OLD SOUTHERN OPEN CLUSTERS.

by

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Being a thesis submitted in part fulfilment of the requirements for the degress of Doctor of Philosophy in the Faculty of Science, University of Cape Town.

December, 1974.

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CONTENTS.

Preface.

The six chapters of this thesis contain the results of four years spent in the investigation of old open clusters at the S A A O. Each chapter is a preprint of a paper which has been submitted or accepted for publication and is therefore an independent entity with its own list of acknowledgements and references. Since each chapter is intelligible without continual reference to its fellow chapters, considerable overlap has sometimes occurred. As a thesis, the end product is of necessity a little disjointed. This approach has been adopted because the publication of the results has higher priority than the presentation of a thesis. The style is as compact as seems consistent with reasonable clarity and I hope that reading it will not present too great a problem of digestion to those interested in the evolution of solar-Type stars.

In addition to the acknowledgements made after the several component papers, I wish to express my gratitude to Mrs A.M.E. Hey who has typed almost all of the six observational chapters at least once. To my wife I also owe a great deal: to her this thesis is affectionately dedicated.

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Introduction.

1. The Field of Research and Possible Methods.

Certain fields of Astronomy become unfashionable relatively rapidly. This can be a consequence of many factors - the deflection of interest to newer and more "exciting" fields, the laborious and sometimes long enduring work involved in making new contributions to knowledge once the initial and more spectacular results have been obtained by the pioneers, and also the "depletion of resources" which occurs if the objects under study are relatively thin on the ground.

All these factors have operated in the field of study of the old open clusters. In the twenty years which have almost elapsed since the colour-magnitude diagram of M67 was published by Johnson and Sandage (1955), studies of objects "older than the Hyades" have appeared at long intervals. When the work here reported was commenced it was not expected that many further projects along these lines would be likely to be undertaken by other astronomers. The survey of southern clusters, indeed, was intended essentially to close the field insofar as the discovery of unknown and spectacularly old systems was concerned. So far as I am aware only one cluster of respectable age South of the Celestial equator was omitted from the survey discussed in Chapter 2.

Contrary to what was anticipated, at least two groups have also continued the study of old open clusters. In addition the theoretically uncomfortable results of the Solar Neutrino experiments have strongly suggested that all is far from well in our theoretical understanding of even such simple problems in stellar structure as the interiors of low mass main sequence stars. An earlier study by this writer has suggested that while our knowledge of the general processes of evolution off the main sequence may be qualitatively satisfactory, attempts to predict in quantitative detail the features of this evolution are largely unsuccessful when confronted with the finer features of the known cluster colour-magnitude diagrams (Hawarden, 1970 and 1971; Demarque and Heasely, 1971).

It is thus that I have no trepidation but a certain feeling of haste in presenting a fairly substantial block of observational data in a field reguarded by many as unexciting and by some, who shall be nameless, as scarcely rewarding of further study.

In subsequent chapters, detailed observational material is presented for the four open clusters NGC 6259, Melotte 66, NGC 2243 and NGC 2204. The first is, for present purposes, a young object and its detailed study was only undertaken in order to establish this fact without ambiguity. It does not, therefore, contribute to the field of prime interest in this thesis but is included since its analysis was a necessary part of the greater project and provided a proving ground for the methods - necessarily somewhat mass-production in nature - used in the study of the older, more challenging and more interesting objects.

The study of these clusters has been undertaken along the classical lines of photographic photometry calibrated and further illuminated by photoelectric observations. As in all "well established" methods, various pitfalls and chimaeras exist to delay and distract the worker.

After a brief flirtation with electronography I resolutely eschewed such high-efficiency techniques regardless of their potential advantages. The difficulties in their practical application foreseen then have been amply illustrated in the labour of certain of my colleagues and would without doubt have added a year or more to the time required to complete this project. I believe that its earlier completion and publication compensates for the additional data which might have been obtained but which at the time of writing have not yet become even potentially accessible.

With more reluctance I abandoned hopes of using photographic calibration techniques as a substitute for the grinding necessities of photoelectric photometry. Some of the methods appear theoretically unsound except under ideal conditions and do not lend themselves to unspectacular projects where "a few tenths of a magnitude" is inadequate precision. Such a method is the use of an objective grating such as has been applied with gratifying results to ω Centauri by Harding, Harbour & Tritton (1971) in the face of considerable difficulties. The method of extrapolation based on densitometric profiles of star images, proposed by King and Hinrichs (1967) was ruled out by the absence of suitable calibration equipment at the telescope and of suitable measuring equipment in the laboratory. Those few applications of this technique which have been made by Burkhead (1969, 1970) do not suggest that great precision can be obtained by its use, although the method is doubtless valuable when no alternative is available.

The method of the "small prism" developed by Racine (1969) showed more promise and could very likely have been applied to the current problems with rewarding results. That it has not been so used is attributable to a natural caution and a reluctance to undertake personally the delicate optical work involved in its construction.

Various other techniques were considered and rejected on the grounds of limited applicability and awkwardness of proper construction, or of excessive light loss. The last consideration together with that of expense led to the rejection of the Calcite Plate technique (Brück, 1970). A scheme for intermittently displacing images by means of a rocking-plate beam shifter was seriously considered but rejected as the mechanical problems were considerable and the development time threatened to exceed the reasonable duration of this thesis.

In the event, the well-known techniques of photographic photometry provided enough unexpected difficulties of method and of data processing to convince me that the decision to avoid newfangled methods was a wise one.

2. The Iris Photometer.

The photographic material was all measured on the Askania Iris Photometer at the SAAO, a type of instrument originally designed by Becker for the measurement of rather small-scale plates such as those obtained on large Schmidt telescopes. Its design precludes the use of low magnifications which would be of advantage in measuring the plates of larger scale which are produced by the long-focus refractors and reflectors used in most high-precision photographic photometry.

The instrument is of the double-beam "null" type. Light from a high-intensity, air-cooled filament lamp is divided into two beams of approximately equal intensity by a beamsplitter. The reference beam is passed through an optical wedge and refocussed on a rotary chopper. The measuring beam is focussed on the specimen by a microscope objective. After passing through the plate, it is refocussed by a second microscope objective on the iris aperture which lies a few inches away from the large ground-glass viewing screen. A fraction of the beam is reflected from an unsilvered glass mirror after passing through the iris. This portion of the beam is twice reflected before being focussed on the rotary chopper. Thereafter it is combined with the reference beam and both beams are directed onto the photomultiplier.

In use, the optical wedge is adjusted to a convenient position and left clamped, while the specimen beam is attenuated by closing the iris around a (previously centred) star image. When the two beams are equal the photomultiplier output (displayed on an oscilloscope) appears as a single line; imbalance produces a double line of varying separation. Maladjustment of the chopper with respect to the two beams produces momentary spikes on the signal as the beams reinforce one another while, if the beams are not coincident at the photocathode considerable noise is generated making the null ill-defined.

When proper adjustment is attained two sources of error remain. Considerable noise is inserted into the specimen beam by vibration of one of the directing mirrors which is also sensitive to slight jars of the instrument, so that delicate operation is demanded. The error arising from this source is similar to that introduced by the operator in centering images and is therefore not especially serious. A more significant problem is generated by the tendency of the response of the photometer to drift with time in a randon fashion. The reason for this is unclear as it does not correlate with temperature and does not, so far as can be ascertained, originate in progressive maladjustment of the optical system. The nature of this drift has been studied at various times with a view to its calculation and correction from repeated measures of selected stars. On occasion the amplitude appears to be a linear function of iris reading but for the most part it appears to affect images of all sizes equally.

The amplitude of this drift is normally such that errors of around $0^{m}.05$ may result over a period of about 2 hours. On occasion larger variations occur in a discontinuous fashion; such events are fortunately rare. An attempt to study the drift over short periods of time suggested that smaller amplitude (ca. $0^{m}.03$) variations can occur with a time scale of a few minutes; such variations are impossible to correct and must be accepted as inherent errors in photographic photometry. The longer-period drift is routinely monitored by remeasurement of four images of intermediate brightness at intervals of not more than an hour throughout a measuring run.

The measuring process involves the identification and centering of the desired star followed by the adjustment of the iris for a null signal on the oscilloscope and the recording of the reading. This last is quite time consuming and considerable improvements in measuring speed would be offered by a digitised readout of the iris setting.

Sources of gross error arise in the possible misidentification of stars and in the misreading of the iris position. The last would be eliminated by the automatic readout suggested. Small errors in the results can be generated by incorrect centering of images, a fact which is aggravated by the slight elasticity and "stickiness" of the plate transport system. An error in centering must have the effect of making the star appear fainter; however such errors are probably roughly random in nature and are in any case generally less than those introduced by the uncorrected short-term drift.

A careful measurer using the equipment as at present set up can achieve a measuring rate of around 200 images per hour. This speed could perhaps be doubled if the iris readout were digitised as advocated above.

3. Reduction of Photographic Iris Photometry.

Recent publications by Hardie (1964) and Burkhead + Seeds (1971) have discussed in some detail the process of deriving magnitudes on a standard system from photographic iris readings. Burkhead, in particular, has concerned himself with the mechanics of curve fitting and the determination of colour equations and concludes that hand-drawn calibration curves give significantly more accurate and consistent results from plate to plate than the rival process of fitting a polynomial to the standard points by the method of least squares. Several aspects of these processes are inadequately treated in the literature, however, and bear mentioning here.

Burkhead's experiments were performed using a sequence containing very many stars with a wide range of colour; most photographic photometry must be done with sequences which are sparse, patchy and which - especially in cluster fields - show a strong systematic dependence of colour on magnitude.

The effect of such a dependence is to mask any colour equation present by small distortions of the calibration curve, at least when the curve is hand-drawn with no previous knowledge of the colour equation of the plate-filter-telescope combination relative to the standard system.

Under these circumstances, proper detection of the colour dependence of photographic measures will involve a quite lengthy process of trial and error unless the sequence includes some segments covering a wide range in colour within a small range in magnitude (Hawarden, 1970).

In the investigations reported in later sections of this thesis a large and rather heterogeneous collection of plates have been analysed. Several general principles have emerged and have led to the reduction methods described below.

Least-squares fitting of a function which includes a linear colour term yields consistent and reliable colour coefficients provided that the "monochromatic" curve can be represented to a good approximation by a cubic or quartic polynomial. Should a sixth or higher-order curve be needed to eliminate "runs" of positive or negative residuals, the colour term is likely to prove unstable, heavily dependent on the order of polynomial selected and very variable from plate to plate. Under these circumstances a hand-drawn curve using corrected magnitudes adjusted according to an assumed colour coefficient will usually yield the best results.

If the photoelectric calibration includes many points with larger-than-normal deviations, the second proceedure of the previous paragraph will once again yield the best results. It may be noted here that occasional photoelectric measures may stand off the calibration curves of several plates in a consistent fashion, indicating a systematic difference of one or more tenths of a magnitude between photographic and photoelectric results for this particular star. This may occur notwithstanding the apparently successful removal of colour effects. The phenomenon has been noted on test plates of such impeccable photoelectric sequences as those in the Havard E-regions where internal errors can scarcely exceed a hundredth of a magnitude. In some cases new photoelectric observations have verified that the earlier results are still valid and that the photographic discrepancies are not a result of variability. Such cases I believe to be quite common in the experience of photographic photometrists (I have heard A.R.Sandage complain of them) but they are largely unremarked upon in the literature.

Stars such as these may represent several percent of the members of well observed photoelectric sequences. Several have been encountered in the present work and have been "smoothed" or omitted with no compunction. Their mysterious behaviour may perhaps be explained as a subtle effect of hidden duplicity or of some Astrophysical property interacting with the peculiarities of the photographic process.

It remains only to remark that a too-tender conscience in the handling of such maverick measurements can seriously degrade the precision of other, better behaved, measures especially if these discrepancies involve objects of fairly extreme colour. It should be stated that this problem arises only in the use of sequences of high quality and becomes trivial in those programmes where many relatively inaccurate photoelectric standards are used in place of fewer stars with high-precision measurements. The widespread practice of "smoothing" such low-precision sequences to take out systematic discrepancies between photographic and photoelectric results is undoubtedly a process of improvement and is probably essential in really crowded fields. It has been avoided in the present work except in a few cases which are pointed out individually as they occur.

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A SEARCH FOR OLD SOUTHERN OPEN CLUSTERS

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Chapter I

Summary

The methods used to identify old open clusters are described and results are given for the clusters studied. A catalogue of clusters older than $\sim 4 \times 10^8$ years is presented. There appears to be a deficiency of old clusters in the direction of the galactic centre and an excess in the anticentre direction.

1 Introduction

Open clusters older that the Hyades are important in the provision of observational tests for theories of stellar evolution. They serve as indicators of the evolution of the chemical composition of the Galactic disk (Eggen and Sandage, 1969) and of variations in composition with position in the galaxy (Arp, 1962; McClure, Forrester and Gibson, 1974). They may also provide information about the dynamic evolution of the Galaxy (Keenan and Inanen, 1974). It is therefore desirable that any incompleteness of the known sample of these clusters, particularly in the South, should be rectified. In 1970-71 a search for clusters older than the Hyades was carried out at the Royal Observatory, Cape (now the South African Astronomical Observatory).

2 Selection and Recognition

A list was drawn up of clusters accessible from the Cape which had no published photometry. King (1964) published a list of clusters which might, judging from their appearance on the Palomar Sky Survey, prove to be older than the Hyades. He assigns to these clusters a number between 1 and 5 to indicate his estimate of the likelihood that the cluster is old, clusters marked 5 being the least likely. He further provides estimates of the magnitudes of the brighter cluster members. Clusters from King's list were included in the search list if they were of likelihood 1, 2 or 3 and were South of the Equator. The last criterion was relaxed to include Trumpler 5, which could be photographed together with a sequence near NGC 2264 on the same plates (Dow and Hawarden, 1970). After some experimenting, clusters fainter than King's "mb" (=medium bright) category were excluded as too faint for convenient study.

The list was supplemented by a selection of clusters which appear rather faint for their angular diameters on the plates of the Atlas of Southern Open Clusters (Hogg, 1965).

The clusters selected were photographed in V and in B with the McClean twin refractors at the S.A.A.O. and star counts on the V plates were used to select areas in each field where the number of probable members was highest. All uncrowded images in the selected areas were measured with the Askania Iris Photometer at the S.A.A.O. and the iris readings were used to construct a pseudo colour-magnitude (CM) diagram for each area.

Clusters somewhat older than the Hyades can be recognised unambiguously on such diagrams - provided they are rich enough - by the presence of a clump of stars somewhat brighter and redder than the termination point of the main sequence (Cannon, 1970). Photoelectric photometry is necessary in younger clusters if Hyades-like systems are to be distinguished from those resembling M11 (Johnson, Sandage and Wahlquist, 1956) as both types have red giants at the same luminosity as the top of the main sequence. The M11-type cluster NGC 6259 was the subject of an investigation of this sort arising from the search.

The results for all the clusters surveyed are listed in Table I. The age classifications shown have been confirmed by detailed photometric investigations in all cases except that of NGC 5999 which was clearly young. The clusters Melotte 71

TABLE 1

Details of Clusters Investigated.

Cluster	α (1975) h	m	δ °	'	l°	b°	age	Reference
NGC 2204	06	14.6	-18	38	226.0	-16.1	Old	
NGC 2243	06	29.8	-31	16	239.5	-18.0	old	
Trumpler 5	06	35.4	+09	28	202.9	1.0	Old	Dow & Hawarden 1970
Melotte 66	07	25.6	-47	41	259.6	-14.3	old	
Melotte 71	07	36.4	-12	00	229.0	4.5	Intermediate	
NGC 3960	11	49.6	-55	33	294.4	6.2	Intermediate	
NGC 5999	15	50.2	-56	23	326.0	-1.9	Young	
NGC 6259	16	58.9	-44	38	342.0	-1.5	Young	Hawarden, 1974

and Melotte 66 have been studied previously by Cuffey (1942) and by Eggen and Stoy (1961) respectively. They have been reinvestigated in detail during the program of which this search formed part and age classifications are given in Table I for completeness. Clusters classified as "intermediate" in the table are probably less than 10^9 years old.

3 List of Clusters Older than ~4×10^8 years

The list of clusters given by Cannon (1970) has been supplemented with the 6 old and intermediate-age objects from Table I and from recently published photometric investigations. The latter categories are identified in the resulting catalogue, Table II, by the appropriate references.

Fig. 1 shows the distribution of these clusters in Galactic longitude. A deficiency occurs in the general direction of the galactic centre and the distribution has a maximum in the anticenter direction, although both features are displaced about 30° from the reference directions towards larger longitudes.

Daltabuit and Meyer (1972) have published distribution curves of neutral Hydrogen at various galactic latitudes. Their curves for b = +15° and +20° are strongly reminiscent of Fig. 1 in that the number density peaks in the vicinity of l = 20° and has a minimum near l = 200°-220°. A subsidiary minimum near l = 80° agrees well with the location of the secondary maximum in Fig. 1, suggesting that the observed cluster distribution is principally a consequence of the effects of interstellar absorption, rather than of a real tendency for old open

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TABLE 11

List of Clusters older than ~4 x 10^8 years.

