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THE CLUSTER SYSTEM IN THE SMALL MAGELLANIC CLOUD

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SUMMARY

Visual examination of 330 star clusters in the SMC on *UBV* plates taken with the UK 48-in. Schmidt telescope allows clusters to be classified by colour and structure into six types. A distinct pattern in the spatial distribution of clusters reported by Hodge is confirmed, though the effective size of the cluster system is the same as that defined by integrated star light. Cluster sizes, excluding red globulars, are on the whole larger than their galactic counterparts.

1. INTRODUCTION

During the first year of operation, the UK 48-in. Schmidt telescope at Coonabarabran, Australia, has provided a series of high quality plates of the Small Magellanic Cloud, including a IIIaJ 1-hr exposure which reaches (B) magnitude 23, the faintest yet achieved on this object. A first examination of the plates revealed a number of star clusters not contained in the well-known catalogues of Kron (1956a) and Lindsay (Lindsay 1958; Lindsay & McFarland 1971) and a search for new clusters was undertaken. Meanwhile, a substantial addition to the SMC clusters was provided by Hodge & Wright (1974) who catalogued 86 new ones, bringing the total known to 220. Of this number, 160 are identified within the $6° \times 6°$ field of the UK plates, where an additional 170 further clusters were found. All objects were examined visually on U, B and V plates to provide estimates of brightness, colour and size.

2. IDENTIFICATION OF CLUSTERS

The initial search was made by examining the IIIaJ plate under low power magnification and recording all objects which might be candidates. In the highly populated regions of the Cloud and among bright nebulosities, many doubtful objects were noted, which were later checked by referring to a less exposed B plate (IIaO emulsion + GG 385 filter reaching $B = 21^{m}\cdot5$) and to a V plate (IIaD emulsion + GG 495 filter reaching $V = 21^{m}$). Objects clearly visible on all three plates were accepted as genuine. Others, which, though visible, did not stand out conspicuously against the general field on the V plate were listed as possible clusters.

For colour classification, a high quality U plate (103aO emulsion + UG1 filter, exposure 1 hr, limiting magnitude 18^{m}) was compared in a blink comparator with the V plate chosen from a number available because it was found to match the U plate excellently as regards image appearance and background density. The contrast between blue and red objects on this pair of plates made colour classification relatively straightforward.

The magnitudes of matching images on the U and V plates differed over the range $V = 12^m$ to 17^m by a constant amount of about 1 mag, the V plate, of course, reaching fainter stars. This was established by comparing a number of UBV photoelectric sequences set up by Butler (1972) in various parts of the Cloud. The colours of clusters could therefore be estimated as less or greater than $(U-V) = -1^m.0$ according as they appeared brighter or fainter on the U plate than on the V.

Many of the clusters appeared more or less identical on both plates, pointing to a blue cluster with vertical main sequence. Clusters which appeared only a little less bright, but otherwise identical, on the U plate, could also be designated 'blue', with $(U-V)$ estimated as certainly negative. Red globular clusters, on the other hand, though conspicuous on the V plate, vanished entirely or almost entirely on the U plates. In other cases, some stars seen in V remained conspicuous on the U plate while others disappeared; such clusters were considered to contain mixed blue and red constituent stars.

Visual classification could be confirmed by viewing clusters with known colour–magnitude diagrams as observed by Arp, Gascoigne and others (see Table I) and using them as standards. To the colour and brightness classification was added estimates of cluster diameters measured on the V plate to the nearest 0·1 mm ($6''.8$). From these various observations it was found that clusters could be broadly divided into six groups as shown in Table I. The larger clusters (types 1–4) were unmistakable by virtue of their size. For the smaller blue clusters (type 5) the limit is dictated by the U plate, and therefore small galactic clusters with brightest members fainter than 18^m ($M_V = -1$) are not recorded.

Of course there is a certain blurring in the distinction between the various types, especially the separation of types 1 and 2, and between 2 and 3. Where blue stars were found mixed with red, it is not always possible to know how great a part of the field stars play in the colour classification, and there are five or six clusters which fall on each borderline and may be wrongly classified. Types 4 onwards are more distinct, the sequence from 4 to 6 representing in general a decrease in both brightness and blueness; all but one of our new clusters fall into these groups.

