Revista Mexicana de Astronomía y Astrofísica, **29**, 163-174 (1994)

THE INTERSTELLAR EXTINCTION LAW

David G. Turner
Department of Astronomy and Physics,
Saint Mary's University, Canada

RESUMEN

Se presenta una discusión, desde el punto de vista de un empírico, sobre algunos temas importantes para el entendimiento actual de la extinción interestelar. Esta discusión incluye el mal empleo de las leyes medias de enrojecimiento diferencial y las variaciones de R, el cociente de extinción total sobre la selectiva. Se demuestra la efectividad de estudios detallados de enrojecimiento —incluyendo la determinación de líneas de enrojecimiento, desenrojecimiento de estrellas individuales y análisis de extinción variable— en cúmulos abiertos. En particular se hace referencia a determinaciones de R en Tr 37 (R = 2.83 ± 0.12), Sco-Oph (R = 3.34 ± 0.08) y NGC 6611 (R = 2.99 ± 0.08, con evidencias que $R = 4.42 \pm 0.10$ en la región polvosa del norte), y al descubrimiento de evidencias nuevas de extinción circunestelar. Se demuestra que las variaciones que se observan en R de 2.8 y 3.0 a 3.3 en estos cúmulos, están relacionadas con variaciones comparables en la pendiente de la línea de enrojecimiento, $E(U-B)/E(B-V)$ en esas direcciones (X=0.80, 0.74 y 0.63 respectivamente), pero que tales evidencias no apoyan los argumentos de estudios infrarrojos en favor de extinciones anómalas con valores $R \sim 4$ o mayores. Surge la pregunta de si las estrellas muy enrojecidas en Sco-Oph sirven como estándares adecuadas para estudios de las variaciones de la ley de extinción.

ABSTRACT

A discussion is presented, from the point of view of an empiricist, of a number of topics which are important to our current understanding of interstellar extinction. These include the misuse of mean reddening laws, the origins of differential reddening, and the question of variations in R, the ratio of total-to-selective extinction. The effectiveness of detailed reddening studies —including reddening line determinations, dereddening of individual stars, and variable-extinction analyses— of open clusters is demonstrated, with particular reference to R-determinations for Tr 37 ($R = 2.83 \pm 0.12$), Sco-Oph ($R = 3.34 \pm 0.08$), and NGC 6611 ($R = 2.99 \pm 0.08$, with some evidence that $R = 4.42 \pm 0.10$ in the dusty northern region) and to the discovery of new evidence for circumstellar extinction. It is demonstrated that the observable variations in R from 2.8 and 3.0 to 3.3 in these cluster fields are tied to comparable variations in the reddening line slope $E(U-B)/E(B-V)$ for these lines of sight (X = 0.80, 0.74, and 0.63, respectively), but that the evidence does not support the arguments from IR studies for anomalous extinction with values of $R \sim 4$ or more. The question is raised as to whether or not the highly-reddened stars in Sco-Oph serve as proper standards for studies of extinction law variations.

Key words: **ISM: DUST, EXTINCTION — OPEN CLUSTERS AND ASSOCIATIONS: INDIVIDUAL (Tr 37, NGC 6611, SCO-OPH)**

1. INTRODUCTION

A full review of our current knowledge of interstellar extinction is far beyond the scope of this brief report. My own experience is restricted mainly to work in the optical spectral region, so this paper deals predominantly with investigations which utilize observations at optical wavelengths. Results based upon observations in the infrared (IR) and ultraviolet (UV) regions are addressed to the extent that they are related to observations in the optical region.

Like Dr. Mendoza, I was introduced to the study of interstellar extinction by the work of Harold Johnson (e.g., Morgan et al. 1953; Johnson & Morgan 1955; Hiltner & Johnson 1956; Johnson 1963, 1965, 1966, 1967, 1968). The various papers by Johnson as well as by Mendoza (e.g., Mendoza 1965, 1968) and others (e.g. Whitford 1958) were strong influences upon my own work in this area. Johnson's approach to the study of interstellar reddening in the Galaxy was both fascinating and controversial, and inspired many subsequent studies. It is a credit to his thoroughness in this endeavor that many of his findings and techniques are still in use today. Currently there are a number of issues which seem to require further elucidation, and these form the basis for the present paper. Specifically they are: the misuse of mean reddening laws, the origins of differential reddening, and the question of variations in $R = A_V/E(B-V)$, the ratio of total-to-selective extinction, and the best methods of deriving this parameter. Each of these issues is addressed separately in what follows.

2. MEAN REDDENING LAWS

Figure 1 of Johnson (1966; see also Johnson & Borgman 1963) presents a graphic illustration of the fact that the interstellar reddening law varies throughout the Galaxy. Although disputed by Schultz & Wiemer (1975), the increasing scatter with increasing color of the $(B-V)$ and $(V-I)$ indices of O-type stars must originate with variations in the reddening proportionality between these two indices, and is a characteristic which, among others, was used by Johnson (1966) to establish his intrinsic color scale for normal stars. Variability of the extinction law throughout the IR, visible, and UV regions is also accepted by most researchers in the field (see Cardelli et al. 1989). The use of mean reddening laws for galactic studies is therefore based upon a condition which does not apply in practice.

Over the years a variety of observational and theoretical studies attempted to establish a universal form for the mean galactic reddening law. In the UBV system the reddening relation is usually expressed as

$$E(U-B) = XE(B-V) + YE(B-V)^2,$$

where X is the slope of the reddening line and Y is its curvature. Historically the theoretical studies (e.g., Blanco 1956, 1957; Gutiérrez-Moreno & Moreno 1975; Straizys et al. 1976; Crawford & Mandwewala 1976; Buser 1978) have given values of X ranging from 0.66 to 0.76 and Y ranging from 0.04 to 0.09 for early-type stars, while observational studies (e.g. Johnson & Morgan 1955; Hiltner & Johnson 1956; Crawford 1958; Serkowski 1963; FitzGerald 1970) have suggested comparable values of X ranging from 0.66 to 0.72 or variable (Wampler 1961, 1962, 1964) and Y ranging from -0.05 to 0.06. My own empirical study (Turner 1989) restricted stars by galactic region and yielded a constant value of $Y = 0.02 \pm 0.01$ but with X varying at least from 0.62 to 0.80. Although a mean value of $\langle X \rangle = 0.72$ was derived, only one of the six fields studied produced a reddening slope consistent with this value, i.e., for any particular field the adoption of a mean reddening relation is most inappropriate. As noted also by Cardelli et al. (1989), the extinction law in fields which do tend to follow a mean relationship quite often differ in detail from the mean extinction law. This means that the reddening in any one field must be approached independently of any preconceptions about mean extinction laws, which therefore serve little practical purpose.