Name (NGC)	l°	b°	Reference
6633	36.1	8.3	
6885	65.5	-4.1	
6882	65.6	-4.0	
6940	69.9	-7.2	
6791	70.0	11.0	
6819	74.0	8.5	Auner, 1974
6866	79.4	6.8	
6811	79.4	12.0	
7062	89.9	2.7	Jones & Altena, 1970
7142	89.9	-2.7	
6939	95.9	12.3	
7226	101.4	-0.6	Yilmaz, 1970
7245	101.4	-1.9	Yilmaz, 1970
7789	115.2	-5.4	
188	122.8	22.5	
559	127.2	0.8	
IC 166	129.5	0.0	Burkhead, 1969
752	137.2	-23.4	
1245	146.6	-8.9	
1342	155.0	-15.0	
1664	161.7	-0.4	Kerridge et al, 1973
1907	172.6	0.3	
Hyades	180.0	-22.4	
1817	186.1	-13.1	
2158	186.6	1.8	
2266	187.8	10.3	
2194	197.3	-2.3	
2141	198.1	-5.8	Burkhead et al, 1972

Table II (continued

Name (NGC)	l°	b°	Reference
2420	198.1	19.7	
2236	204.4	-1.7	Rahim, 1970
2362(Praesepe)	205.8	32.5	
2324	213.5	3.3	
2682(M67)	215.6	31.7	
2215	216.0	-10.1	
2204	226.0	-16.1	Table 1
Haffner 8	227.5	1.3	Fenkart et al, 1972
Haffner 6	227.8	0.2	Fenkart et al, 1972
Melotte 71	229.0	4.5	Table 1
2360	229.8	-1.4	
2423	230.5	3.6	
2506	230.6	9.9	
Ruprecht 46	238.4	5.9	Vogt & Moffat, 1972
2243	239.5	-18.0	Table 1
2477	253.6	-5.8	
Melotte 66	259.6	-14.3	Table 1
2818	262.0	8.6	Tifft et al, 1972
2660	265.8	-3.0	Hartwick & Hesser, 1973
3680	286.8	16.9	
3496	289.6	-0.4	
3960	294.4	6.2	Table 1
5823	321.2	2.5	
5822	321.7	3.6	
6208	333.7	-5.8	Lindoff, 1972
6134	334.9	-0.2	Lindoff, 1972
IC 4651	340.1	-7.9	Eggen, 1971
6281	347.8	2.0	Feinstein & Forte, 1974

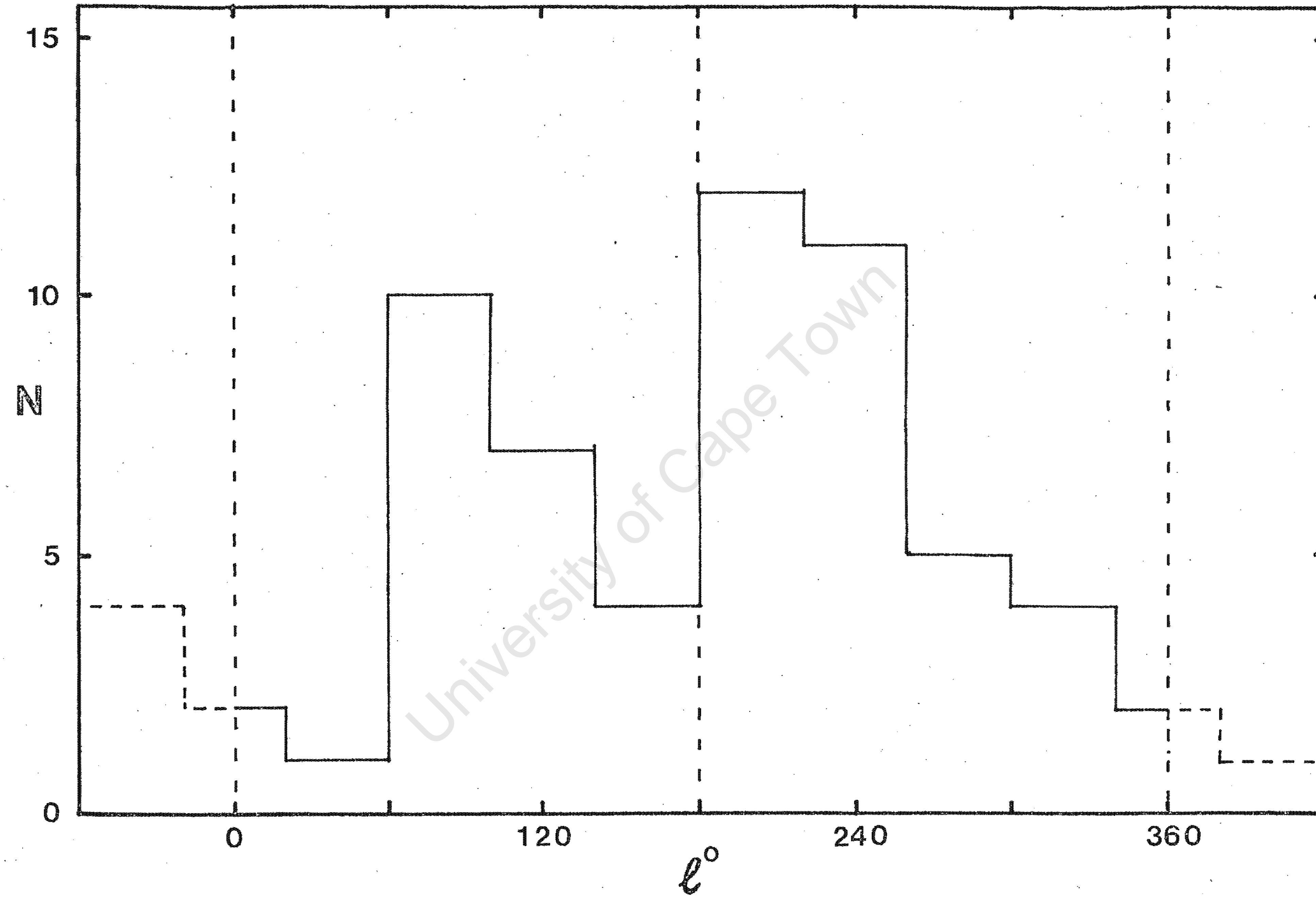

Fig. 1. The distribution with galactic longitude of open clusters older than ~4 x 10^8 years.

clusters to avoid the half of the sky towards the galactic centre. It should be noted, however that the distribution curves for neutral hydrogen south of the galactic equator show no agreement with Fig. 1 and appear almost featureless.

4. Acknowledgements

Several of the earlier plates were measured by vacation students M.J. Dow and M. Trott. The work reported in this paper represents a portion of a Ph.D. thesis at the University of Cape Town.

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Chapter II.

NGC 6259: SOUTHERN IMAGE OF M11

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(Communicated by A. J. W. Cousins)

(Received 1974 July 24)

SUMMARY

Photoelectric *UBV* and photographic *BV* photometry of stars in the open cluster NGC 6259 have been used to determine the reddening, distance and age of this object. It has a colour excess $E(B-V) = 0{\cdot}65 \pm 0^{m}{\cdot}01$ and true distance modulus $(m-M)_0 = 11^{m}{\cdot}3 \pm 0^{m}{\cdot}3$. Its age is about 2×10^8 yr. The cluster is closely similar to M11 in age and in the details of the colour–magnitude diagram.

INTRODUCTION

The rich open cluster NGC 6529 is located at $\alpha = 16^{h}\,58^{m}{\cdot}9$, $\delta = -44°\,38'$ (1975) with galactic coordinates $l = 342°{\cdot}0$, $b = -1°{\cdot}5$. It is number 996 in the catalogue of Alter, Ruprecht & Vanysek (1970) and is included in the *Atlas of Southern Open Clusters* (Hogg 1965) wherein it appears rather faint for its angular diameter. It was therefore included in a search for old open clusters which was conducted at the Royal Observatory, Cape (now the South African Astronomical Observatory).

In the course of this search a preliminary study was made using photographs taken with the 46- and 60-cm McClean refractors of the SAAO in yellow and blue light, respectively. The yellow plate was a Kodak 103aD with Omag 301 filter and the blue was an unfiltered IIaO plate. The exposures were both 45 min. Star counts to the limit of the yellow plate were made over an area 32 min square and the resulting density distribution suggested that the cluster has a limiting radius of about 8′. Measurements were made of all stars lying within a region of 4′ radius centred on the peak of the density distribution, using the Askania Iris Diaphragm photometer at the SAAO. The resulting pseudo-colour–magnitude diagram suggested that the cluster resembled M11 but an unambiguous age estimate proved impossible. A more detailed study was therefore required.

PHOTOMETRY IN THE CLUSTER

Photoelectric *UBV* photometry was obtained for 23 stars in the cluster vicinity, using the 1-m reflector of the SAAO in 1970 and 1971 before its transfer to Sutherland and the 0·5-m reflector at the Sutherland station in 1972 and 1973.

Zero-point determinations were made by observing stars in the nearby Harvard Region E7 between each series of cluster stars. The 1970 measures were related initially to the stars Q46 and Q23. The latter was found to have varied since the observations summarized by Cousins & Stoy (1964). As a result three nights in 1970 were reduced relative the Q46 only, although no variation of Q23 has been detected since this observing run. New values for Q23 were determined and these agree to within $0^m{\cdot}01$ with values obtained subsequently by Cousins (1972, private communication). The new values are: $V = 7^m{\cdot}22$, $B-V = 0^m{\cdot}62$, $U-B = 0^m{\cdot}54$. While the variations of Q23 are evidently few and probably slow, the star is unsuitable for use as a standard. Observations in 1971 and later years were reduced relative to Q46 and Q32.

Transformation of instrumental magnitudes to the *UBV* system was done by means of observations of stars in several E regions made concurrently with the measures in NGC 6259. The transformations are apparently linear and have coefficients less than $0^m{\cdot}04$. Their determination for very red stars is not as secure as might be desired owing to the lack of standards with large $B-V$. The internal consistency of the present reddening results suggest that systematic errors do not exceed a few hundredths of a magnitude in the vicinity of $B-V = 1^m{\cdot}8$.

Mean extinction coefficients were assumed, based on the same E region observations used to determine the system transformations. The zero-point stars are not far from the cluster so that air mass differences never exceeded $0^m{\cdot}2$. Small errors in the assumed extinction coefficients can therefore have had little effect.

The photoelectric results are given in Table I. The formal internal standard errors of the V and $B-V$ values vary from about $0^m{\cdot}01$ at $V = 13^m{\cdot}0$ to $0^m{\cdot}03$ at $V = 15^m{\cdot}0$. This is also true of the errors of the $U-B$ values excepting those for the red stars which have formal SE's around $0^m{\cdot}03$.

The distribution of colour with magnitude in the sequence has been chosen to permit a good determination of the colour coefficients of the photographic plates.

TABLE I

Star	V	$B-V$	$U-B$	Nights	Source	Note
2023	11·64	0·34	0·12	1	C	
4039	11·76	2·08	2·22	2	S	
A	11·89	1·89	1·98	4	C, S	
2007	12·45	0·60	0·37	1	C	
1013	12·47	1·76	1·71	3	C, S	
3017	12·66	1·64	1·51	2	S	
4014	12·80	1·81	1·79	1	S	
1038	12·92	0·66	0·32	1	C	
1008	13·11	0·62	0·38	2	C	
3037	13·26	0·58	0·32	2	C	
4040	13·49	0·72	0·51	2	C	
2032	13·58	0·59	0·40	1	S	
3044	13·63	0·74	0·39	1	C	
1001	13·71	0·52	0·32	3	C	
3025	13·77	0·62	0·35	2	S	*
1027	13·77	0·87	0·43	2	S	
2030	13·91	0·60	0·41	1	S	
4029	14·00	0·56	0·35	1	C	*
4031	14·10	0·60	0·42	2	S	
4038	14·14	0·62	0·44	2	S	
4028	14·37	0·74	0·50	2	S	
3035	14·92	0·75	—	4	S	
3018	14·98	0·69	—	4	S	
2037	15·29	0·86	—	4	S	

Notes:

* V_{pe} discordant with V_{pg} not used in plate reductions.
Source: C = Cape observation; S = Sutherland observation.

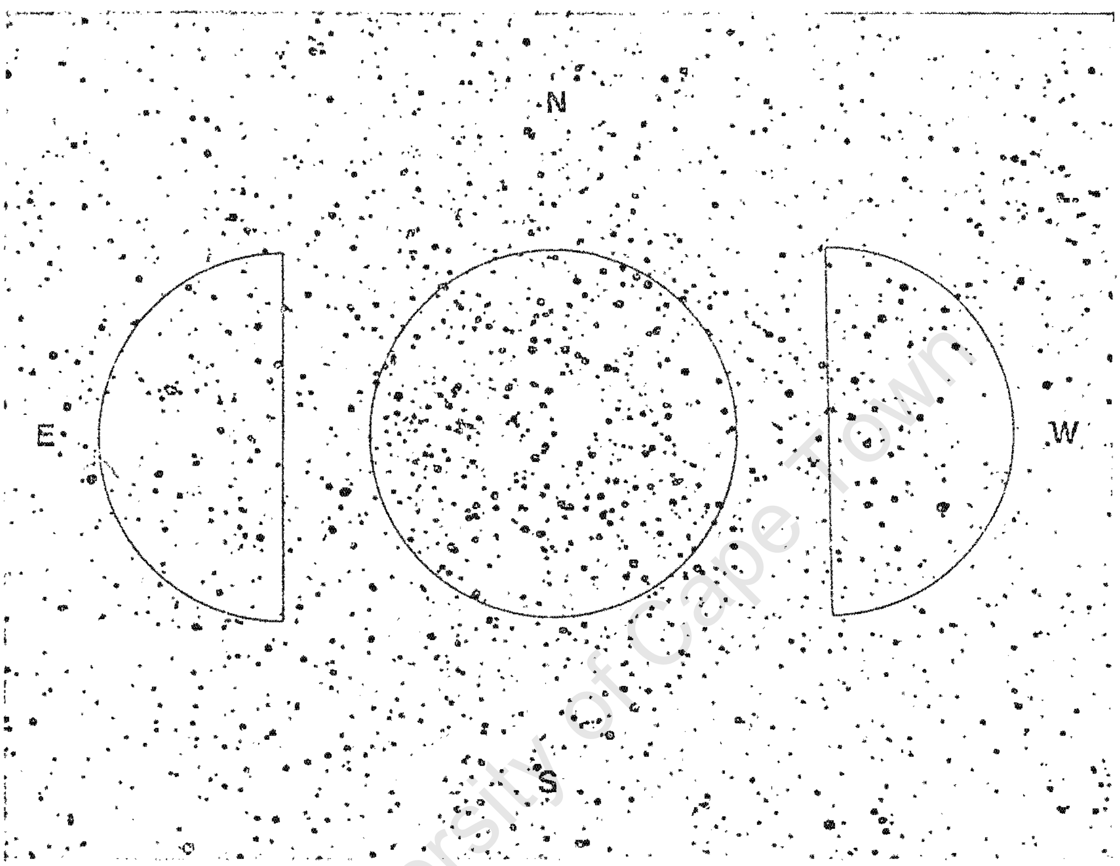

PLATE I. *NGC* 6259 *and vicinity, taken from a 45-min V exposure with the 18-in. refractor.*

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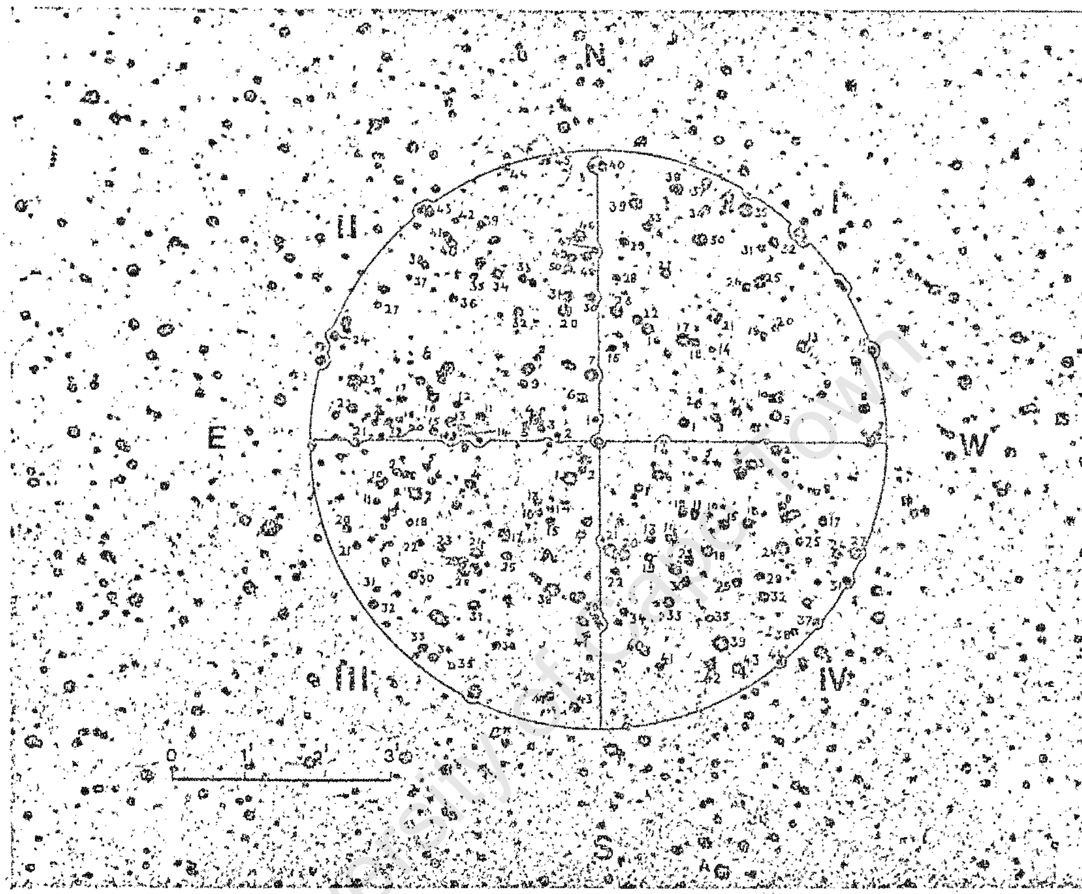

PLATE II. *Central region of NGC* 6259 *showing stars for which results are given in Tables I and II. Taken from the same plate as Fig.* 1.

The environs of NGC 6259 are shown in Plate I. The central, circular area has a radius of 4′ and is centred on the peak of the projected star density distribution, while the semicircular comparison stars are located with their centres 2 min arc inside the detectable edge of the star density excess associated with the cluster.

Almost all uncrowded stars within these regions, down to $V = 15^{m}\cdot 3$ were measured on two V and two B plates with the Askania Iris Photometer. Calibration was performed by making a least squares fit of a polynomial to the iris–magnitude relation. A linear colour term was included in each solution. Multiple solutions were performed using the NOVA 1220 computer at the SAAO. Goodness of fit was judged from the values of the rms deviation from the photoelectric values of the magnitudes computed from the iris readings and from the presence or otherwise of systematic 'runs' of adjacent residuals. In all cases a polynomial of order 3 was selected for the final solution. The combined results for the stars in the central region are listed in Table II and the stars are identified on Plate II.

THE FEATURES OF THE CLUSTER CM DIAGRAM

Fig. 1(a) and (b) show the CM diagrams of the central region and the two comparison regions, respectively. In Fig. 1(a) a well-defined, well-populated main sequence extends from $V = 12^{m}\cdot 1$ to the calibration limit. The curvature of this sequence indicates that all or most of the stars included are significantly evolved.

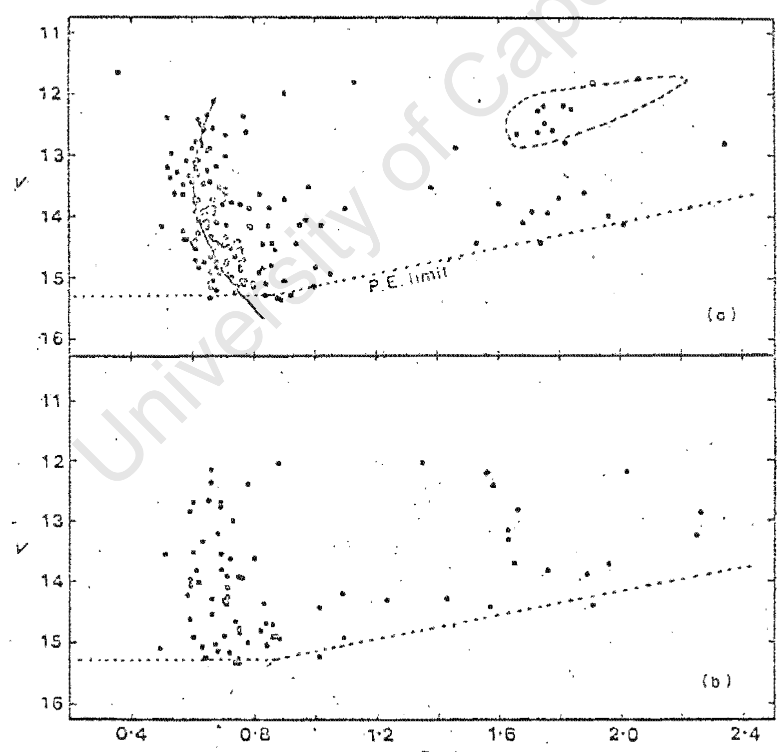

FIG. 1. *Colour–magnitude diagram of the photographic results in NGC 6259, (a) Central 4′ radius region; (b) combined outer regions. Each diagram represents stars from an equal area of sky.*

Table II. Photographic results for stars in NGC 6259.

