RevMexAA (Serie de Conferencias), **2**, 75-82 (1995)

THE EXTINCTION LAW IN THE CARINA NEBULA

P.S. Thé and F. Graafland
Astronomical Institute "Anton Pannekoek", University of Amsterdam, The Netherlands

RESUMEN

La ley de extinción en la dirección de los cúmulos abiertos Tr 14, Tr 15, Tr 16 y Cr 228 ha sido estudiada empleando nuevas mediciones fotométricas e información tomada de la literatura. Se muestra que una ley anormal de extinción se debe aplicar hacia estrellas individuales en la región nebular. Por consecuencia, no es posible adoptar una ley promedio de extinción hacia los cúmulos individuales como fue hecho por Smith (1987) y Tapia et al. (1988). Valores individuales de la razón de extinción total comparada con la extinción selectiva, R = $A_V/E(B-V)$, fueron determinados para cada estrella en nuestro programa usando tres métodos diferentes. La relación entre los valores promedio de R y el tipo espectral muestra que no están correlacionados.

ABSTRACT

Using new photometric data and data gathered from the literature the extinction law towards stars in the open clusters Tr 14, Tr 15, Tr 16 and Cr 228 in the Carina Nebula (NGC 3372) has been studied. It is shown that anomalous extinction applies towards individual stars in the nebular region. It is therefore not relevant to adopt a unique average extinction law towards each cluster such as was done by Smith (1987) and Tapia et al. (1988). Individual values of the ratio of total to selective extinction R = $A_V/E(B-V)$ were determined for each program star using three different methods. A study of the relation between the average R values and the spectral types shows that they are not correlated.

Key words: **DUST, EXTINCTION — OPEN CLUSTERS AND ASSOCIATIONS**

1. INTRODUCTION

It is well known that the Carina Nebula (NGC 3372) region contains a large number of OB-type stars. Numerous papers were published presenting the results of studies of the nebula itself, the OB-type stars, the open clusters to which these stars belong, the extinction law towards the nebular region, the emission at radio wavelengths, etc. It is to be expected that in this young star-forming region objects like Herbig Ae/Be stars and T Tauri stars should be present. However, because of its distance of about 2.5 kpc, and the strong radiation of the H II regions, it is very difficult to find these less luminous objects. It should also be mentioned that since the projected surface density of the OB-type stars at some places in the nebular region is quite high, it is impossible to study all stars individually through the large apertures of *ANS* or of *IRAS*.

Photometric studies of stars in the Carina Nebula should be done carefully because of the influence of the radiation of the H II regions, which is strong and which varies from place to place. Several authors have observed the OBA-type stars in the Johnson *UBV* and in the Cousins *VRI* systems, and also in the near-infrared *JHKLM* system. Observations in the Walraven *WULBV* system have been published by Thé et al. (1980); they will be used for the determination of the R values using the Kurucz model fitting method. Our *UBVRIJHKLM* observations, supplemented to those of Feinstein, Smith, and Tapia et al. form the basis of our study of the extinction law in the direction of the Carina Nebula.

Spectroscopic observations have been published by several authors (Walborn 1973; Levato & Malaroda 1981; Morrell & García 1988). However, the data are far from being complete, especially the fainter stars lack spectral types and luminosity classes. In order to complement the spectroscopic data, Tapia et al. (1988, hereafter TRMR) have determined spectral types of a large number of stars using the Q-method (Johnson & Morgan 1953).

The most intriguing problem of the Carina Nebula region is its extinction law. Several authors (e.g., Herbst 1976; Forte 1978) found a general anomalous extinction law in the direction of the nebular region. However, re-observations of stars by Thé et al. (1980) and Thé and Groot (1983) have shown that the extinction is anomalous towards individual stars, in the sense that generally speaking the value of total to selective extinction R = $A_V/E(B-V)$ is smaller according as the spectral type is later. The question is whether this is true or whether it is caused by selection effects. Since the sample of stars used in afore mentioned study is small, it is worthwhile to repeat it, employing published and newly obtained photometric data.