It should also be noted that these conclusions apply to any problem involving reddening corrections, including those based upon Johnson $BVRI$ or Stromgren photometry (see Turner 1985). This calls into question the use of so-called reddening-independent parameters such as Q or $[c_1]$. How can $Q = (U-B) - X(B-V)$ be reddening independent when its value depends upon the choice of the reddening slope X that is adopted?

The variability of the extinction law from one region of the Galaxy to another also implies commensurate variations in the properties of the dust grains responsible for the extinction. Variations in mean cross section are implied by variations in the color excess ratio $E(U-B)/E(B-V)$. Since small particles are highly selective absorbers at optical wavelengths in comparison with the more constant absorption properties of larger particles, high values of $E(U-B)/E(B-V)$ imply a dominance by dust grains of small cross section while small values of $E(U-B)/E(B-V)$ imply a dominance by dust grains of large cross section. Comparisons f $E(U-B)/E(B-V)$ and R values with λ_{max} values from polarization studies (see Serkowski et al. 1975; Vhittet & van Breda 1978; Whittet 1977, 1979; Clayton & Mathis 1988; Clayton & Cardelli 1988; Turner 989) provide important confirmation of these predictions, although the details regarding R variations are still matter of debate.

Large values of $E(U-B)/E(B-V)$ imply smaller than average values of $R = A_V/E(B-V)$ since the average ust grain sizes must be smaller than average, whereas small values of $E(U-B)/E(B-V)$ imply correspondingly rger than average values of $R = A_V/E(B-V)$. As possible justification for this statement it can be noted aat Hiltner & Johnson (1956) found $R = 2.1$ for OB stars in the Cygnus Rift where $E(U-B)/E(B-V) = 0.83$ Turner 1989). However, this result has never been confirmed and no strong dependence of this type was noted the study of cluster fields by Turner (1976b). This suggests that the actual range of variation in R associated ith changes in $E(U-B)/E(B-V)$ may be smaller than advocated by Serkowski et al. (1975) and others, ho based their conclusions mainly upon the results from IR studies (see § 4).

3. ORIGINS OF DIFFERENTIAL REDDENING

It appears to be a tenet of interstellar extinction studies (e.g., Martin & Whittet 1990) that there are two istinct sources for extinction by interstellar grains, namely a diffuse component associated with the general nterstellar medium and a variable component associated with localized regions of higher mean density. It is ccepted that $R \sim 3$ for the diffuse component, but that R can range from 3 to 6 for the variable component, epending upon the conditions and mechanisms operating for the region in question. On this basis my study Turner 1976b) of variable extinction in the directions of 51 open clusters, which generated $\langle R \rangle = 3.08 \pm 0.03$, is aken to be confirmation of the overall uniformity of the diffuse component of interstellar dust, with perhaps some nall variations due to grain alignment in the galactic magnetic field superimposed. Studies at IR wavelengths hich argue that $R > 3$ in specific regions are taken to be direct evidence for the existence of the variable omponent.

It needs to be recognized, however, that the existence of variable extinction across the fields of most open usters is not due to density variations in either the diffuse dust component spread out over the entire line f sight to the cluster or to dust intermingled with cluster stars. Careful variable-extinction studies of most uster fields (e.g., Turner et al. 1992, 1994; Turner 1992, 1993) reveal that the extinction generally originates one or two relatively nearby diffuse dust clouds which are located in the line of sight to the cluster. In other ords, the light from distant clusters in the galactic plane passes mainly through relatively transparent regions n its journey to us. Most of the reddening originates within dust clouds which probably have relatively small imensions (scales of parsecs) in comparison with the distances (kiloparsecs) over which the light travels. The elative uniformity of the extinction properties of this dust may therefore be related to the relative proximity f these dust clouds to the sun. It is noteworthy in this light to recall that one of the results which led Hiltner Johnson (1956) to adopt a value of $R = 3.0 \pm 0.2$ in our galaxy was a determination by Stebbins (1950) of $= 3.0$ for the dust in the Andromeda Nebula M31 [although van den Bergh (1968) has advocated the value f ~ 2.5 found by Kron & Mayall (1960)]! The uniformity of dust properties in the diffuse interstellar medium apparently universal.

4. VARIATIONS IN R

Although many of Johnson's original arguments for significant variations in R were repudiated by later tudies, there are still strong arguments that $R > 3$ along several lines of sight (e.g., Cardelli et al. 1989). It is ignificant, however, that different techniques for deriving R can give different results for the same field.

The variable-extinction technique, in which one modifies the distance modulus relation for a cluster or ssociation of stars at a common distance to the form

$$V - M_V = (V_0 - M_V - 5\log\ d) + R\ E(B-V),$$

as been improved considerably since the early studies by Hiltner & Johnson (1956) and Whitford (1958). is no longer acceptable to derive R-values when the scatter in apparent distance modulus $V - M_V$ is of he order of $\pm 1^{\mathrm{m}}.0$. A scatter of less than $\pm 0^{\mathrm{m}}.5$ in $V - M_V$ can be obtained with reliable two-dimensional pectral classification for early-type stars in clusters and associations (Garrison 1970, 1977), while zero-age ain-sequence (ZAMS) fitting of young clusters using photoelectric data can produce a scatter of less than $0^{\mathrm{m}}.2$ in $V - M_V$ (Turner 1976a). It is also not necessary to accept Becker's (1966) natural scatter as the explanation for the dispersion in cluster color-magnitude diagrams. This scatter arises from various identifiabl sources, namely photometric errors, duplicity, rotation, evolution, and, most importantly, differential interstella reddening. Corrections for differential reddening are easy to apply, and are necessary if one is to make meaningfu astrophysical analyses of open cluster color-magnitude diagrams (see Turner 1994).