STAR	V	B-V	STAR	V	B-V	STAR	V	B-V
1001	13.65	0.56	1015	14.48	0.69	1029	13.87	0.84
1002	14.52	0.60	1016	12.80	0.60	1030	12.24	1.33
1003	13.92	0.64	1017	12.12	0.66	1031	14.46	0.82
1004	13.44	0.65	1018	13.93	1.70	1032	13.52	1.37
1005	12.79	0.59	1019	14.86	1.24	1033	13.53	0.97
1006	14.84	0.99	1020	14.41	0.74	1034	13.88	1.10
1007	13.68	0.69	1021	15.04	0.76	1035	11.83	1.12
1008	13.13	0.60	1022	13.24	0.64	1036	12.37	0.76
1009	14.84	0.67	1023	12.79	2.33	1037	13.54	0.59
1010	13.81	0.60	1025	12.67	0.70	1038	12.93	0.64
1011	13.49	0.56	1026	13.78	0.70	1039	12.64	0.77
1012	14.14	1.02	1027	13.72	0.89	1040	13.64	0.81
1013	12.48	1.74	1028	14.79	0.70			
2001	14.71	0.76	2018	14.73	0.60	2038	14.16	0.49
2002	15.10	0.76	2019	13.92	0.63	2039	14.80	0.75
2003	14.60	0.75	2020	15.09	0.83	2040	13.70	1.79
2004	12.57	0.63	2022	13.61	1.87	2041	14.07	0.96
2005	14.93	0.68	2023	11.65	0.35	2042	14.91	0.65
2006	13.81	0.75	2024	13.80	1.60	2043	13.96	1.74
2007	12.43	0.61	2027	14.67	0.73	2044	15.21	0.67
2009	14.24	0.56	2029	12.29	1.73	2045	14.92	0.81
2011	13.88	0.78	2030	13.93	0.60	2046	12.00	0.89
2012	14.85	0.82	2031	13.11	0.57	2047	14.51	0.71
2013	12.81	0.62	2032	13.63	0.53	2048	14.00	1.95
2014	12.88	1.45	2033	13.88	0.65	2049	13.78	0.72
2015	14.17	0.78	2034	13.45	0.59	2050	14.38	0.57
2016	12.90	0.65	2035	14.39	0.57			
2017	14.15	0.94	2037	15.29	0.83			
3001	12.19	1.81	3016	14.50	0.61	3030	14.44	0.85
3002	14.44	0.93	3017	12.65	1.65	3031	15.17	0.65
3003	12.81	0.62	3018	14.99	0.72	3032	13.75	0.60
3004	13.48	0.63	3019	15.09	0.79	3034	13.81	0.69
3005	14.44	0.67	3020	14.44	0.73	3035	14.88	0.75
3006	14.56	0.75	3021	14.66	0.65	3036	14.54	0.86
3007	12.59	1.77	3022	14.93	0.70	3037	13.27	0.54
3008	14.34	0.70	3023	14.79	0.85	3038	12.36	0.64
3009	14.94	1.04	3024	12.58	0.66	3039	14.58	0.74
3010	14.16	0.70	3025	13.66	0.70	3041	14.76	0.61
3011	15.05	0.76	3026	15.13	0.74	3042	15.13	0.79
3013	15.25	0.73	3027	14.76	0.67	3043	14.10	1.68
3014	15.10	0.65	3028	12.89	0.59	3044	13.64	0.70
3015	14.32	0.65	3029	13.38	0.52			
4001	15.06	0.89	4016	13.18	0.67	4031	14.11	0.64
4002	13.20	0.51	4017	14.06	0.61	4032	13.22	0.60
4003	12.97	0.52	4018	13.32	0.61	4033	13.34	0.58
4004	15.05	0.66	4019	14.24	0.75	4034	14.33	0.61
4006	13.02	0.70	4020	12.55	0.62	4035	14.43	1.52
4007	13.96	0.62	4021	12.39	0.51	4037	14.42	1.73
4008	14.74	0.70	4022	14.39	0.60	4038	14.12	0.63
4009	14.52	0.66	4023	13.74	0.61	4039	11.76	2.06
4010	15.27	0.80	4024	12.20	1.74	4040	13.53	0.68
4011	14.13	2.00	4025	14.44	0.59	4041	14.74	0.63
4012	14.19	0.64	4026	13.97	0.66	4042	14.11	0.57
4013	14.18	0.84	4027	12.62	1.73	4043	13.09	0.61
4014	12.81	1.81	4028	14.42	0.66	4044	14.85	0.71
4015	13.73	0.66	4029	13.88	0.66			

A compact group of 9 or 10 stars lies level with the top of the main sequence in Fig. 1(a), centred near $B-V = 1^m \cdot 8$. These stars are very probably red giant members of the cluster, an assertion supported by the absence of such a grouping of stars in Fig. 1(b). Conversely the scattering of stars to the red of $B-V = 1^m \cdot 0$ within about 1 mag of the plate limit matches in both number and general distribution a similar scattering in Fig. 1(b), indicating that most or all of these stars are not cluster members.

The rich main sequence of Fig. 1(a) is still detectable in Fig. 1(b) where the rather sparser sequence has precisely the same position and shape in the CM diagram. This suggests that no systematic variation of reddening occurs across the width of the cluster. Also, a sprinkling of stars occurs in Fig. 1(a) below $V = 13^m \cdot 5$, lying up to several tenths of a magnitude to the red of the main sequence proper. This group may have a sparse counterpart in Fig. 1(b). If so the stars in question are probably main sequence members of the cluster afflicted with anomalously heavy reddening.

THE REDDENING OF THE CLUSTER

Fig. 2 shows the two-colour diagram for those stars with photoelectric $U-B$ measures. A compact group of main sequence stars lies near $B-V = 0^m \cdot 60$ with $U-B$ between $0^m \cdot 30$ and $0^m \cdot 45$. Somewhat to the red lie several stars which may be

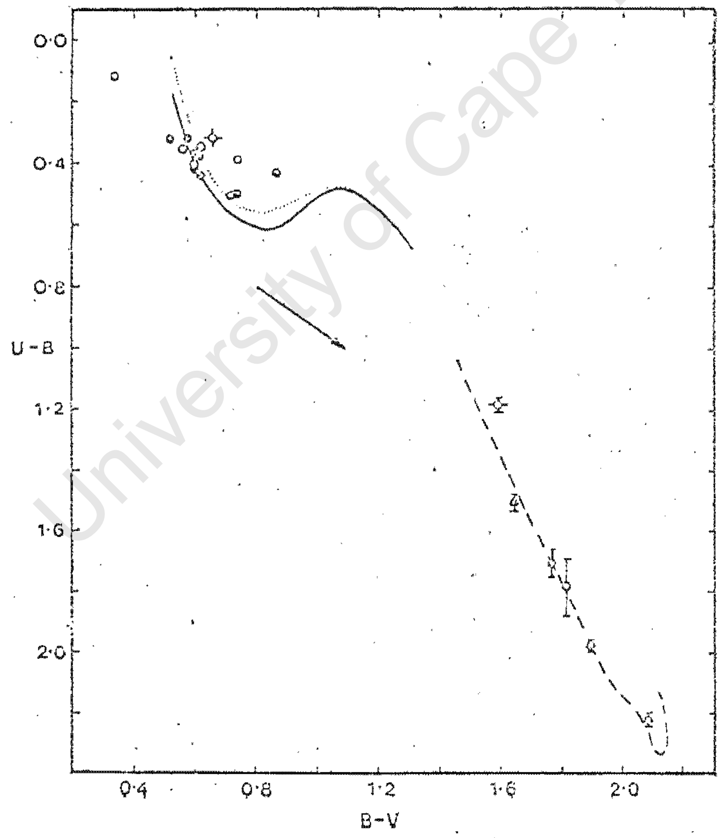

FIG. 2. *Photoelectric two-colour diagram for stars in NGC 6259. Open circles represent stars observed on one night only. Open circles with appended crosses are double stars.*

non-members or anomalously reddened main sequence objects. They have been excluded from the determination of the reddening of the main sequence which has been derived from the nine single stars with $B-V$ between $0^m{\cdot}50$ and $0^m{\cdot}70$.

In presenting a revised relationship between $(U-B)_0$ and $(B-V)_0$ for unevolved main sequence stars, Straizys & Kavaliauskaite (1967) have pointed out that earlier versions of this relation refer to stars which are in fact significantly evolved, at least to the blue of $(B-V)_0 = 0^m{\cdot}40$. Since the curvature of the main sequence in Fig. 1(a) indicates that all nine stars available here are evolved, the standard ZAMS two-colour relationship published by Eggen (1965) has been used in place of that of Straizys & Kavaliauskaite.

Each of the nine stars was moved along the reddening trajectory

$$E(U-B) = 0{\cdot}72\,E(B-V) + 0{\cdot}05\,E^2(B-V)$$

onto the standard curve. The mean of the resulting displacements gives $E(B-V) = 0^m{\cdot}65$ which has been adopted as the main sequence reddening of NGC 6259. The solid curve in Fig. 2 is the standard relation of Eggen (1965) reddened by this amount. The dotted curve shows the two-colour standard relationship given by Straizys & Kavaliauskaite, similarly displaced.

The positions of six giant stars are also plotted in Fig. 2. The attached error bars represent twice the SE of the mean result for each star. Each of the five single giant stars was moved along the reddening trajectory until it coincided with the standard two-colour relationship for luminosity class III stars given by Johnson (1966). The resulting mean reddening is $E(B-V) = 0^m{\cdot}54$. The dashed curve in Fig. 2 shows the standard relationship, reddened appropriately.

Hartwick & McClure (1972) pointed out that reddening estimates for giants give systematically smaller values than those for dwarfs in the same cluster. Using their estimate of 0·82 for the ratio between $E(B-V)$ for giant and main sequence stars gives a value for the dwarfs in NGC 6259 of $E(B-V) = 0^m{\cdot}66$ in very good agreement with that derived above. The reddening can be regarded as well determined for the majority of main sequence stars and lies very near to $E(B-V) = 0^m{\cdot}65$,

RESULTS: AGE AND DISTANCE

The colour-magnitude diagram (Fig. 1(a)) bears a strong resemblance to that of M11 (Johnson, Sandage & Wahlquist 1956). The schematic C–M diagram of the latter cluster is shown in the figure, where it has been displaced $0^m{\cdot}23$ redwards and $0^m{\cdot}75$ fainter in order to obtain the superposition shown. If it be postulated that the intrinsic colours of the vertical main sequences of these clusters are identical, a reddening $E(B-V) = 0^m{\cdot}42$ is derived for M11, in rather good agreement with the value $E(B-V) = 0^m{\cdot}45$ obtained for this object by Hartwick & McClure (1972).

The very exact agreement between the shapes of the main sequences, between the relative positions of the main sequences and giant branches and the near agreement between the intrinsic main sequence colours of these two objects suggest that they are closely similar in age and probably also in chemical composition, an interesting result in view of their differing locations in the galaxy. Their primary difference seems to be in numbers of stars, M11 being richer by a factor of about 2, judging from the relative numbers of giants.

The standard zero age main sequence of Eggen (1965), appropriately reddened, can be fitted to the main sequence curve in Fig. 1(a) by assuming an apparent distance modulus $m-M = 13{\cdot}45 \pm 0{\cdot}15$ (estimated uncertainty). If the ratio $R = A_V/E(B-V) = 3{\cdot}0$ the resulting true distance modulus is $(m-M)_0 = 11{\cdot}50$ corresponding to a distance of 2·02 kpc.

The age of the cluster must be very close to that of M11 for which Cannon (1970) gives a value of $2{\cdot}0 \times 10^8$ yr, based on evolutionary calculations by Iben. This value can therefore be adopted for NGC 6259.

ACKNOWLEDGMENTS

I wish to thank Dr A. W. J. Cousins for redetermining the magnitude and colours of star Q23 in E7 and Mr J. Churms for very kindly obtaining the second plate pair of NGC 6259. An anonymous referee made several valuable suggestions which have led to a considerable extension of this investigation. The work discussed here is a portion of a thesis in partial fulfilment of the requirements for the degree of Ph.D. in the Department of Astronomy at the University of Cape Town. The supervision of Professor Brian Warner is gratefully acknowledged.

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Received in original form 1973 July 12

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The Old, Metal - Poor Open Cluster NGC 2243

by

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Chapter III

Summary

Photoelectric UBV and photographic BV photometry of the Southern open cluster NGC 2243 is presented. The reddening and ultraviolet excess are determined by a general method which has been tested on several better-observed clusters. The adopted values for NGC 2243 are $E(B-V)= 0^m.06$, $\delta(U-B)_{0.6} = 0.15 \pm 0^m.035$. The latter result indicates a deficiency in heavy elements exceptional among open clusters. The metal abundance is estimated to be $[Fe/H] = -0.5$ relative to the sun. The cluster CM diagram shows sparse giant and subgiant branches and a giant branch clump or red horizontal branch containing about 10 stars at $V=13^m.9$. The upper main sequence is well defined and a gap appears therein notwithstanding the low heavy-element abundance and the unusually large age, $(5.0\pm0.8)\times10^9$ years, deduced from the colour of the main sequence turnoff for an assumed helium abundance Y=0.30. A distance modulus $(m-M)_0=12^m.8$ is derived but the luminosity of the zero-age main sequence is very uncertain for this composition. The adopted value implies that the cluster lies more than a kiloparsec from the galactic plane. The need for more detailed investigations of the cluster is stressed.

1. Introduction

The open cluster NGC 2243 is located at $\alpha = 06^h 28^m.7$, $\delta = -31° 16'$ (1975) with galactic coordinates l=239°.5, b=-18°.0. It is number 644 in the list of open clusters in the catalogue of Alter, Ruprecht and Vanysek (1970). NGC 2243 was included by King (1964) in a list of clusters likely to prove older than the Hyades. It was therefore investigated during a search for old open clusters (Hawarden, 1975a) the results of which suggested an age substantially larger than 10^9 years.

Such an object is in itself worthy of detailed investigation, the more so as no previous photometry has, to my knowledge, been published. On the Palomar Sky Survey charts, moreover, the cluster has an unusually small angular diameter - about 7 minutes of arc - which, combined with its high galactic latitude, suggests that it lies exceptionally far from the galactic plane. The present paper reports the results of photoelectric UBV and photographic BV photometry and confirms the suggestion that NGC 2243 is an exceptionally interesting cluster.

2. Photoelectric Observations

Photoelectric measures in the UBV system have been obtained for 22 stars in NGC 2243. These observations form part of a more extensive program which includes several other clusters. The observations comprising this program were made with the 100cm telescope at the Cape in 1971, with the Radcliffe 188cm telescope in 1972 and with the 51cm and 100cm telescopes at the Sutherland observing station of the S.A.A.O. during 1973 and 1974. Difficulties with the equipment and with the determination of instrumental colour equations have led to the exclusion of the Radcliffe observations from the published results. Nonetheless these observations were of great value for preliminary calibration of photographic material used in the selection of stars for later observation at Sutherland.

A Radcliffe plate reaching to about $V=20^m$ was used to select stars free of companions brighter than this limit and to find nearby sky holes similarly uncontaminated. A preliminary photographic CM diagram was used to identify probable cluster members. Photoelectric measures of both main sequence and giant members are needed for the determination of the reddening and ultraviolet excess of the cluster. A high proportion of cluster members among the photoelectric standards also helps to define correctly the colours of the principal sequences, in the presence of uncertainties in the photographic colour equations. Conversely, the proper determination of these colour equations requires the inclusion of stars with a wide range in colour within a limited range in magnitude. First priority was given to those stars lying within the coma-free field of the Radcliffe telescope when the latter is used at the Newtonian focus for photography at full aperture. The dearth of blue stars within this region has meant that the present sequence is not adequate for determining the photographic colour transformations.

All observations were made using EMI 6256A photomultipliers which were thermo-electrically cooled to -10°C during the Sutherland observations. The filters used were OG 515 (2mm) for V, BG 12 (1mm) + GG 385 (2mm) for B and UG 2 (1mm) for U. Four filter sets, in all, were used.

The bulk of the Sutherland measures were made with a 2 channel "Peoples" photometer used in single channel mode for flexibility in the selection of stars, with signal recording by DC integrations. Many observations were also made with a semi-automatic single-channel photometer (van Breda, Carr & Kelly, 1974) using pulse-counting techniques. The observations with the 51cm telescope were made with diaphragm apertures of 17 arc seconds while those with the 100cm telescope were generally made with apertures of 12.6 or 11.0s.

Both photometers used at Sutherland have been modified and equipped with Varo type 8858 image intensifier tubes which can be used to view the relayed image of the focal plane from below the aperture plate. On the 100cm telescope under optimum conditions these tubes permit stars as faint as $V=18^{m}.5$ to be seen and centred. Provision is made in both instruments for a wide-aperture position so that the observer can view a star field some minutes of arc across. The long afterglow of the output phosphor allows him to generate an after-image of the working aperture by briefly switching on the field illumination at high intensity before changing to the wide-field aperture. This after-image decays to invisibility in about 30 seconds and during this period it is seen superimposed on the star field. The ability to see the actual size and instantaneous position of the working aperture relative to the star background is of great advantage in the rapid centering of faint stars and in the positioning of the aperture at the selected sky holes.

The cluster stars were tied to the UBV system by a hybrid technique. Initially two stars in the vicinity of the cluster were tied to

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nearby E region standards (Cousins, 1973) by observations at equal altitudes on several nights, with apparently satisfactory results. During the observing at Radcliffe, however, the chief local standard (HD 45095) was found one night to be much fainter than expected. The star is believed to be an eclipsing binary of long period. The magnitude and colours at maximum are $V=7^m.52$, $B-V= -0^m.03$, $U-B= -0^m.02$.

The remaining local standard was used exclusively thereafter. On all nights but one it was supplemented by observations from time to time of E region stars and standard stars in other clusters, observed at equal or symmetric altitudes. This second standard, star A in Table III, appears constant to within the errors of the 9 transfer observations. The mean results given have internal standard errors of $0^m.004$ in V and in B-V and $0^m.008$ in U-B. In the final reductions the zero points in each run were adjusted to this star, a process which has in no case altered the results for a given night by more than $0^m.02$. The stated uncertainties reflect the internal precision of the tie-in of the zero points of the present results to the UBV system.

The observing method described is not sensitive to errors in the extinction coefficients and mean values were therefore adopted throughout. Transformations from the various natural systems were determined from numerous observations of E region stars made with the same instruments from time to time by the regular observers at Sutherland. These transformations are stable with time and are very nearly linear. It must be noted, however, that, owing to the dearth of standards of these types, the UBV system is poorly defined for stars with $(B-V)>1.5$ and for stars of abnormal composition. As has been pointed out by Cannon & Stobie (1973) uncertainties of $0^m.05$ might be anticipated for extremes of both sorts, at least in U-B. Measures of stars in the very metal-poor globular cluster

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ω Cen show good agreement in V and in B-V with those of Cannon and Stobie. In the present program stars of extreme colour have been observed in more than one instrumental system wherever possible. The results suggest that for stars with B-V $\lessapprox$ $1^{m}.8$ the transformation errors are less than $0^{m}.03$.