Smith (1987) and TRMR have published the results of their study of the interstellar extinction towards the Carina Nebula. Smith concluded from a study of the reddening law for the nebula that it is clearly anomalous, characterized by a unique value of R = 4.8. This result is based on a sample of 21 OB-type stars having well-known spectral types and luminosity classes. Smith also presented an alternative interpretation of the anomalous extinction law by normalizing the colour-excess ratios with respect to $E(V-J)$ rather than to $E(B-V)$. He shows that it is also possible to say that longward of 0.55 μm (V passband) the extinction law is normal and that shortward of this wavelength the extinction is lower than normal. In fact TRMR's results concerning the extinction law in the Carina Nebula region, based on a larger number of OB-type stars, is comparable to that of Smith. They found that, except in Tr 15, the intracluster redding is characterized by a "normal" extinction law at $\lambda > 0.5$ μm and that in the U and B passbands the extinction is highly anomalous and variable. In this paper it will be shown that the statements of Smith and TRMR are to be expected from theoretical calculations of anomalous extinction laws for various values of R > 3.1, by Steenman & Thé (1989, 1991).

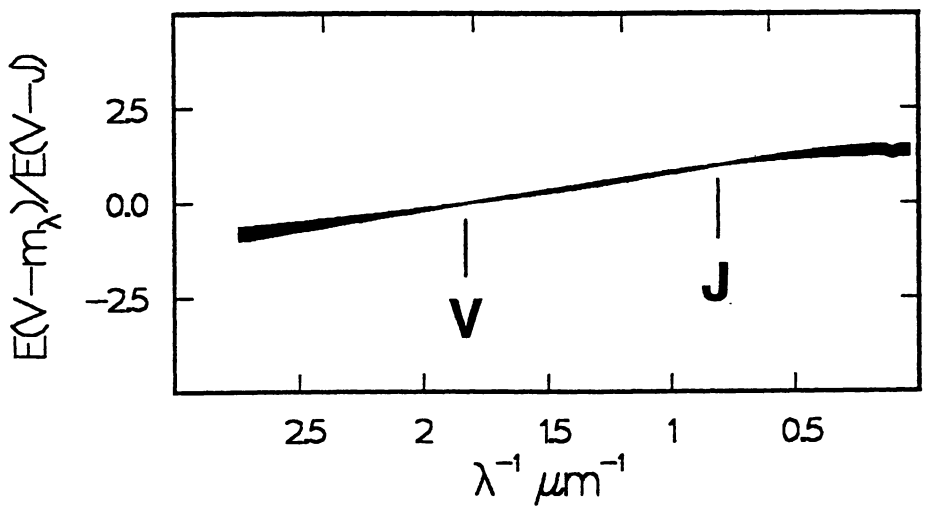

Fig. 1. Theoretical extinction laws for R between 2.5 and 5.9 normalized to $E(V-J)=1$.

When the observed spectral energy distribution (SED) of an O-type star located in the Carina Nebula is corrected for normal extinction with R = 3.1 and then compared with Kurucz' (1979) theoretical SED model, appropriate to the spectral type and luminosity class of the star, normalized at the B and V passbands, the stellar SED exhibits an excess of radiation in the near IR. In the past such an excess was interpreted as due to free-free emission. However, it was shown theoretically by Groot & Thé (1983) that free-free emission in the near-IR up to about 5 μm can be expected only when the mass loss rate of the O-type star is very large and when the velocity of the outflowing matter is very low, like in the star P Cygni. An observational proof for this theoretical conclusion is published by Thé et al. (1989). Therefore, in the present paper it is assumed that for each star the near-IR excess, if any, is due to anomalous extinction. It is generally believed that anomalous extinction is caused by the presence of too many large dust grains in the surroundings of the studied stars. This means that in such an environment, the average size distribution of the dust grains is abnormally too large. However, it is also possible that the anomalous extinction law is caused by a depletion of small grains (about 0.01 μm) in the surroundings of the star (Steenman & Thé 1991), because in this case the average size distribution of these grains is also too large. Methods for the determination of the R-values will be explained briefly in § 3. Then it will be examined whether there is a correlation between these R-values and the spectral type of the stars.

