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# Radial Distribution of the Integrated Light and Photometric Colours in Open Star Clusters

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**Abstract**. Mass segregation in the form of preferential concentration of more massive stars in the central regions of a number of open star clusters has been known for some time. In this paper, integrated *UBV* colours in concentric zones have been estimated for 12 nearby open clusters using the observations of individual cluster members. It is found that the clusters showing pronounced mass segregation also show significant radial variations in the integrated colours. However, the effects of stochastic fluctuations around the massive portion of the mass distribution function on the integrated colours should be taken into consideration, if they are present.

*Key words*: integrated light and colours—star clusters—population synthesis

## 1. Introduction

Star clusters in a galaxy are valuable tools for studying the, star formation histories, structure and evolution of the galaxy. These studies can be done in a relatively greater detail if the individual members of a star cluster are observed. For example, in nearby galactic open star clusters as well as in the star clusters of Magellanic Clouds, individual member stars are resolved and a number of studies are possible and have been done (*cf.* Sagar *et al.* 1986; Janes, Tilley & Lynga 1988; Mateo 1988 and references therein). Effects such as mass segregation have been observed in a number of galactic open clusters (Sagar *et al.* 1988 and references therein). Unfortunately, in distant star clusters of our galaxy as well as of external galaxies, observations of individual members are impractical even with the largest size ground-based optical telescopes. Although the Hubble Space Telescope whose resolution is expected to be at least 10 times better than the best that can be achieved on the earth, will push the distance limit approximately 10 times farther from the resolution point of view, but still cannot resolve the individual members of star clusters in M 31 and M 33 galaxies. On the other hand, observations of their integrated light can be made. One then needs to devise procedures to interpret such observations.

Here we show, how by performing multiple aperture surface photometric observations of distant star clusters where individual stars are unresolved, we can get information on the effect of mass segregation in such objects which otherwise is not possible.

Mass segregation in the form of a preferential concentration of more massive and hence the brighter member stars towards the inner regions of the cluster has been known for a number of clusters (*e.g.* see Sagar *et al.* 1988). In young open star clusters (age< $10^7$ yr), they are early-type main-sequence and/or blue supergiants, and cones quently have relatively bluer colours. The effect of mass segregation on the radial distribution of integrated colours is to provide relatively bluer colours for the inner cluster regions compared to the outer regions. However, contrary effect will be observed in relatively older open clusters because in such cases, massive and hence brightest stars are giants and/or late-type supergiants, depending upon the cluster age.

We have taken *UBV* photometric observations of those 12 nearby galactic open star clusters where the effect of mass segregation has generally been observed (Mathieu 1984; Sagar *et al.* 1988). By integrating the light of cluster members located in a circular region in each photometric passband, we have studied its radial distribution and have also tried to understand them in terms of the cluster age and stellar distribution in the colour-magnitude diagram which are known from the observations of individual cluster members.

The observational materials used in the study have been described in the next section. Estimation of integrated photometric colour from the observations of individual cluster members and study of its variation with radial distance are the topics of the remaining sections of the paper.

## 2. Observational data

The sources of the *UBV* photometric data as well as other general information about the star clusters included in the present study are given in Table 1. Photoelectric and homogeneous *UBV* data for nine of them namely IC 1805, NGC 581, 654, 2264, 6530, 6611, 6823, 6913 and Tr 1 have been taken earlier by us. In these clusters, membership is based on proper motion studies carried out by other investigators. The *UBV data*, for NGC 869 and 884; and BV data for NGC 6705 are photographic and are of relatively poor accuracy (0.05–0.08 mag) compared to the photoelectric ones (0.02–0.03 mag). However, this accuracy is sufficient for the present work. In these clusters membership has been determined using both the proper motion and photometric data.

