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Study of interstellar extinction in some young open clusters

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Summary. Interstellar extinction has been studied in 15 open clusters, based on reliable cluster members and precise observational data. Out of these, 10 show non-uniform extinction across the cluster region. Most of these show random variation of colour excess over the cluster face except NGC 6530 and 6611, where a systematic spatial variation of reddening is observed. The scatter in colour excess does not depend upon the spectral class between O and K. Only in some of the young clusters (age $\leq 5\times10^6$ yr) the variation of $E(B-V)$ correlates with luminosity and spectral class, in the sense that brighter cluster members are more highly reddened. Present analysis indicates that there is no uniformity in the relationship of extinction spatially, or with spectral type or luminosity or age, among these clusters and hence, explanation of non-uniform extinction in all young open clusters requires a complicated physical scenario.

1 Introduction

Study of the tenuous matter between stars known as interstellar matter is one of the hot topics of present day astronomical research. Interstellar matter plays an important role in the evolution and formation of stars and of the Galaxy, e.g. groups of new stars like those in the ϱ-Ophiuchus cloud (Vrba *et al.* 1975) and in a heavily obscured cluster in Ara (Koornneef 1977) are believed to have their birth places within gravitationally bound interstellar molecular clouds and are still embedded in dust and gas clouds. With time ($\approx 10^7$–10^8 yr) this dust and gas is either used in star formation processes or blown away by radiation pressure of hot stars present in such systems. Consequently, in young ($\leq 10^8$ yr) open clusters variable amount of dust and gas may be present either inside the open cluster or in the immediate vicinity of it. Study of interstellar matter present between members of a young star cluster helps in understanding the star formation processes in it. For example, Krelowski & Strobel (1979) have provided observational support for the sequential star formation process proposed by Elmegreen & Lada (1977) and Thaddeus (1977) on the basis of presence of non-uniform extinction in young open clusters and associations. According to sequential star formation processes, massive stars in open clusters should be younger than low-mass stars (*cf.* Margulis & Lada 1984 and the references therein) and the pre-main-sequence (MS) evolutionary scenario given by Larson (1973) suggests that, as the pre-MS stellar core evolves to MS, it is surrounded by a circumstellar envelope of parent material that continues to be accreted by the core. This view is observationally supported by Warner, Strom & Strom (1976) and McNamara (1976) on the basis of infrared observations of pre-MS objects in NGC 2264 and Orion Nebula cluster respectively and by Barry, Cromwell & Schoolman (1979) on the basis of spectroscopic analysis of F and G type pre-MS stars in NGC 2264. As they age, they approach the MS and dissipate their circumstellar material by either accretion onto or repulsion away from the star. Obviously, the time taken in dissipating the circumstellar material by the star depends upon the accretion rate during pre-MS evolutionary phase and upon the strength of radiation pressure and stellar wind produced during MS lifetime. Apart from these, young stars in clusters like Orion nebula (NGC 1976) show spectral blue veiling, ultraviolet excess, etc. (*cf.* Walker 1983 and the references therein). These effects make a star's $(B-V)$ colour too blue for its spectral type and a negative value of colour excess $E(B-V)$ for the star will be observed if the blueing effect of the blue continuum is greater than the reddening effect of interstellar absorption. Such values have been observed for few stars in NGC 1976 by Walker (1983). These discussions indicate that a combination of all these effects will produce the observed non-uniform extinction amongst the members of young open clusters. Whatever is the cause of non-uniform extinction in young open clusters, its careful study will definitely help in understanding the star formation processes in open clusters.

Wallenquist (1975, 1979) studied the presence of interstellar matter in open clusters and in their surroundings by star counts. Burki (1975) studied non-uniform extinction in intermediate age open clusters. Non-uniform extinction is present in many young open clusters. In some of these variation in colour excess, $E(B-V)$, is either systematic or random with respect to position (Sagar 1985) while in others it is a function of luminosity of stars (Blanco & Williams 1959; Reddish 1967) in the sense that most luminous stars have more colour excess. Most of the studies of non-uniform extinction in young open clusters are based either on photometry without reliable cluster members or vice versa. The importance of the use of accurate photometry and spectroscopic observations and reliable cluster members in the analysis of non-uniform extinction in extremely young clusters and asociations has been shown by Bohannan (1975). He re-analysed those 10 young clusters and associations which according to Reddish (1967) showed a strong increase of $E(B-V)$ with increasing stellar luminosity, using new photometric and spectroscopic data, by indentifying possible foreground stars etc., and found no correlation of reddening with luminosity in nine objects.

In the light of above discussions, a systematic study of non-uniform extinction in young open clusters based on reliable cluster members and their precise photometry and spectral classification is desirable. Recently the required data have become available for some young open clusters and the present work makes use of these valuable data in studying their non-uniform extinction.

2 Observational material

This section describes the criteria used for the selection of open clusters, data used in $E(B-V)$ estimation and method used for cluster membership.

2.1 STAR CLUSTERS AND DATA

From the catalogue of Lyngå (1984) 15 open clusters having *UBV* photoelectric photometric and spectroscopic data in the catalogue of Mermilliod (1986) for at least 20 proper motion members (discussed in Section 2.2) and younger than few hundred million yr where non-uniform extinction is expected, are included in the present work. The general informations about these clusters are listed in Table 1. Photometric data have accuracies generally better than ± 0.025 mag in V and

Table 1. General information and proper motion details of clusters under study. N_S, P_M and N_F respectively represent number of sample stars, median membership probability of the sample, and statistically expected number of field stars in the sample.

IAU Number	Sequence number	OCL number	Other names	l (deg)	b (deg)	Proper motion details: Accuracy (arc sec/ century)	Proper motion details: Source *	N_S	P_M (%)	N_F
C 0140 + 616	NGC 654	330		129.09	- 0.36	0.07	1	61	93	4
C 0228 + 612	IC 1805	352		134.73	0.92	0.16	1	92	80	18
C 0532 - 054	NGC 1976	528	Trapezium	209.02	-19.36	0.4	2	153	94	9
C 0629 + 049	NGC 2244	515		206.43	- 2.01	0.06	3	45	94	3
C 0638 + 099	NGC 2264	495		202.95	2.21	0.1	1	62	86	9
C 0757 - 607	NGC 2516	776		273.94	-15.88	0.07	4	65	99	1
C 1104 - 584	NGC 3532	839		289.64	1.47	0.13	5	84	87	11
C 1250 - 600	NGC 4755	892	K Crucis	303.20	2.53	0.06	6	32	90	3
C 1614 - 577	NGC 6087	948		327.75	- 5.41	0.15	7	21	97	1
C 1801 - 243	NGC 6530	19		6.12	- 1.35	0.06	1	65	88	8
C 1816 - 138	NGC 6611	54	M 16	16.99	0.78	0.07	1	30	88	4
C 1825 + 065	NGC 6633	90		36.11	8.27	0.07	1	21	85	3
C 1941 + 231	NGC 6823	124		59.41	- 0.16	0.08	1	38	94	2
C 2022 + 383	NGC 6913	168	M 29	76.92	0.61	0.25	1	55	73	15
C 2213 + 496	NGC 7243	221		98.87	- 5.55	0.28	8	23	-	-

*References:

1. Zhao *et al.* (1985).
2. McNamara & Huels (1983).
3. Marschall, van Altena & Chiu (1982).
4. King (1978b).
5. King (1978a).
6. King (1980).
7. King (1982).
8. Van Schewick (1957).