An attempt to assign ages to the various cluster types on the basis of visual estimates of stellar content is of necessity extremely crude. In the case of those clusters with well determined colour–magnitude diagrams mentioned in column 5 of Table I, age determinations are available and are given in the last column of the table. These ages, however, are far from finally settled: according to Gascoigne (1966) those listed as types 1 and 2 belong to the same age group (10^9 yr); other observers (references in the table) find an age distinction, making Kron 3 and NGC 121 older than NGC 361 and 419 which are the well-known clusters of globular appearance discovered by Arp containing both blue and red stars. Types 3 and 4 are luminous young blue objects differing only in their relative star density. Type 3 resemble the compact groups in the LMC whose ages are given as 6×10^6 yr by Westerlund (1961a), though it ought to be mentioned that Heckman (1974) using the method of population synthesis derives an age of 7×10^7 for NGC 458, a typical member.

TABLE I

Cluster types

Type	No. of clusters	Average diameter (pc)	Description	Matching CM diagram	Reference	Estimated age of matching clusters (yr)
1	27	20	Mainly globular in appearance, red stars only, invisible in U	Kron 3	Gascoigne (1966), Walker (1970)	10^9–10^{10}
				NGC 121	Tifft (1963)	
2	21	10	Mainly globular in appearance, less red than type 1 with mixture of blue stars	NGC 419	Arp (1958a) Walker (1972)	10^9
				NGC 361	Arp (1958b)	
3	34	10	Spherical compact, predominantly blue, diameters >5 pc	NGC 330	Arp (1959b) Robertson (1974)	10^6
				NGC 458	Arp (1959a)	5×10^7
4	82	10	Loose resolved groups, blue with vertical ms, diameters ≥ 5 pc	NGC 456	Westerlund (1961b)	10^6–10^7
				NGC 371	Andrews (1971)	
5	112	2	Small groups, blue stars but less luminous than type 4, brightest stars $M_V \simeq -2{\cdot}5$, diameters <5 pc	Pleiades		5×10^7
6	54	5	Probable clusters, fainter than type 5; mainly small			10^8?

TABLE II

List of clusters of types 1 to 3

Type 1	L3, 4, 5, 6, 7, 8 (Kron 3), 9, 10 (NGC 121), 11, 12, 14, 15, 17, 18, 19, 20, 27, 36, 38, 46, 55, 57, 68, 91, 110, 111, 112
Type 2	L13, 23, 26, 43, 58, 59, 67 (NGC 361), 78, 81, 82, 85 (NGC 419), 86, 93, 102, 106, 108, HW 14, 57, 61, E109
Type 3	L22, 21, 28, 30, 31, 34, 35, 37, 39, 40, 44, 47, 49, 50, 52, 53, 54 (NGC 330), 56, 63, 64, 65, 66, 70, 72, 74, 77, 79, 80, 87, 89 90, 96 (NGC 458), 100, HW77

L, Lindsay numbers (1958); HW, Hodge & Wright (1974); E109 lies between L42 and L44.

Table II lists the clusters which fall into categories 1–3. The remainder are not individually listed but are distinguished in the plots in Fig. 1. A complete list with charts will appear in *Publications of the Royal Observatory Edinburgh*, **9**, No. 5.