The observing program was designed to keep the internal standard error of a mean result for a star observed on a single night below $0^{m}.03$ in V and B-V and below $0^{m}.04$ in U-B. Where necessary, repeat observations were added to bring the observed s.e. of the mean within the desired range. On certain nights the zero point variations during the observing run exceeded the desired precision and on occasion multiple observations obstinately continued to yield standard errors larger than was satisfactory. Where either measure of the error may exceed twice the desired precision the results are included in the final means with half weight while observations with possible errors exceeding three times the desired criteria of accuracy were rejected. Exceptions were occasionally allowed when sufficient additional measures of the offending star have not been obtained; no such exceptions were made in NGC 2243.

Below are tabulated the mean internal standard errors of the final results in NGC 2243 and in NGC 2204, another cluster observed in this program.

V Range	Mean s.e.(V)	Mean s.e.(B-V)	Mean s.e.(U-B)	N. stars
11 to 15	0.013	0.010	0.020	15
15 to 16	0.023	0.014	0.027	7
16 to 17	0.023	0.037	0.038	6
17 to 18	0.031	0.030	-	4

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This observing strategy runs contrary to that normally adopted in the establishment of faint photoelectric standard sequences for the calibration of photographic photometry. It is common for observers to measure many stars with low precision rather than a few stars to high accuracy, as was attempted here. The ultimate results must then rely on photographic smoothing. This policy is necessary when serious background problems occur. It is viable provided a large number of photoelectrically observable stars are available and a good collection of photographic plates can be obtained. None of these circumstances occured in NGC 2243. In this and in other clusters of this program I have attempted to obtain photoelectric observations of a precision equal to or better than that which might be expected from good photographic photometry at the same magnitude level.

Table I gives the results of the photoelectric photometry in NGC 2243. The star numbers specify quadrant and radial zone as the first and second digits respectively. Stars and regions are identified in Plate I which is a reproduction of a 30 minute exposure in V obtained with the Radcliffe telescope at full aperture in unusually good seeing. The column headed N gives the number of nights from which observations of the star have been retained.

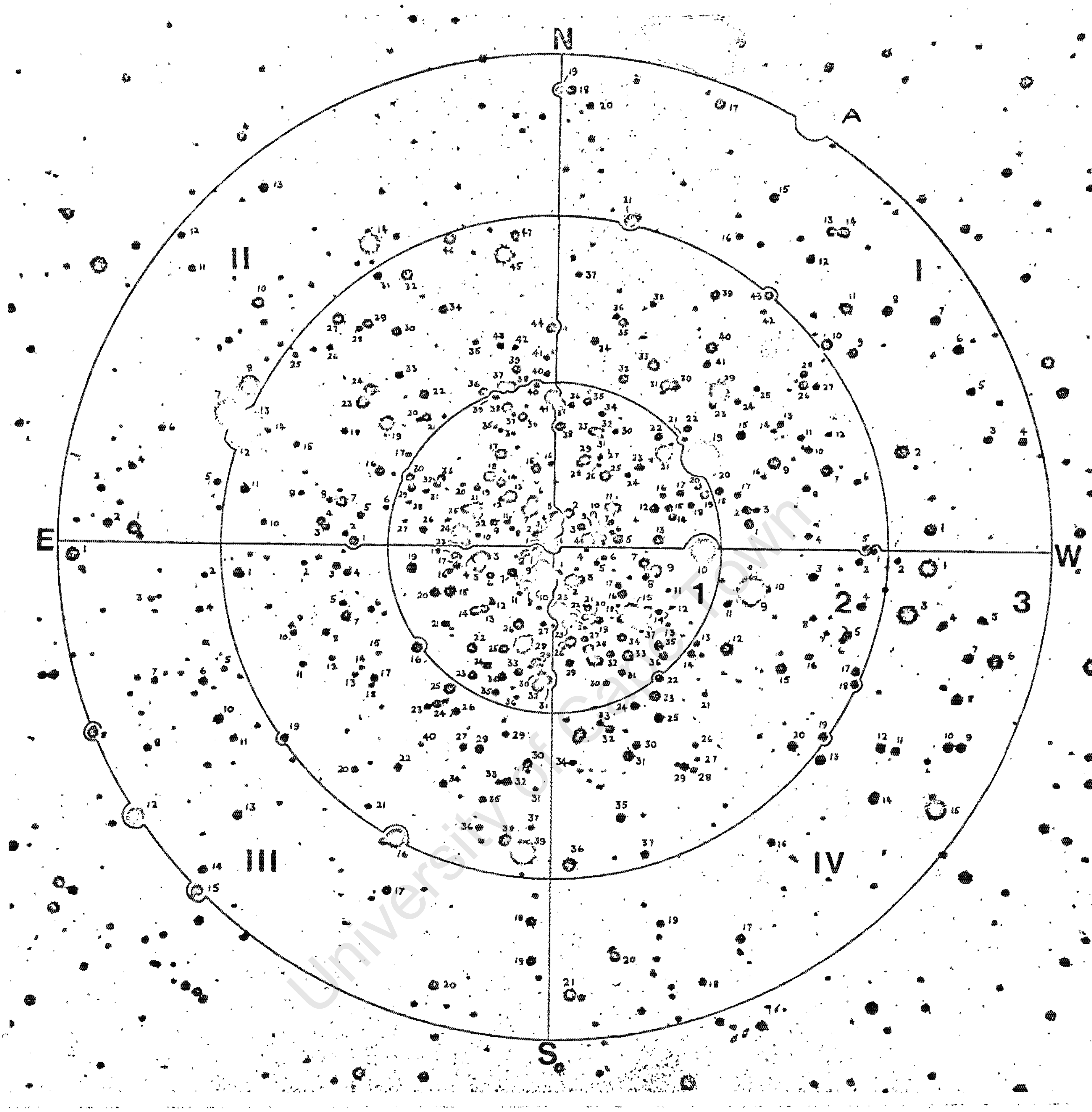

Plate 1. Identification chart for stars in NGC 2243 for which photometry is given in the text. The radii of the circles are approximately 75, 150 and 225 seconds of arc. The original plate is a 45 minute exposure in Yellow light taken with the Radcliffe 188cm telescope at full aperture in good seeing.

Table I

Photoelectric Results for Stars in NGC 2243

Star	V	B-V	U-B	n	Remarks
B	9.97	0.33	-0.01	1	=CPD -31° 1196
A	11.20	0.65	0.18	9	Std
C	11.36	0.66	0.16	2	=CPD -31° 1187
1219	11.81	1.09	1.00	1	
4209	12.03	1.43	1.40	2	
2307	12.18	0.79	0.49	1	
4110	12.85	1.11	0.80	3	May be double
2314	13.60	0.98	-	1	C
2308	13.62	0.98	0.52	2	
4303	13.73	0.94	0.50	2	
2245	14.11	0.94	-	1	C
4301	14.18	0.86	0.49	3	
4236	15.15	0.89	0.43	2	
2227	15.69	0.57	-0.01	2	
3216	15.86	0.52	0.02	2	
3119	16.17	0.47	-0.02	2	
2230	16.62	0.49	-0.06	3	
3222	16.92	0.59	-	2	
2233	17.23	0.61	-	3	
3208	17.36	0.52	-	1	
3221	17.95	0.67	-	2	
1206	17.98	0.65	-	2	

N.B. The two stars observed only at the Cape, marked C, have not been used in the photographic reductions.

3. Photographic Photometry

Five V and five B plates have been obtained with the McClean refractors and with the Radcliffe telescope used both at full aperture (188cms) and stopped down to 112 cms. Details of these plates are given in Table II.

The full-aperture Radcliffe plates have a coma-free field about 170 seconds of arc in radius. The zone boundaries in Plate I are at radii of about 75, 150 and 225 seconds and measures on the full-aperture plates have therefore been confined to zones 1 and 2 only. On the remaining plates all uncrowded images in the three zones have been measured, down to the limit of reasonable accuracy on each plate. The measures were obtained with the Askania Iris Photometer at the S.A.A.O.

The results for the photoelectric standards in Table I were used to construct hand-drawn calibration curves for each plate. Iris readings were plotted against a photographic magnitude Mpg given by the usual colour equation $M=Mpg + \beta\,(B-V)$, M being the photoelectric magnitude on the UBV system. For the Radcliffe V plates the usual value of β for the plate-filter combination used here is 0.07 (Menzies, 1972) and this value appeared satisfactory. For the Radcliffe B plates a value $\beta=0$ was suggested by LLoyd-Evans (private communication) and has also proved adequate. After some experimentation values of 0.16 and 0.02 were adopted for the McClean V and B plates respectively. These values differ from those which I have obtained for similar plates using other sequences more suited to such analysis; the shortcomings of the present sequence in this respect have been remarked upon. The colour equations must be regarded as uncertain and the photographic results for stars which lie far from the principal cluster sequences in the CM diagram may be systematically in error by several hundredths or even tenths of a

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Table 11

Plates used in Photographic Photometry of NGC 2243

Plate	Type	Telescope	Exposure	Date
A 7065	V	Radcliffe (188cm)	30 min	1972 Feb 11
A 7093	V	Radcliffe (112cm)	20 min	1972 Feb 13
47121V	V	McClean (46cm)	90 min	1971 Nov 19
47106V	V	"	60 min	1971 Nov 13
45941V	V	"	34 min	1970 Nov 4
A 7066	B	Radcliffe (188cm)	30 min	1972 Feb 11
A 7094	B	Radcliffe (112cm)	20 min	1972 Feb 13
47121P	B	McClean (61cm)	90 min	1971 Nov 19
47106P	B	"	60 min	1971 Nov 13
45941P	B	"	34 min	1971 Nov 4

magnitude. The large proportion of cluster members among the photoelectric standards ensures that the better populated features of the CM diagram are not significantly affected.

A computer program was used to interpolate between points read off from the final calibration curves. A second program combined the resulting magnitudes and applied the colour equations before deriving the residuals from the mean for each star of the measures on the individual plates. These residuals were scrutinised and a few outstandingly inconsistent measures were deleted from the final results. The mean internal standard errors of these results for stars with more than one measure in the appropriate colour are $0^{m}.024$ in V and $0^{m}.038$ in B.

Table III lists the final results for the stars measured photographically. The numbering system is the same as that used in Table I and the stars are among those identified on Plate I.

Table III

Photographic photometry of stars in NGC 2243. Results indicated by a (:) were derived from measures on a single plate in one or both of V and B.

STAR	V	B-V	STAR	V	B-V	STAR	V	B-V
				RING 1				
1102	16.06:	0.46;	1117	17.22;	0.47:	1129	15.78:	0.54:
1105	16.37:	0.42:	1118	17.50:	0.63:	1133	16.13:	0.51:
1107	17.59:	0.53:	1121	14.17	0.15	1134	18.27:	0.22:
1112	16.42	0.46	1122	16.91:	0.48:	1135	16.95:	0.50:
1113	16.01	0.45	1125	15.86	0.51	1138	16.53	0.37
2109	17.22:	0.49:	2118	15.69:	0.52:	2136	16.40	0.45
2113	15.31	0.16	2119	17.76:	0.36:	2138	15.97	0.46
2114	16.56:	0.40:	2126	17.33:	0.63:	2140	18.10:	0.35:
2115	16.42	0.51	2130	16.81:	0.47:	2141	14.96:	0.83:
3101	15.92:	0.43:	3122	16.09	0.50	3129	16.18	0.47
3106	17.10:	0.56:	3123	16.50	0.46	3133	16.58	0.47
3110	13.70	0.99	3124	16.79	0.57	3134	16.56	0.45
3115	15.97	0.70	3125	16.28	0.46	3135	17.36:	0.72:
3119	16.16	0.50	3126	15.91	0.40			
3120	16.41	0.40	3128	13.97	0.88			
4107	16.23:	0.55:	4123	14.18	0.99	4131	17.42:	0.55:
4109	15.64:	0.81:	4126	15.52	0.60	4133	15.60	0.77
4110	12.85	1.09	4128	15.80:	0.50:	4134	16.46	0.61
4115	14.43:	0.73:	4129	16.76	0.33			
4116	16.26:	0.62:	4130	17.80:	0.49:			
				RING 2				
1201	16.27	0.48	1217	17.30:	0.55:	1232	16.34	0.47
1204	17.54:	0.65:	1218	16.74:	0.47:	1233	15.91	0.81
1206	17.96:	0.52:	1219	11.81:	1.07:	1234	17.16:	0.35:
1207	15.73	0.52	1220	15.45:	0.81:	1239	16.54	0.46
1208	17.16:	0.58:	1222	17.03:	0.56:	1240	15.85	0.44
1209	15.28	0.17	1224	17.61:	0.56:	1241	17.24:	0.55:
1211	17.51:	0.63:	1225	18.35:	0.14:	1242	18.20:	0.46:
1215	16.51	0.33	1229	13.73	0.92	1243	16.68:	0.45:
2201	16.34:	0.42:	2219	14.76	0.59	2233	17.21:	0.62:
2205	17.36:	0.63:	2222	16.42	0.45	2234	16.79:	0.58:
2207	15.92:	0.44:	2223	15.32	0.80	2236	16.84	0.37
2210	18.26:	0.42:	2224	15.42	0.41	2239	16.73:	0.75:
2211	16.70:	0.38:	2226	18.03:	0.51:	2240	17.92:	0.52:
2213	11.90:	0.66:	2227	15.70	0.55	2243	18.10:	0.40:
2215	18.13:	0.53:	2230	16.61	0.51	2244	16.28	0.45
2216	16.50	0.63	2231	16.90:	0.51:	2245	14.20	0.96
2218	17.95:	0.36:	2232	15.87	0.72	2246	15.89	0.46

Table III (continued)

STAR	V	B-V	STAR	V	B-V	STAR	V	B-V
3201	16.32	0.66	3212	18.15:	0.43:	3229	18.05:	0.37:
3202	18.37:	0.44:	3216	15.87	0.49	3230	16.27:	0.43:
3203	16.89:	0.48:	3219	16.90:	0.31:	3234	17.03:	1.71:
3204	17.30:	0.53:	3220	17.36:	0.62:	3235	17.26:	0.41:
3205	17.75:	0.78:	3221	18.02:	0.70:	3236	17.29:	0.54:
3206	17.57:	0.63:	3222	16.92:	0.58:	3237	18.11:	0.55:
3207	16.12	0.94	3225	15.72	0.51	3238	15.43	0.49
3208	17.36:	0.53:	3227	17.25:	0.84:	3239	12.55	0.70
3211	17.92:	0.43:	3228	16.62	0.47			
4202	17.10:	0.49:	4217	16.69:	0.46:	4225	16.24	0.36
4203	16.76:	0.41:	4218	16.69:	0.46:	4231	15.90	0.73
4204	16.52	0.98	4219	16.43	0.53	4234	17.61:	0.62:
4208	17.82:	0.39:	4220	16.09	0.51	4235	16.57	0.47
4209	12.11	1.35	4222	16.77	0.46	4236	15.13	0.91
4212	15.28	0.78	4223	15.82	0.54	4237	16.94:	1.04:
4215	15.89	0.46	4224	16.73	0.41			

RING 3

1301	15.72	0.59	1308	16.18	0.58	1313	16.41:	0.72:
1302	15.22	0.87	1309	16.34	0.51	1314	16.02:	0.35:
1306	16.48	0.46	1310	15.70	0.61	1317	16.53:	1.10:
1307	16.24	0.51	1311	15.72	0.86	1321	15.62:	0.35:
2301	15.16	0.79	2308	13.62	0.94	2313	16.34	0.47
2307	12.13	0.81	2310	15.72	0.57	2314	13.68	1.04
3301	15.07	0.93	3313	16.34	0.57	3319	16.46	0.53
3308	15.92	0.47	3315	15.72	0.54	3320	16.32	0.67
3310	16.42	0.44	3316	13.76	1.04			
3312	14.11	0.87	3318	16.40	0.56			
4301	14.18	0.88	4308	15.83	0.51	4313	16.01	0.63
4303	13.74	0.95	4309	16.28:	0.56:x	4315	13.51	0.62
4306	15.04	0.74	4310	16.16:	0.95:x	4321	15.67	0.54
4307	16.07	0.49	4312	16.32:	0.50:x			

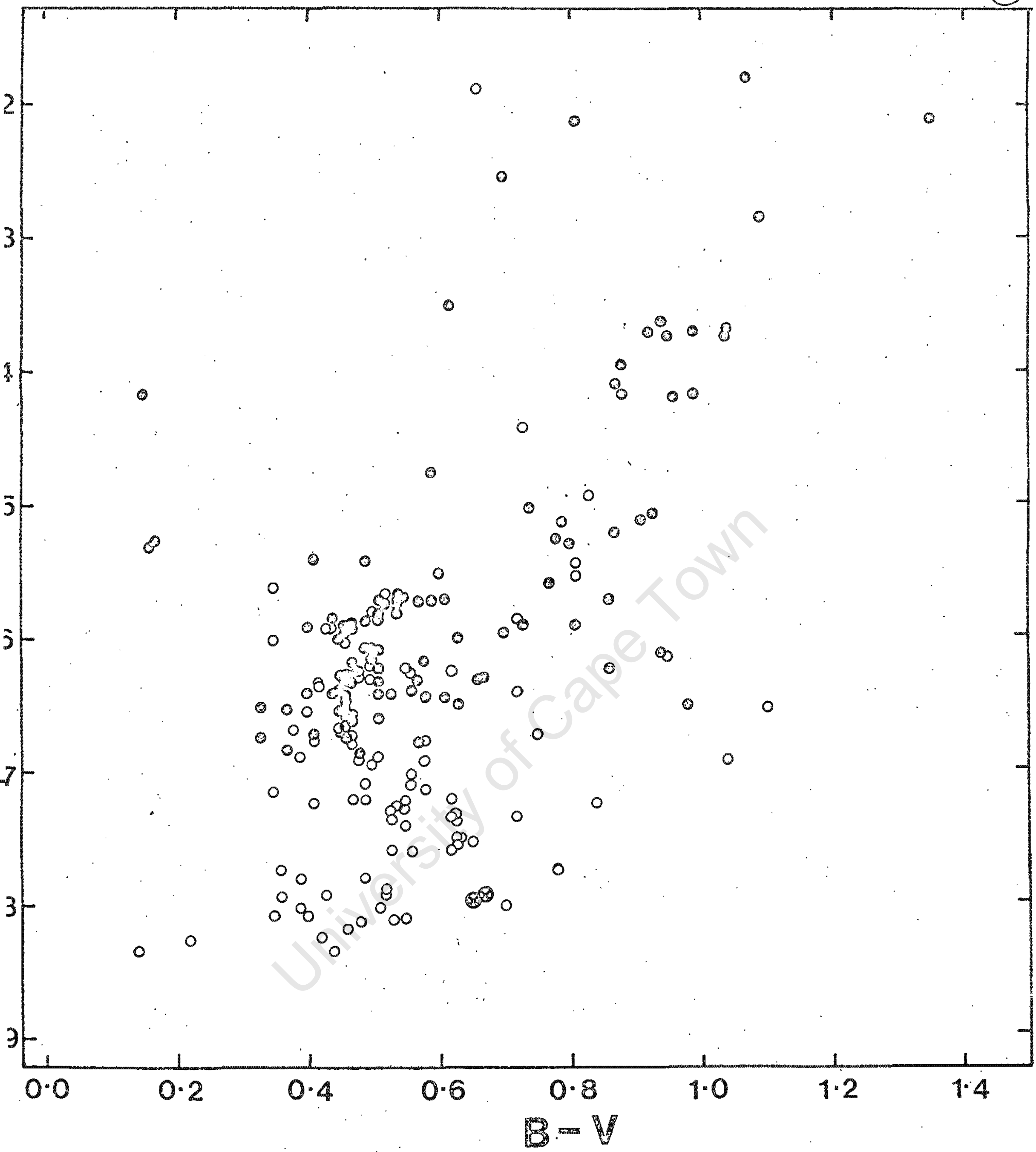

Fig. 1. The Colour-Magnitude array of NGC 2243 from the photographic data. Filled circles represent stars measured on at least two plates in each colour and the circled crosses show the two faintest photo-electric standards.