$(B-V)$ and ± 0.03 mag in $(U-B)$. The accuracy of MK classification is generally better than a subclass in spectral type and a class in luminosity.

2.2 CLUSTER MEMBERSHIP

Photometric, spectroscopic, statistical and kinematic methods are the most commonly used criteria for the separation of cluster members from field stars (*cf.* Sagar 1985; Sagar *et al.* 1986 and the references therein). Recently, proper motion studies have been carried out in the region of several young clusters (van Leeuwen 1985) because the proper motion criteria (i.e. kinematical criterion) do the job in a relatively better way than others if the accuracy of determination is good enough to separate cluster motion from the motion of field stars. In the absence of such type of data, photometric and spectroscopic criteria are the best tool of cluster membership. Proper motion studies are available for all the clusters under study and their details are listed in Table 1. In Fig. 1, we have constructed histograms of membership probability (p) of all investigated stars in the region of NGC 2516, 3532, 4755 and 6087. For other clusters such diagrams are available in the sources listed in Table 1. All these histograms indicate that most of the investigated stars are either in low p group ($\leqslant$10 per cent) or in high p group ($\geqslant$70 per cent). It means that the proper motion studies of these regions have been able to segregate cluster members from field stars and, hence, proper motion criteria have been used for the membership in clusters under study. Due to homogeneity in the p assignment of stars, we adopted the p values given by Zhao *et al.* (1985) for NGC 654, 2264, 6530, 6611, 6633, 6823, 6913 and IC 1805 instead of taking it from the original source of proper motion analysis of these clusters. The probability of inclusion of field stars in the sample will be reduced, if one considers only stars with $p \geqslant 50$ per cent and the same has been done

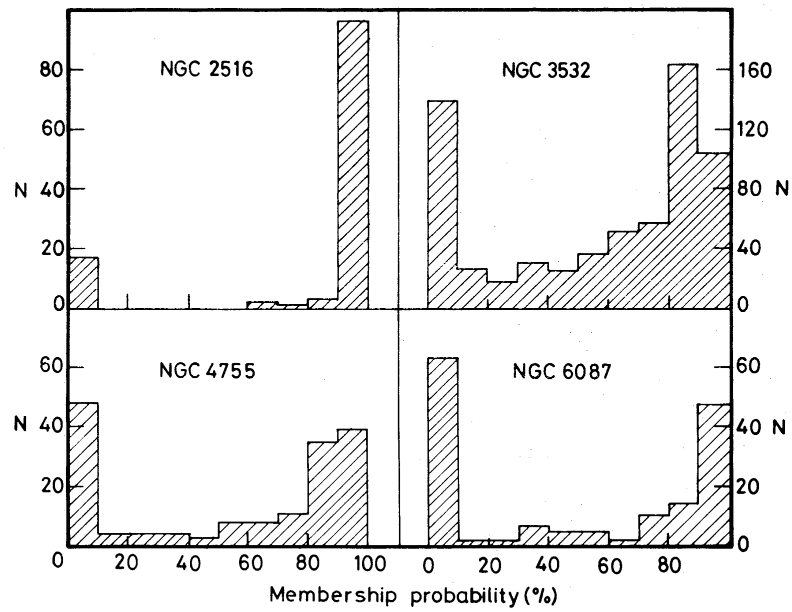

Figure 1. Membership probability distribution of stars investigated for proper motion analysis in the region of NGC2516, 3532, 4755 and 6087. The source of data is indicated in Table 1.

here for all except NGC7243. For the stars of this cluster, membership probabilities are not available, so we have considered only those stars which are members according to proper motion study by van Schewick (1957). Statistically expected number of field stars in our sample is estimated on the basis of median p of the sample and is listed in Table 1. Thus, one can say that presence of field stars in our sample will not affect the conclusions of present analysis.

3 Colour excess and non-uniform extinction

The procedure for the estimation of $E(B-V)$ and the criterion used for the presence of non-uniform extinction in the open clusters are described in this section.

3.1 ESTIMATION OF COLOUR EXCESS

From the MK classification of members an intrinsic $(B-V)_0$ index was assigned using the tabulation in Schmidt-Kaler (1982) and spectroscopic $E(B-V)$ has been estimated using photoelectric $(B-V)$ index of the cluster members. MK classification based on relatively higher dispersion and/or modern spectrograms was preferred in cases where it is available from more than one source. Wherever possible, homogeneous *UBV* photoelectric photometric data have been used. Most of the *UBV* data used for NGC 654, 2264, 6530, 6611, 6823, 6913 and IC 1805 are taken by us from the same instrumental set up (*cf.* Sagar 1985) and consequently form a homogeneous set of data. All these were done to increase the accuracy of $E(B-V)$ estimation. For the analysis in the Sections to come, $E(B-V)$ for statistically significant number of stars is required and spectroscopic $E(B-V)$ values for such number of members are available in NGC 1976, 2264 and 4755 amongst the clusters under study and show non-uniform extinction. In other clusters, to increase the sample we selected O and B MS proper motion members with photoelectric *UBV* values from the colour–magnitude diagram of the clusters and estimated photometric $E(B-V)$ using Q-method in the same way as described by Sagar & Joshi (1979). In order to put spectroscopic and photometric $E(B-V)$ values of a cluster on the same scale, we estimated photometric $E(B-V)$ values for O and B MS cluster stars with known MK classification and compared it with spectroscopic $E(B-V)$ values. Generally they agree, except a few cases where a small (≈0.02 mag) systematic difference has been observed and accounted for in the further analysis.

3.2 CRITERION FOR THE PRESENCE OF DIFFERENTIAL EXTINCTION

As the factors other than non-uniform extinction produce a maximum range in $E(B-V)$ of the order of 0.11 mag for MS members (*cf.* Burki 1975; Sagar 1985), we considered the presence of non-uniform extinction in the cluster region, if $\Delta E(B-V)$ $(=E(B-V)_{max}-E(B-V)_{min})$ for MS members is more than 0.11 mag, where $E(B-V)_{max}$ and $E(B-V)_{min}$ are estimated on the basis of respectively five highest and the same number of lowest $E(B-V)$ values of MS cluster members. In this way, evidence for the presence of non-uniform extinction is observed in all the clusters under study except NGC 2516, 3532, 6087, 6633 and 7243. Presence of non-uniform extinction in these clusters has also been noticed by earlier investigators, e.g. in NGC 654 by Pesch (1960), Moffat (1972), Stone (1977, 1980) and Joshi & Sagar (1983b); in NGC 1976 by Walker (1969) and Breger (1976); in NGC 2244 by Ogura & Ishida (1981); in NGC 2264 by Young (1978) and Sagar & Joshi (1983); in NGC 4755 by Dachs & Kaiser (1984); in NGC 6530 by Sagar & Joshi (1978) and Bohm-Vitense, Hodge & Boggs (1984); in NGC 6611 by Walker (1961), Kamp (1974) and Sagar & Joshi (1979); in NGC 6823 by Erickson (1971), Moffat (1972), Turner (1979) and Sagar & Joshi (1981); in NGC 6913 by Morgan & Harris (1956) and Joshi, Sanwal & Sagar (1983); and in IC 1805 by Johnson *et al.* (1961), Vasilevskis, Sanders & van Altena (1965), Ishida (1969), Moffat (1972) and Joshi & Sagar (1983a). Average value of $E(B-V)$, nature of reddening over the cluster region, true distance modulus, galactocentric distance and age of the clusters under study are listed in Table 2. This table indicates that generally clusters younger than 10^7 yr have non-uniform extinction.