2. THE OBSERVATIONAL DATA

Johnson-Cousins *UBVRI* measurements of stars in the open clusters were obtained during several observing runs with the ESO 50-cm telescope on La Silla, Chile. This telescope was equipped with a one channel photometer with an RCA 31034A (Quantacon) photomultiplier. An aperture of 15″ was used throughout. The standard stars were chosen from the catalogue of Menzies, Bamfield, & Laing (1980). Near-IR measurements in the *JHKLM* system were obtained using the ESO 1-m telescope with the InSb photometer. The diaphragm used is 13″. The standard stars employed are those taken from the list of Koornneef (1983).

In the literature many observations of stars in the Carina Nebula can be found in the Johnson-Cousins *UBVRI* system and in the near-IR *JHKLM* system. More than 300 stars, mostly in the Tr 14, Tr 15, Tr 16 and Cr 228 open clusters, were measured by different authors: Feinstein, Marraco, & Muzzio (1973), Herbst (1976), Forte (1978), Feinstein, Marraco, & Forte (1976), Feinstein, FitzGerald, & Moffat (1980), Thé et al. (1980), Feinstein (1982), Turner & Moffat (1980), Thé & Groot (1983), Smith (1987) and Tapia et al. (1988). For our study we have used a selection of those data, supplemented with *UBVRI* data of Feinstein and co-workers, and with *JHKL* data of TRMR. The systematic differences between our data and those of Feinstein and TRMR have been corrected, in such a way that all data are on the Feinstein and TRMR systems.

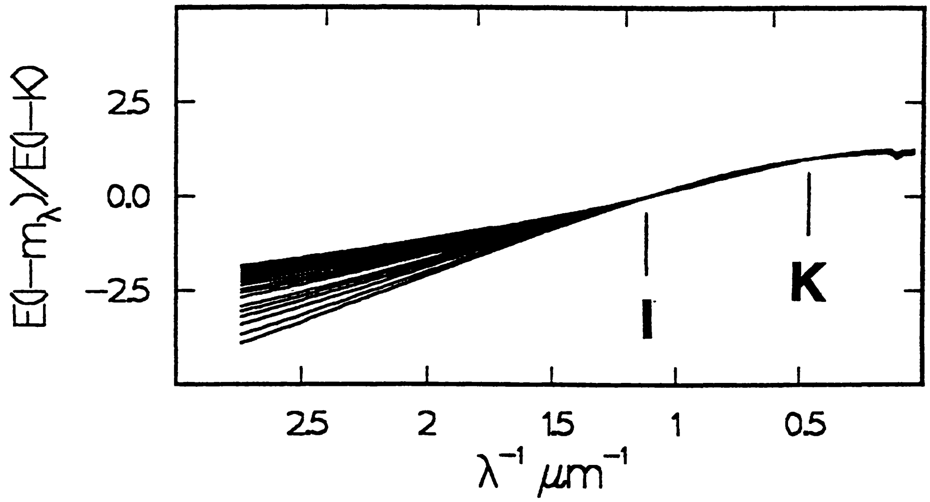

Fig. 2. Theoretical extinction laws for R between 2.5 and 5.9 normalized to $E(I-K)=1$.

The spectral types of most of the program stars were taken from TRMR, who had assembled them from the literature; in these cases the luminosity classes of the stars are known. For a part of the rest TRMR had employed the Q-method (Johnson & Morgan 1953; Gutiérrez-Moreno 1975) and the equivalent method by Feinstein et al. (1973) for the determination of the spectral types. In these methods, which are applicable up to spectral type A0 only, it is assumed that the stars are of luminosity class V. It should be noted here, that the stars in the open cluster known as Cr 232 are considered to be members of Tr 16, such as was done by Feinsten et al. (1973).