The use of ZAMS fitting with the variable-extinction technique has generated much criticism in th literature (see Sherwood 1975), much of it unwarranted. The technique does require a reliable knowledge c the intrinsic colors for main-sequence stars and the reddening relation applicable to the field, and is susceptibl to the systematic effects of photometric errors (Turner 1976a), particularly systematic errors, as illustrated b the case of IC 2581 (Turner 1973, 1978). It is also necessary to be careful deriving proper reddening solution for cluster stars and to be wary of the accidental inclusion in the sample of non-ZAMS stars (Turner 1976a or foreground and background stars (Garrison 1970). However, as illustrated by Turner et al. (1994) for th cluster Anon. Platais, the technique can generate realistic values of R even in cases where it might not normall be attempted.

Another modification of the variable-extinction technique is to use it in clusters or associations whic contain several stars of identical spectral type and luminosity class (e.g., Hiltner & Johnson 1956; Mendoz 1965). This tends to reduce the sample size for the R determination, however, and can produce spuriou results when the spectral classifications are not reliable (Turner 1977). It is therefore not recommended in mos cases. It is also possible to derive mean values of R for the extinction towards emission nebulae by comparin their radio and optical emission measures (e.g., Gebel 1968), although the results are model-dependent an lack high precision. The technique of comparing B and V star counts for the fields of diffuse dust clouds ha also been used on occasion (Schalen 1975), but is likewise susceptible to many practical problems. Variou other techniques are described in the literature —cluster diameters, globular clusters, R associations, groups c galaxies, and planetary nebulae (see Hawley & Duncan 1976; Stasinska et al. 1992)— and these generally giv results consistent with $R \sim 3$ (or less) for the diffuse interstellar medium.

The main alternative approach to deriving R is via the color difference method whereby one compare the flux variations with wavelength of a reddened star (across the UV-IR region) with either an unreddene standard or with the intrinsic colors expected for a star of its type. In recent years many studies in the I have made use of Koornneef's (1983) calibration of IR colors for early-type stars rather than that of Johnso (1966), although it has never been demonstrated that they are an improvement (see below). Of concern fc workers in the IR is that any infrared excesses they detect can be due either to anomalous extinction or t intrinsic IR emission from various sources (see comments by Mendoza 1968; and others). Supportive evidenc from UV anomalies and polarization observations are often used to strengthen a case for anomalous extinctio Where there is disagreement with the results of variable-extinction studies, the usual argument is that tl variable-extinction technique samples only the variable component of reddening along the line of sight, where the color difference method samples the extinction along the entire line of sight. It has also been argued th the technique of variable-extinction analysis using cluster ZAMS fitting with lower envelope selection is tc subjective, and cannot be made impersonal. The results therefore depend heavily upon the personal views the practitioner. As a response to this criticism, I am presenting in this paper three examples for consideratio Examined here are three regions where R is believed to be anomalous, namely Trumpler 37 where R is considere to be smaller than normal ($R = 2.6 - 2.8$), Upper Scorpius where R is considered to reach larger than norm values ($R \sim 4 - 5$), and NGC 6611 where R is argued to vary between 3 and 5.

4.1. Trumpler 37

Tr 37 is a very young cluster embedded in the diffuse H II region IC 1396. Spectral types and photoelectr UBV photometry for bright cluster stars have been published by Garrison & Kormendy (1976), while more extensive photoelectric UBV survey of cluster stars was made by Marschall et al. (1990). A valı of $R = 2.91 \pm 0.21$ was derived for Tr 37 by Turner (1976b) from a variable-extinction analysis of the Garrisc & Kormendy data. This data set, although reduced both by hand and by multivariate analysis, was normalize to the latter. However, the data are in much better agreement with the Marschall et al. photometry if the are renormalized to the hand-reduced set, so this adjustment has been adopted here. A plot of color excess for spectroscopically-observed cluster stars is given in Figure 1. The best-fitting line through the most reliab data yields a reddening slope of $E(U-B)/E(B-V) = 0.80 \pm 0.02$ for this field, consistent with what has bee found for spatially adjacent fields (Turner 1976b).

According to Clayton & Fitzpatrick (1987) the far ultraviolet extinction towards Tr 37 is larger than norma a feature which is generally attributed to excess extinction by small dust grains (e.g., Greenberg & Chlewic 1987). This result, the large UBV reddening slope, and the rather small IR excesses derived for cluster sta

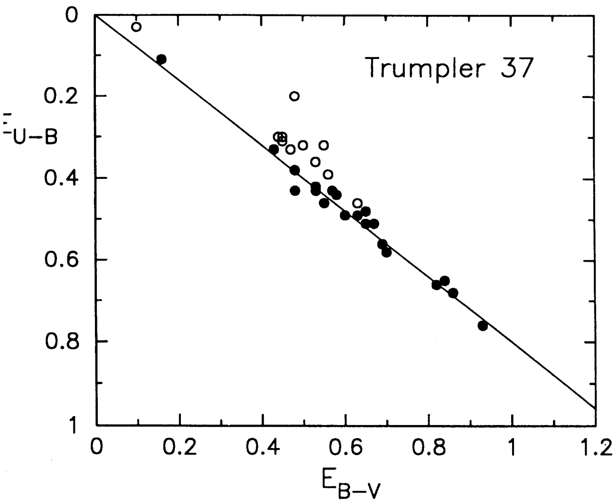


Fig. 1. Color excesses for spectroscopically observed stars in Tr 37. The reddening line fit to the most reliable data (filled circles) assuming $Y = 0.00$ has slope $X = 0.80$.

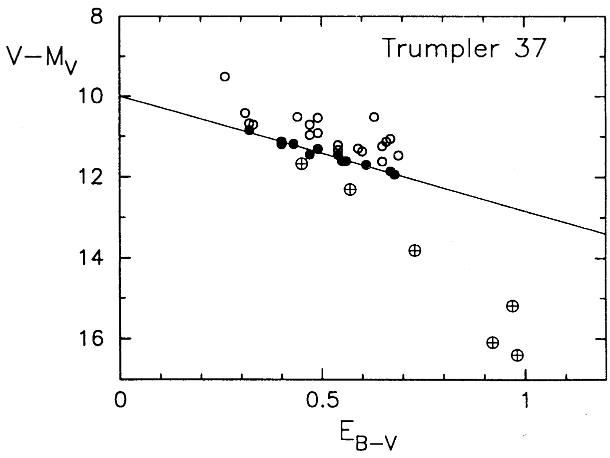


Fig. 2. Internal evolution of the $\eta = 1.0$ model. The variables are normalized to the values indicated.

by Roth (1988) are all consistent with a skewing of the dust particle size distribution in this field towards small cross sections. Roth estimates that $R = 2.82 \pm 0.15$ in this field, a value which is anomalously smaller than normal. Slightly smaller values of $R = 2.6$ are estimated by Clayton & Cardelli (1988) and Cardelli et al. (1989).