Table 2. Reddening, distance modulus $(V-M_V)_0$ and age estimates along with the source for the clusters under study. R_G is the galactocentric distance in kpc assuming Sun at 8.8 kpc.

Cluster	R_G (Kpc)	Average E(B-V) (mag)	Reddening over the cluster region	$(V-M_V)_0$ (mag)	Age (10^6 yrs)	Source
NGC 654	10.4	0.88 ± 0.16	variable	11.85	35	Joshi & Sagar (1983b)
IC 1805	10.6	0.78 ± 0.21	variable	11.90	1	Joshi & Sagar (1983a)
NGC 1976	9.2	0.10 ± 0.09	variable	8.37	3	Walker (1969)
NGC 2244	10.1	0.43 ± 0.18	variable	10.75	4	Ogura & Ishida (1981)
NGC 2264	9.5	0.09 ± 0.07	variable	9.5	5	Sagar & Joshi (1983)
NGC 2516	8.8	0.14 ± 0.04	uniform	7.9	55	Dachs (1970)
NGC 3532	8.6	0.06 ± 0.03	uniform	8.45	200	Fernandez & Salgado (1980)
NGC 4755	7.8	0.41 ± 0.06	variable	11.82	10	Dachs & Kaiser (1984)
NGC 6087	8.0	0.18 ± 0.05	uniform	9.8	20	Landolt (1964)
NGC 6530	7.0	0.36 ± 0.05	variable	11.3	2	Sagar & Joshi (1978)
NGC 6611	5.8	0.78 ± 0.17	variable	12.5	5	Sagar & Joshi (1979)
NGC 6633	8.5	0.17 ± 0.05	uniform	7.5	1000	Hiltner et al (1958)
NGC 6823	7.6	0.85 ± 0.19	variable	12.7	5	Sagar & Joshi (1981)
NGC 6913	8.6	0.78 ± 0.20	variable	10.85	1	Joshi, Sanwal & Sagar (1983)
NGC 7243	9.0	0.21 ± 0.05	uniform	9.7	25	Lyngå (1984)

4 Cause of non-uniform extinction

To understand the possible cause of non-uniform extinction observed in the clusters under study, variation of $E(B-V)$ with spatial position, luminosity and spectral class of members have been studied as described in this section.

4.1 SPATIAL VARIATION OF REDDENING

We divided the cluster field into equal areas of small sizes to study the spatial variation of reddening across the cluster region. The variation of $E(B-V)$ is shown in Table 3 for NGC 1976, in Table 4 for NGC 2244 and in Table 5 for NGC 4755. For NGC 654, IC 1805, NGC 2264, 6530, 6611, 6823 and 6913 it has been shown earlier by us (see references in Table 2). Except for IC 1805, NGC 6530 and 6611, in other cluster regions the spatial variation of $E(B-V)$ is random. In NGC 6530 and 6611, $E(B-V)$ varies systematically with position. For example, in NGC 6530 the obscuration generally increases as one goes from west to east and, less generally so, as one goes from north to south across the cluster (Sagar & Joshi 1978). Similarly in the northern half of NGC 6611, the reddening increases as one goes from east to west and generally also, as one goes from south to north, being maximum for the north-west region of the cluster. But in the southern half of the cluster, $E(B-V)$ is relatively small and is constant (Sagar & Joshi 1979). In IC 1805, reddening in agreement with the findings of Moffat (1972), seems to be correlated with position of

Table 3. Spatial variation of reddening across the Orion Nebula cluster (NGC 1976). The average value of $E(B-V)$ in mag with standard deviation in areas 10×10 arcmin² is indicated in the appropriate boxes, with the number of stars used for this purpose given in brackets. Coordinates are in arcmin relative to $\alpha = 05^h 30^m 10^s$ and $\delta = -5° 20'$ (1900).

$\Delta\delta$ \ $\Delta\alpha$	-35 to -25	-25 to -15	-15 to -5	-5 to 5	5 to 15	15 to 25	25 to 35	35 to 45
-75 to -65						0.40 (1)		
-65 to -55								
-55 to -45	0.10±0.02 (2)	0.07 (1)	0.05 (1)	0.07±0.01 (3)	0.06 (1)		0.03±0.03 (2)	
-45 to -35		0.06 (1)	0.02 (1)	0.06±0.03 (10)	0.06±0.00 (2)		0.05±0.05 (2)	0.04 (1)
-35 to -25			0.12±0.03 (2)	0.05 (1)	0.03 (1)		0.71 (1)	0.08 (1)
-25 to -15		0.06±0.01 (2)	0.12±0.00 (2)	0.15±0.03 (2)	0.31±0.22 (5)	0.04 (1)	0.19±0.10 (2)	
-15 to -5			0.15±0.15 (4)	0.30±0.14 (10)	0.17±0.08 (7)	0.33±0.37 (3)		
-5 to 5	0.05±0.01 (2)		0.00 (1)	0.37±0.17 (6)	0.46±0.42 (4)	0.20 (1)		
5 to 15	0.03 (1)	0.39±0.33 (2)	0.31±0.37 (4)	0.27±0.22 (5)	0.26±0.32 (9)	0.03±0.03 (2)	0.06 (1)	
15 to 25	0.10 (1)	0.11±0.01 (2)		0.56 (1)	0.07±0.03 (3)		0.07 (1)	0.09 (1)
25 to 35			0.12±0.08 (3)	0.18±0.11 (4)	0.21±0.06 (2)			
35 to 45	0.37±0.13 (2)		0.02 (1)	0.12±0.08 (3)			0.71 (1)	
45 to 55	0.02±0.01 (2)		0.07±0.01 (4)	0.10±0.07 (5)	0.10±0.01 (2)	0.03±0.01 (2)	0.09 (1)	
55 to 65			0.10 (1)	0.02 (1)				

Table 4. Spatial variation of reddening across the cluster NGC 2244. The average value of $E(B-V)$ in mag with standard deviation, in areas 5×5 arcmin^2 is indicated in appropriate boxes, with the number of stars used for this purpose given in brackets. Coordinates are in arcmin relative to $\alpha=06^h 29^m 20^s$ and $\delta=04° 55'$ (1950).