## 3. Estimation of the radial distribution of integrated colours

For this, the point of maximum stellar density has been considered as the cluster centre which has been determined with an accuracy of ~ 1 arcsec (*cf.* Sagar *et al.* 1988). The cluster region is then divided into two or three concentric regions, depending upon the total number of stars in the cluster so that each region has generally more than 20 stars. Integrated colours $I(B-V)$ and $I(U-B)$ in a region have been estimated from the integrated *U*,*B* and *V* magnitudes which are evaluated as

$$I(m_j) = -2.5 \log\left(\sum_{i=1}^{N} 10^{-0.4 m_j}\right),$$

where $m_j$ are the observed magnitudes of a cluster member in *j* photometric passband and *N* is the total number of observed stars in the region. Contribution from unobserved faint cluster members to the integrated magnitude has been estimated by extrapolating the observed $I(m_j)$ against $m_j$ curve (*cf.* Sagar, Joshi & Sinvhal 1983;

**Table 1.** Sources of *UBV* data and other general information about the clusters considered here. Cluster age and number of member stars are denoted by '$t$' and $N$ respectively.

| Cluster designation | | $l$ | $b$ | | | |
|---|---|---|---|---|---|---|
| IAU | Others | (degree) | (degree) | $\log t$ | $N$ | Source of *UBV* data |
| C0129+604 | NGC 581, M 103 | 128.01 | −1.75 | 6.4 | 73 | Sagar & Joshi (1978a) |
| C0132+610 | Tr 1 | 128.22 | −1.13 | 7.4 | 37 | Joshi & Sagar (1977) |
| C0140+616 | NGC 654 | 129.09 | −0.36 | 7.6 | 88 | Joshi & Sagar (1983a) |
| C0215+569 | NGC 869, h Persei | 134.62 | −3.73 | 7.1 | 464 | Muminov (1983) |
| C0218+568 | NGC 884, χ Persei | 135.08 | −3.60 | 7.1 | 376 | Muminov (1983) |
| C0228+612 | IC 1805 | 134.73 | 0.92 | 5.8 | 169 | Joshi & Sagar (1983b) |
| C0638+099 | NGC 2264 | 202.95 | 2.21 | 7.0 | 139 | Sagar & Joshi (1983) |
| C1801−243 | NGC 6530 | 6.12 | −1.35 | 6.3 | 101 | Sagar & Joshi (1978b) |
| C1816−138 | NGC 6611, M 16 | 16.99 | 0.78 | 6.4 | 50 | Sagar & Joshi (1979) |
| C1848−063 | NGC 6705, M 11 | 27.3 | −2.8 | 8.3 | 860 | Mathieu (1984) |
| C1941+231 | NGC 6823 | 59.41 | −0.16 | 6.4 | 41 | Sagar & Joshi (1981) |
| C2022+383 | NGC 6913, M 29 | 76.92 | 0.61 | 6.1 | 103 | Joshi, Sanwal & Sagar (1983) |

Spassova & Baev 1985). Fortunately, these corrections are very small and also statistically insignificant for the clusters under discussion.

The integrated photometric colours are

$$I(B-V)=I(B)-I(V),$$

and

$$I(U-B)=I(U)-I(B),$$

where $I(U)$, $I(B)$ and $I(V)$ are the integrated magnitudes in *U, B* and *V* photometric passbands respectively. Table 2 lists the integrated (*B–V*) and (*U–B*) colours alongwith the average radii for the different regions of the clusters studied here. The various factors which can affect the accuracy of the integrated colours of clusters have been discussed in detail elsewhere (Sagar, Joshi & Sinvhal 1983). The accuracy of the integrated colours in a cluster region is ~0.05 mag and ~0.1 mag for photoelectric and photographic observations respectively.

## 4. Dependence of integrated colours on radial distances

Integrated (*B – V*) and (*U – B*) colours of all the clusters' regions have been plotted against their average radii in Fig. 1. Based on the differences between the integrated colours (*B – V), (U – B)* and (*U – V*) of outer and inner regions of the clusters given in Table 2 and the radial variations shown in Fig. 1, clusters can be classified into the following three groups:

(a) For the clusters namely IC 1805, NGC 884, 6823, 6705, Tr 1 and NGC 6530 belonging to this group, integrated colours of inner regions are bluer ($\Delta(U-V) > 0.15$ mag) than that of outer regions. Integrated colours seem to become systematically redder as one moves from inner regions to outer regions.

(b) No significant radial variation ($-0.15$ mag $< \Delta(U-V) < 0.15$ mag) of integrated colours is observed in the clusters namely NGC 581, 869, 6611 and 6913 of this group.