4. The Colour-Magnitude Diagram

Figure 1 shows the CM diagram of NGC 2243, constructed from the photographic results in Table III. Stars measured on at least 2 plates in each colour are represented by filled circles, those measured on only one plate in one or both colours by open circles.

Below $V = 17^{m}.0$ the main sequence is ill-defined, partly because fainter stars were measured on only one plate in each colour and partly because these measures were confined to zones 1 and 2 where the number of measureable stars is severely restricted by crowding. The sparse population of the lower main sequence in Fig.1, therefore, does not necessarily represent a real peculiarity of the luminosity function of the cluster.

The two circled crosses near $V=18^{m}.0$ represent the photoelectric results for the two faintest standards. It is here that the attempt to retain a relatively high precision in the photoelectric results for the faint stars appears valuable. The close agreement in the colours of these stars suggest that both are main-sequence cluster members, as does their location in the figure.

Above $V=17^{m}.0$ most stars have been measured on two or more plates in each colour and the main sequence is consequently well defined, despite a scattering of deviant points. Many of these are presumably field stars and others have perhaps been systematically affected by crowding. Among the deviants are probably several unresolved binaries. A star in the vertical main sequence at $V=16^{m}.75$, if combined with an unevolved main sequence star at $V=18^{m}.0$ will appear in Fig.1 $0^{m}.3$ brighter and $0^{m}.06$ redder. This region of the diagram is reminiscent of the CM diagram obtained by Racine (1971) for M67, which led him to suggest that the main sequence of that cluster contains a large proportion of unresolved binaries.

The upper main sequence exhibits a distinct gap at $V=16^{m}.05$. The ridge line deviates markedly to the red below this level and above it commences about $0^{m}.06$ to the blue. The gap is therefore principally a discontinuity in colour rather than in magnitude.

Above the gap the main sequence deviates rapidly to the red, with a peak luminosity around $V=15^{m}.70$. Three stars near $V=15^{m}.9$, $B-V=0^{m}.71$ suggest the existence of a horizontal subgiant branch. Centred at $V=15^{m}.5$, $B-V=0^{m}.8$ lies a loose grouping of starswhich are presumably subgiants commencing their evolution up the giant branch. The area between $V=15^{m}.0$ and $V=16^{m}.0$ with $0.7 \leqslant B-V \leqslant 1.0$ contains 14 points, 4 from zone 3 and 10 from zones 1 and 2 which together have only 4/5 the area of zone 3. Furthermore the representation of the 2 inner regions in Fig.1 is severely reduced by crowding problems; it therefore appears that most of the stars in the area indicated are cluster members.

About 2^{m} above the main sequence termination appears a group of 11 stars centred at $V=13^{m}.90$, $B-V=0^{m}.95$. These represent the giant branch clump or red horizontal branch. Above them again 2 stars are located suggestively near the expected giant locus; somewhat to the blue lie four stars of uncertain identity. The membership of several of these bright stars is discussed in more detail below.

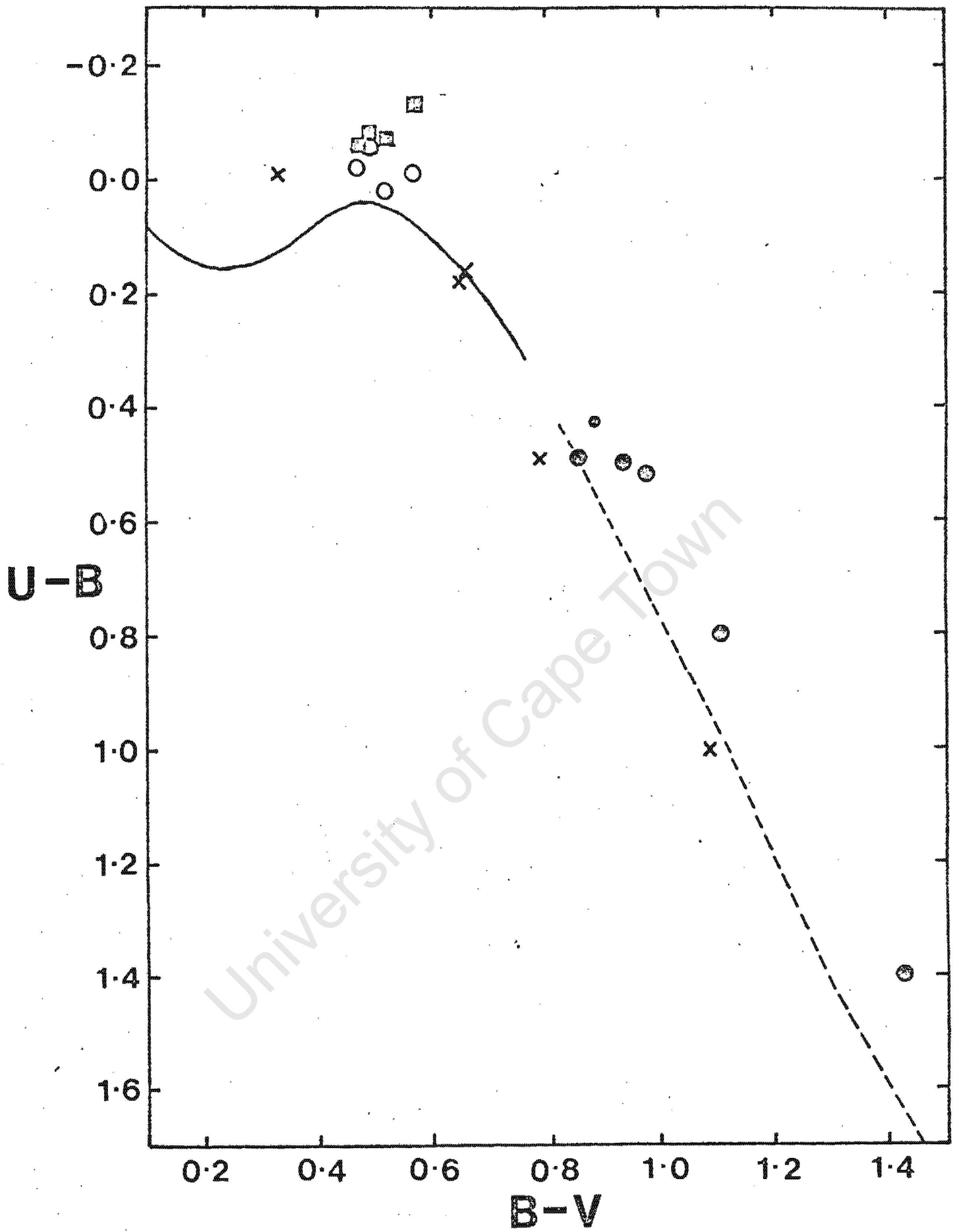

Fig. 2. The 2-colour diagram for stars in NGC 2243 measured photoelectrically. Filled circles represent probable cluster giants, the small filled circle represents a subgiant and the open circles indicate main sequence stars. Filled squares show the position of these stars after the application of gravity corrections. The crosses show stars believed to be foreground objects. The continuous curve is the Class V standard relationship and the broken curve is the combined Class III - Class V standard relationship. These are reddened by $E(B-V) = 0\overset{m}{.}06$ and $E(B-V) = 0\overset{m}{.}05$ respectively.

5. The 2-Colour Diagram and Cluster Membership

Figure 2 shows the 2-Colour diagram of the stars in Table I for which U-B values are listed. The cluster CM diagram, Fig.1, has been used to identify probable members of the principal sequences. In Fig. 2 main sequence stars are represented by open circles, the subgiant by a small filled circle, giants by filled circles and non-members by crosses. The filled squares indicate the location of the main sequence stars after correction for the gravity effect (section 6).

The standard relationships for dwarf (Class V) and giant (ClassIII) stars have been taken from Johnson (1966). These have been joined at their point of intersection near B-V=$1^{m}.0$. Many recent workers including Cannon & Stobie (1973) and Eggen & Sandage (1969 and, apparently, 1964) have used this subterfuge in the analysis of the ultraviolet colours of subgiants, red horizontal branch stars and other objects which may be too blue to be accommodated in the colour range within which the standard Class III 2-colour relationship is defined. This practise is supported by the apparently smooth overlap of giant(s) and dwarf relationships in the Hyades moving group. The Class III relation of Johnson, however, after crossing the locus of the dwarfs, terminates several hundredths of a magnitude bluer in U-B than the Class V relationship at the same B-V. If this difference is real the use of a fused relationship in this vicinity may lead to a significant overestimate of the ultraviolet excess of the bluest giants.

The standard relationships are shown in Fig.2, where the solid curve represents the Class V relationship and the dashed curve is the fused Class V-Class III curve. These have been reddened by amounts E(B-V) =$0^{m}.06$ and $0^{m}.05$ respectively, along the standard reddening trajectory. The derivation of these values is discussed in the next section.

While none are certain, four of the symbols assigned to stars in Fig. 2 are particularly open to debate. Stars 2307 ($V=12^{m}.17$, $B-V=0^{m}.79$, $U-B=0^{m}.49$) and 1219 ($V=11^{m}.81$, $B-V=1^{m}.09$, $U-B=1^{m}.00$) are shown as non-members. They are much bluer than would be expected of normal giants in Fig. 1 and, in Fig. 2, lie well below the stars with similar B-V colours which are better candidates for cluster membership. Conversely, the two putative red giants of Fig.1, Stars 4209 ($V=12^{m}.03$, $B-V=1^{m}.43$, $U-B=1^{m}.40$) and 4110 ($V=12^{m}.86$, $B-V=1^{m}.11$, $U-B=0^{m}.80$) are shown in Fig.2 as cluster giants. Neither can be a normal foreground dwarf: Star 4209 lies outside the possible dwarf domain in Fig.2 while 4110 would have to be far more heavily reddened than the cluster stars if it were a normal foreground giant or dwarf.

The use of comparative arguments of this type is dangerously circular. While this is recognised, it must be remembered that for present purposes we are concerned with obtaining as unexceptional a sample of cluster members as possible in order to use standard relationships for "normal" stars in their analysis. Occam's razor therefore indicates that the two first mentioned stars should be treated as non members and that the latter be accepted as cluster giants. On this basis, then, the analysis of Fig.2 is continued.

6. Reddening and Ultraviolet Excess

The reddening and ultraviolet excess of NGC 2243 may be determined simultaneously by a method akin to that used by Eggen and Sandage (1964) in M67. To do this it is necessary to assume a relationship between the ultraviolet excesses of giants and dwarfs of similar composition and to make corrections for certain distorting effects.

Eggen and Sandage assume that δ(U-B) measured for giants near $(B-V)_o=1^m.0$ and for dwarfs near $(B-V)_o=0^m.6$ is the same for stars of the same composition, an assertion supported by the approximate agreement between these quantities observed by Sandage (1970) in the globular clusters M15 and M92 which have large ultraviolet excesses. Wallerstein (1962) and Wallerstein and Helfer (1966) have compared δ(U-B) with [Fe/H] determined from Coudé spectroscopy of G dwarfs (relative to the sun) and of G and K giants (relative to the Hyades), respectively. Abundances [Fe/H] relative to the sun have been determined for Hyades dwarfs by Alexander (1967), by Griffin (1969), by Nissen (1970) and by Chaffee, Carbon and Strom (1971) who obtain, respectively, 0.25, 0.15, 0.38 and 0.15. The mean of these values [Fe/H] = 0.24 was applied to the zero-point of the abundance scale of the δ(U-B) vs [Fe/H] calibration obtained by Wallerstein and Helfer. Displaced by this amount the calibration for giants becomes almost indistinguishable from that for dwarfs, providing strong support for the assumption of Eggen and Sandage which is accordingly adopted here.

Variation of δ(U-B) with colour among dwarfs of similar composition is discussed by Sandage (1969) who provides tables of the effect. Eggen and Sandage (1964) suggest that this guillotine effect, attributable to the variation with colour of the slope of the blanketing vector in the 2-colour diagram, may be small or absent in giants. This surmise is supported by the recent extensive photoelectric results of

Cannon and Stobie (1973a;b) in the metal-poor globular clusters ω Cen and NGC 6752 where the giants show little or no dependence of δ(U-B) on colour.

The last mentioned results do show a dependence of δ(U-B) on gravity amongst the subgiants, similar to that predicted by Sandage and Walker (1966) and by Bell (1970). This effect can also be seen in 47 Tuc (Cannon, 1974). The effect results in larger δ(U-B) values among the fainter subgiants with higher gravities. This can be detected in faint, red subgiants in NGC 2420 if the recent results of McClure, Forrester and Gibson (1974) (hereinafter referred to as MFG) are examined. The subgiant star 4236 in NGC 2243 has therefore been excluded from the analysis.

As stars evolve off the main sequence their surface gravity decreases. In dwarfs with $(B-V)_o$ between $0^m.2$ and $0^m.6$ the reduction in gravity is accompanied by a reduction in electron pressure and hence in the H^- opacity, which reduction enhances emission at wavelengths longwards of the Balmer discontinuity. The result is a depression of their (U-B) colours in the 2-colour diagram, relative to those of unevolved stars. Eggen (1966) provides a table by means of which the effect can be corrected provided that the luminosity excess ΔM_V of the evolved star above the ZAMS is known. This effect is ubiquitous in open clusters in the intermediate age group, being particularly prominent in NGC 752 (Arp, 1962; Gunn and Kraft, 1963; Eggen, 1963), in NGC 2360 (Eggen, 1968) and in IC 4651 (Eggen, 1971).

Variation of the reddening trajectory with colour has been examined in several open clusters by Hartwick and McClure (1972) who find that the colour excesses of giants and main sequence stars, determined by means of the standard trajectory, satisfy the relationship $E(B-V)_g=0.82\ E(B-V)_m$. This has been found to hold for the cluster NGC 6259 (Hawarden, 1975b) which has $E(B-V)=0^m.65$.

The ultraviolet excess and reddening are determined by an iterative process. An estimate of $E(B-V)_g$ is made and the standard relationship, appropriately reddened in each case, is used to determine $\delta(U-B)$ for the giants and dwarfs. The mean excess for the giants is used to predict guillotined values for the dwarfs at their appropriate intrinsic colours. These values are compared with those derived from the 2-colour diagram using the current estimate of $E(B-V)_m$. If the measured values, in the mean, are larger than those predicted then the reddening has been overestimated. The cycle is repeated using an adjusted estimate of $E(B-V)$, until the preducted and observed values of $\delta(U-B)$ agree.

The resulting ultraviolet excess is now used to derive a mean blanketing correction $\Delta(B-V)$ from the table provided by Wildey, Burbidge, Sandage and Burbidge, (1962) and the main sequence in the CM diagram is appropriately corrected and reddened, when it may be approximately fitted to the standard ZAMS. Values of ΔM_V are now determined for the main sequence stars in the 2-colour diagram and appropriate gravity corrections are applied. The process of the previous paragraph is repeated and new values of $\delta(U-B)_{0.6}$ and $E(B-V)$ are obtained. The ultraviolet excess will be increased and the reddening correspondingly decreased, relative to the first solution. The decreased reddening will act to compensate for the resulting increased blanketing correction $\Delta(B-V)$; since the standard sequence changes slope rather slowly it is unlikely that the new solution will introduce significant changes in the ΔM_V values. If these occur the whole cycle must be repeated.

In NGC 2243 the initial solution gives $E(B-V)_m = 0^m.11$, $\delta(U-B)_{0.6} = 0^m.095 \pm 0^m.035$. The uncertainty in the last result reflects the standard error of the mean ultraviolet excess of the giants. The points representing the main sequence after the application of gravity corrections — filled squares in Fig. 2 — show an interesting reduction in scatter. The final solution for NGC 2243 is then:

$$E(B-V)_m = 0.06; \quad \delta(U-B)_g = \delta(U-B)_{0.6} = 0.15 \pm 0.035 \text{ (s.e.)}$$

This is the largest ultraviolet excess that has yet been observed in an open cluster. It is therefore of interest to apply the method to other objects. Eggen (1969) obtains a reddening $E(B-V) = 0^m.04$ for the cluster NGC 3680 which leaves the giants with an ultraviolet excess relative to the main sequence stars. Application of the present method gives $E(B-V)_m = 0^m.09$, $\delta(U-B)_{0.6} = \delta(U-B)_g = 0^m.04 \pm 0^m.01$. These results are in excellent agreement with those obtained by McClure (1972) using intermediate-band (DDO) photometry.

Eggen (1971a) has published detailed UBV photometry of IC 4651 for which he obtains a reddening $E(B-V) = 0^m.15$ from nearby early-type stars. This leaves the cluster giants with zero ultraviolet excess as against $\delta(U-B) = 0^m.06$ for (unevolved) main sequence stars. The evolved main sequence shows an ultraviolet depression in excellent agreement with that expected from the tabulated values (Eggen, 1966) used earlier. The present method applied to IC 4651 gives $E(B-V)_m = 0^m.12$, $\delta(U-B)_{0.6} = \delta(U-B)_g = 0^m.058 \pm 0^m.009$.

The largest ultraviolet excess previously found in an open cluster is the value $\delta(U-B)_{0.6} = 0^m.10$ obtained by MFG for NGC 2420. These workers obtain a reddening $E(B-V) = 0^m.02$ from DDO photometry. The present method was applied to 9 giants (excluding the subgiants, the BaII star X and the bluish giant F) and to 7 unevolved main sequence stars, giving $E(B-V) = 0^m.00$, $\delta(U-B)_g = \delta(U-B)_{0.6} = 0^m.093 \pm 0^m.012$. If the evolved main sequence stars (mostly omitted by MFG) are used instead, the result after application of corrections for the gravity and guillotine effects is $\delta(U-B)_{0.6} = 0\overset{m}{.}097$, in excellent agreement. Inclusion of the giant F increases the reddening to $0\overset{m}{.}02$ leaving the ultraviolet excess essentially unaffected.

7. Chemical Composition

The ultraviolet excess of NGC 2243 indicates a composition resembling the globular clusters NGC 6981 (Dickens, 1972) and NGC 6723 (Menzies, 1974). The results of Alexander (1967) imply, for $\delta(U-B) \leq 0.16$ a relation $[Fe/H] = -4.68\ \delta(U-B)$ relative to the Hyades. Combining this with the Hyades metal abundance $[Fe/H] = 0.24$ relative to the sun - derived in the previous section - gives the metal abundance of NGC 2243, likewise relative to the sun as $[Fe/H] = -0.46$. If a solar abundance $Z = 0.02$ is adopted a corresponding value $Z = 0.006$ is obtained for NGC 2243.

Alexander's calibration is valid to $\delta(U-B) = 0^{m}.16$ only; the earlier calibration by Wallerstein (1962) begins to exhibit significant curvature near this point, above which $[Fe/H]$ varies more rapidly with $\delta(U-B)$. The present estimates of the heavy element abundance in NGC 2243 may therefore prove to be rather high.