$\Delta\delta$ \ $\Delta\alpha$	-25 to -20	-20 to -15	-15 to -10	-10 to -5	-5 to 0	0 to 5	5 to 10	10 to 15	15 to 20	20 to 25	25 to 30
-20 to -15		0.00 (1)	0.03 (1)								
-15 to -10	0.77±0.15 (2)	0.09 (1)									
-10 to -5			0.43±0.27 (3)								
-5 to 0				0.46±0.06 (3)	0.49 (1)	0.46±0.05 (4)					
0 to 5				0.07 (1)	0.46±0.04 (7)	0.48±0.04 (5)	0.55±0.02 (2)				
5 to 10				0.44 (1)	0.44±0.03 (3)	0.50±0.02 (2)				0.86 (1)	
10 to 15						0.44±0.02 (2)	0.39 (1)				
15 to 20											0.23 (1)
20 to 25							0.25 (1)			0.35±0.11 (2)	

Table 5. Spatial variation of reddening across the cluster NGC 4755. The average value of $E(B-V)$ in mag with standard deviation, in areas 2×2 arcmin² is indicated in appropriate boxes, with the number of stars used for this purpose given in brackets. Coordinates are in arcmin relative to $\alpha=12^h40^m$ and $\delta=-60°06'$ (1950).

Δδ \ Δα	−6 to −4	−4 to −2	−2 to 0	0 to 2	2 to 4	4 to 6
−4 to −2						0.31 (1)
−2 to 0	0.38±0.01 (2)	0.43 (1)	0.37±0.02 (3)	0.41±0.02 (4)	0.42±0.08 (3)	0.44 (1)
0 to 2		0.47±0.02 (2)	0.42±0.03 (3)	0.47±0.05 (2)	0.43±0.03 (3)	
2 to 4	0.34±0.02 (2)			0.48±0.02 (3)		0.41 (1)

the stars (Joshi & Sagar 1983a). Generally, relatively large values of $E(B-V)$ are for the members located in the western region of the cluster. However, some small areas distributed randomly across the entire cluster region also show larger values of $E(B-V)$ compared to their neighbouring areas. Recently, an UV extinction study by Bohm-Vitense *et al.* (1984) has shown that the extinction law for stars in NGC 6530 may be correlated with its position in the cluster.

For NGC 6823, our observation (Sagar & Joshi 1981) that there is a little evidence for a spatial correlation of $E(B-V)$ agrees very well with the same of Moffat (1972) and Turner (1979). In agreement with Stone (1980) we noticed very patchy distribution of reddening across the entire region of NGC 654 (Joshi & Sagar 1983a). However, we both observe, contrary to the findings of Moffat (1972) and Samson (1975) for NGC 654 that reddening does not depend upon the distance from the cluster centre.

4.2 VARIATION OF REDDENING WITH SPECTRAL TYPE

Variation of $E(B-V)$ with spectral type is shown for Orion Nebula cluster (NGC 1976) in Fig. 2, for NGC 2264, 654, 6823, 2244 and IC 1805 in Fig. 3 and for NGC 4755, 6530, 6611 and 6913 in

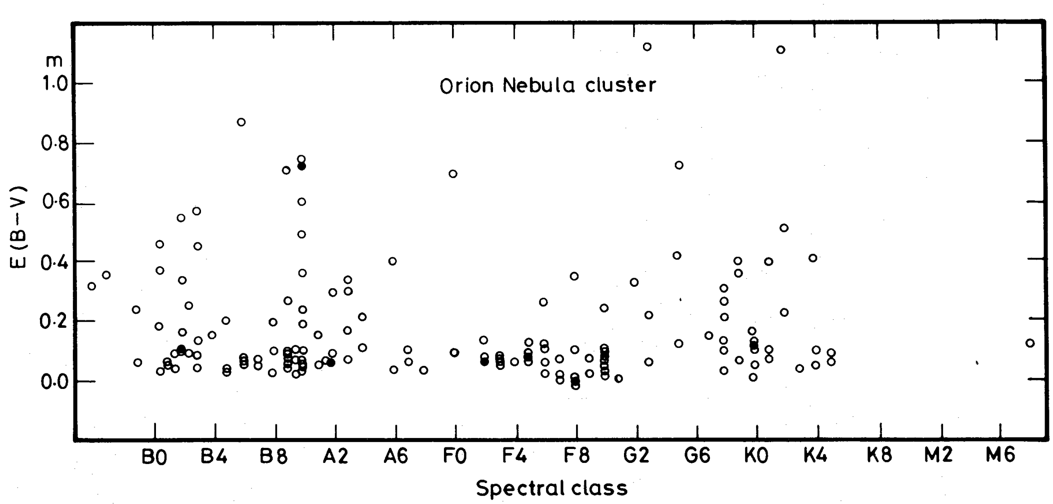

Figure 2. $E(B-V)$ versus spectral type plot for NGC 1976. Filled circles denote two coincident points.