3. THE THEORETICAL EXTINCTION LAW

Based on the Mie-theory and by making the upper size cut-off of the grain size distribution subsequently larger, Steenman & Thé (1989) had calculated the extinction laws in the form A_λ/A_V for R-values ranging from

2.5 to 5.9. The results, normalized to $E(B-V)=1$, are shown in their Figure 4, for uneven values of R between 2.5 and 5.9. Because of this normalization the curves coincide between the B and V passbands, and are then spread out from wavelengths longer than 0.55 μm and shorter than 0.44 μm. Furthermore, it is clear from this figure that up to R = 5.1 the shapes of the extinction curves are similar for large values of the wavelength. The difference is that they become steeper for larger R values. For this reason, when the same laws are normalized to $E(V-J)=1$, the curves will almost coincide with each other for $0.55 < \lambda < 1.25$ μm, somewhat spread for $1.25 < \lambda < 3.6$ μm and also spread out at the U and V passbands. This behaviour is shown in Figure 1, and is similar as found observationally by Smith (1987) (see his Fig. 6). It is conceivable that if the normalization of the same laws is made between the Johnson I and K passbands, for example, the spread in the IR direction will be less, whereas towards the blue it will become much larger (see Figure 2).

It should be realized that the diagrams in Figs. 1 and 2 are obtained by suppression of the different anomalous extinction curves. This means that although the observationally obtained extinction curve, normalized to $E(V-J)=1$, gives the impression that the extinction law in the infrared is normal, in reality this is not the case, i.e., the extinction law in the infrared remains anomalous. The apparent difference is only caused by a different normalization of the same anomalous laws.

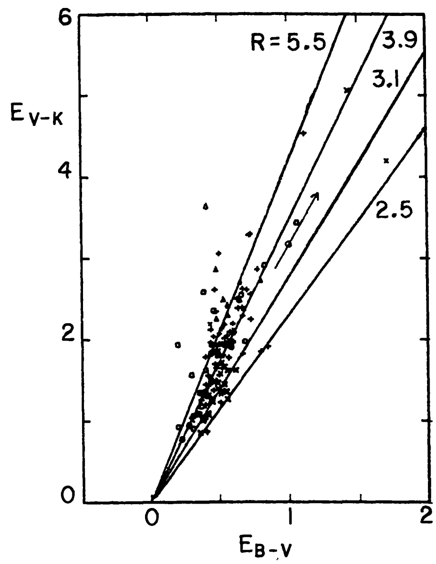

Fig. 3. $E(V-K)$ vs. $E(B-V)$ reproduced from TRMR's Fig. 4. Reddening directions for diverse values of R are superimposed.

Smith (1987) has derived a unique value of R = 4.8 towards the Carina Nebula using the formula $R = 1.1E(V-K)/E(B-V)$, and the assumption that R is a constant. If one writes $E(V-K) = (R/1.1)E(B-V)$, then R/1.1 is indeed equal to the slope of data points in a $E(V-K)$ vs. $E(B-V)$ plot, such as shown by Smith (1987) in his Fig. 5 for 21 stars. From this diagram it is apparent that the datapoints are located along a line with a certain slope, from which Smith has derived his R = 4.8. TRMR have also made a similar plot using a larger number of stars. From the left diagram in their Fig. 4 it is clear that the datapoints of the $E(V-K)$, $E(B-V)$ relation are located in a curved area. This means that there is no unique slope of this relation.

TRMR came to the conclusion that the extinction law in the Carina Nebula is normal for $\lambda > 0.55$ μm by plotting colour excesses, such as $E(V-K)$ vs. $E(B-V)$, $E(V-J)$ vs. $E(H-K)$, $E(V-K)$ vs. $E(J-K)$, $E(V-R)$ vs. $E(B-V)$ and $E(V-R)$ vs. $E(B-V)$. The datapoints are spread along a line in the direction of the normal reddening law. In the $E(V-K)$ vs $E(B-V)$ diagram the datapoints are distributed in a curved area, such as already mentioned above.