(c) Integrated colours are relatively redder ($\Delta(U-V) < -0.15$ mag) for the inner cluster region compared to its outer region. Only two clusters (NGC 654 and 2264) belong to this group.

### 4.1 *Effects of Stochastic Fluctuations in the Mass Function of a Cluster Region on Integrated Colours*

As most of the clusters under study are young and also are generally not very rich (see Table 1), stochastic fluctuations around the massive portion of the mass distribution function of a cluster region can sometimes produce a large change in the integrated colours of the cluster members of that particular region. This is mainly because of large changes in effective temperature and consequently, in *(B–V)* and *(U–B)* colours of a star during its post-main sequence evolution. Effect of such factors on the integrated magnitude and colours have been discussed earlier in detail by Barbaro & Bertelli (1977), Sagar, Joshi & Sinvhal (1983), Chiosi, Bertelli & Bressan (1988) and more recently by Pandey *et al.* (1989). In order to see whether such effects are present in this

**Table 2.** Integrated $(B-V)$ and $(U-B)$ colours and average radii $R_{av}$ of different regions of clusters. $\Delta$ is the difference between the integrated colours of outer and inner regions of a cluster.

| Cluster name | Innner region | | | Middle region | | | Outer region | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $I(B-V)$ (mag) | $I(U-B)$ (mag) | $R_{av}$ (arcmin) | $I(B-V)$ (mag) | $I(U-B)$ (mag) | $R_{av}$ (arcmin) | $I(B-V)$ (mag) | $I(U-B)$ (mag) | $R_{av}$ (arcmin) | $\Delta(B-V)$ (mag) | $\Delta(U-B)$ (mag) | $\Delta(U-V)$ (mag) |
| NGC 581 | 0.40 | −0.36 | 1.5 | — | — | — | 0.34 | −0.18 | 3.0 | −0.06 | 0.18 | 0.12 |
| Tr 1 | 0.32 | −0.31 | 0.5 | — | — | — | 0.41 | −0.10 | 1.5 | 0.09 | 0.21 | 0.30 |
| NGC 654 | 1.08 | 0.49 | 3.0 | — | — | — | 0.58 | −0.06 | 14.0 | −0.50 | −0.55 | −1.05 |
| NGC 869 | 0.39 | −0.44 | 3.2 | 0.40 | −0.42 | 6.7 | 0.34 | −0.47 | 10.9 | −0.05 | −0.03 | −0.08 |
| NGC 884 | 0.44 | −0.51 | 3.4 | 0.62 | −0.10 | 7.0 | 0.82 | −0.18 | 10.8 | 0.38 | 0.33 | 0.71 |
| IC 1805 | 0.56 | −0.42 | 4.2 | 0.58 | −0.36 | 13.8 | 0.80 | −0.07 | 24.0 | 0.24 | 0.35 | 0.59 |
| NGC 2264 | −0.05 | −0.60 | 8.0 | — | — | — | −0.20 | −1.02 | 16.0 | −0.15 | −0.42 | −0.57 |
| NGC 6530 | 0.12 | −0.68 | 3.8 | — | — | — | 0.45 | −0.40 | 22.0 | 0.33 | 0.28 | 0.61 |
| NGC 6611 | 0.50 | −0.62 | 2.4 | — | — | — | 0.48 | −0.56 | 12.0 | −0.02 | 0.06 | 0.04 |
| NGC 6705 | 0.47 | — | 1.7 | 0.57 | — | 4.6 | 0.75 | — | 9.0 | 0.28 | — | — |
| NGC 6823 | 0.55 | −0.49 | 3.0 | — | — | — | 0.93 | −0.11 | 12.8 | 0.38 | 0.38 | 0.76 |
| NGC 6913 | 0.68 | −0.10 | 5.0 | — | — | — | 0.65 | −0.05 | 13.4 | −0.03 | 0.05 | 0.02 |