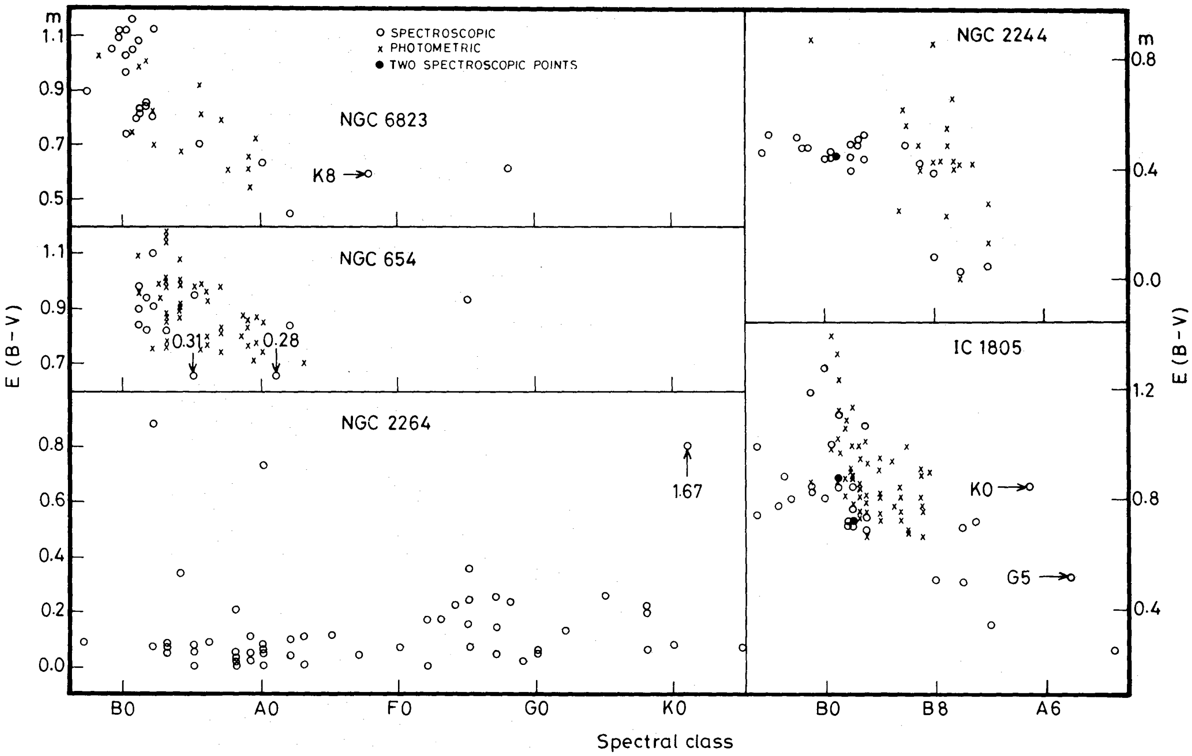

Figure 3. Plot of $E(B\text{–}V)$ versus spectral type for NGC 2264, 654, 6823, 2244 and IC 1805. Spectroscopic and photometric $E(B\text{–}V)$ values are denoted by open circles and crosses respectively. Filled circles denote two spectroscopic coincident points.

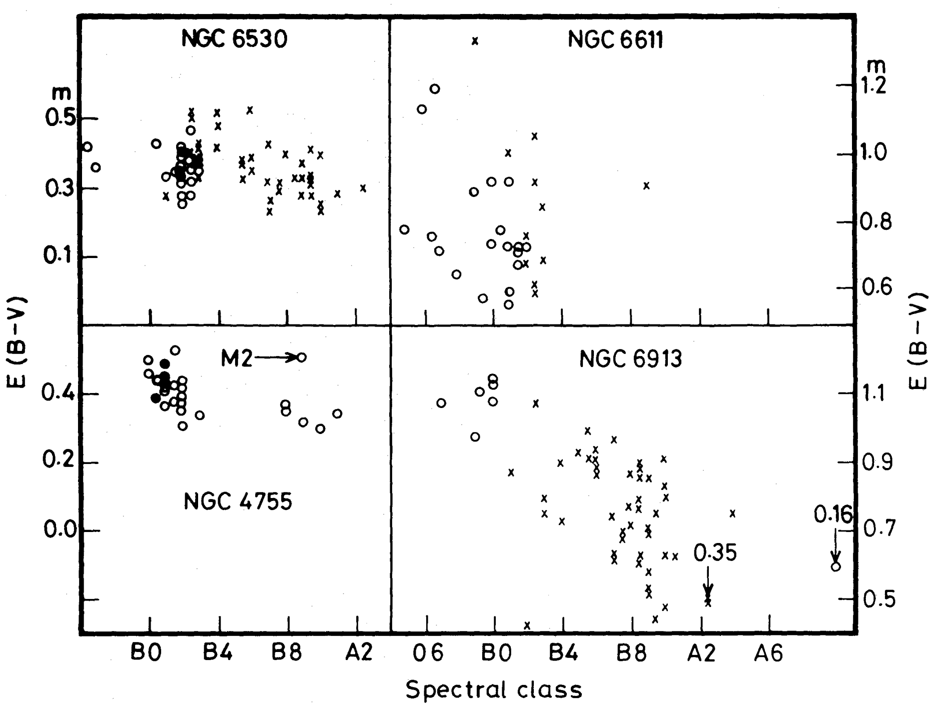

Figure 4. Plot of $E(B\text{–}V)$ versus spectral type for NGC 4755, 6530, 6611 and 6913. The notations are the same as in Fig. 3.

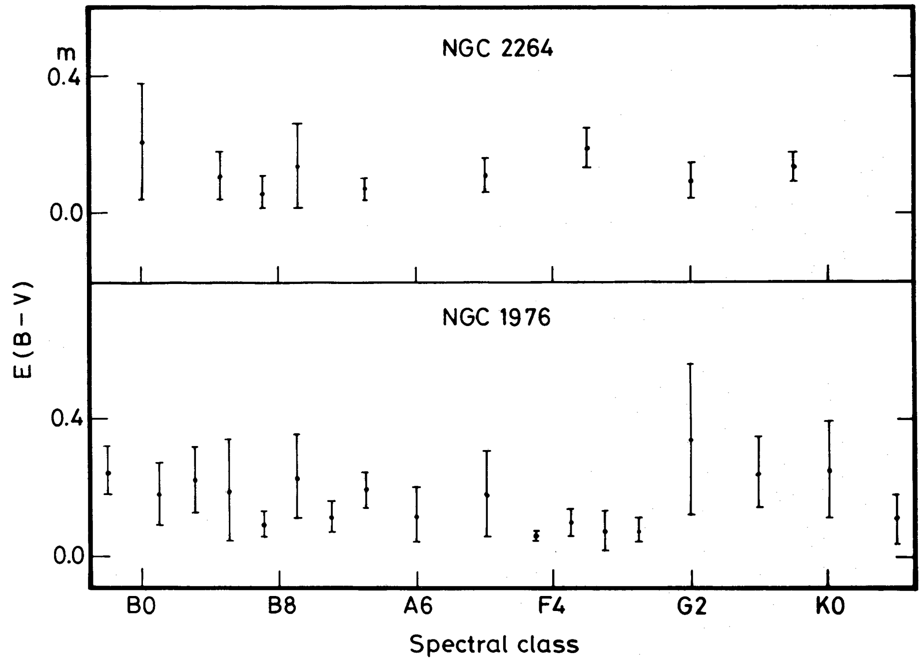

Figure 5. Plot of mean $E(B\text{–}V)$ and its standard deviation with spectral type for NGC 1976 and 2264. The length of the bar represents the value of standard deviation at that point.