Our theoretical calculations of the anomalous extinction law for different R-values (Steenman & Thé 1989) can be compared with TRMR's results. In Figures 3 and 4 we have made the same plots with TRMR's data, on which lines are superposed giving the reddening direction for different R values. As is apparent in Fig. 3 the curved area, mentioned above, coincides with different values of R, despite of the uncertainties in the measurements. This is to be expected since for larger values of R the slopes of the extinction laws (normalized to $E(B-V)=1$) become gradually steeper (see Fig. 4 of Steenman & Thé 1989). In principle for colour excesses based on passbands with effective wavelengths larger or equal to 0.55 μm the influence of the change in the slope of the extinction curves for larger R-values is smaller. At the same time the shape of these curves for $\lambda > 1.25$ μm does not change much. For these reasons the datapoints in Fig. 4 are spread along one reddening direction, that of the normal reddening law. Similar results can be obtained using the other TRMR's colour-excess plots, mentioned above.

From Figs. 3 and 4, but especially from Fig. 3, it is clear that every datapoint lies on a line with a slope corresponding to a certain R-value. In every figure there is quite a large spread of colour-excesses in both the horizontal and vertical axis. This spread is certainly not only caused by observational errors in the determination of the colour excesses in both the horizontal and vertical directions. Partly it must be due to the fact that towards individual stars the extinction law is not always the same, i.e., the ratio of total to selective extinction towards individual stars is not always equal to R = 3.1. In the above study we have used theoretical values derived by Steenman & Thé (1989). In this section we have made it clear that the extinction laws in the Carina Nebula region are not normal towards individual stars of the open cluster. This is reasonable because stars lying in a star-forming region are generally associated with dusty areas of different density and different abundances of the constituents, in which the size distribution of the dust particles can be different from the general interstellar medium. Usually one tends to average the R-values of individual stars, and use this mean R-value to study the cluster further. This procedure will influence the location of the stars in the HR-diagram, and will thus also influence the study of the evolutionary state of the cluster in general and the individual stars in particular (see Thé et al. 1990, in which the results of a study of the very young open cluster NGC 6611 are presented). For this reason we want to stress that in the study of open clusters embedded in nebulosity it is essential to observe the stars not only in *UBV*, or in *UBVRI*, but also in the near-IR *JHKLM*.

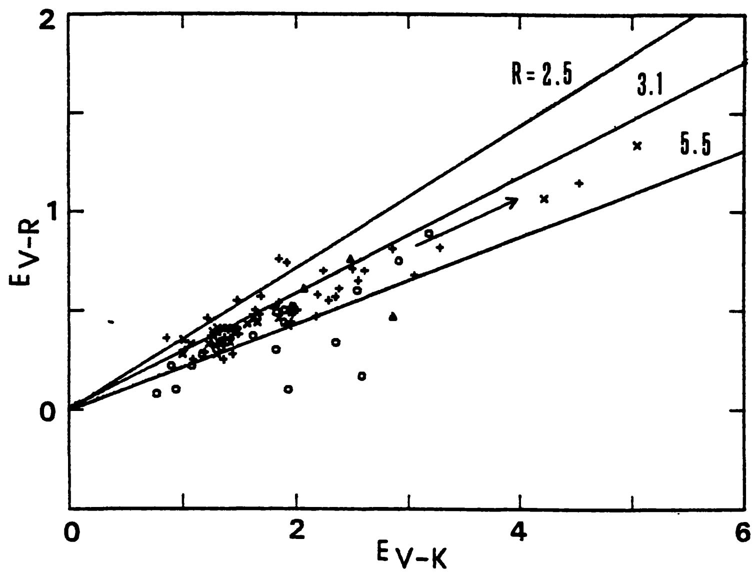

Fig. 4. $E(V-R)$ vs. $E(V-K)$ reproduced from TRMR's Fig. 5. Reddening directions for several R values are superimposed.

4. THE DETERMINATION OF THE R-VALUES

In the previous section it was shown that the R-value differs from star to star. It is not advisable to use a unique average value for the extinction correction towards the Carina Nebula. We will now discuss the various methods which can be used for the determination of the R-values: the *K*-method, the colour-difference method and the Kurucz model fitting procedure.