Where a comparison could be made, our colour classification agrees with the

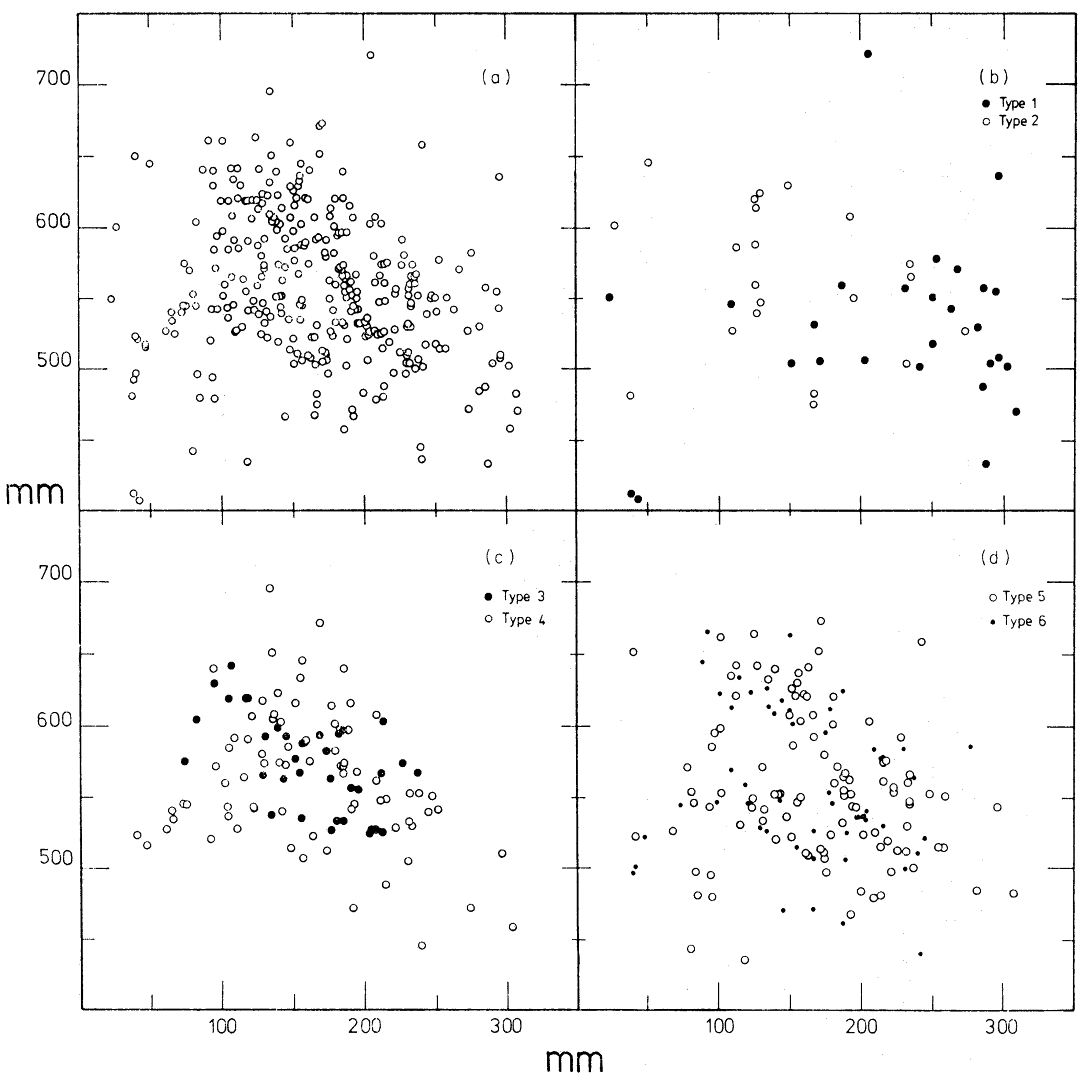

FIG. 1. *Distribution of clusters (a) all types, (b) red, (c) blue, (d) small open clusters. Scale 68″ per mm.*

visual colours of Kron (1956a) estimated from a blink comparison of blue and red plates taken with the ADH Schmidt telescope and the integrated colours of van den Bergh & Hagen (1968).

3. COMPLETENESS OF THE SURVEY

While potentially our plates are capable of reaching open clusters as faint as the Hyades whose brightest stars would have magnitude 20 in B and V, in practice such clusters are impossible to identify positively. In size their diameters are of the order of only one or two stellar images; the field stars are likely to be as bright in V as their brightest members, and they would be entirely invisible on the U plate. Consequently, though a number of objects would could well be clusters were noted, they could not be confirmed. In addition, irregular strings of stars and groups which are subdivisions of larger clusters were also in general excluded. By adopting these criteria of shape and colour it is hoped that random groupings are eliminated and the majority of genuine clusters down to Pleiades type discovered.