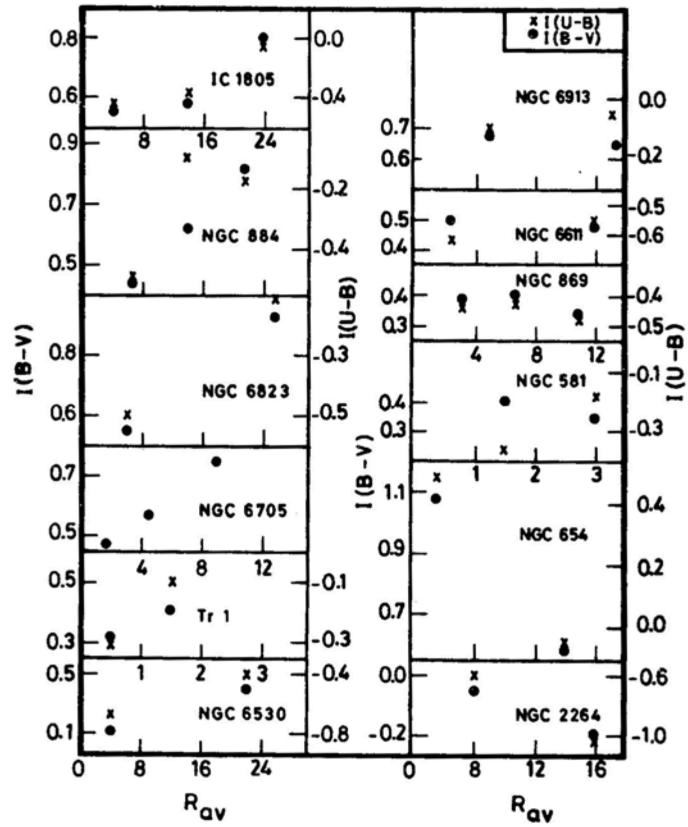


**Figure 1**. Radial variation of integrated *(B–V)* and *(U—B)* colours for all the clusters under study. $R_{av}$ represents the average radius for the region in arcminutes.

analysis or not, the distribution of cluster members with respect to *V* magnitude is studied. For illustration, the distribution of members of NGC 581,2264,654 and 869 is shown in Fig. 2. The histograms for the different regions of NGC 869 can be considered as representative for the distribution of members in the remaining clusters discussed here. It can be clearly seen that in one of the regions of NGC 581, 654 and 2264, the differences between the *V* magnitudes of brightest and next brightest stars are large, more than 2 mag. In the case of NGC 654 and 2264, their colours also differ appreciably. In such situation, the integrated photometric parameters of that particular region are strongly affected by the brightest member, as it has been shown numerically in our earlier work (Sagar, Joshi & Sinvhal 1983) as well as in the analysis to follow.

The integrated colours, when the brightest stars in both the inner and outer regions are excluded, have been estimated in the way described in Section 3 and are listed in Table 3. By excluding the contribution of the brightest star to the integrated light, one can avoid or reduce considerably the effects of stochastic fluctuations around the massive portion of the mass distribution function of a cluster region on the integrated colours because the brightest star not only dominates the integrated light of poor clusters but also is the one most likely to be somewhat evolved, with unpredicted

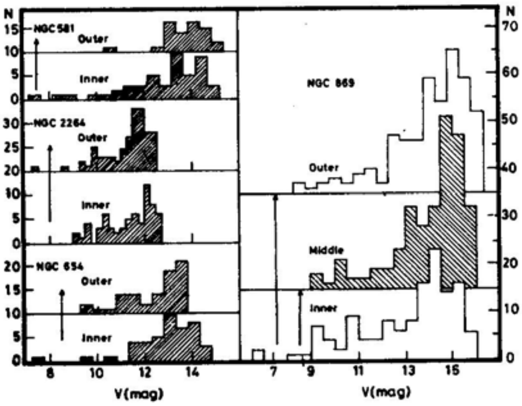


**Figure 2**. Distribution of stars with respect to *V* magnitude in different regions of NGC 654, 2264,581 and 869. *N* is the number of stars in a magnitude bin. Arrow denotes the amount off-set for the upper histogram.

colours. A comparison of Δ (*U* – *V)* values listed in Table 3 with those given in Table 2, clearly indicates that the effect of stochastic nature of the brightest stars has been minimum on massive clusters like NGC 869, 6705 and 6823. In others, the values of Δ(*U* – *V*) have generally increased indicating relatively much more uniform radial variations in integrated colours.