Since the standardization of the photometry in the visible is important to the IR extinction results, we redid Roth's analysis using UBV data on the Marschall et al. (1990) system along with the derived reddening slope of 0.80. The R-value deduced using $E(V-K)/E(B-V)$ with Koornneef's (1983) intrinsic colors is 2.71 ± 0.18 for 16 cluster stars, but is 2.84 ± 0.17 using Johnson's (1966) intrinsic colors. Note the smaller scatter in the R-value obtained from the use of Johnson's intrinsic color scale, which is probably more reliable.

A variable-extinction analysis of Tr 37 based upon ZAMS fitting is presented in Figure 2. Since the errors in the photoelectric data are relatively small, the likely scatter in $V - M_V$ for lower envelope stars should be no larger than about $\pm 0^{\mathrm{m}}.10$. Objects populating this envelope are identified in Figure 2, while other stars represent non-ZAMS objects (due to evolution, rotation, and duplicity), background stars (the field is relatively transparent), and possibly one object which may be a main-sequence emission-line star (for which one invariably deduces incorrect parameters by standard dereddening techniques). An unprejudiced estimate of R from the lower envelope data using least squares and non-parametric straight line fitting techniques is 2.83 ± 0.12, in excellent agreement with the results from IR photometry.

A value of R for this field as small as 2.6 would be difficult to reconcile with the data of Figure 2 or Figure 1. If $R = 2.8$ is assumed to hold only for the variable component, then the foreground component must be described by $R = 2.4$ to obtain an average value of $R = 2.6$ for this line of sight. A value of $R = 2.4$ for the foreground component would likely be associated with a very steep UBV reddening slope for the foreground extinction, and this is clearly not allowed by the data of Figure 1. The dust along the entire line of sight to Tr 37 must be described by $R = 2.8$, which is already somewhat smaller than normal. It would be interesting to make a detailed variable-extinction study of the Cyg OB2 association where $E(U-B)/E(B-V) = 0.83$, since one might expect a small R-value to apply in this region as well. A study by Turner (1993) of the cluster Roslund 3 where $E(U-B)/E(B-V) = 0.84$ provided no strong evidence that R is significantly smaller than 3.0 in this field. A larger sample of regions of large reddening slope needs to be investigated before one can safely conclude what the smallest values of R in the Galaxy may be.

4.2. Upper Scorpius

The extinction in upper Scorpius and around ρ Oph has been studied by quite a number of researchers, and is regarded by many as a classic case of anomalous reddening. The low reddening slope for this field (Turner

1989), the low extinction in the far ultraviolet (Bohlin & Savage 1981), and the long wavelengths at whicl maximum polarization occurs for stars in this field (see Clayton & Mathis 1988) all indicate extinction by dus particles with a size distribution skewed to larger-than-average dimensions. How this affects the value of R fo this field is still a matter of active debate.

Studies of the IR extinction towards stars in the Sco-Oph region have produced mixed results. The origina studies by Johnson (1965, 1968) gave a value of $R = 3.3$ for this field, and a very similar value ($R = 3.0$) wa inferred for the A5 II star o Sco by Rieke & Lebofsky (1985). However, studies by Iriarte (1969), Carrasco et al (1973), van Breda et al. (1974), Vrba et al. (1975), Whittet & van Breda (1975), Chini (1981), and Vrba et al (1993) have all argued for $R \sim 4$ for the dust extinction, particularly for heavily-reddened stars. A compariso of radio and optical emission measures by Brown & Zuckerman (1975) for six presumed compact H II region associated with stars in the Ophiuchus dark cloud appears to support such a large R-value. Dickman & Herbs (1990) argue against such a large value of R for this field, however, an important consideration (often ignored is that an application of the variable-extinction method to Sco OB2 (Garrison 1977) gives $R = 3.1 \pm 0.2$. Thi last value is supported by the work of Cudworth & Rees (1991), who found $R = 3.3 \pm 0.7$ for the extinctio across the face of the globular cluster M4 (located between α Sco and σ Sco) by minimizing the dispersion i the photometry for its horizontal branch and subgiant branch stars.

It has long been argued (Johnson 1967; Schmidt-Kaler 1967, 1971; Sherwood 1975; Mendoza 1968; Beh 1970, among others) that circumstellar IR emission may be affecting the IR photometry of stars which exhibi the characteristics of Sco-Oph stars. Similar problems appear to affect recognized emission-line stars (Whitte & van Breda 1980; Gorti & Bhatt 1993), and it can be noted that IR emission has been detected around some c the early-type stars in this field (Elias 1978; de Geus & Burton 1991). This is far too serious a problem to hav been ignored as an inconvenience in the development of a universal working model for interstellar extinctio (Cardelli et al. 1989; Martin & Whittet 1990; Steenman & Thé 1989 1991).

The present contribution consists of a second look at the implications of IR observations for stars in Sco Oph and a new approach to the variable-extinction analysis of association members. The first step included reanalysis of the IR data of Carrasco et al. (1973) and Vrba et al. (1975) in connection with a recompilatio of optical photometric data (Hardie & Crawford 1961; Garrison 1967; Graham 1967; Crawford et al. 197(Glaspey 1971, 1972) for early-type stars in this field. R-values were deduced using $E(V-K)/E(B-V)$ an $E(V-L)/E(B-V)$ excesses, and the results are illustrated in Figures 3, 4, and 5 as functions of $E(B-V$ $(B-V)_0$, and M_{bol}, respectively. Similar diagrams to Figure 3 have been illustrated previously by Carrasc et al. (1973) and Whittet & van Breda (1975), and have been used to argue for an increase in mean particl size for the dust in Sco-Oph as a function of optical depth in the clouds. From Figures 4 and 5, however, i

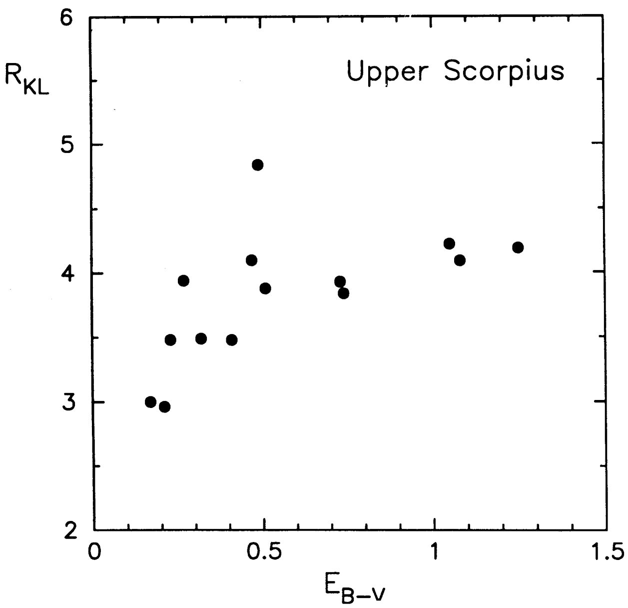


Fig. 3. R_{KL} values for Sco-Oph stars plotted as a function of E_{B-V} for the stars.