An estimate of completeness could be made by comparing our list with Hodge & Wright's. Of the 67 clusters in the field which have been given confident identification by these authors, all but four have also been recorded on our plates, though some were later excluded on one of the grounds described above. Of Hodge & Wright's 14 doubtful identifications, only three appear among our adopted clusters. Where we overlap with these authors, our finding rate is probably better than 90 per cent.

4. DISTRIBUTION OF CLUSTERS

Fig. 1(a) is a plot of the positions of all the clusters. In addition to the overall roughly elliptical appearance, the bar is clearly outlined around (190, 550) and the wing pointing south-east at (70, 550). The central gap to which Hodge (1974) draws attention, is also clearly visible at (160, 540); this is a region of diameter equivalent to about 40 pc containing no clusters which coincides with a region of low luminosity in blue. It would appear also that there is a similar blank gap on the opposite side of the bar, at about (190, 570).

In Fig. 1(b), (c) and (d), cluster positions are plotted by type. In Fig.1(b), showing types 1 and 2, the very red clusters are seen to separate from the others, as already shown in a diagram of de Vaucouleurs' (1972). Fig. 1(c) shows that the associations define the wing and bar and also form a sharp boundary on the NW side, while the compact clusters tend to occur in the centre. The overall pattern follows Westerlund's (1971) account of population types in the SMC.

The small open clusters in Fig. 1(d) form the most regular distributions, with 90 per cent of them falling within the elliptical envelope shown in Fig. 2 which is centred on $0^h\ 55^m$, $-72°\ 50'$ (1975), position angle 55°, semi-major axis 270′, ratio of minor to major axes 0·62.

5. POSITION ANGLE AND ORIENTATION OF CLUSTER SYSTEM

The outline of the small clusters has been chosen as most suitable for defining the position of the disk of the Cloud, as these clusters are the most numerous, are of uniform size and age and are expected to belong to the disk. The position angle,

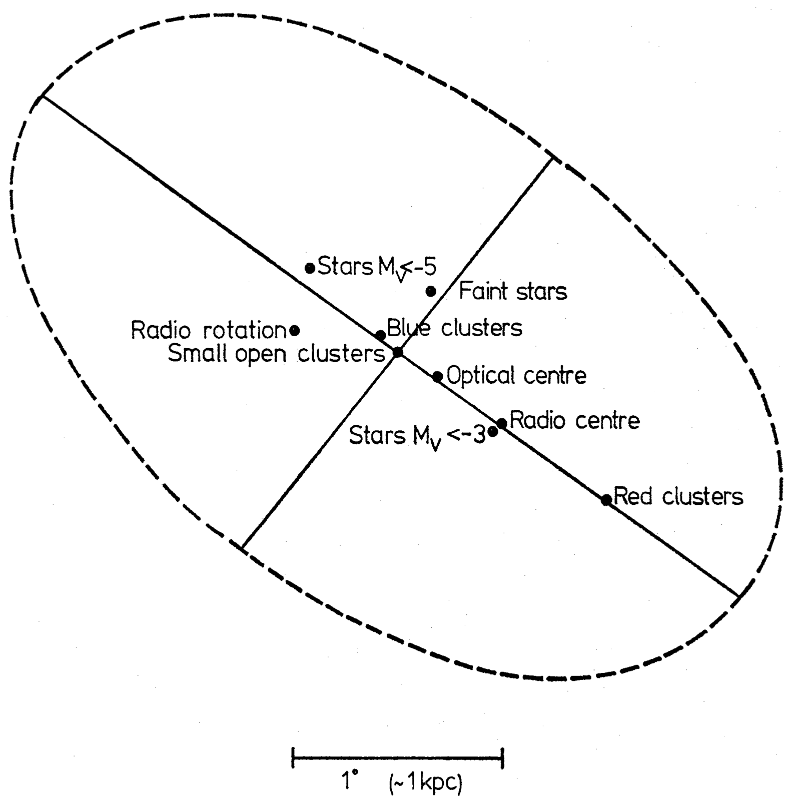

FIG. 2. *Outline of the SMC from small open clusters, showing also the centres of red (type* 1) *clusters; blue (types* 3 *and* 4) *clusters; centres for stars to magnitudes* $M_V = -3$ *and* $M_V = -6$ (*de Vaucouleurs* 1955)*; faint stars* (*MacGillivray* 1975)*; optical centre* (*de Vaucouleurs* 1960)*;* 21-*cm radio centre and centre of* 21-*cm radio rotation curve* (*Hindman* 1967).