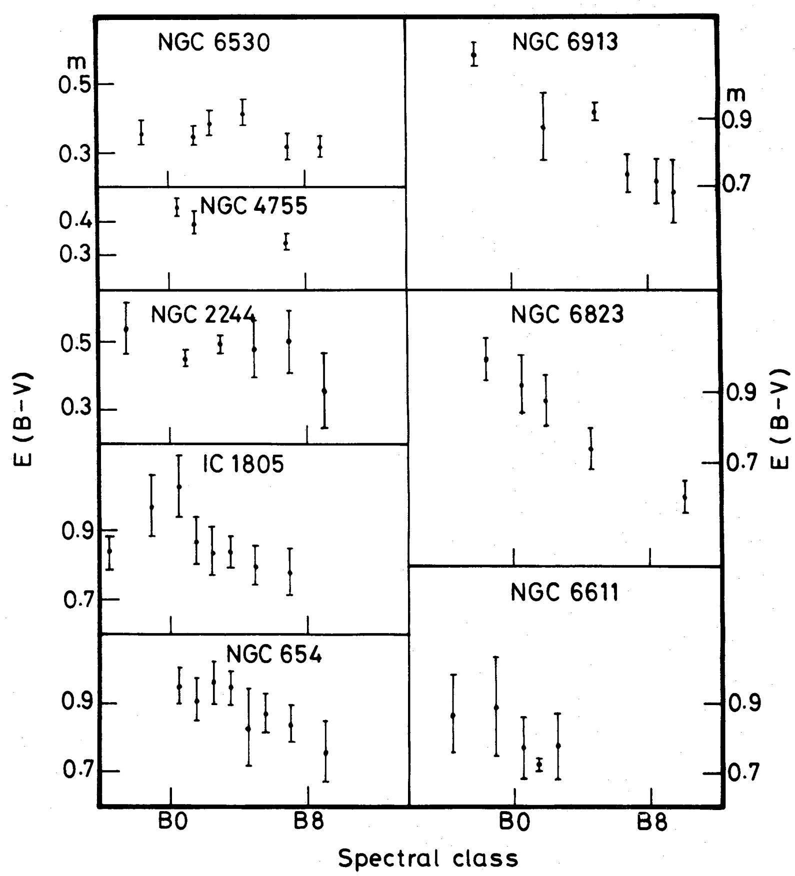

Figure 6. Plot of mean $E(B\text{–}V)$ and its standard deviation with spectral type for NGC 654, IC 1805, NGC 2244, 4755, 6530, 6611, 6823 and 6913. Symbols are the same as in Fig. 5.

Fig. 4. In these plots, for stars having photometric $E(B-V)$, spectral types have been estimated from its intrinsic $(B-V)_0$ value using the $(B-V)_0$–spectral type relation given by Schmidt-Kaler (1982). Except for NGC 1976 and 2264, where we have wide coverage of spectral type (from O to M), others have mainly early type of stars. These diagrams indicate that there is no correlation of $E(B-V)$ with spectral type for NGC 1976, 2244, 2264, 4755, 6530 and 6611. However, for IC 1805, NGC 6823 and 6913 the value of $E(B-V)$ generally decreases as one moves from early type to late type stars and less generally so for NGC 654. Bohannan (1975) also found, in agreement with us, no correlation of colour excess with spectral type for NGC 6611.

We plotted mean $E(B-V)$ and its standard deviation with spectral type in Fig. 5 for NGC 1976 and 2264 and in Fig. 6 for remaining clusters, to study the variation of scatter in $E(B-V)$ with spectral type. For estimating these values, we grouped cluster stars in such a way that generally five or more stars are used. In Figs 5 and 6, length of the bar represents the value of standard deviation (i.e. an indication of scatter) at that point. These diagrams indicate that scatter does not depend upon spectral type at least in the range of O to K. Bohannan (1975) has also observed that the dispersion in $E(B-V)$ of stars in young clusters and associations does not depend upon its spectral type. However, this does not agree with the findings of Krelowski & Strobel (1979) who found a large scatter in $E(B-V)$ for O to B3 and substantially smaller for B4 and later spectral type stars. The variation of scatter in $E(B-V)$ value with spectral type found by Krelowski & Strobel (1979) for NGC 1976 (Orion Nebula), 2264 and 6611, is distinctly different from the one observed here for these clusters. The difference may be due to the fact that the former, contrary to us, have

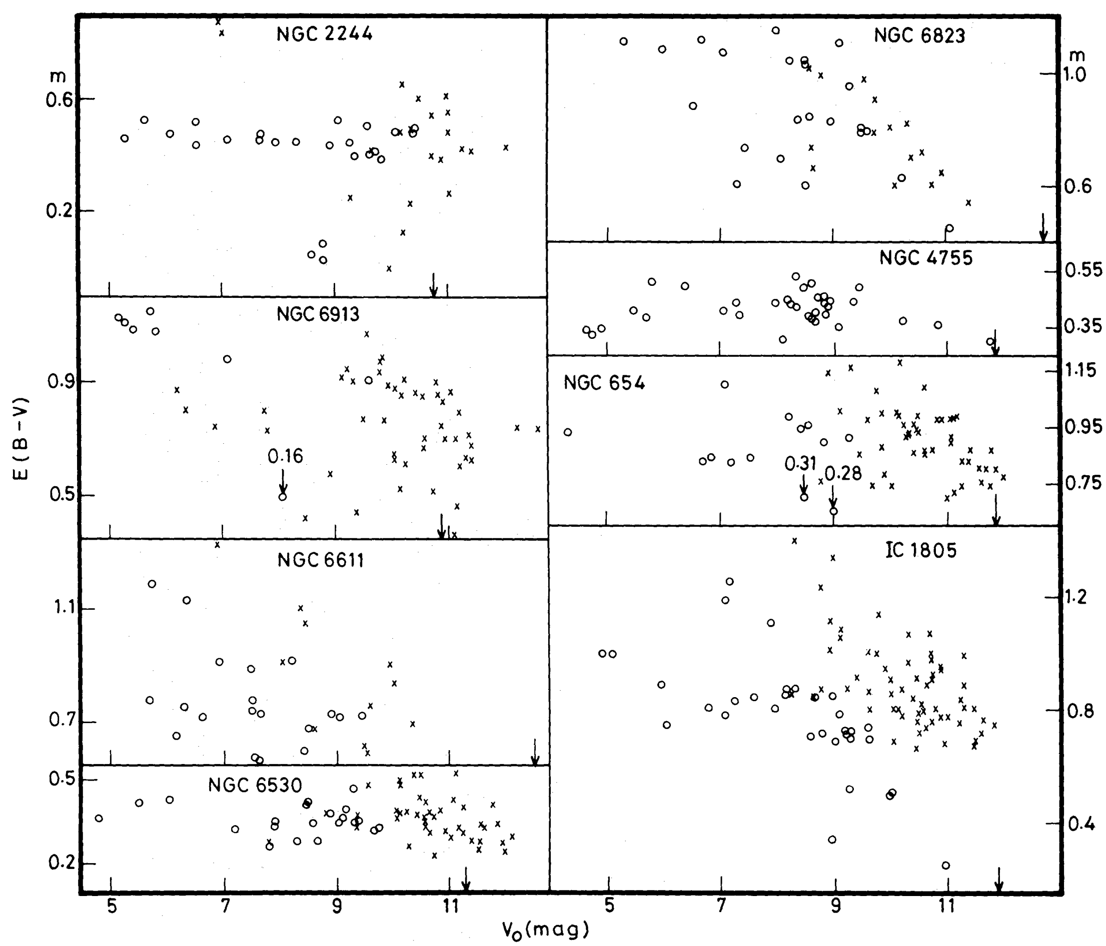

Figure 7. $E(B-V)$ versus V_0 diagram for NGC 6530, 6611, 6913, 2244, 6823, 4755, 654 and IC 1805. Symbols are the same as in Fig. 3. Arrow on V_0 axis denotes the value of true distance modulus of the cluster, i.e. M_V=0.0 mag.

not used the relatively reliable membership criteria (i.e. proper motion analysis) for separating the cluster members from field stars.