The least accurate method is the K-method, named after the near-IR passband employed. The reason is that it is based on three datapoints only, the B, V and K magnitudes of the star. The R-value is calculated using the formula:

$$\mathrm{R} = 1.1E(V-K)/E(B-V) \ .$$

More accurate is the colour-difference method. In this method the colour excesses $E(V-m_\lambda)$ are normalized to $E(B-V)=1$. These colour excesses are then plotted with respect to $1/\lambda$. Now a curve must be drawn through the datapoints in such a way that it crosses the vertical line at $1/\lambda = 0$, perpendicularly. The R-value can then be read at the vertical axis $1/\lambda = 0$. The values of the extinction A_λ are given by the distances between the horizontal zero-line and the extinction curve at the corresponding value of $1/\lambda$. This procedure is clarified in Figure 5. We can compute the R-value by fitting the datapoints to a 5th degree polynomical in $1/\lambda$ representing the extinction law:

$$E(V-m_\lambda)/E(B-V) = a + b(1/\lambda) + c(1/\lambda)^2 + d(1/\lambda)^3 + e(1/\lambda)^4 + f(1/\lambda)^5,$$

in which a, b, c, d, e and f are constants to be determined. In order to make the extinction curve intersect the vertical $1/\lambda = 0$ perpendicularly we should take $b = 0$. We then have that $a = \mathrm{R}$ and the extinction curve takes the form:

$$E(V-m_\lambda)/E(B-V) = \mathrm{R} + c(1/\lambda)^2 + d(1/\lambda)^3 + e(1/\lambda)^4 + f(1/\lambda)^5.$$

To fulfill the condition that the $E(V-m_\lambda)$ values are normalized to $E(B-V) = 1$, we should give the datapoints corresponding to $1/\lambda_B$ and $1/\lambda_V$ an arbitrary chosen weight equal to 5 times those of the other datapoints. In this way we achieve that the extinction curve goes through the datapoints $E(m_V - V)/E(B-V) = 0$ and $E(m_B - V)/E(B-V) = 1$, eventhough the scatter in the near-IR datapoints due to inaccuracies of the measurements may be large. It is possible to check this procedure by applying it to the theoretical data of Steenman & Thé (1989). For ten different cases we obtained an average standard deviation of the R-values equal to 0.13. The resulting R-value must then be corrected for the fact that the near-IR datapoints may not include the M passband and sometimes even both the L and M passbands, because for many stars the near-IR data are not complete. For this purpose we have used the theoretical data of Steenman & Thé (1989). For ten different cases we re-determine the R-values with the polynomial procedure using all data except that of M. We then do the same by omitting both the L and M data. The corresponding R-values differ on the average

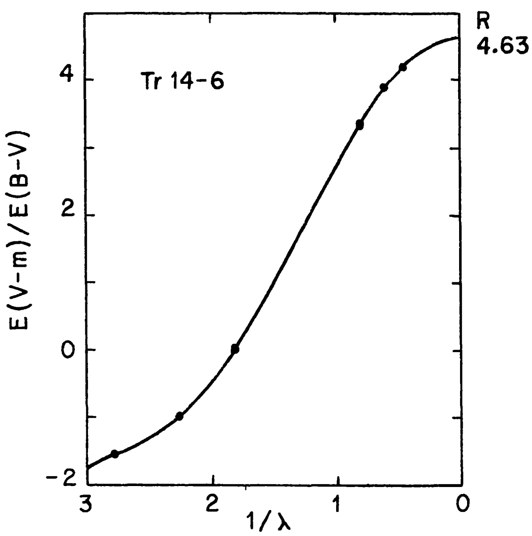

Fig. 5. The determination of R using the colour difference method.

in the first case by -0.03 and in the second case by -0.14 in the sense that the calculated values are higher than the theoretical ones. These systematic differences can then be applied to correct the R-values obtained for the various program stars. An example of the extinction curve determined using the above explained method is shown in Figure 5.