55°, is the same as that given by Lindsay (1958) and Hodge (1974), and agrees with the direction of maximum velocity gradient in 21-cm radio contours (Hindman 1967; Kerr 1971). It differs, however, from the value adopted by de Vaucouleurs & Freeman (1972), namely 45°, which is a mean of values derived from integrated light, star counts and star density gradients. Recently MacGillivray (1975) in the course of a galaxy count programme in the SMC field has produced an isodensity contour of stars to magnitude $B = 23$. An analysis of the contour also gives a position angle 55°.

The ratio b/a of 0·62 for the elliptical distribution of clusters is greater than the value 0·5 found by Lindsay & Hodge, and adopted also by de Vaucouleurs (1960) from star counts and integrated light. If, however, we confine ourselves to the region of high cluster density, a value of 0·5 also fits our clusters. Hindman finds a ratio 0·4 from radio contours as does MacGillivray from the faint star contour. If interpreted solely as due to foreshortening, these ratios indicate inclinations of 50°–70° to the line of sight. However, some of the apparent ellipticity may be due to a real ellipticity in shape of the SMC itself, as is found in general for such galaxies (de Vaucouleurs 1974).

The various values of position angle and ellipticity and also of the location of the SMC centre as derived from different observations, illustrates the irregular nature of the SMC rather than conflict in results.

6. SPATIAL DISTRIBUTION OF CLUSTERS

Hodge (1974) has analysed the variation in the number of clusters per unit area with distance from the centre of the cluster and has concluded that the falling off of density with distance could be approximated to the exponential law found originally by de Vaucouleurs (1955) from star counts. We have repeated Hodge's analysis using the now larger sample, and have found the same pattern of variation as he did.

Using the value 0·62 for b/a as found from the small clusters, a set of concentric ellipses were drawn with this axial ratio, and the number of clusters within zones of 20′ width separation in major axis counted. The cluster density per unit area was then calculated as a function of major axis. The results, plotted logarithmically in Fig. 3 curve a, show the same trend as Hodge's plot, namely, a lack of clusters at the centre, followed by a peak, a uniform region and a rapid falling off in density