The possibility exists that microturbulence in stellar atmospheres may stimulate the effect on $\delta(U-B)$ of metal enrichment. This is discussed in section 10. It appears unlikely to be of large influence here.

8. The Age of NGC 2243

The effective temperatures of computed stellar models are very sensitive to uncertainties in the theory of surface convection (Demarque, 1968) so that it is usual for cluster ages to be determined by comparison of observed and predicted turnoff luminosities (eg., Sandage, 1970) which are relatively unaffected by the treatment of convection. The distance modulus of NGC 2243 (discussed in section 9) is far from certain and a luminosity-based estimate of the age is likely to be correspondingly unreliable. The age of the cluster has therefore been derived from the turnoff colour by means of comparisons with other systems which have relatively well-determined ages. Due account is taken of differences in heavy element abundance (Z) and, in principle, in Helium abundance (Y) from cluster to cluster.

Turnoff temperatures were obtained from sets of theoretical isochrones computed under identical conditions but for different compositions and ages. In some cases evolutionary tracks, rather than isochrones, were used. All isochrones which show a discontinuity resulting from rapid evolution during the core hydrogen exhaustion phase (HEP) have maximum effective temperature T_e at the blue limit of the discontinuity. "Isochronal" turnoff temperatures and ages (T_9) in units of 10^9 years were therefore derived from the tracks by adopting the temperature and age of the first model subsequent to the rapid blueward evolution during the HEP.

Comparison of the temperatures and ages thus obtained yielded the values of the derivatives ($\partial \log Te/ \partial \log T_9$), ($\partial \log Te/ \partial \log Z$) and ($\partial \log Te/ \partial Y$) which are given in Table IV. Also specified are the conditions under which these values obtain and the sources of the

Table IV

Dependence on Y,Z and age of the turnoff temperature of theoretical isochrones

Source	Quantity	Conditions				Value
		$\overline{Z}$	$\overline{Y}$	$\overline{T_9}$	$\overline{\text{Log Te}}$	
DG: Isochrones		0.01	0.25	3.9	3.807	-0.153
"		"	0.35	3.9	3.818	-0.184
"		"	"	5.9	3.788	-0.122
HB: Isochrones		"	0.40	5.0	3.802	-0.142
"	$A = \dfrac{\partial \log T_e}{\partial \log T_9}$	"	"	6.0	3.792	-0.096
"		"	0.30	5.0	3.795	-0.119
"		"	"	7.3	3.777	-0.105
"		"	0.20	7.3	3.772	-0.105
"		"	"	11.0	3.754	-0.092
ADM: Track C and 0.98 M☉		0.03	0.30	5.4	3.769	-0.110
ADM: Tracks C & F		0.04	0.30	4.9		-0.077:
ADM: Tracks C & E; HB: Isochrones	$B = \dfrac{\partial \log T_e}{\partial \log Z}$	0.02	0.30	4.9		-0.046:
DMA: Single tracks And $Z=10^{-3}$ series		3×10^{-3}	0.25	7.1		-0.012
"		3×10^{-4}	0.25	7.1		-0.012
DMA: Isochrones		10^{-3}	0.37	10		0.336
"	$C = \dfrac{\partial \log T_e}{\partial Y}$	10^{-3}	0.12	10		0.184
HB: Isochrones		0.01	0.30	6.0		0.05:
DG: Isochrones		0.01	0.30	5.9		0.08:
ADM: Tracks A&E		0.03	0.30	4.9		0.08:

isochrones and evolutionary tracks used. These sources, with the abbreviations used in Table IV and elsewhere hereinafter are: Aizenman, Demarque & Miller (1969)(ADM); Demarque, Mengel & Aizenman (1971)(DMA); Hartwick & van den Berg (1973)(HB); Demarque & Gisler (isochrones and theoretical main sequence loci published by MFG) (DG). Additional results by Demarque & Heasley (1971) and by Hartwick & Hesser (1973) were investigated but do not add materially to the present data. All the models used were computed with similar or identical programs and input physics. This might be expected to minimise the uncertainties which are introduced when models from different publications are compared. Investigation of variations of the values of the derivatives with composition and age must perforce be based on such comparisons.

Derivative A = $(\partial \log T_e / \partial \log T_9)$ is rather closely dependant on $\log T_e$. B = $(\partial \log T_e / \partial \log Z)$ varies with z but is unfortunately poorly determined, as is C = $(\partial \log T_e / \partial$ Y,) which is also a function of Z.

The basic information used in comparing the clusters is given in Table V(a). Turnoff colours, reddening and blanketing values for M67 and NGC 188 were taken from Eggen & Sandage (1964;1969) and the cluster ages from Sandage & Eggen (1969). The requisite values for NGC 2420 were taken from the results of MFG but the mean blanketing corrections therein were replaced by values determined specifically for the main sequence turnoff. The age of NGC 2420 obtained by MFG may be in error, for reasons discussed in section 9. Conversion of reddening-free blanketing-corrected turnoff colours to values of $\log T_e$ was effected using the calibration by Schlesinger (1969).

Heavy element abundances relative to the sun, given in Table V(a) were derived from several sources. Barry & Cromwell (1974) obtain spectroscopic abundances for stars in M67 and the Hyades which imply that

Table V

(a) Properties of Clusters

Cluster	$[Fe/H]_{\odot}$	$(B-V)_{o,T}$	$\Delta(B-V)$	$(B-V)_{o,c}$	log T_e	T_9
NGC 188	0.00	$0^m.59$	$0^m.03$	$0^m.62$	3.766	9.0
M67	0.11	0.51	0.03	0.54	3.784	5.5
NGC 2420	-0.26	0.38	0.04	0.42	3.825	(3.3)
NGC 2243	-0.46	0.39	0.06	0.45	3.815	-

(b) Differential Age Determinations

Cluster	Reference Cluster	Δ log T_e	Δ log Z	A	B	T_9
NGC 2243	M67	0.031	-0.57	-0.145	-0.044	5.0
NGC 2243	NGC 188	0.049	-0.46	-0.123	-0.040	5.1
NGC 2420	M67	0.041	-0.37	-0.152	-0.048	3.9

M 67 has [Fe/H] = -0.13 relative to the Hyades. Intermediate band (DDO) photometry of the Hyades giants gives cyanogen strength indices with a mean excess $\delta CN = 0^m.06$ (McClure & van den Bergh, 1968; Demarque & McClure, 1973) while Janes (1974) and Osbourne (1974) obtain $\delta CN = 0^m.03$ for M 67. McClure & Osbourne (1974) quotes a calibration of this index by Janes who obtains [Fe/H] = 4.5 δ CN -0.2, where [Fe/H] is given relative to the sun. This implies an abundance for the Hyades, relative to the sun of [Fe/H] = 0.07, an unacceptably low figure in view of the results of the recent determinations mentioned in section 6. The present adopted abundance for the Hyades, [Fe/H] = 0.24 relative to the sun, indicates that a calibration [Fe/H] = 4.5 δ CN -0.03 is more appropriate. Irrespective of the zero-point, Janes' calibration gives for M67 an abundance relative to the Hyades of [Fe/H] = -0.135 in excellent agreement with that derived from the results of Barry & Cromwell.

Demarque & McClure (1973) quote unpublished results by McClure who obtains $\delta CN = 0.00$ for giants in NGC 188. A solar abundance is therefore adopted in Table V(a). For NGC 2420 the reanalysis of the UBV photometry given by MFG which was performed in section 6 gives a mean $\delta(U-B)_{0.6} = 0^m.095$ in agreement with the mean of the values for giants and dwarfs obtained by MFG. Their cyanogen-strength excess $\delta CN = -0^m.06$ implies [Fe/H] = -0.54 relative to the Hyades while Alexander's calibration of $\delta(U-B)_{0.6}$ gives an abundance relative to the Hyades of [Fe/H] = -0.44. The mean value adopted by MFG, [Fe/H] = -0.5 relative to the Hyades, is therefore accepted here; after correction for the Hyades abundance a value [Fe/H] = -0.26 relative to the sun is given in Table V(a).

It should be noted that spectrum-scanner studies by Spinrad & Taylor (1969) and by Spinrad, Greenstein, Taylor & King (1970) are interpreted by these workers as indicating that M67 and NGC 188 are "Super

Metal-Rich", i.e. have abundances much larger than the Hyades. Their interpretation of the scanner results for field stars (Spinrad & Taylor, 1969) have been criticised by Eggen (1971b) and more recently by Blanc-Visiaga, Cayrel & Cayrel (1973). Furthermore all subsequent observational studies of M67 including the spectroscopy by Barry & Cromwell (1974), the DDO photometry by Janes (1974) and Stromgren photometry by Bond & Perry (1971) and by Strom, Strom & Bregman (1971) are unanimous in their rejection of the conclusions of Spinrad and his co-workers. Accordingly the metallicity estimates used here assume that the general results of wide-band (UBV) photometry are in fact correct.

For each cluster comparison values of the derivatives A and B from Table IV were graphically interpolated according to the cluster characteristics in Table V(a). Differential ages were then obtained by assuming

$$\Delta \log T_9 = \frac{1}{A}\Delta \log T_e - \frac{B}{A}\Delta \log Z - \frac{C}{A}\Delta Y \text{----}(1)$$

where the present estimates assume Y = 0.3 and thus $\Delta Y = 0$ in all cases. The estimated values of A and B are given in Table V(b) together with the resulting age estimates for NGC 2243 and for NGC 2420 (see section 10).

The determinations of the derivatives involve considerable uncertainties and a single age estimate derived using (1) probably has a fractional standard error of about 10%. The observational determinations of $\log T_e$ and log Z for NGC 2243 generate additional uncertainties: if the turnoff colour has standard error $\pm 0^m.02$ and the s.e. of $\delta(U-B)_{0.6}$ is $0^m.035$ as given in section 6, the resulting fractional standard error of the age determination is about 15%, somewhat larger than the uncertainty inherent in the method. The age of NGC 2243 is then taken to be $(5.0 \pm 0.8) \times 10^9$ years, slightly less than that of M67.

9. Distance Modulus and Location in the Galaxy

Normal points defining the main sequence of NGC 2243 are listed in columns 1 and 2 of Table VI. These were derived from curves drawn by eye through the ridge line of the upper main sequence in Fig.1, smoothly extrapolated along the subgiant branch to the points near $V = 15^{m}.9$, $B-V = 0^{m}.7$ and along the lower main sequence to the mean of the two faintest photoelectric standards. Because of these extrapolations the first two and the last points in Table VI are probably unreliable.

Attempts to correct these points individually for the deblanketing effects of metal deficiency produce considerable distortion of the resulting sequences owing to the rapid variations of the guillotine and blanketing effects with colour. Mean blanketing corrections $\Delta(B-V) = 0^{m}.10$ and $\Delta V = -0^{m}.04$ were therefore applied in deriving the unreddened, blanketing-free points in columns 3 and 4 of Table VI. As a result the turnoff colour in column 4 is significantly redder than that given in Table V(a). The points in columns 3 and 4 were then compared with the standard ZAMS (Eggen, 1965) to give the values of $(V_{o,c} - M_V)$ and M_V listed in columns 5 and 6 and plotted in Fig. 3, the evolutionary deviation diagram. Those points considered to be unreliable are indicated in Fig. 3 by crosses.

An evolutionary deviation curve derived from the DG isochrones is tabulated by MFG; this may be fitted to the points in Fig. 3 in two ways. The points derived from the main sequence above the HEP in Fig.1 yield a distance modulus $(m-M)_o = 12^{m}.93$ while those from below the discontinuity give $(m-M)_o = 12^{m}.63$. The dashed line in Fig.3 shows the location of this theoretical curve fitted with the latter distance modulus. Evidently the main sequence gap in Fig. 1 is much less well developed than that shown by the models used in constructing the isochrone from which this evolutionary deviation curve was derived.

Table V1

Normal Points in NGC 2243

V	(B-V)	$V_{o,c}$	$(B-V)_{o,c}$	$(V_{o,c} - M_V)$	M_V
18.00:	0.65:	17.76	0.69	12.49	5.27
17.50:	0.57:	17.24	0.61	12.42	4.82
17.00	0.49	16.76	0.53	12.46	4.30
16.70	0.46	16.46	0.50	12.36	4.10
16.50	0.46	16.26	0.50	12.16	4.10
16.20	0.48	15.96	0.52	11.73	4.23
16.08	0.51	15.83	0.55	11.38	4.45
16.05	0.45	15.81	0.49	11.76	4.05
15.90	0.47	15.66	0.51	11.49	4.17
15.80	0.49	15.56	0.53	11.26	4.30
15.75	0.52	15.50	0.56	11.00	4.50
15.70	0.58	15.44	0.62	10.57	4.87
15.80:	0.67:	15.56	0.71	10.18	5.38

Table VII

Evolutionary Deviation Curve: 5×10^9y, Y = 0.30, Z = 0.01

ΔM	M_v (ZAMS)
0.06	5.41
0.13	5.17
0.19	4.96
0.24	4.71
0.36	4.50
0.45	4.39
0.57	4.29
0.67	4.25
0.93	4.21
1.18	4.29
1.68	4.50
1.86	4.71
2.16	4.96
2.52	5.17
2.66	5.41
2.88	5.61
3.11	5.84

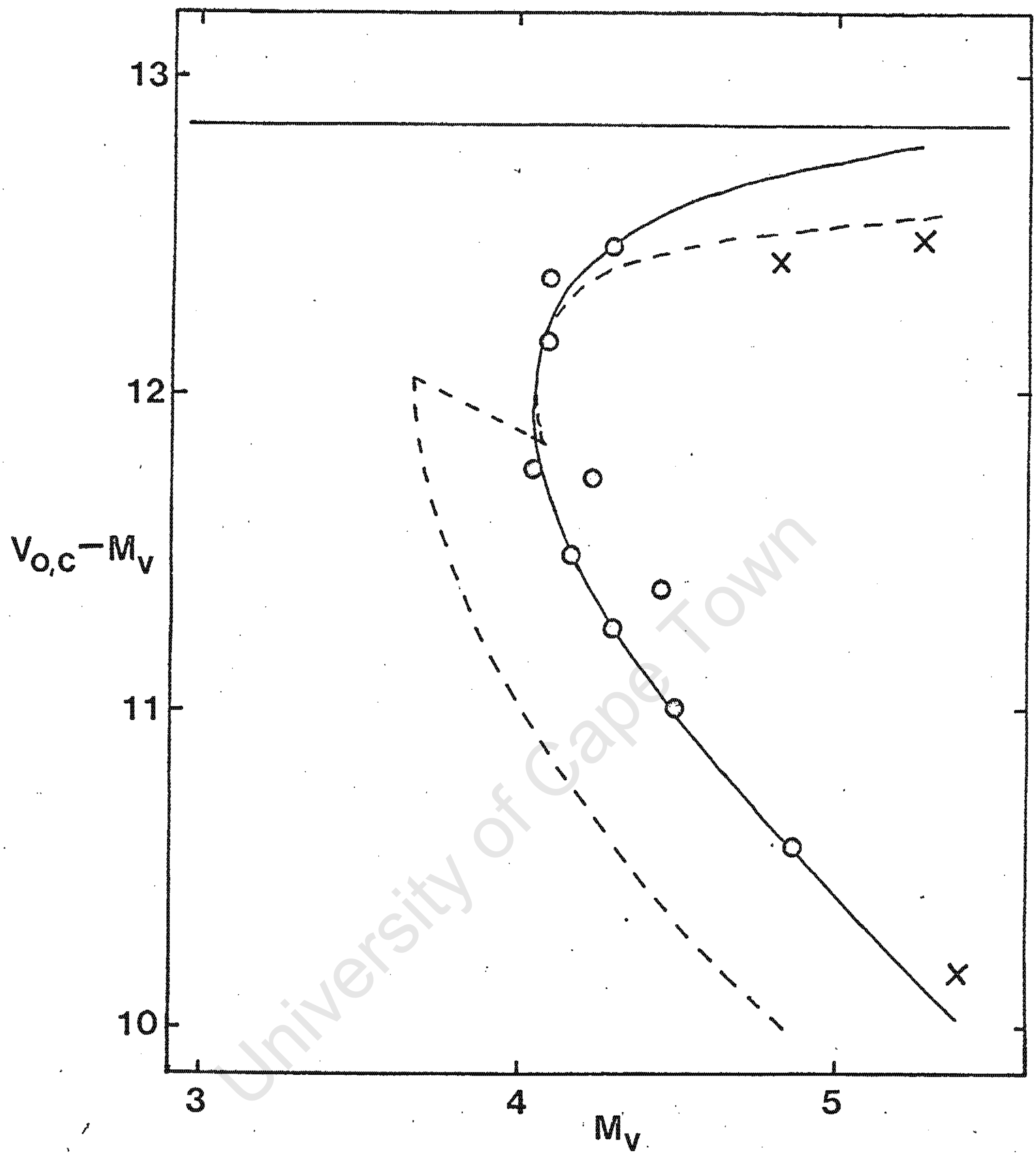

Fig. 3. The evolutionary deviation curve of NGC 2243 derived from the normal points in Table VI. The broken curve is the theoretical evolutionary deviation curve from MFG shown with $(m-M)_o = 12^m.63$. The continuous curve is derived from an isochrone by HB and is shown fitted with $(m-M)_o = 12^m.85$.

10. Uncertainties in the ZAMS luminosity

In their determination of the distance modulus of NGC 2420 MFG apply a correction of $0^{m}.4$ to allow for the depression of the main sequence luminosity with reduced heavy element abundance which is uniformly predicted by theoretical investigations. This effect is discussed by Faulkner (1967) and by Cayrel (1968); MFG derive their correction from theoretical main sequences computed for values of Z between 0.06 and 0.01 by Demarque and Gisler. The corresponding correction for NGC 2243, assuming a Hyades abundance $Z = 0.035$ ($Z_{\odot} = 0.02$, Hyades $[Fe/H] = 0.24$ relative to the sun) is about $0^{m}.8$. The corrected distance modulus would make the mean absolute magnitude of the horizontal branch in NGC 2243 $M_v \sim 1^{m}.7$, fainter than any other known (Cannon, 1970). The distance modulus derived by MFG for NGC 2420, adjusted for the higher Hyades abundance adopted here, makes the absolute magnitude of the horizontal branch $M_v \sim 1^{m}.3$; the resulting suggestion of a downward trend of horizontal branch luminosity with decreasing metal abundance would have alarming implications if extrapolated to the great globulars.

In a study of the old disk stars in the solar neighbourhood Eggen (1973) has shown that while very metal deficient stars are indeed underluminous by about a magnitude in the (M_{bol}, R -I) plane, unevolved stars with $Z > 0^{m}.008$ lie along a main sequence locus indistinguishable from that of the Hyades. This is true also of the main sequences of the 61 Cygni, Wolf 640 and Arcturus moving groups which have ultraviolet excesses $\delta(U-B)_{0.6} = 0^{m}.075$, $0^{m}.065$ and $0^{m}.11$ respectively. NGC 2243 has $\delta(U-B)_{0.6} = 0^{m}.15$ and it is therefore reassuring to note that the main sequence of the σ Puppis group which has $\delta(U-B)_{0.6} = 0^{m}.17$ coincides with that of the Arcturus group in the (M_{bol}, R -I) plane (Eggen, 1971b). The use of (R-I) colours in this context is particularly convenient because they are essentially unaffected by blanketing and therefore provide a measure of log T_e without the complications attendant upon the use of blanketing corrections in B-V. Eggen derives an ultraviolet excess Δ(U-B) in the (U-B, R-I) plane which is closely analogous to the blanketing correction Δ(U-B) tabulated by Wildey et al. (1962). Their values for B-V = $0^m.60$ indicate that, to a good approximation, $\delta(U-B)_{0.6} = 0.53\Delta(U-B)$. The smallest ultraviolet excess for which Eggen finds a significant luminosity deficiency is Δ(U-B) = $0^m.23$ which would appear to correspond to $\delta(U-B)_{0.6}$ = $0^m.12$. The star in question (-24°17814A) is rather red but this result serves to emphasise the fact that there is no reason to assume that the transition between Hyades-like and subdwarf-like luminosities must occur at a consistent value of $\delta(U-B)_{0.6}$. Thus, while the observational evidence suggests that the distance moduli of NGC 2243 and NGC 2420 should be left uncorrected for abundance-dependent luminosity effects, the results must be regarded with some caution.