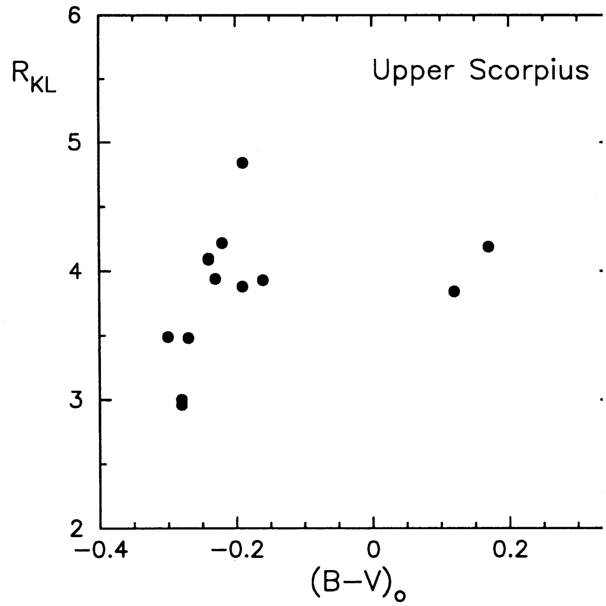
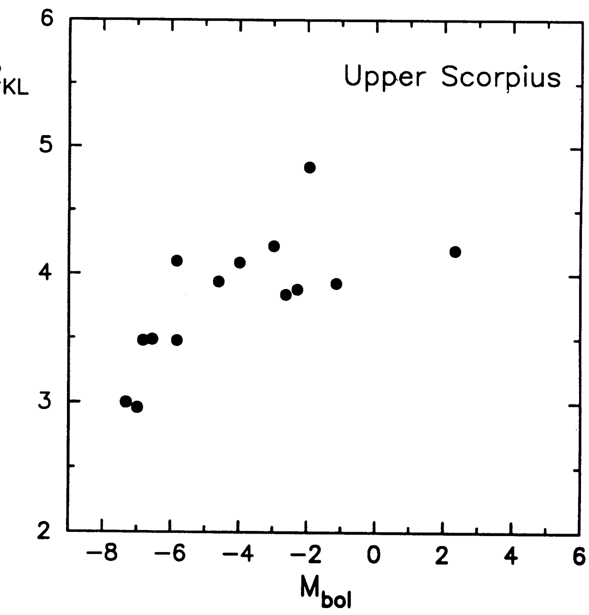


Fig. 4. R_{KL} values for Sco-Oph stars plotted as function of $(B-V)_0$ for the stars.



ʼig. 5. R_{KL} values for Sco-Oph stars plotted as a unction of M_{bol} for the stars.

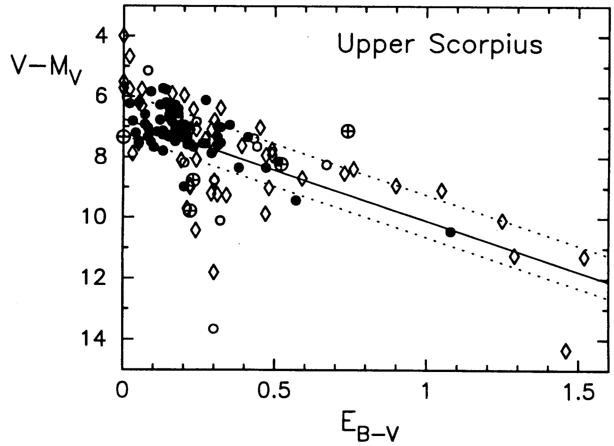


Fig. 6. Variable-extinction diagram for Sco-Oph stars with luminosities inferred from Hβ photometry with $V \sin i$ corrections (filled circles), Hβ photometry with mean $V \sin i$ corrections (open circles), ZAMS fitting (diamonds), and spectral types (circled plus signs). The solid line and two dotted lines have slope $R = 3.34$.

ıould be clear that optical depth is not the only parameter with which one could correlate R in this field. The lternative possibility that the anomaly is related to circumstellar emission from the lower temperature and ›wer luminosity stars in this complex creates fewer problems for understanding the extinction. In this case, $R\rangle = 3.28 \pm 0.28$ for the five uncontaminated stars, and the relatively normal location of all of these stars ›xcept SR 5 which has no U observation) in the color excess diagram (Figure 5 of Turner 1989) argues that ıey are all affected by dust particles which have relatively similar extinction properties.

A variable-extinction diagram for the early-type stars in this complex is given in Figure 6, where luminosities ›r each star have been estimated using H$\beta - M_V$ values corrected for $V \sin i$ (see Turner 1986) based on measures ʼom Slettebak (1968), Hβ $- M_V$ corrected for the mean $V \sin i$ of stars of that spectral type (Fukuda 1982), AMS fitting, and MK spectral type. No attempt has been made to eliminate stars which are not members of ıe main complex. Nevertheless, it is possible to detect a major concentration of objects in this diagram, and ›ast squares and non-parametric fitting to the 26 stars best defining this group yields $R = 3.34 \pm 0.08$ for the ›gion, consistent with the IR result. This main clump of stars is centred on $V_0 - M_V = 6.76$ (d = 225 pc), nd upper and lower envelopes in Figure 6 of identical R-value at $V_0 - M_V = 5.90$ and 7.30 (151 and 288 pc) ›ntain all but a few likely foreground and background stars to Sco OB2. A spread in line of sight distance of :65 pc is consistent with the observed angular extent on the sky of $\sim 32°$ for stars in this complex.