When the brightest stars are excluded, the clusters NGC 581, 6611 and 6913 join group ‘a’ while NGC 2264 joins group ‘b’ clusters whereas NGC 654 still belongs to group ‘c’ but the variation in integrated colours are reduced significantly. Therefore, when the effects due to stochastic fluctuations in the mass function of a cluster region are taken into consideration, then nine clusters namely IC 1805, NGC 581, 884, 6530, 6611,6705,6823,6913 and Tr 1 belong to group ‘a’; two clusters (NGC 869 and 2264) populate group ‘b’; and only NGC 654 remains in group ‘c’.

### 4.2 *The Observed Radial Variation of Integrated Colours*

Most of the brightest and hence massive stars in group ‘a’ clusters are of early type because of their young age (see Table 1). Mass segregation has also generally been observed in them (Mathieu 1984; Sagar *et al.* 1988). Consequently, for group ‘a’ clusters, relatively bluer integrated colours observed for the inner regions compared to the outer regions can be due to the presence of mass segregation in them. Similarly, the observed variation of integrated colours for the only group ‘c’ cluster can also be understood because its massive stars are either late type super giants or red giants (Joshi & Sagar 1983a) and Sagar *et al.* (1988) indicate the possibility of the presence of mass segregation in the cluster. We, therefore, observe in group ‘a’ and ‘c’ what one expects. On the other hand, absence of significant radial variation of integrated colours in the group ‘b’ cluster NGC 869 is contrary to expectation. However, it may be noted that the mass segregation effect in this cluster is not very pronounced (Sagar *et al.* 1988). NGC 2264 has two cluster centres (Sagar *et al.* 1988) and this could vitiate the search for colour gradients.

Mass segregation in clusters that produces the observed colour gradients could either be of primordial origin from the time of star formation in the cluster (Sagar *et al.* 1988) or be due to dynamical evolution. While the observed mass segregation in young clusters (<a few $10^7$ yr)must necessarily be of primordial origin, in the relatively older ones it could be either due to dynamical effects or a combination of both. A plot of the colour difference $\Delta$ ($U - V$) (computed after excluding the brightest stars to remove stochastic fluctuation effects) given in Table 3 against the cluster age is shown in Fig. 3, where a weak correlation can be seen. The cluster NGC 6705 (not shown in Fig. 3) is relatively old, but the colour gradient($\Delta$ ($B - V$)) found in the cluster indicates that it belongs to group 'a'. This could be due to the fact that the number of evolved massive red stars in the cluster is low (Mathieu 1984). Such things can be observed if star formation in the cluster was not coeval and more massive stars were formed towards the end in the central region.

The effect of mass segregation is to flatten the slope of stellar mass function in the inner regions as compared to the outer regions. Also a consequence of this is that the upper mass limit of the mass spectrum is higher in the inner regions compared to the outer regions. Theoretical calculations indicate that a change in the slope of mass function affects the integrated colours very little (Searle, Sargent & Bagnuolo 1973). Contrary to this, the increased upper mass limit of the mass spectrum affects significantly the integrated colours as observed here.

## 5. Conclusions

Following useful conclusions can be drawn from the present analysis:

(1) In the absence, or after removal or reduction of stochastic fluctuations towards the massive portion of the mass distribution function of a cluster region, the presence of mass segregation in star clusters generally produces a radial variation of integrated colours.

**Table 3**. Integrated ($B - V$) and ($U - B$) colours when the brightest stars in both inner and outer regions are excluded. Their differences in the same sense as given in Table 2 are also listed.