4.3 VARIATION OF REDDENING WITH LUMINOSITY

To study the variation of reddening with luminosity, we plotted $E(B-V)$ against $V_0[=V-3.25\ E(B-V)]$ or M_V for NGC 6530, 6611, 6913, 2244, 6823, 4755, 654 and IC 1805 in Fig. 7, and for NGC 1976 and 2264 in Fig. 8. In these diagrams, the arrow on V_0 axis denotes the point with M_V=0.0 mag. The location of the arrow has been decided using the value of true distance modulus of the cluster given in Table 2. To see the variation of scatter in colour excess with luminosity, we grouped cluster members in such a way that mean $E(B-V)$ and its standard deviation are generally based on five or more stars and plotted them against M_V in Fig. 9 which shows that scatter in $E(B-V)$ is generally independent of luminosity. It is in agreement with the finding of Section 4.2. An inspection of Figs 7–9 shows that:

(i) There is not a statistically significant dependence of $E(B-V)$ on luminosity (i.e. M_V) for NGC 654, 1976, 2244, 2264, 4755 and 6530. However, within the central region of NGC 654, the value of $E(B-V)$ for each star depends weakly upon its luminosity (Joshi & Sagar 1983b).

(ii) For NGC 6823, 6913 and IC 1805, generally $E(B-V)$ decreases with the M_V of cluster members in the sense that the brighter ones have relatively higher values of $E(B-V)$ than their faint counterparts. In the same sense, $E(B-V)$ has a weak dependence on luminosity for NGC 6611. For NGC 6823, Turner (1979) noticed a decrease in colour excess with M_V and Moffat (1972) also noticed the same dependence but only for stars brighter than V_0=9 mag. For IC 1805, Moffat (1972) contrary to us, did not find any dependence of reddening on luminosity.

Amongst the clusters discussed here, NGC 654, IC 1805, NGC 2244, 2264, 6530, 6611, 6823

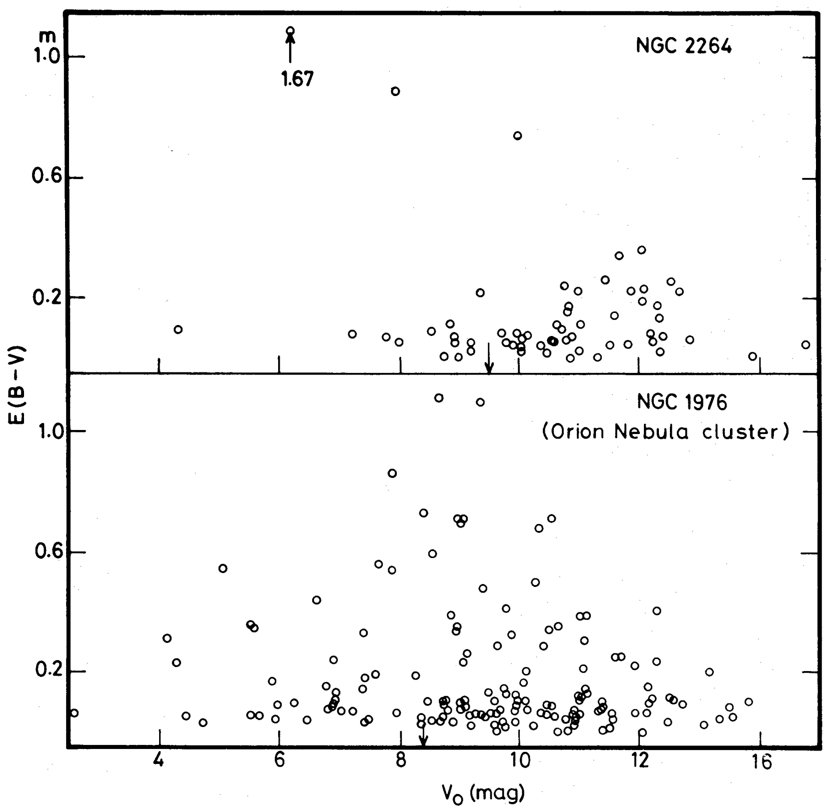

Figure 8. Plot of $E(B-V)$ versus V_0 for NGC 2264 and 1976. Arrow on V_0 axis denotes the same as in Fig. 7.

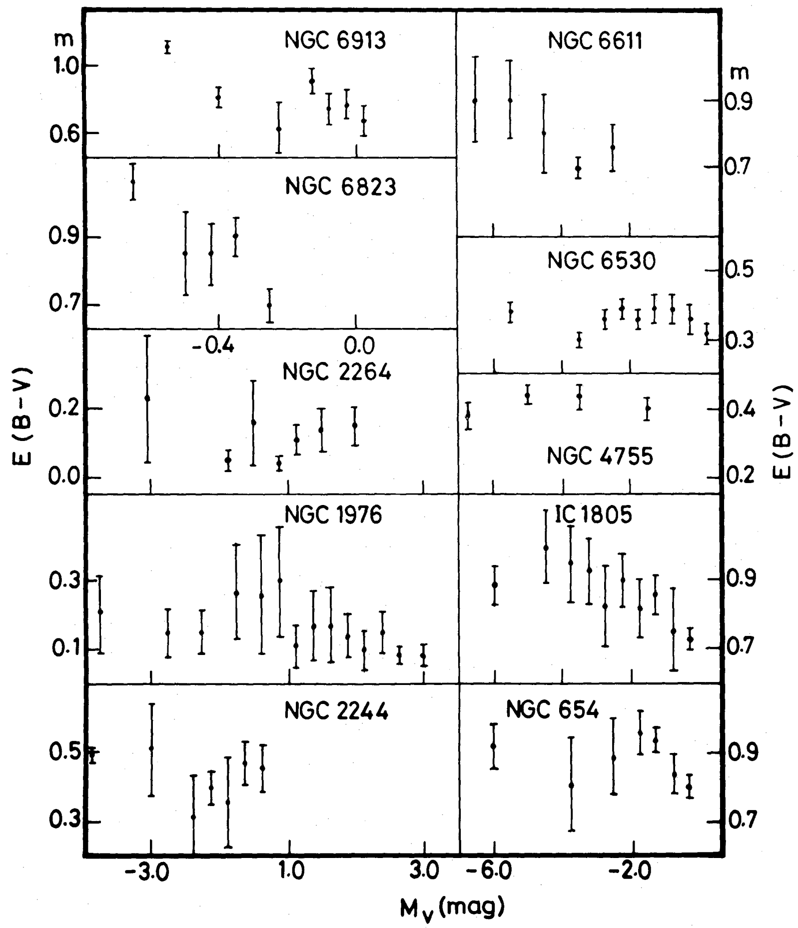

Figure 9. Plot of mean $E(B–V)$ and its standard deviation with M_V. Symbols are the same as in Fig. 5.

and 6913 have also been studied by Reddish (1967) for the dependence of interstellar reddening on luminosity. Variation of $E(B–V)$ with luminosity noticed here generally agrees with the findings of Reddish (1967). The main difference between the two works is that present analysis is based on relatively reliable segregation of cluster members and precise observational data.