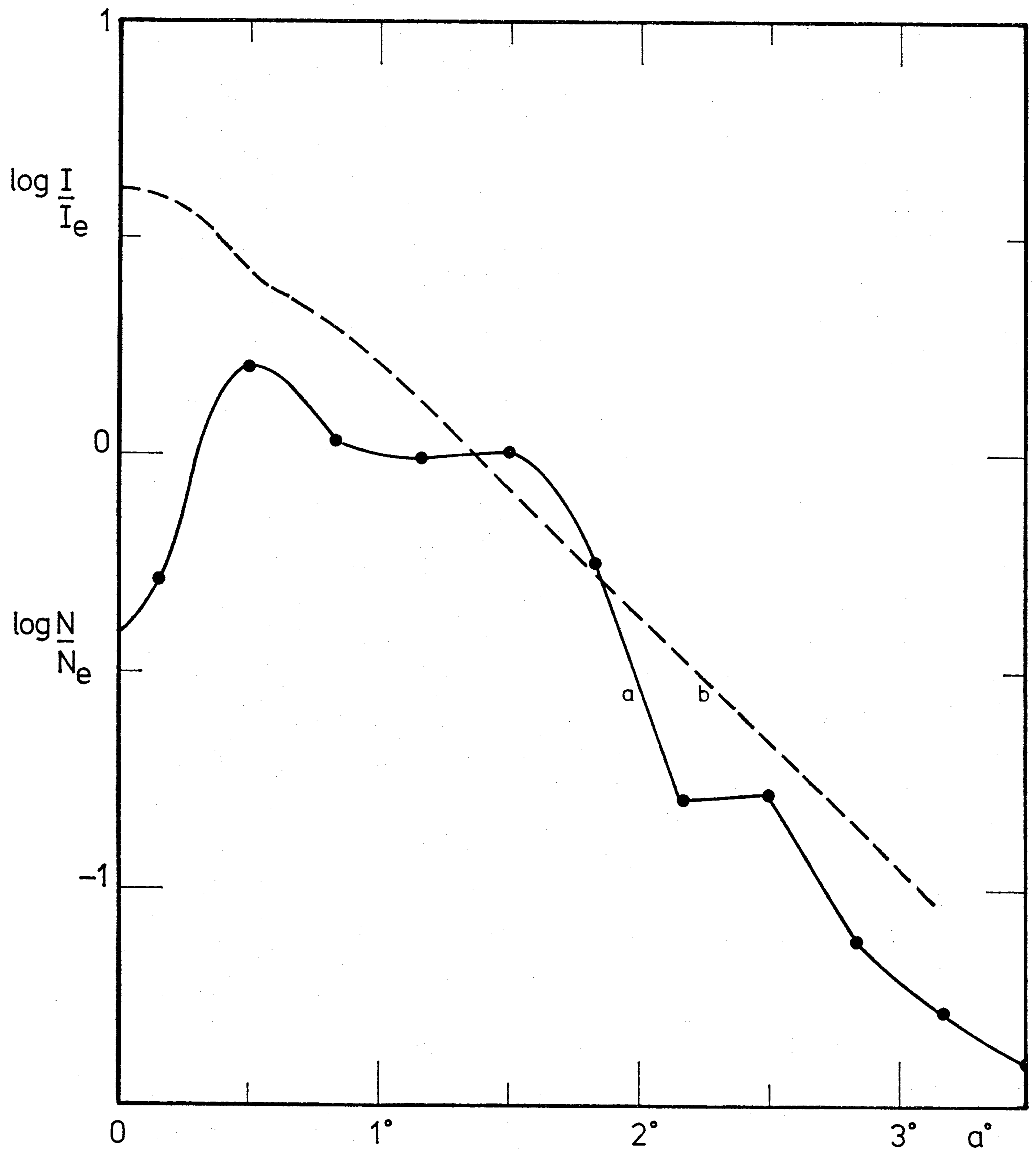

FIG. 3. *Radial distribution of clusters and integrated light. Variation in the logarithm of (a) the cluster density N, and (b) the integrated light intensity I within elliptical contours as a function of distance along the major axis from their respective centres which are separated by 30′. (N_e and I_e are defined in the text.)*

beyond $1^\circ \cdot 5$. The toe of the curve beyond 3° is due to red clusters which are not disk members; the very last point, corresponding to distances beyond our field was taken from Hodge's figures.

While, for a study of the disk, halo objects ought to be omitted, the red clusters form such a small proportion of the total that their inclusion does not distort the result: the same analysis carried out on the small blue clusters only (types 5 and 6) gave the same pattern.

The average gradient of the curve beyond $1^\circ \cdot 5$ is about 0·75 in $\log N$ per degree, compared with Hodge's 0·57. The difference is due to the fact that our densities refer to elliptical zones whereas Hodge's are given in radial distances from the centre. The ratio of the gradients should be a mean of 1 and a/b (1·3), which in fact it is. The two results are therefore in agreement, and as the details of Hodge's distribution curve are endorsed by the additional data, it is concluded that they are real.

The light density distribution in the SMC has been fully analysed by de Vaucouleurs (1960) from photoelectric data. Intensities per unit area were computed within elliptical isophotes and plotted in terms of B magnitude per unit area against the equivalent radius $(A/\pi)^{1/2}$, where A is the area within the isophote. In Fig. 3, curve b, de Vaucouleurs' data have been replotted in terms of $\log I/I_e$ against a, the equivalent semimajor axis of the isophote, using $b/a = 0{\cdot}47$, the mean axial ratio of his isophotes. Here I_e is the intensity per unit area at the effective distance a_e (i.e. the equivalent semimajor of the isophote within which half the total light is contained). Cluster members in curve a are similarly given in terms of the number per unit area at the effective distance $1^\circ \cdot 48$, derived below.