It is difficult to reconcile the data of Figure 6 with larger R-values for the heavily-reddened stars. In many ›ses this would place the foreground objects into the main complex! The dispersion in distance modulus for ›ars with R_{KL} values is $\pm 0^{m}81$ using the individual R-values inferred from IR photometry, but is only $\pm 0^{m}64$ sing a constant value of $R = 3.34$. Although Whittet (1974) has used a variable-extinction study based upon β luminosities to argue that $R = 4.2 \pm 0.5$ for Sco-Oph stars in nebulosity, no such distinction was evident in ıe present study. The use of the Hβ index as a luminosity indicator does require some care. It can be noted ıat the present analysis of a much more extensive data set than used by Whittet appears to contradict his ›sults. The value of R in Sco-Oph appears to be close to 3.3, consistent with all of the indicators for extinction y larger-than-average dust particles.

4.3. NGC 6611

NGC 6611 is an extremely young cluster embedded in the bright H II region M16. An extensive photoelectric nd photographic UBV survey of cluster stars by Walker (1961) has always formed the standard reference for ıis cluster, which was incorporated (erroneously) into Blaauw's (1963) ZAMS. However, a comparison of Valker's photometry with contemporaneous observations by Hiltner (1956), Hoag et al. (1961), Johnson &

Borgman (1963), Johnson (1968), and Hiltner & Morgan (1969) —all of which are in excellent agreement wit one another— indicates that Walker's photometric colors for cluster stars are consistently too blue, by up to 0^{m} in $(U - B)$ (see Hiltner & Morgan 1969). I have confirmed this from a few unpublished UBV observations i this cluster made at Kitt Peak National Observatory several years ago. More recent photoelectric observation of cluster stars by Sagar & Joshi (1979), Neckel & Chini (1981), Chini & Wargau (1990), and Thé et al. (199(appear to exhibit much more scatter relative to the earlier epoch photometry, and this may be a consequenc of the bright nebulous background in this field combined with photometric systems in current use which ar not fully tied to Johnson's original system. The results presented here were derived from published photometr tied to the observations by Hiltner and Johnson and their collaborators.

A value of $R = 3.04 \pm 0.10$ was derived for the main extinction in NGC 6611 by Turner (1976b) from variable-extinction analysis of cluster stars. Evidence for anomalous extinction in the northern portion of th cluster was also noted, although the results were never fully described except in an unpublished source (Turne 1974). Figure 7 presents the variable-extinction data for cluster stars which led to these results, and they hav been reanalyzed for this paper. The value of R for the majority (87) of cluster members is 2.99 ± 0.08, but i 4.42 ± 0.10 for 13 anomalous objects in the northern part of the cluster, including the O8 Ibf star Walker 24(A similar result was found by Turner (1979) for NGC 6823 stars in the dusty southeastern region of the H] region NGC 6820.

It is not clear whether or not 4.4 is a valid estimate of R in the dusty regions north of the core regio of NGC 6611 since it depends upon two tenuous assumptions, namely that the objects in question are cluste members rather than background stars and that their photometry, which was derived by adjusting Walker' original data, is reliable. The placement of the O8 Ibf supergiant Walker 246 in this group also depends upon it spectroscopic luminosity estimate and possible cluster membership, either of which could be disputed on variou grounds. Neckel & Chini (1981), Chini & Krugel (1983), Chini & Wargau (1990), and Thé et al. (1990) have a argued that R $\sim$ 4 for portions of the extinction in NGC 6611, but the evidence for this from IR photometr is much like that for stars in Sco-Oph where circumstellar or localized emission appears to be important. value of $R = 2.5 \pm 0.6$ was derived for M16 by Gebel (1968) from a comparison of radio and optical emissio measures for this H II region, and this value agrees with the value of $R = 2.99 \pm 0.08$ obtained for the majorit of cluster stars in Figure 7.

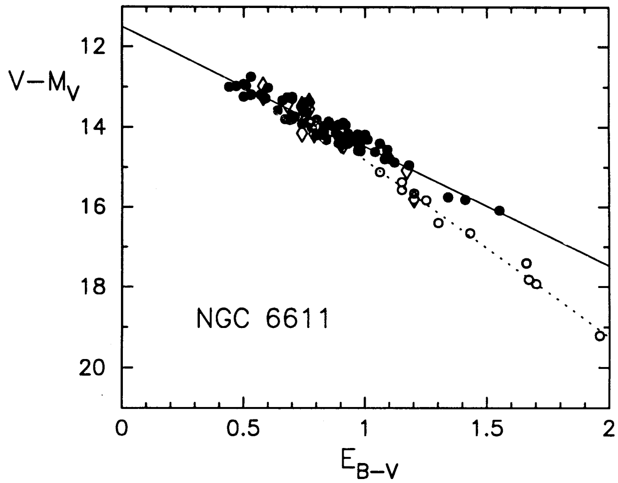


Fig. 7. Variable-extinction diagram for NGC 6611 stars with luminosities inferred from ZAMS fitting (fille and open circles) and spectral types (diamonds). The solid line has slope $R = 2.99$, and the dotted line slop $R = 4.42$.

NGC 6611 is therefore a bit of an oddity. It appears to be a cluster in which the extinction propertie of the dust are relatively normal, like those in most regions of the Galaxy. However, the extreme range c reddening for cluster stars suggests that much of the extinction originates in dust which is directly associate with this extremely young cluster. There may be evidence for anomalous extinction on the dusty north side c the cluster, but this clearly requires further observational tests —more than just IR photometry of the stars involved. Walker 246, if it is indeed anomalously reddened, is not distinguishable from other stars in NGC 6611 in the reddening curve for this field (Figure 1 of Turner 1989). This result can only be reconciled with its location in Figure 7 by the presence of a neutral extinction component along the line of sight to the star; a skewing of the dust particle dimensions in this region towards larger-than-average sizes would otherwise decrease the reddening slope $E(U-B)/E(B-V)$ for this one star. Clearly, further study is required.

5. DISCUSSION

For the three regions investigated in this study the derived values of R from variable-extinction analyses range from 2.83 in Tr 37 and 2.99 in NGC 6611 to 3.34 in Sco-Oph, consistent with the variations in reddening slope $E(U-B)/E(B-V)$ observed for these fields -0.80 for Tr 37, 0.74 for NGC 6611, and 0.63 for Sco-Oph. Reddening law variations throughout the galactic plane are an observational fact which needs to be more generally recognized. Indeed, it would be remarkable if the properties of interstellar dust particles were so homogeneous that they produced identical extinction properties for all lines of sight. Amongst other difficulties which this would entail, there would be the added problem of explaining variations in interstellar polarization which are well correlated with mean particle size (Greenberg & Chlewicki 1987; Clayton & Mathis 1988; Clayton & Cardelli 1988).