The reason for the lack of a correlation between the main sequence luminosity deficiency and the heavy element abundance derived from the ultraviolet excess is entirely unclear. Eggen (1973) suggests that the range in δ(U-B) observed among disk stars may be generated by variations in microturbulence in stellar atmospheres. On this assumption a population of homogeneous composition might include "pseudo-metal-rich" stars such as the Hyades, with large microturbulent velocities and small ultraviolet excesses together with stars like the members of NGC 2243 and the σ Puppis group with exceptionally low microturbulence and correspondingly high ultraviolet excesses.

Without entering this controversial field it may be remarked that the metal abundance differences found by Griffin (1969) in analyses of high-dispersion spectrograms of Hyades stars and Arcturus, which results are presumably almost immune to the effects of microturbulence, agree well with the abundance differences derived from the ultraviolet excesses of the Hyades cluster and the Arcturus group. Photoelectric measures of weak lines in Hyades stars by Nissen (1970) also indicate that this cluster does not owe its low ultraviolet excess to the effects of microturbulence.

An alternative hypothesis put forward by Eggen postulates a variation in helium abundance among disk stars sufficient to offset the effects of the range in heavy-element abundances. For example Faulker (1967) gives a quasi-homology relation which implies that

$$\text{Log } L = 2.67 \log(X+0.4) + 0.455 \log(Z+0.01) + \text{Const} \quad \text{--------(2)}$$

A constant main sequence luminosity can then be maintained in the face of variations in Z from, eg, 0.03 to 0.006 if Y is simultaneously reduced from a conventional 0.30 to 0.15. However the guillotining effect of the constant 0.01 in the second RHS term in (2) limits the excursions of the main sequence, for constant Y, to about $0^m.7$ which is probably inadequate to explain the observed luminosity deficiency of the extreme subdwarfs.

Against the suggested variation in Y must be set the evidence of globular cluster studies which imply a primeval helium abundance around Y = 0.3 (Sandage, 1970). Although Koester & Weidemann (1973) suggest that the Hyades have Y = 0.36 the general agreement between the globular cluster helium abundances and those few available for solar neighbourhood stars argues against the existence of the degree of variation required.

There is thus little hope for a clarification of the problem of whether or not the distance modulus of NGC 2243 has been overestimated. The observational evidence indicates that the result derived in the previous section is correct in the present circumstances and that the adjustment of the distance modulus of NGC 2420 by MFG is unnecessary. The revised distance modulus for that cluster is $(m-M)_o = 11^m.8$ in good agreement with the value $(m-M)_o = 12^m.0$ derived by MFG from intermediate band (DDO) photometry of the giants.

The assumption of a constant main sequence location in the (M_{bol}, log Te) plane, independent of Z, leads to complications in the use of luminosity-based age determinations. The blue edges of the HEP discontinuities in the DG isochrones for Z = 0.01 and Y = 0.30 satisfy

$$\log Te = 0.324\, M_{bol} - 0.526 \quad \text{------------(3)}$$

which may be adjusted for variations in Z by means of the relationship between log T_9, M_{bol}, log Z and Y given by HB. The latter used isochrones exhibiting no HEP discontinuity but differential application of their results to the relation (3) gives, for Z = 0.006, Y = 0.30

$$\log Te = 0.338\, M_{bol} - 0.543 \quad \text{------- (4)}$$

The blue edge of the gap in the main sequence of NGC 2243 lies at $V = 16^m.05$, $B-V = 0^m.45$. The adopted reddening and ultraviolet excess and the Bolometric Corrections of Schlesinger (1969) give $M_{bol} = 15^m.83$. If $(m-M)_o = 12^m.85$ the absolute bolometric magnitude of the turnoff, defined as above, is $M_{bol} = 2^m.9$. Substitution in (4) gives an age 2.7×10^9 years, far smaller than the value deduced from the turnoff colour.

If metal abundance variations are constrained to affect only the shape of the evolved main sequence but not the location of the ZAMS in the (M_{bol}, log Te) plane it appears logical (if naive) to adjust the isochrones used in obtaining (3) and (4) to the standard ZAMS before deriving these expressions. The equivalent effect can be obtained by using the "corrected" modulus of NGC 2243, $(m-M)_o = 12^m.0$ to derive the cluster age using (4). The resulting turnoff magnitude $M_{bol} = 3^m.7$ gives an age of 5.1×10^9 years in excellent agreement with that derived in Section 8.

No account has been taken of the effects of differences in helium abundance from cluster to cluster which may well be substantial if Eggen's second suggested explanation for the absence of Z-dependent main-sequence variations is correct.

A realistic overall discussion of this problem will not be possible until consistent sets of isochrones have been computed for suitably wide ranges in Y and Z so that improved versions of the quasi-homology relation (2) can be derived. It does not appear useful, in the meantime, to attempt to refine further the age estimates obtained in this and other discussions of old open clusters. Such an attempt should await a convincing explanation of the constancy of the observed main sequence location.

11. Discussion

The observational properties of NGC 2243 are discussed below with emphasis on their relation to results for other clusters and on comparisons with stellar evolution theory. It should be recognised that the deduced properties of this cluster have large uncertainties. Particularly critical is the ultraviolet excess which affects the estimates of reddening and distance modulus. The uncertainties in the physical theory upon which many of the results are based have been stressed in the relevant sections, above.

(1) NGC 2243 has ultraviolet excess $\delta(U-B)_{0.6} = 0^m.15 \pm 0^m.035$ which implies [Fe/H] = -0.46 relative to the Sun. The cluster is in this respect similar to the globular clusters NGC 6981 (Dickens, 1972) and NGC 6723 (Menzies, 1974). The absence of the blue horizontal branch and RR Lyrae variables present in these systems is presumably a consequence of the much lower age of NGC 2243. The correspondingly larger mass of the evolved cluster members confines them to the red end of the horizontal branch during the core helium-burning phase of their evolution (Gross, 1973; Demarque & Mengel, 1971).

(2) NGC 2243 appears to lie about 1100 parsecs from the galactic plane, further than any other known open cluster. In this respect also, it suggests a condition intermediate between the open and globular clusters. The open clusters with distances from the galactic plane (/Z/) most similar to that of NGC 2243 are NGC 2420 (/Z/ = 800 pc if the distance modulus is revised as suggested in the previous section) which also has a large ultraviolet excess and a low heavy element content, Melotte 66 (Hawarden, 1974c) at /Z/~ 1 kpc, also exceptionally metal poor, and NGC 6791 for which Kinman (1965) derives /Z/ = 970 pc. While Kinman suggests that this cluster may be metal poor, the scanner results of Spinrad & Taylor (1971) give [Fe/H] = 0.7 relative to the sun. More detailed analyses of NGC 6791 would be most valuable.

(3) NGC 2243 exhibits a well-defined gap in the upper main sequence which is principally manifest as a discontinuity in colour. The tendency of the main sequence in Fig. 1 to deviate to the red immediately below the gap is universally characteristic of those theoretical isochrones which show the HEP discontinuity but has nowhere before been observed so clearly in a real cluster. The normal points for NGC 2420 listed by MFG show this effect but these workers freely admit that they have introduced this deviation more to secure agreement with the predictions of theory than to represent the observed CM diagram. In contrast, the CM diagram of M67 derived by Racine (1971) which is of much higher precision than Fig. 1 shows little or no discontinuity in colour across the gap.

(4) The main sequence in Fig.1 rises about $0^{m}.35$ above the upper edge of the gap. Racine (1971) finds that the corresponding segment of the main sequence in M67 has a height $\Delta M \sim 0^{m}.5$ which suggests a downward trend of ΔM with decreasing Z. This is in direct contradiction with the theoretical predictions of Demarque & Heasely (1971) who find that ΔM should decrease with increasing Z. However the results in NGC 2243, in M67 and in Melotte 66 (Hawarden, 1975b) are in excellent agreement with new model computations by M.J.Prather and P.Demarque (1974, Preprint) who include allowance for the effect of mixing by convective overshoot at the boundary of the core. The resulting admixture of hydrogen-rich material substantially prolongs the duration of core hydrogen-burning so that the post-HEP segment of the main sequence is considerably reduced. Furthermore their isochrones for Y=0.25, Z=0.02 now exhibit significant gaps at ages up to 9×10^{9} years which removes the necessity for invoking a high helium abundance to explain the presence of a gap in NGC 2243 ($Y > 0.35$ if DG results are used).

(5) The probable existence of a loose grouping of subgiants at the base of the rising giant branch in Fig. 1 was demonstrated in section 4. These stars have mostly been measured on several plates and the apparent colour dispersion of the upper main sequence therefore suggests that their spread of about $0^m.2$ in B-V is real. A similar spread is shown by the photoelectric results of Eggen & Sandage (1969) for corresponding stars in NGC 188 but no such scatter is apparent in the CM diagrams of M67 (Racine, 1971) or NGC 2420. Current evolutionary theories offer no obvious explanation for such a scatter.

Further and more detailed study of NGC 2243 is very desirable. Intermediate band photometry of giants on the DDO system would be especially valuable as a check on the very low heavy element abundance implied by the ultraviolet excess derived here. UBV photometry of additional main sequence stars and better definition of the lower main sequence is also urgently needed to confirm or improve the present results. Radial velocities of the brighter cluster members will improve the definition of the giant branch in the CM diagram and provide information about the kinematic properties of the cluster which are completely unknown at present. Segregation of members by proper motions cannot be achieved at present as no suitable first epoch plates are available. It nonetheless appears certain that this cluster will handsomely repay further investigation.

Acknowledgements

Many members of the staff of the S.A.A.O have contributed to this work. In particular I wish to thank Mr. G.A. Harding for his continued support and encouragement, Dr. Peter Warren, for many enlightening and stimulating discussions and Dr. Drummond Laing for extensive assistance with the darkroom work. Mr. Hennie Barnard is largely responsible for successful observing at Sutherland and the comfort of visiting astronomers is efficiently supervised by Ms. Hettie Barnard. This work forms part of a Ph.D. Thesis at the University of Cape Town and I owe much to the encouragement and supervision of Professor Brian Warner. I am grateful to the Large Telescope Users Panel for allocation of time on the Radcliffe telescope. Dr. Peter Andrews was extremely generous with his assistance during the observing in Pretoria on this and related projects.

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THE OLD OPEN CLUSTER MELOTTE 66

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Chapter IV

Summary

Photoelectric UBV and photographic BV photometry of stars in and near the open cluster Melotte 66 shows that the cluster is probably exceptionally old. The CM diagram shows a long red giant branch, a prominent giant branch clump and a well-populated rising subgiant sequence. No horizontal subgiant sequence is detectable. The upper main sequence has a distinct gap and several blue stragglers are present. A group of bright blue stars may include clusters members. The red giant branch appears to be composed of two parallel sequences of stars, the bluer of these being preferentially populated by stars in the outer portions of the cluster. This feature is tentatively identified as an analogue of the asymptotic branch in globular clusters. The 2-colour diagram indicates a small reddening and significant ultraviolet excess. Use is made of the colour difference between the main sequence turnoff and the subgiant branch in several clusters in an attempt to resolve uncertainties in the age and composition of Melotte 66. It is tentatively concluded that the cluster has $E(B-V) = 0\overset{m}{.}17$, $\delta(U-B)_{0.6} \sim 0\overset{m}{.}1$ and $[Fe/H]_{\odot} \sim -0.2$. A distance modulus $(m-M)_0 = 12\overset{m}{.}4$ is derived which implies that Melotte 66 lies 750 parsecs from the galactic plane. The age of the cluster is believed to be about 7×10^9 years, intermediate between M67 and NGC 188.

1. Introduction

The open cluster Melotte 66 is located at $\alpha = 07^h\ 25^m.6$, $\delta = -47°\ 41'$ (1975) with l = 260°, b = -14°3. The cluster is no. 739 in the catalogue of Alter, Ruprecht and Vanysek (1970).

Eggen & Stoy (1963) obtained photographic BV photometry based on a photoelectric UBV sequence reaching $V = 15^m.3$. They derived a reddening value $E(B-V) = 0^m.13$ and their colour-magnitude (CM) diagram, heavily contaminated by field stars, showed a long giant branch, typical of an old cluster. At $V \sim 15^m$ a narrow Hertzsprung gap seemed to occur. On the basis of these results King (1964) included the cluster in a list of open clusters believed to be older than 4×10^8 years.

A chart of the cluster appears in the Atlas of Southern Open Clusters (Hogg, 1965). Star counts on this chart were used to construct a contour diagram of star density in the cluster vicinity which showed a density excess with angular diameter about 13 arc minutes. A region of 5' radius centered on this excess was selected together with a comparison region in the form of a ring of inner radius 10' concentric with the central region but having twice the area. Two plates from the material used by Eggen & Stoy, 100 minute exposures in V (103a D + O mag 301) and in B(IIa-O + GG13) were used for an initial study. These plates had been taken with the McClean 61cm photographic and 46cm photovisual refractors at the Royal Observatory, Cape (now the South African Astronomical Observatory).

The Askania Iris Photometer at the S.A.O. was used to measure on these plates all uncrowded stars brighter than $V = 15^m.5$ in the selected regions. The measures were calibrated by means of the existing photoelectric sequence. A rough-and-ready subtraction method was used to correct for the effects of contamination by non-members in the central region. The resulting CM diagram showed a long giant branch extending to below the calibration limit. A prominent grouping of giants was evident at V ~ $14^{m}.5$; on the CM diagram of Eggen & Stoy (1963) this feature combines with the distribution of the field stars to present the appearance of a Hertzsprung gap.

The original plate material included a B and a V plate, both 60 minute exposures taken with the Radcliffe telescope diaphragmed to 112cms. This pair had been used by Eggen & Stoy for "extrapolation" photometry in the original study. Iris measures were made of all stars in a central 3' radius area on these plates in order to get some idea of the nature of the fainter regions of the CM diagram. A well populated main sequence appeared at "V" = $16^{m}.3$ and extended beyond the limit to which enthusiasm could be permitted to extrapolate the photoelectric calibration, somewhat fainter than "V" = 17^{m}.

2. Photoelectric Photometry

The original sequence by Eggen & Stoy is inadequate for further study of the cluster and a new sequence has therefore been observed. The stars marked E6 and E7 on Plate I were tied to the UBV system by observations of E region stars on 4 nights in 1970 and on 4 and 5 nights respectively in 1974. The mean results are included in Table I and have internal standard errors less than $0^{m}.01$. No suggestion of variability has been encountered.

The fainter stars observed were selected to include a high proportion of cluster members and care was taken to include stars covering a fairly wide range in colour in order to facilitate the determination of the photographic colour equations.

The observations were made with the Cape 100cm and the Radcliffe 188cm reflectors in 1970 and with the 100cm telescope at the Sutherland observing station of the S A A O in 1974. Reductions were performed using mean extinction coefficients for each observing site and transformations to the UBV system were determined for each telescope-filter-photocathode combination from observations of numerous E-region stars. The transformations for the Radcliffe equipment in 1970 were determined by Dr. P.J. Andrews while those applied to observations at the Cape and at Sutherland were obtained from observations made on a regular basis by all observers using the equipment. The transformations are generally almost linear with small coefficients and in all cases are known to be stable.

In all, 27 stars with $8^{m}.03 \leqslant V \leqslant 17^{m}.62$ have been observed. The results are given in Table I. The numbering system specifies the quadrant on Plate I as the first digit and the radial zone as the second. Under the heading "Source" the letters R, C and S represent observations obtained at the Radcliffe, Cape and Sutherland Observatories, respectively. The column "n" gives the number of nights on which the star was observed. Under "Notes" the letters G, HB, SG or M indicate respectively that the star is believed to be a

Notes to TABLE 1.

(1) 4151 and 4152 measured together; photographic measures of 4152 subtracted above.

(2) Not used in photographic reductions.

(3) Image double on deep plates - not used in photographic reductions

(4) Discordant photographic results - may be variable

(5) Smoothed (photographic) V = 14.70

(6) "Smoothed" (photographic) V = 17.48, B-V = 0.68

red giant, horizontal branch ("giant clump"), subgiant or main sequence cluster member on the basis of its location in the CM diagram.

Most stars in Table I were observed on only one night and the data is heterogeneous so that assessment of its precision is difficult. Experience with the same equipment used under similar conditions on other programs suggests that the s.e. of a result based on measures from a single night varies from $0^m.01$ in V and (B-V) at $V = 8^m$ to $\sim 0^m.03$ in V and $\sim 0^m.04$ in (B-V) at $V = 16^m$, reaching $\sim 0^m.06$ in V and $\sim 0^m.07$ in (B-V) at $V = 17^m.6$. In (U-B) the s.e. may reach $0^m.05$ for the faintest stars observed in U.

Notwithstanding these estimates, the photographic results for stars 3148 and 4121 are internally consistent but deviate markedly from the mean photoelectric results. In the final photographic reductions "smoothed" values have been used. These are given in the footnote to Table I. Since 4121 is the faintest star in the sequence and determines the location of the calibration curves for the last $0^m.3$ in each colour it can be regarded as "smoothed" in a euphemistic sense only; the use of the last $0^m.3$ of the main sequence in determining distance moduli, etc. must therefore be regarded with suitable suspicion.

3. Photographic Photometry

Three V plates (103aD + GG 11) and 3 B plates (103aO + GG 13) have been measured for the photographic photometry. All were taken with the Radcliffe telescope diaphragmed to 112cms. One V and one B plate, each exposed for 60 minutes, form part of the plate material used by Eggen & Stoy (1963). The remaining plates were each exposed for 45 minutes. One of these, a V plate taken in good seeing, is reproduced in Plate I. The three regions outlined thereon have boundaries at radii of 3', 5' and 7' from the adopted cluster centre which is believed to lie within 30" of the true centroid of the cluster members. Within the two inner zones all uncrowded stars brighter than V ~ $17^{m}_{\cdot}5$ were measured on the three plates in each colour. The outer edge of zone 3 is close to the coma-free limit of the Radcliffe telescope used at 112cms aperture so that small systematic effects may be present. The uncrowded stars in this zone were therefore measured on the two plates in each colour taken under the worst seeing conditions. This measurement was carried out separately from that of the stars in zones 1 and 2; the results were separately reduced and are therefore presented in a separate table.