It is evident from Fig. 3 that there are distinct differences between the cluster distribution and the purely exponential distribution of curve b. The main features in the cluster distribution are the lack in the central region resembling Freeman's type II disk (Freeman 1970) where the radial luminosity distribution near the centre falls below the exponential distribution in the outer parts; and the apparent tendency for clusters to favour particular zones in the disk, at distances of $0^\circ \cdot 5$, $1^\circ \cdot 5$ and $2^\circ \cdot 5$ (0·6, 1·7 and 2·9 kpc) from the centre. The maximum at $0^\circ \cdot 5$ is partly caused by the bar; as regards the $1^\circ \cdot 5$ zone, it is worth noting that the compact blue clusters (Fig. 1(b)) are almost entirely concentrated in this area.

The local variations in cluster numbers may be smoothed out by plotting the quantity K defined by de Vaucouleurs (1960) as the fraction of the total light (in this case cluster numbers) enclosed within an isophote, against radius. This is done in Fig. 4 together with the corresponding curve from de Vaucouleurs' paper for blue light. As in Fig. 3, effective semidiameter is used instead of effective radius. The diagram illustrates the relative lack of clusters in the inner region and a corresponding faster filling up of numbers compared with the integrated light at larger distances. The effective semidiameter a_e (i.e. the value at $K = \frac{1}{2}$) is $1^\circ \cdot 48$ (1·70 kpc) for the clusters, equivalent to an effective radius of $1^\circ \cdot 17$ compared with de Vaucouleurs' effective radii of $0^\circ \cdot 92$ and $1^\circ \cdot 12$ for integrated blue and red light respectively.

Allowing for a 5 per cent cluster finding error and an uncertainty of $\pm 0^\circ \cdot 03$ in the effective cluster radius depending on whether or not the red clusters and those beyond our field are included in the total, an uncertainty of the order of $0^\circ \cdot 1$ is found for the radius. The difference between the cluster and the integrated light radii cannot therefore be considered significant.