The most accurate method to determine the R-value of individual stars is the Kurucz model fitting procedure. The measured magnitudes in the different passbands can be transformed into energy fluxes using appropriate constants; for *UBV* the calibration constants published by Johnson (1966) are used, for Cousins' *VRI* system those published by Bessell (1979), for Walraven *WULBV* those of de Ruyter & Lub (1986) and for *JHKLM* the constants published by Koornneef (1983). When these spectral energy fluxes of most stars in the Carina Nebula region are corrected for foreground extinction with an R-value of 3.1 and then compared to a Kurucz (1979) model for the appropriate spectral type and luminosity class, an excess is apparent in the

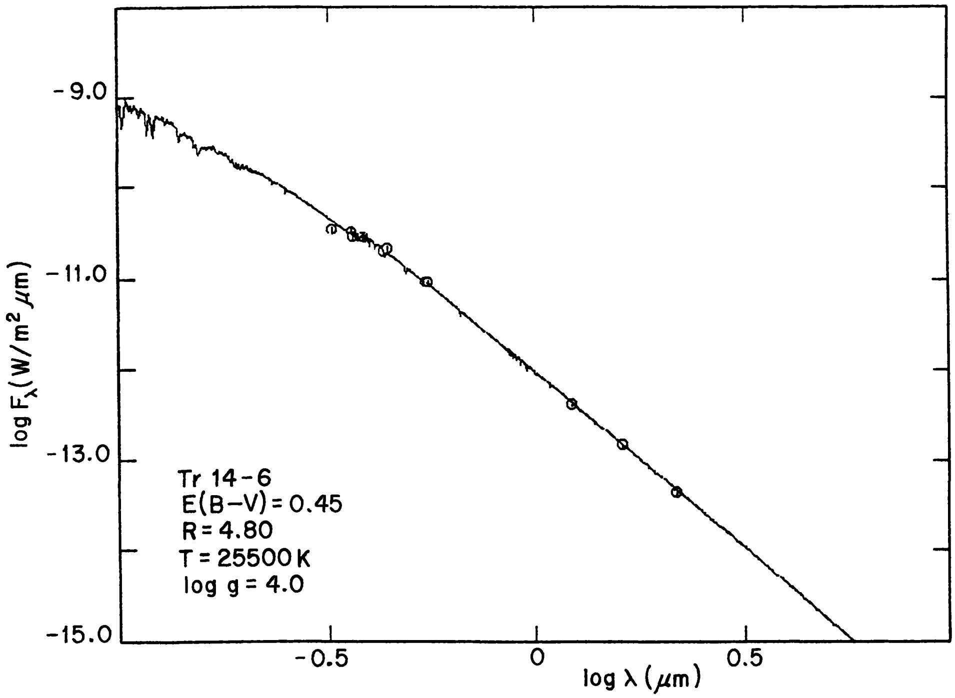

Fig. 6. The R value determined using the Kurucz model fitting procedure.

infrared region. Now one must use a higher value of R to correct the spectral energy distribution and compare it with the Kurucz model again. Then it will be found that the excess becomes less. This procedure has to be repeated until no infrared excess is still present and the applied value of R is the appropriate value for this star. The procedure can be done on a computer using a χ^2 fitting program to compare the corrected spectral energy distribution with the appropriate Kurucz model. The correction can be done by using files containing the A_λ/A_V extinction values for each R-value and for each passband. Also a Kurucz model plotfile is needed for every spectral type. Figure 6 is an example of a plot in which the result of above mentioned method is shown.

It has been suggested by Thé & Groot (1983) that there is a general trend of the R-values to be larger for earlier-type stars. We have studied this using more stars. In Figure 7 we have plotted the average R-values against the spectral types of the stars. The average values of R are calculated by giving double weight to those obtained with the colour difference method and the Kurucz model fitting procedure, whereas those calculated using the K-formula are given single weight. From Fig. 7 we can draw the conclusion that there is no correlation between the spectral types and the R-values.