The study of interstellar extinction requires multi-wavelength observations and not just observations in one spectral region. My own bias is towards the results implied by studies at optical wavelengths, although the results from other spectral regions must of necessity complement these. Polarization data appear to be particularly valuable where they are capable of indicating the value of λ_{max} for the dust extinction. Integrated multi-wavelength analyses such as that of Cardelli et al. (1989) are valuable contributions to such studies, although I believe that too much weight has been given to IR anomalies which appear not to be due to extinction. A similar criticism might be made of the often quoted study by Serkowski et al. (1975), despite its unique appeal. No mention has been made here of the anomalies in Orion and Carina, which are also controversial. They are quite as interesting as the regions which were selected for discussion.

Studies in the optical region are still capable of generating new knowledge about interstellar extinction. A few years ago I was puzzled by some stars in the open cluster Roslund 3 which were more heavily reddened than other stars in the field. Since the cluster lies 5° below the galactic plane in a region where the extinction is otherwise small and smoothly-varying, the extra reddening for these stars was rather difficult to explain. A follow-up spectroscopic study (Turner 1993, Figure 10) revealed a correlation of the reddening for bright cluster members with their projected rotational velocities $V \sin i$, as if the excess reddening originated in circumstellar equatorial dust rings associated with the most rapidly rotating cluster stars. Similar photometric discrepancies have also been observed in a few other clusters (Turner 1991; Harris 1993), which means that this particular circumstellar extinction phenomenon may be fairly commonplace. Although further study is in progress, the results for Roslund 3 already suggest that the extinction properties of this circumstellar component are very similar to those of interstellar extinction, as argued previously by Allen (1976). There is clearly a lot more to be learned.

REFERENCES

Allen, D.A. 1976, MNRAS, 174, 29P
Becker, W. 1966, ZAp, 64, 77
Behr, A. 1970, Minutes of Commission 33 Meetings, IAU General Assembly, p. 20
Blanco, V.M. 1956, ApJ, 123, 64
______. 1957, ApJ, 125, 209
Blaauw, A. 1963, in Basic Astronomical Data, ed. K.A. Strand (Chicago: U. Chicago Press), Chapt. 20
Bohlin, R.C., & Savage, B.D. 1981, ApJ, 249, 109
Brown, R.L., & Zuckerman, B. 1975, ApJ, 202, L125
Buser, R. 1978, A&A, 62, 411
Cardelli, J.A., Clayton, G.C., & Mathis, J.S. 1989, ApJ, 345, 245
Carrasco, L., Strom, S.E., & Strom, K.M. 1973, ApJ, 182, 95
Chini, R. 1981, A&A, 99, 346
Chini, R., & Krugel, E. 1983, A&A, 117, 289
Chini, R., & Wargau, W.F. 1990, A&A, 227, 213
Clayton, G.C., & Cardelli, J.A. 1988, AJ, 96, 695

Clayton, G.C., & Fitzpatrick, E.L. 1987, AJ, 93, 157
Clayton, G.C., & Mathis, J.S. 1988, ApJ, 327, 911
Crawford, D.L. 1958, ApJ, 128, 185
Crawford, D.L., & Mandwewala, N. 1976, PASP, 88, 917
Crawford, D.L., Barnes, J.V., & Golson, J.C. 1970, AJ, 75, 624
Cudworth, K.M., & Rees, R.F. 1991, in The Formation and Evolution of Star Clusters, ASP Conference Series Vol. 13, ed. K. Janes (San Francisco: ASP), p. 256
de Geus, E.J., & Burton, W.B. 1991, A&A, 246, 559
Dickman, R.L., & Herbst, W. 1990, ApJ, 357, 531
Elias, J.H. 1978, ApJ, 224, 453
FitzGerald, M.P. 1970, A&A, 4, 234
Fukuda, I. 1982, PASP, 94, 271
Garrison, R.F. 1967, ApJ, 147, 1003
______. 1970, AJ, 75, 1001
______. 1977, BAAS, 9, 373
Garrison, R.F., & Kormendy, J. 1976, PASP, 88, 865
Gebel, W.L. 1968, ApJ, 153, 743
Glaspey, J.W. 1971, AJ, 76, 1041
______. 1972, AJ, 77, 474
Gorti, U., & Bhatt, H.C. 1993, A&A, 270, 426
Graham, J.A. 1967, MNRAS, 135, 377
Greenberg, J.M., & Chlewicki, G. 1987, QJRAS, 28, 312
Gutiérrez-Moreno, A., & Moreno, H. 1975, PASP, 87, 425
Hardie, R.H., & Crawford, D.L. 1961, ApJ, 133, 843
Harris, G.L.H. 1993, private communication
Hawley, S.A., & Duncan, D.K. 1976, PASP, 88, 672
Hiltner, W.A. 1956, ApJS, 2, 389
Hiltner, W.A., & Johnson, H.L. 1956, ApJ, 124, 367
Hiltner, W.A., & Morgan, W.W. 1969, AJ, 74, 1152
Hoag, A.A., Johnson, H.L., Iriarte, B., Mitchell, R.I., Hallam, K.L., & Sharpless, S. 1961, Pub.US Naval Obs. 17, 345
Iriarte, B. 1969, Bol. Obs. Tonantzintla y Tacubaya, 5, 101
Johnson, H.L. 1963, in Basic Astronomical Data, ed. K.A. Strand (Chicago: U. Chicago Press), Chapt. 11
______. 1965, ApJ, 141, 923
______. 1966, ARA&A, 4, 193
______. 1967, ApJ, 150, L39
______. 1968, in Nebulae and Interstellar Matter, ed. B.M. Middlehurst, & L.H. Aller (Chicago: U. Chicag Press), Chapt. 5
Johnson, H.L., & Borgman, J. 1963, BAN, 17, 115
Johnson, H.L., & Morgan, W.W. 1955, ApJ, 122, 142
Koornneef, J. 1983, A&A, 128, 84
Kron, G.E., & Mayall, N.U. 1960, AJ, 65, 581
Marschall, L.A., Comins, N.F., & Karshner, G.B. 1990, AJ, 99, 1536
Martin, P.G., & Whittet, D.C.B. 1990, ApJ, 357, 113
Mendoza, E.E., V. 1965, Bol. Obs. Tonantzintla y Tacubaya, 4, 3
______. 1968, Publ. Univ. Chile Dept. Astron., Vol. I, no. 7, 106
Morgan, W.W., Harris, D.L., & Johnson, H.L. 1953, ApJ, 118, 92
Neckel, T., & Chini, R. 1981, A&AS, 45, 451
Rieke, G.H., & Lebofsky, M.J. 1985, ApJ, 288, 618
Roth, M. 1988, MNRAS, 233, 773
Sagar, R., & Joshi, U.C. 1979, Ap&SS, 66, 3
Schalen, C. 1975, A&A, 42, 251
Schmidt-Kaler, T. 1967, in Radio Astronomy and the Galactic System, IAU Symp. No. 31, ed. H. van Woerder p. 161
______. 1971, in Structure and Evolution of the Galaxy, ed. L.N. Mavridis (Dordrecht: Reidel), p. 85
Schultz, G.V., & Wiemer, W. 1975, A&A, 43, 133
Serkowski, K. 1963, ApJ, 138, 1035
Serkowski, K., Mathewson, D.S., & Ford, V.L. 1975, ApJ, 196, 261