4.4 EFFECT OF CALIBRATION SCALES ON THE VARIATION OF REDDENING

If there is any systematic error in intrinsic colour given by Schmidt-Kaler (1982) with luminosity or spectral type, this could produce a spurious correlation of $E(B–V)$ with either of these. The following arguments can rule this out:

(i) Use of the relations of $(B–V)_0$ with luminosity or spectral type given by Straizys (1977), Morton & Adams (1968) and Johnson (1966) produces only small ($\leqslant$0.02 mag) random changes in the $E(B–V)$ values used in the present analysis.

(iii) Observed relations of $E(B–V)$ with spectral type or luminosity of cluster members in Sections 4.1–4.3 are different for different clusters.

4.5 DISCUSSION ON VARIABLE REDDENING

We divided the cluster sample into the following groups on the basis of observations in Sections 4.1–4.3:

(A) Clusters namely IC 1805, NGC 6823 and 6913 show a clear dependence of $E(B–V)$ on spectral type and luminosity in the sense that colour excess increases with luminosity and effective temperature of the star. Ages of these clusters are ≤5 Myr (see Table 2). Except for IC 1805, there is no spatial correlation of reddening in the cluster region.

(B) Clusters belonging to this group are NGC 654 and 6611. They show weak dependence of colour excess with either spectral type or luminosity or both. Ages of NGC 654 and 6611 are respectively 35 Myr and 5 Myr (see Table 2). NGC 654 shows random spatial distribution of reddening while NGC 6611 indicates a systematic one over the cluster region.

(C) Clusters namely NGC 1976, 2244, 2264, 4755 and 6530 show no dependence of $E(B-V)$ with either spectral type or luminosity, belong to this group. Their ages are $\leq 10^7$ yr (see Table 2). Except for NGC 6530, all show random spatial distribution of reddening over the cluster region.

In addition to the above, we noticed that in NGC 2264, generally members brighter than $M_V=1.0$ mag have low value of $E(B-V)$ in comparison to faint members (1.0 mag$<M_V<3.3$ mag), if one discards the most discrepant points in Fig. 8. Similarly, Fig. 7 shows that relatively small number of bright IC 1805 members ($M_V<-4.0$ mag) are less reddened than the faint stars (-4.0 mag$<M_V<-1.0$ mag). Fig. 3 also indicates that stars with spectral type earlier than B0 in IC 1805 are relatively less reddened and stars in spectral range B0 and B2 have maximum reddening.

There are theoretical as well as observational grounds to believe that observed correlation of $E(B-V)$ with spectral type and luminosity for group A clusters may be due to presence of circumstellar material around young massive stars. For example, Krelowski & Strobel (1981 and references therein) on the basis of ultraviolet observations indicate that highly reddened luminous stars in associations and young clusters may have relict circumstellar matter around them. On the other hand, theoretical models for star formation processes given by Yorke & Krugel (1976) and Bhattacharjee & Williams (1980) suggest that the relative mass of a relict envelope present around a newly formed massive star is positively correlated with the stellar mass. According to the picture of sequential star formation processes in extremely young open clusters (*cf.* Margulis & Lada 1984) massive stars should be younger than low-mass stars. Ages of group A clusters are based on pre-MS stars, i.e. relatively low-mass stars. It means that massive stars in these clusters should be younger than the cluster age, i.e. they may have just arrived on the MS. It may indicate that in NGC 6823 and 6913, luminous stars might not find enough time to blow off their relict circumstellar material while stars brighter than $M_V=-4.0$ mag (i.e. spectral type earlier than B0) in IC 1805 and $M_V=1.0$ mag in NGC 2264 have been able to do so. Bright stars in NGC 2264 have been able to blow off the relict circumstellar material of relatively low-mass stars in comparison to the same in IC 1805. It may be because of the fact that the former are relatively older than the latter. However, the physical scenario presented above could not explain the following observed facts:

(i) The ages of some clusters in group B and C namely NGC 1976, 2244, 6530 and 6611 are comparable to the same of group A clusters and they also contain massive stars. Why do the stars in these clusters not show any dependence of colour excess either on luminosity or spectral type?

(ii) Luminous stars in IC 1805, NGC 1976, 2244, 6611 and 6823 have low as well as high values of reddening. Why is it so?

It is true that massive MS stars emit strong stellar winds and ultraviolet radiation. But the time required to blow off their relict circumstellar material will depend upon factors like mass of relict envelope, resistance offered by the immediate vicinity of it, etc. and hence, one may say that during the star formation processes in molecular cloud, conditions around the massive MS stars of group A cluster are such that relict circumstellar material is still present around them while it has been blown away from them in other clusters under discussion. The same argument can also be put forward to explain the observed low and high value of reddening around luminous stars in IC 1805, NGC 1976, 2244, 6611 and 6823. However, polarimetric, infrared and ultraviolet observations of heavily reddened massive stars in group A clusters as well as in NGC 1976, 2244 and 6611 are required to prove the reality of the existence of relict circumstellar matter.

5 Conclusions

In this work 15 open clusters selected from the catalogue of Lyngå (1984) have been studied. Photoelectric photometric and spectroscopic data are taken from the catalogue of Mermilliod (1986). Cluster members are selected on the basis of proper motion analysis. The assigned cluster membership probability indicates that the number of field stars included in the sample is statisticaly insignificant for the present work. Reddening estimates are based on MK classification and/or photoelectric *UBV* data. Study of the variation of reddening across the cluster face, with the spectral type and luminosity indicates that the observed variation of reddening in young open clusters may not be explained by, a 'simple', or even 'relatively simple' physical scenario. Actually, it depends upon the factors like age of cluster members, initial spatial distribution of matter in the molecular cloud, subsequent star formation processes and distribution of massive stars in the cluster and its location in the Galaxy, etc. However, following conclusions may be drawn from the present analysis:

(i) The observed systematic spatial variation of $E(B-V)$ in NGC 6530 and 6611 may be because of the presence of systematically varying amount of gas and dust either inside the cluster region or in its immediate vicinity. In these clusters no dependence of $E(B-V)$ either on luminosity or spectral class is observed.

(ii) Contrary to Krelowski & Strobel (1979), we observed that the scatter in $E(B-V)$ does not depend upon the spectral class at least in spectral range of O to K. However, in this regard our conclusions agree with that drawn by Bohannan (1975).

(iii) Random variation of $E(B-V)$ over a cluster face may be caused by either patchy distribution of interstellar matter across the cluster region or presence of circumstellar shells around young massive stars or a combination of both.

(vi) Variation of $E(B-V)$ with either luminosity or spectral type is not observed in all the clusters younger than 5×10^6 yr and which have massive stars. It may indicate that the factors responsible for this variation are not present in all the clusters under discussion.

(v) Variation of reddening across the cluster face, with spectral type and luminosity of members in clusters under study cannot be correlated with its galactocentric distance, R_G (see Table 2).

On the basis of above, one may conclude that the variation of reddening in one cluster is distinctly different from the others and there is no uniformity in the relationship of extinction spatially, or with spectral type or luminosity or age, among these clusters. All these indicate that a complicated physical scenario is required to explain the non-uniform extinction in all young open clusters.

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