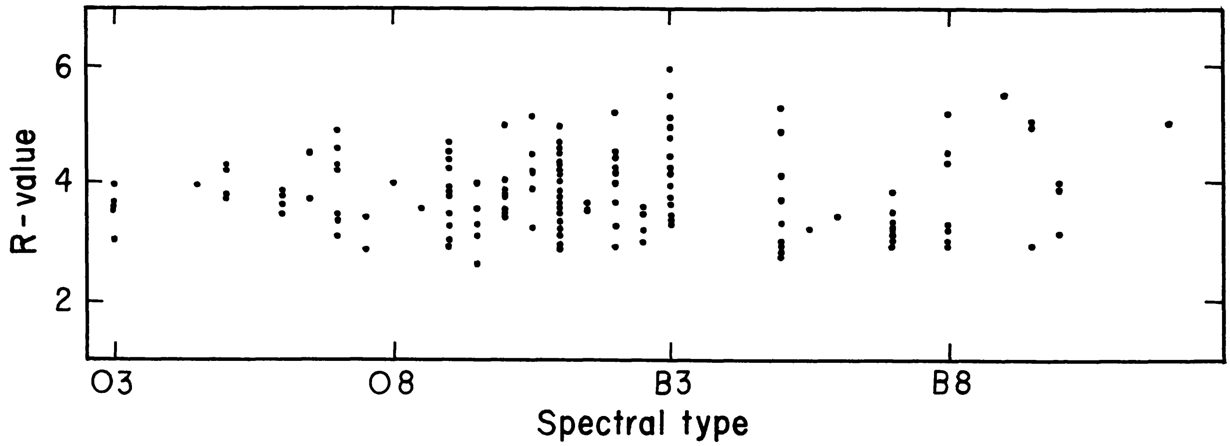

Fig. 7. The relation between R-values and spectral types.

5. CONCLUSIONS

From the results of our calculations, we conclude that the extinction laws towards individual stars in the open clusters Tr 14, Tr 15 and Cr 288 are anomalous. We found that the individual ratios of total to selective extinction have values varying from 2.61 to 5.94. Therefore, no unique R-value should be applied to a further study of the above mentioned open clusters. The results of this study will be published in a forthcoming paper.

In Figure 7 the R-values of the individual stars are plotted against the spectral types of the stars. From this plot we can conclude that there is no obvious relation between the R-values and the spectral types.

REFERENCES

Bessel, M.S. 1979, PASP, 91, 589
Feinstein, A., Marraco, H.G., & Muzzio, J.C. 1973, A&AS, 12, 331
Feinstein, A., Marraco, H.G., & Forte, J.C. 1976, A&AS, 24, 389
Feinstein, A., FitzGerald, M.P., & Moffat, A.F.J. 1980, AJ, 85, 708
Feinstein, A. 1982, AJ, 87, 1012
Forte, J.C. 1978, AJ, 83, 1199
Groot, M., & Thé, P.S. 1983, A&A, 120, 89
Gutiérrez-Moreno, A. 1975, PASP, 87, 805
Herbst, W. 1976, ApJ, 208, 923
Johnson, H.L., & Morgan, W.W. 1953, ApJ, 117, 313
Johnson, H.L. 1966, RevMexAA, 4, 193
Koornneef, J. 1983, A&AS, 51, 489
Kurucz, R.L. 1979, ApJS, 40, 1
Levato, H., & Malaroda, S. 1981, PASP, 93, 714
Menzies, J.W., Bamfield, R.M., & Laing, J.D. 1980, Circ. SAAO, 1, 5
Morrell, N., & García, B. 1988, PASP, 100, 1431
de Ruyter, H.R., & Lub, J. 1986, A&AS, 63, 59
Smith, G.S. 1987, MNRAS, 227, 943
Steenman, H., & Thé, P.S. 1989, Ap&SS, 159, 189
______. 1991, Ap&SS, 184, 9
Tapia, M., Roth, M., Marraco, H., & Ruiz, M.T. 1988, MNRAS, 232, 661
Thé, P.S., Bakker, R., & Antalova, A. 1980a, A&AS, 41, 93
Thé, P.S., Bakker, R., & Tjin A Djie, H.R.E. 1980, A&A, 89, 209
Thé, P.S., & Groot, M. 1983, A&A, 125, 75
Thé, P.S., de Winter D., Arens, M., Heijblok, & M., Nieuwland, E.R. 1989, A&AS, 81, 115
Thé, P.S., de Winter, D., Feinstein, A., & Westerlund, B.E. 1990, A&AS, 82, 319
Turner, D.G., & Moffat, A.F.J. 1980, MNRAS, 192, 283
Walborn, N. 1973, ApJ, 179, 517