ıerwood, W.A. 1975, Ap&SS, 34, 3
lettebak, A. 1968, ApJ, 151, 1043
tasinska, G., Tylenda, R., Acker, A., & Stenholm, B. 1992, A&A, 266, 486
tebbins, J. 1950, Observatory, 70, 203
teenman, H., & Thé, P.S. 1989, Ap&SS, 159, 189
_____. 1991, Ap&SS, 184, 9
traizys, V., Sudzius, J., & Kuriliene, G. 1976, A&A, 50, 413
'hé, P.S., de Winter, D., Feinstein, A., & Westerlund, B.E. 1990, A&AS, 82, 319
'urner, D.G. 1973, AJ, 78, 597
_____. 1974, Ph.D. Thesis, University of Western Ontario
_____. 1976a, AJ, 81, 97
_____. 1976b, AJ, 81, 1125
_____. 1977, Cassiopeia, No. 16, 23
_____. 1978, AJ, 83, 1081
_____. 1979, JRASC, 73, 74
_____. 1985, in Cepheids: Theory and Observations, ed. B.F. Madore (Cambridge: Cambridge U. Press), p. 209
_____. 1986, AJ, 92, 111
_____. 1989, AJ, 98, 2300
_____. 1991, JRASC, 85, 216
_____. 1992, AJ, 104, 1865
_____. 1993, A&AS, 97, 755
_____. 1994, JRASC, 88, in press
'urner, D.G., Forbes, D., & Pedreros, M. 1992, AJ, 104, 1132
'urner, D.G., Mandushev, G.I., & Forbes, D. 1994, AJ, 107, 1796
'urner, D.G., van den Bergh, S., Younger, P.F., Danks, T.A., & Forbes, D. 1993, ApJS, 85, 119
an Breda, I.G., Glass, I.S., & Whittet, D.C.B. 1974, MNRAS, 168, 551
an den Bergh, S. 1968, Observatory, 88, 168
'rba, F.J., Coyne, G.V., S.J., & Tapia, S. 1993, AJ, 105, 1010
'rba, F.J., Strom, K.M., Strom, S.E., & Grasdalen, G.L. 1975, ApJ, 197, 77
Valker, M.F. 1961, ApJ, 133, 438
Vampler, E.J. 1961, ApJ, 134, 861
_____. 1962, ApJ, 136, 100
_____. 1964, ApJ, 140, 1615
Vhitford, A.E. 1958, AJ, 63, 201
Vhittet, D.C.B. 1974, MNRAS, 168, 143
_____. 1977, MNRAS, 180, 29
_____. 1979, A&A, 72, 370
Vhittet, D.C.B., & van Breda, I.G. 1975, Ap&SS, 38, L3
_____. 1978, A&A, 66, 57
_____. 1980, MNRAS, 192, 467

DISCUSSION

Herbig: a) Can you imagine any test that one could apply to an arbitrary star, that would indicate the appropriate value of the extinction law in that direction?, i.e., does the interstellar extinction itself in some way (spectroscopic, polarimetric, ...), observed over a limited spectral region, contain some information on this question? b) What upper limit can be set on the amount of neutral extinction?

Turner: a) From purely optical observations one could use accurate spectral classification with continuum colors to estimate reddening slope, which appears related to other properties of the extinction, including λ_{max}. I do not know of any distinct spectroscopic characteristic which is uniquely related to the nature of the interstellar extinction law. b) My impression is that regions where "real" neutral extinction exists are very uncommon. The northern dusty regions of NGC 6611 may be one example, although I think that this requires further tests.

Philip: If you restrict yourself to regions at the galactic halo, are the R values more normal?

Turner: The extinction near the galactic poles is so small that I don't think it is possible to say much about reddening slope or R-value in these directions.

Carrasco: When looking at anomalous extinction one has to concentrate on well defined areas. Grain growtl is best seen in individual clouds, where the wavelength of maximum polarization is well correlated with th derived values of R from photometric and spectroscopic data. If you extend your analysis to larger areas, yo would miss the specific trends in a given region, and end up with a "local" average value of R, that would b weighted towards an arbitrary ratio of stars with normal and abnormal extinctions. In other words extinctio towards individual stars in dark clouds is an individual characteristic, to derive a proper extinction curve fo those stars is a really complicated matter.

Turner: Yes, but in this Sco-Oph region, as an example, the optical reddening line analysis implies that th dust properties are fairly similar across the entire region. If there were such extreme anomalies as implied b the analysis of IR photometry, these stars should also exhibit deviant $E(U-B)$ and $E(B-V)$ excesses in th optical. Extinction by dust with $R=4$ should produce optical extinction with X smaller than other stars i the field. No such effect is seen. In Sco-Oph I also feel that it is incorrect to assume that optical depth is th true parameter which governs the variations in R_{KL}. The variation with M_{bol} is somewhat better, which woul imply that the R_{KL} variations depend upon circumstellar emission. Local anomalies in this field may not exist

D.G. Turner: Department of Astronomy, St. Mary's University, 923 Roble St., Halifax NS, B3H 3C3 Canad
e-mail: turner@husky1.stmarys.ca.