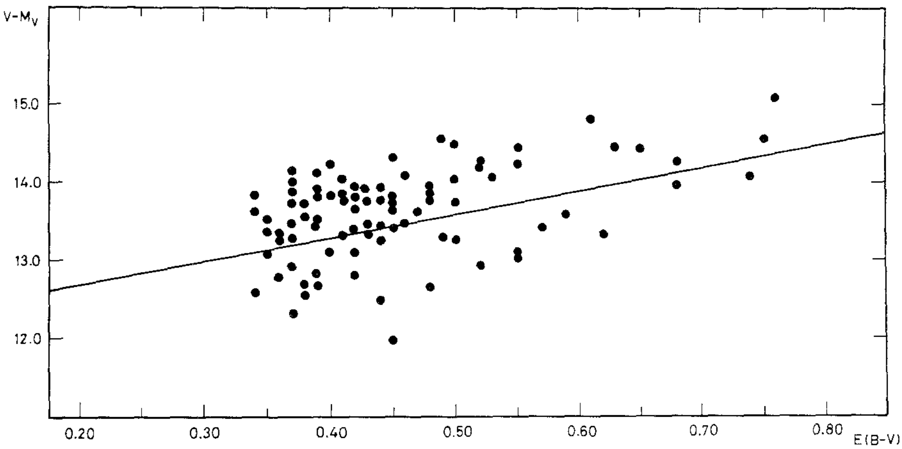

Fig. 2. Variable extinction diagram for members of the Car OB2 association. The line, adjusted by least squares, has a slope of 3.0.

An effect that should be taken into account in the foregoing determination is the possibility that there exists a real dispersion in the individual distances of the association members. If this is the case, differentiating Equation (1) with respect to $E(B - V)$ (assuming R constant) gives

$$\mathrm{d}(V - M_v)/\mathrm{d}E(B - V) = R + 5r^{-1} \log_{10}e \, [\mathrm{d}r/\mathrm{d}E(B - V)] \,. \tag{3}$$

If we assume that the interstellar matter is uniformly distributed between the members of Car OB2 so that $r = qE(B - V)$, q being constant, we obtain

$$\mathrm{d}(V - M_v)/\mathrm{d}E(B - V) = R + 5r^{-1} q \log_{10}e \,. \tag{4}$$

The application of the variable extinction method in this case leads to overestimate the value of R in the quantity

$$\Delta R = 5 \langle r \rangle^{-1} q \log_{10}e \,, \tag{5}$$

where $\langle r \rangle$ is the mean distance of the association stars.

If there is no uniform distribution of the interstellar matter, but we admit the validity of the expression $r = qE(B - V)$, where q is a variable parameter, the variable extinction analysis overestimates R in the quantity

$$\Delta R = \{[\mathrm{d}q/\mathrm{d}E(B - V)]E(B - V) + q\} \times 5 \langle r \rangle^{-1} \log_{10}e \,. \tag{6}$$

In any of these cases, however, it should be noted that ΔR decreases as r increases so that this effect, if it really exists, cannot be important given the appreciable distance ($r = 3.1$ kpc) of the association.

Summarizing, if the members of Car OB2 are at the same distance r from the Sun, the variable extinction method shows that the ratio of total to selective absorption appears to be normal ($R = 3.0$) in the region. If, on the contrary, r is not constant and varies with $E(B - V)$, linearly or not, the value of R can be even smaller than 3.0. In both cases, however, R does not seem to exceed the normal value.

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Appendix

Crawford and Mandwewala (1976) determined the nature of the reddening trajectory in the $(U - B)/(B - V)$ diagram, evaluating in function of the spectral type and the luminosity class, the constants α, β, and γ of the cubic equation

$$E(U - B) = \alpha E(B - V) + \beta E(B - V)^2 + \gamma E(B - V)^3 \,. \tag{7}$$

If we examine carefully the values of Crawford and Mandwewala's Table IV, we can conclude that: (1) Regardless the spectral type and luminosity, the parameter γ appears to be less or equal to 0.01, so that the third term in Equation (7) can be neglected. (2) For all stars earlier than A2, independently of their luminosity, β is practically constant and equal to 0.05. (3) If we consider only stars earlier than A2 and we average the values obtained from the reddening curves of Whitford (1958) and Nandy (1969), the parameter α varies slightly between 0.70, for the A2Ia-type, and 0.74 for a Main-Sequence star of spectral type O. Thus, if we only consider stars within this spectral range, Equation (7) can be approximated by

$$E(U - B)/E(B - V) = 0.72 + 0.05E(B - V) \,. \tag{8}$$

This equation is exactly the same found by Hiltner and Johnson (1956) using 262 O-type stars.

The small dependence of the ratio $E(U - B)/E(B - V)$ on the reddening causes Johnson's Q parameter, defined as

$$Q = (U - B) - [E(U - B)/E(B - V)]\,(B - V) \,, \tag{9}$$

to be practically independent of interstellar reddening. In fact, if Q and Q_0 represent the parameters of a reddened and unreddened star of a certain spectrla type, then from Equations (8) and (9) we get

$$\Delta Q = Q - Q_0 = -0.05E(B - V)\,(B - V)_0 \,, \tag{10}$$

where

$$Q_0 = (U - B)_0 - 0.72(B - V)_0 \,. \tag{11}$$

The quantity ΔQ of (10) is evidently very small as, if we consider stars earlier than A2V, the most unfavourable value of $(B - V)_0$ is about -0.30 and, therefore, the highest value ΔQ will be $\sim 0.05E(B - V)$. For the extreme case of a colour excess of two magnitudes, equivalent to an absorption of about six magnitudes, ΔQ is hardly 0.03.

On the other hand, the intrinsic colours $(B - V)_0$ and $(U - B)_0$ in the range $(U - B)_0 \leq 0.0$ present a correlation which approaches a straight line

$$(B - V)_0 = a_1(U - B)_0 + a_2 . \tag{12}$$

The parameters a_1 and a_2 can be obtained by least squares. The problem that comes up now is that the pairs of values $(U - B)_0$ and $(B - V)_0$ of the different MK-types vary according to different authors. Among others, the following authors have published relations between intrinsic *UBV* colours: Johnson (1963), Schmidt-Kaler (1965), Fitzgerald (1970), Heintze (1973), Deutschmann *et al.* (1976), Guttierrez-Moreno (1979), and Mermilliod (1981). Given the quality and quantity of *UBV* data used, the relation between $(U - B)_0$ and $(B - V)_0$ derived by Mermilliod (1981) for Main-Sequence stars seems to be the most refined and reliable one. A least-squares fit to the data of Mermilliod's Table V yields

$$(B - V)_0 = 0.220(U - B)_0 - 0.05 . \tag{13}$$

Eliminating $(U - B)_0$ from Equations (11) and (13) and taking into account that $Q \simeq Q_0$, we have

$$(B - V)_0 = 0.261Q - 0.059 . \tag{14}$$

Finally, from Equations (8), (9), and (14) we obtain Equation (2) used in Section 5.1. This expression replaces and improves the one previously obtained by Clariá (1977). Although its application is restricted to Main-Sequence stars earlier than A2, its extension to stars of luminosity classes III–IV does not introduce appreciable errors into the reddening, and consequently absorption values.

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