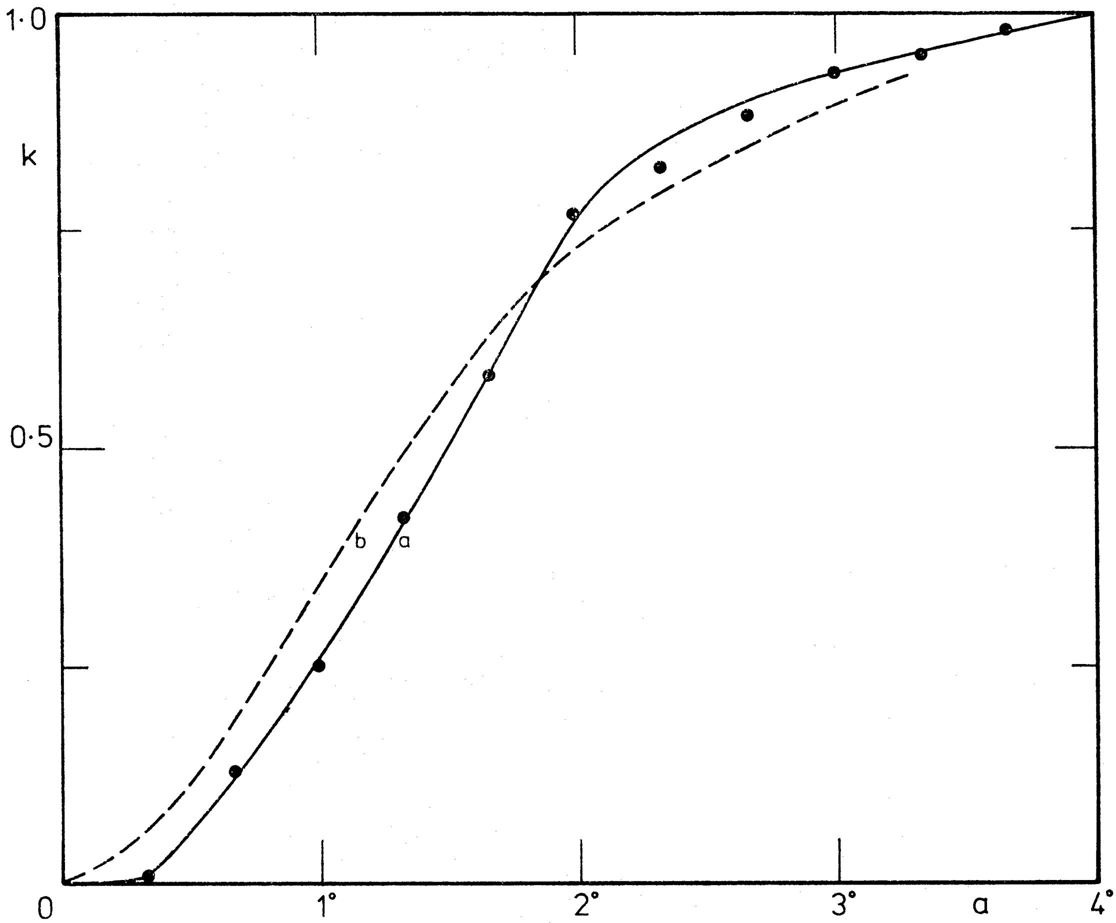

FIG. 4. *Fractional number of clusters (a) within elliptical contours as a function of semi-major axis compared with the same quantity for integrated blue light, (b) (de Vaucouleurs 1960).*

The conclusion is that on a large scale the disk as defined by the clusters has the same effective size as that defined by the stars, but that variations in the local distribution of clusters is considerably more marked. The effective integrated light intensity I_e per square degree is equivalent to 7·9 stars of (*B*) magnitude 10. The corresponding cluster density N_e is 36·3 per square degree, or 22·5 per square degree for an unforeshortened circular disk. In the inner zone which is favoured by the blue compact clusters the integrated light intensity is equivalent to about 20 stars of magnitude 10 per square degree; it would appear that at densities below this value such clusters are not produced.

7. CLUSTER SIZES

Kron (1956b) compared the dimensions of a sample of SMC open clusters with galactic ones; his result shows (using the modern distance modulus) that the SMC clusters are about 25 per cent larger on average.

It has been mentioned in Section 2 that cluster sizes were approximately estimated on the *V* plate. The estimates are considered meaningful in the case of blue clusters where the relatively sharp limits of the more luminous stars appeared the same in *U*, *B* and *V*. The distribution of non-red clusters (types 3 to 6) by size is given in Table III.

TABLE III

Distribution of cluster diameters for blue clusters

Diameter (0·1 mm units)	(pc)	Percentage
1	~1	25
2	2·8	28
3	1·9	19
4	7·1	10
5	9·2	7
6	11·4	6
7	13·5	1
8	15·7	0
9	17·8	1
10	20·0	2
>10	>20	1

Half of the clusters have diameters of 4 pc or less, exactly as is found in galactic open clusters (Landolt-Börnstein 1972; Schmidt 1963), the peak frequency is 2·5 pc (Galaxy 3·8 pc) and the overall average diameter 5 pc (Galaxy 4 pc). There appears to be a somewhat greater proportion of large clusters in the SMC than in the Galaxy, objects above 10 pc diameter being relatively twice as common in the SMC. There is no standard convention as to what constitutes a cluster diameter in the Galaxy, but certainly they cover a larger extension than is possible in the SMC. For example, the Pleiades, if observed at the distance of the SMC would show only the naked-eye members which cover a diameter of only 2 pc, half of its true value.

A factor of $1\frac{1}{2}$ or 2 between diameters seen at the distance of the SMC and the Galaxy appears reasonable and would bring the diameters of the smaller SMC clusters into line with their galactic counterparts. The large clusters, however, would become even larger after correction and are not matched in the Galaxy—apart from the considerably larger (30 pc) and relatively fewer OB associations.

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