| Cluster name | Inner region $I(B-V)$ (mag) | Inner region $I(U-B)$ (mag) | Outer region $I(B-V)$ (mag) | Outer region $I(U-B)$ (mag) | $\Delta(B-V)$ (mag) | $\Delta(U-B)$ (mag) | $\Delta(U-V)$ (mag) |
|---|---|---|---|---|---|---|---|
| NGC 581 | 0.59 | −0.32 | 0.44 | 0.02 | −0.15 | 0.34 | 0.19 |
| Tr 1 | 0.32 | −0.35 | 0.44 | −0.05 | 0.12 | 0.30 | 0.42 |
| NGC 654 | 0.79 | 0.04 | 0.57 | −0.02 | −0.22 | −0.06 | −0.28 |
| NGC 869 | 0.37 | −0.44 | 0.36 | −0.45 | −0.01 | −0.01 | −0.02 |
| NGC 884 | 0.45 | −0.49 | 0.76 | −0.29 | 0.31 | 0.20 | 0.51 |
| IC 1805 | 0.52 | −0.44 | 0.81 | 0.10 | 0.29 | 0.54 | 0.83 |
| NGC 2264 | −0.01 | −0.48 | −0.05 | −0.47 | −0.04 | 0.01 | −0.03 |
| NGC 6530 | 0.12 | −0.65 | 0.64 | −0.12 | 0.52 | 0.53 | 1.05 |
| NGC 6611 | 0.53 | −0.60 | 0.58 | −0.36 | 0.05 | 0.24 | 0.29 |
| NGC 6705 | 0.47 | — | 0.75 | — | 0.28 | — | — |
| NGC 6823 | 0.56 | −0.46 | 0.94 | −0.06 | 0.38 | 0.40 | 0.78 |
| NGC 6913 | 0.73 | −0.14 | 0.67 | 0.08 | −0.06 | 0.22 | 0.16 |

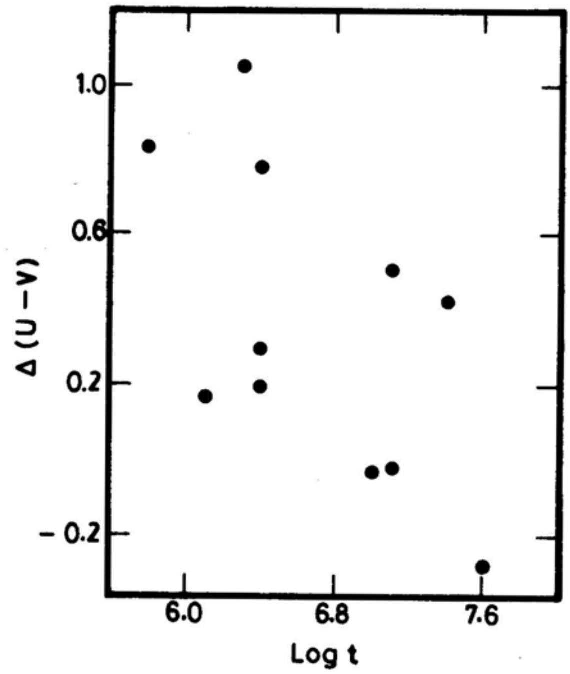


**Figure 3.** Plot of ($U$ — $V$) versus log of age.

(2) The effects of stochastic nature of the brightest stars are very small on the intergrated colours of massive clusters. This is important because observations of integrated light of star clusters in other galaxies will be mainly restricted to the most massive ones, where it may be possible in some cases to remove the effects of one or two brightest stars even though the cluster is not fully resolved. Consequently, by performing multiple aperture surface photometry in such clusters, one can learn something about mass segregation.

(3) The differences between the integrated colours of outer and inner regions of the clusters listed in Table 2, indicate that the variation is generally more *in* $I(U–V)$ compared to either $I(B–V)$ or $I(U–B)$. In fact, it generally increases in a systematic manner if $I(V)$ in the difference ($I(U)–I(V)$), is replaced by $I(R)$, $1(1)$, $I(J)$, $I(H)$ and $I(K)$ respectively (*cf.* Tarrab 1982). This implies that wider the separation between the effective wavelengths of the photometric passbands used for the estimation of integrated colour, more pronounced is the effect of mass segregation on its radial variation. Consequently, from the point of view of observations, a study of mass segregation in terms of $I(U–K)$ will be more useful compared to $I(U–V)$ or $I(V–R)$, etc. However, one should account for the effects of stochastic fluctuations before drawing any conclusion about mass segregation from such observations as they will also increase with the increase of colour baseline.

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