Calibration curves were drawn by hand using different values of an assumed linear colour transformation coefficient. The same value of this colour coefficient was used for all plates of one type. Points read from these curves were used for computer-interpolation of magnitudes in the photographic system from each plate which were then averaged and corrected for the assumed colour equation. The corrected results were then compared with the photoelectric measures and the colour coefficients appropriately adjusted for the next attempt. The final results show no detectable dependance of the residuals on colour (or on magnitude); these residuals, in the sense (M_{pg}-M_{pe}), are shown in Figure 1 where the open circles denote the unsmoothed residuals for stars 3148 and 4121. The final colour equation adopted for the V plates agrees with that applied by Menzies (1972). The photographic B magnitudes

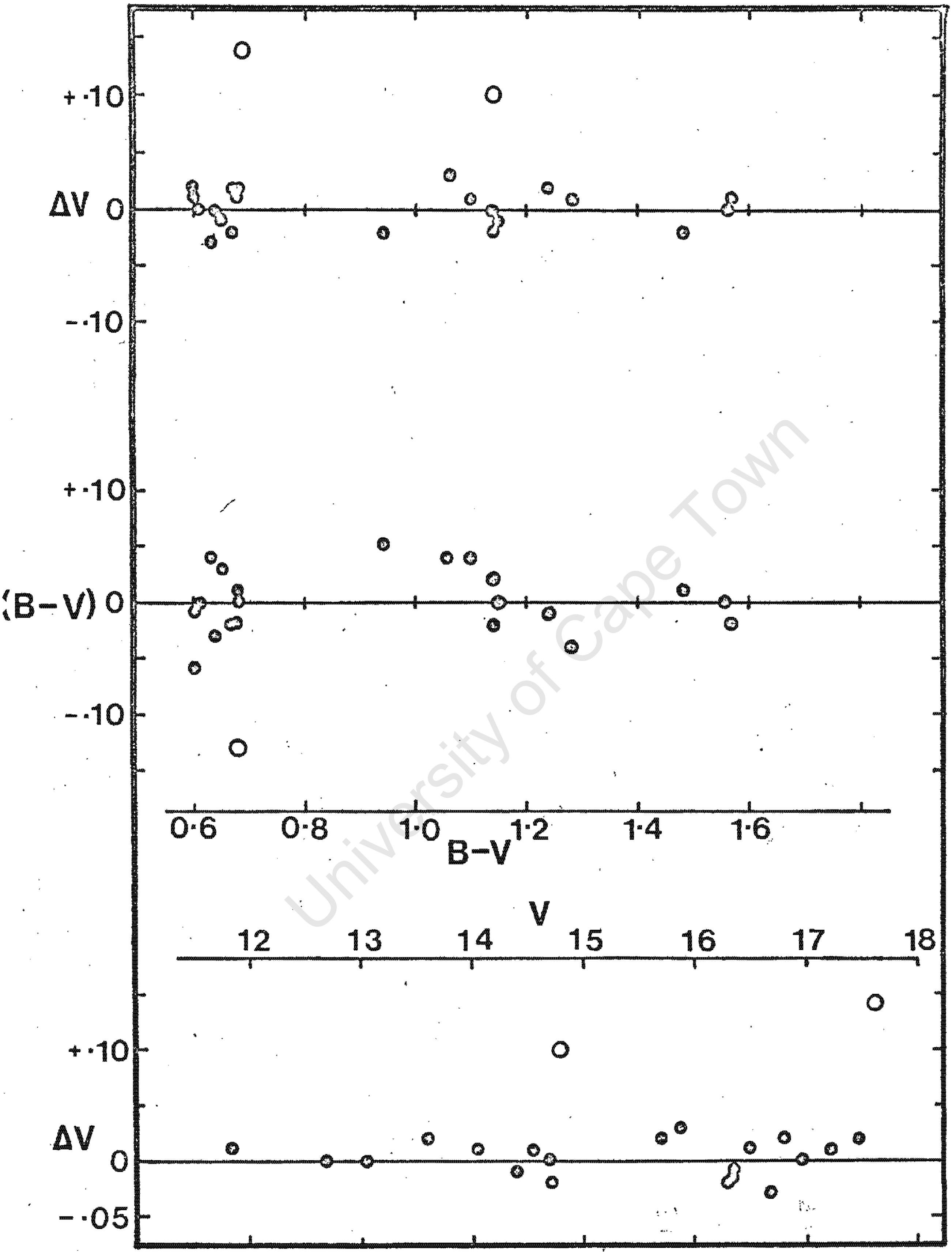

Fig. 1. Residuals of the photographic results in Table II from the photoelectric values of the same quantities in Table I, expressed in the sense =Mpe -Mpg. The open circles indicate the unsmoothed residuals for stars 3148 and 4121.

require a slightly larger coefficient that usually adopted for Radcliffe plates of the same type in order to remove all colour-dependance of the residuals.

Table II lists the results for stars in zones 1 and 2 which are unaffected by crowding. All these results are derived from measures on at least two plates in each of B and V and stars with measures exhibiting a total range in either colour exceeding $0^m.30$ have been excluded. The results retained include no individual measures deviating from the mean for that star by more than 3 times the average of the root-mean-square deviations for all plates of the particular type. These average r.m.s. deviations are, for the results retained, $0^m.045$ in V and $0^m.053$ in B.

Table III lists the results of the measures in zone 3 which were reduced in a similar fashion to those in Table II. All stars in this table are represented by measures on both plates in each colour. The stars in Tables II and III are identified in Plate I according to the four-digit system used for the photoelectric results in Table I.

Table II. Photographic magnitudes and colours for stars within 5' of the center of Melotte 66.

STAR	V	B-V	STAR	V	B-V	STAR	V	B-V
				RING 1				
1101	17.22	0.67	1121	16.77	0.66	1143	17.37	0.89
1102	17.06	0.60	1122	17.31	0.59	1144	17.05	0.67
1103	16.47	0.72	1123	16.31	0.69	1145	17.04	0.82
1104	16.98	0.67	1124	16.74	1.02	1147	16.45	0.75
1105	15.58	1.03	1125	16.69	0.90	1148	15.79	0.32
1107	17.12	0.71	1126	16.70	0.59	1149	13.77	0.59
1108	15.81	0.56	1127	16.19	1.01	1150	13.38	0.62
1109	17.39	0.89	1128	17.00	1.14	1151	17.21	0.65
1110	17.26	0.74	1129	15.74	0.98	1152	17.11	0.69
1111	16.12	0.92	1130	16.53	0.64	1153	16.78	0.67
1112	16.42	0.68	1131	17.17	0.70	1154	17.05	0.70
1113	16.07	0.94	1132	15.40	1.08	1158	17.07	0.63
1114	15.46	0.74	1135	14.40	1.13	1159	16.94	0.67
1115	17.44	0.74	1139	16.49	0.70	1160	17.23	0.73
1116	17.26	0.66	1140	16.83	0.71	1164	17.37	0.81
1119	17.45	0.70	1141	14.63	0.71			
1120	15.91	0.99	1142	16.98	0.50			
2101	17.27	0.71	2122	16.41	0.70	2143	15.82	0.99
2102	15.87	0.62	2123	15.44	1.08	2144	17.12	0.70
2103	17.18	0.82	2124	16.54	0.70	2145	16.85	0.88
2105	17.29	0.90	2125	17.17	0.68	2146	15.90	0.74
2107	14.69	1.18	2127	16.71	0.96	2147	17.08	0.75
2108	15.41	0.73	2128	16.75	1.02	2148	16.78	0.61
2109	17.07	0.77	2129	15.88	0.91	2149	16.27	0.89
2111	16.53	0.70	2132	17.43	0.80	2150	16.59	0.58
2112	17.07	0.71	2133	13.16	1.47	2151	16.10	0.59
2114	16.13	0.58	2135	17.27	0.76	2152	15.56	0.60
2118	16.38	0.37	2136	17.03	0.56	2153	17.01	0.88
2119	16.77	0.74	2140	17.02	0.69	2154	16.73	1.17
2120	14.44	1.11	2141	16.35	0.62			
2121	16.87	0.68	2142	16.48	0.61			
3101	15.09	1.09	3123	16.57	0.55	3148	14.70	1.16
3102	17.34	0.82	3125	17.44	0.71	3152	16.22	0.92
3104	17.36	0.85	3126	15.86	1.01	3157	17.13	0.66
3105	17.31	0.73	3129	16.08	0.62	3158	16.58	0.65
3106	16.27	0.52	3130	16.41	0.64	3160	16.86	0.65
3107	16.95	0.65	3131	16.89	0.73	3162	17.31	0.77
3108	17.02	0.71	3132	17.07	0.70	3163	16.22	0.47
3109	17.00	0.73	3133	14.06	1.26	3164	16.86	0.60
3110	16.66	0.47	3134	17.16	0.74	3165	17.39	0.86
3111	17.24	0.73	3137	17.27	0.77	3166	17.27	0.70
3112	15.62	1.00	3138	17.12	0.67	3167	16.49	0.64
3114	16.80	0.73	3139	16.52	0.66	3169	17.04	0.74
3117	15.52	0.66	3142	15.95	1.00	3170	16.65	0.76
3119	16.40	0.64	3143	17.03	0.69	3171	16.21	0.88
3120	16.34	1.08	3144	17.20	0.74	3175	17.44	0.70
3121	14.50	1.05	3145	15.62	0.36	3176	17.46	0.83
3122	14.27	0.50	3147	16.79	0.69	3177	17.36	0.65

Table II (continued).

STAR	V	B-V	STAR	V	B-V	STAR	V	B-V
4101	15.56	0.25	4120	16.91	0.63	4142	15.33	0.62
4102	15.76	0.83	4121	17.46	0.68	4144	16.62	0.84
4103	16.53	0.62	4122	16.62	0.52	4145	17.07	0.61
4107	16.19	0.57	4123	15.79	0.97	4146	16.63	0.79
4108	17.25	0.66	4124	16.68	0.56	4147	16.53	0.63
4110	14.54	1.06	4125	17.17	0.59	4150	17.18	0.57
4112	16.51	0.62	4128	16.86	0.68	4151	12.69	1.56
4113	14.46	0.73	4131	15.00	0.94	4153	16.78	0.94
4114	17.15	0.56	4133	17.07	0.65	4154	16.70	0.59
4115	17.06	0.56	4134	17.28	0.78	4155	16.13	0.98
4116	15.80	0.93	4135	16.92	0.71	4156	17.41	0.65
4117	16.67	1.00	4138	16.56	0.62	4159	17.24	0.78
4118	14.51	1.10	4139	17.44	0.69			
4119	13.20	0.43	4140	16.82	0.59			

RING 2

STAR	V	B-V	STAR	V	B-V	STAR	V	B-V
1201	15.24	1.00	1219	16.69	0.68	1236	17.25	0.78
1202	16.49	0.58	1220	16.50	0.61	1237	16.42	0.59
1203	14.19	1.05	1221	16.54	0.59	1238	17.37	0.80
1204	16.10	1.00	1223	16.14	0.62	1239	16.05	1.19
1205	14.43	1.08	1224	16.97	0.56	1240	15.57	0.73
1207	17.42	0.68	1225	15.64	0.80	1241	16.11	0.68
1209	16.66	0.70	1226	17.14	0.73	1242	12.81	1.56
1210	15.90	0.94	1227	17.23	0.76	1244	14.22	0.96
1211	16.87	0.58	1229	15.21	0.69	1245	14.41	1.19
1212	16.95	0.54	1230	15.84	1.02	1246	13.57	0.56
1213	15.73	0.79	1231	16.88	0.67	1250	15.13	1.03
1214	15.46	0.79	1232	17.06	0.88	1251	16.71	0.64
1215	16.60	0.55	1233	16.99	0.96	1252	16.38	0.85
1216	16.67	0.52	1234	17.03	0.72	1300	17.29	0.59
1218	16.65	0.72	1235	16.90	0.70			

2201	16.71	0.68	2228	16.52	1.05	2251	16.65	0.91
2202	14.18	1.02	2229	16.57	0.62	2252	16.29	0.64
2203	16.46	0.70	2230	17.10	0.70	2253	14.71	0.87
2204	14.56	1.22	2231	16.98	0.70	2254	16.53	0.82
2206	12.59	1.46	2232	16.13	0.66	2256	17.21	0.56
2207	16.97	0.71	2233	15.39	1.05	2259	13.28	0.96
2208	16.05	1.20	2234	17.08	0.69	2261	13.58	1.25
2209	16.97	0.71	2235	16.54	1.06	2262	15.79	0.75
2210	16.22	0.63	2236	16.45	0.65	2265	13.39	0.47
2211	13.37	0.50	2238	16.31	0.89	2266	16.67	0.99
2212	17.18	0.53	2239	11.83	1.59	2267	16.65	0.53
2213	16.93	0.71	2240	16.47	1.00	2268	16.52	0.44
2215	13.47	1.66	2241	16.48	0.69	2269	14.19	1.01
2216	17.04	0.70	2242	16.47	0.66	2271	16.75	1.15
2217	14.05	1.32	2243	17.33	0.66	2272	16.53	0.86
2220	17.23	0.79	2244	14.43	1.10	2274	16.34	0.97
2221	14.51	1.14	2245	15.64	1.02	2275	14.92	0.86
2222	15.33	0.86	2246	16.69	0.68	2277	13.75	1.79
2223	17.21	0.78	2249	16.47	0.67	2279	16.94	0.68
2224	16.97	0.61	2250	16.88	0.71	2280	16.86	1.01

Table II (continued)

STAR	V	B-V	STAR	V	B-V	STAR	V	B-V
3201	15.95	0.77	3227	13.04	0.61	3245	17.16	0.74
3205	16.20	0.61	3229	13.90	1.18	3246	16.26	0.99
3207	17.27	0.80	3230	15.62	0.70	3247	17.43	0.66
3208	15.86	0.83	3234	16.79	0.89	3249	17.07	0.69
3209	16.33	1.08	3235	14.63	1.12	3251	15.55	0.92
3211	17.22	0.66	3236	17.46	0.61	3252	15.68	0.70
3213	14.42	1.15	3238	16.88	0.55	3253	16.76	1.20
3214	16.33	0.78	3239	15.99	0.86	3258	17.07	0.71
3216	15.93	0.75	3241	17.33	0.74	3259	14.38	1.12
3219	14.71	1.09	3242	17.01	0.43	3260	14.50	1.25
3221	17.30	0.75	3243	16.51	0.84	3261	17.18	0.82
3226	16.60	0.88	3244	13.72	0.56	3263	17.02	0.71
4201	16.01	0.62	4220	16.84	0.70	4239	17.12	0.57
4202	16.63	0.66	4221	15.67	0.63	4241	16.73	0.72
4203	15.16	1.10	4222	17.34	0.66	4245	16.57	0.92
4204	16.38	0.98	4223	15.35	0.67	4247	16.01	0.64
4205	14.45	1.21	4224	16.72	0.61	4248	16.54	0.60
4207	17.43	0.72	4225	16.75	0.89	4249	16.47	0.66
4208	15.80	0.74	4226	16.78	0.97	4250	16.58	0.65
4209	16.51	0.62	4227	15.56	1.01	4252	16.95	0.70
4210	15.09	1.09	4228	16.19	0.54	4253	17.27	0.80
4211	17.35	0.64	4229	13.61	1.36	4254	17.18	0.81
4212	17.44	0.36	4230	14.73	0.85	4258	17.24	0.79
4213	17.35	0.74	4231	17.19	0.66	4259	16.59	0.98
4214	13.13	0.90	4232	15.08	0.66	4262	15.34	1.03
4216	16.92	0.63	4233	16.37	1.00	4264	14.74	1.12
4217	17.43	0.69	4236	17.25	0.61	4265	14.01	1.26
4218	16.87	0.69	4237	16.40	0.83	4266	14.56	1.12
4219	13.78	0.57	4238	15.50	1.03			

Table III. Photographic magnitudes and colours for stars from 5' to 7' from the center of Melotte 66.

STAR	V	B-V	STAR	V	B-V	STAR	V	B-V
				RING 3				
1301	17.28	0.57	1316	16.31	1.01	1331	17.05	0.53
1302	15.39	2.29	1318	17.36	0.65	1332	14.37	1.15
1303	16.30	0.71	1319	16.03	0.64	1333	17.15	0.76
1304	17.29	0.63	1320	17.04	1.21	1334	17.01	0.99
1305	16.82	0.84	1321	12.96	1.56	1335	16.81	0.65
1307	17.48	0.55	1322	13.32	0.62	1336	15.48	1.12
1308	17.01	0.62	1323	15.58	0.90	1337	16.44	0.75
1309	16.95	0.80	1324	16.36	1.49	1338	16.43	0.99
1310	13.81	0.66	1325	17.03	0.62	1339	17.07	0.52
1311	14.49	0.12	1326	14.18	0.56	1341	17.16	0.49
1312	16.24	0.55	1328	15.35	1.24	1344	17.01	-0.56
1313	16.59	0.56	1329	17.43	0.63			
1314	17.09	0.60	1330	16.69	0.72			
2303	13.30	0.92	2326	16.17	0.91	2342	13.39	1.27
2304	16.24	0.64	2329	14.30	1.10	2343	16.73	0.68
2307	14.91	0.64	2332	17.24	0.73	2345	17.10	0.68
2308	12.99	0.87	2333	17.17	0.66	2346	16.80	0.59
2309	13.41	1.21	2334	14.70	0.76	2348	16.06	1.06
2312	16.65	0.96	2336	15.82	0.57	2349	16.29	0.70
2314	16.63	0.83	2337	16.31	0.22	2350	16.12	0.76
2315	16.54	0.84	2338	14.09	1.14	2352	16.31	1.08
2321	15.88	0.61	2339	16.30	0.83	2353	17.01	0.62
2323	15.09	0.98	2341	14.81	0.58	2360	15.13	0.75
3301	15.56	0.61	3332	16.62	1.15	3355	16.73	1.13
3305	17.14	0.70	3334	13.39	0.85	3356	17.39	0.62
3307	15.18	1.10	3335	16.24	0.79	3359	16.90	1.23
3312	15.38	0.79	3336	15.32	0.72	3363	16.27	0.94
3313	16.50	0.76	3337	17.32	0.74	3364	14.71	1.25
3314	12.92	1.33	3338	16.68	0.71	3365	16.84	0.97
3318	16.70	0.86	3340	17.28	1.02	3366	13.95	1.00
3319	15.94	0.94	3343	14.16	0.54	3368	16.01	0.71
3323	16.84	1.05	3346	15.80	0.91	3369	16.76	0.79
3324	16.44	1.10	3347	17.06	0.68	3370	16.38	0.91
3327	16.18	1.24	3348	16.63	1.01	3372	16.97	0.70
3328	14.60	1.08	3354	17.27	0.68	3373	16.04	0.64
4304	17.10	0.70	4319	16.80	1.00	4341	17.14	0.70
4305	17.04	0.61	4320	16.15	0.91	4342	15.96	1.07
4306	15.85	0.67	4326	12.66	1.32	4343	17.23	0.59
4307	16.79	0.87	4327	16.42	0.64	4345	17.28	0.54
4308	16.84	0.97	4329	13.58	0.76	4347	14.37	1.11
4309	15.27	0.99	4330	15.03	1.14	4349	16.22	0.21
4311	16.99	0.91	4331	16.55	0.58	4351	13.15	1.40
4312	15.93	0.83	4332	16.91	0.63	4352	16.92	1.26
4313	16.43	0.73	4335	15.64	1.11	4354	16.21	0.88
4314	15.50	0.24	4337	15.70	0.58	4355	14.81	1.07
4316	16.51	0.61	4338	16.40	0.58			
4318	16.34	0.66	4340	16.59	0.99			

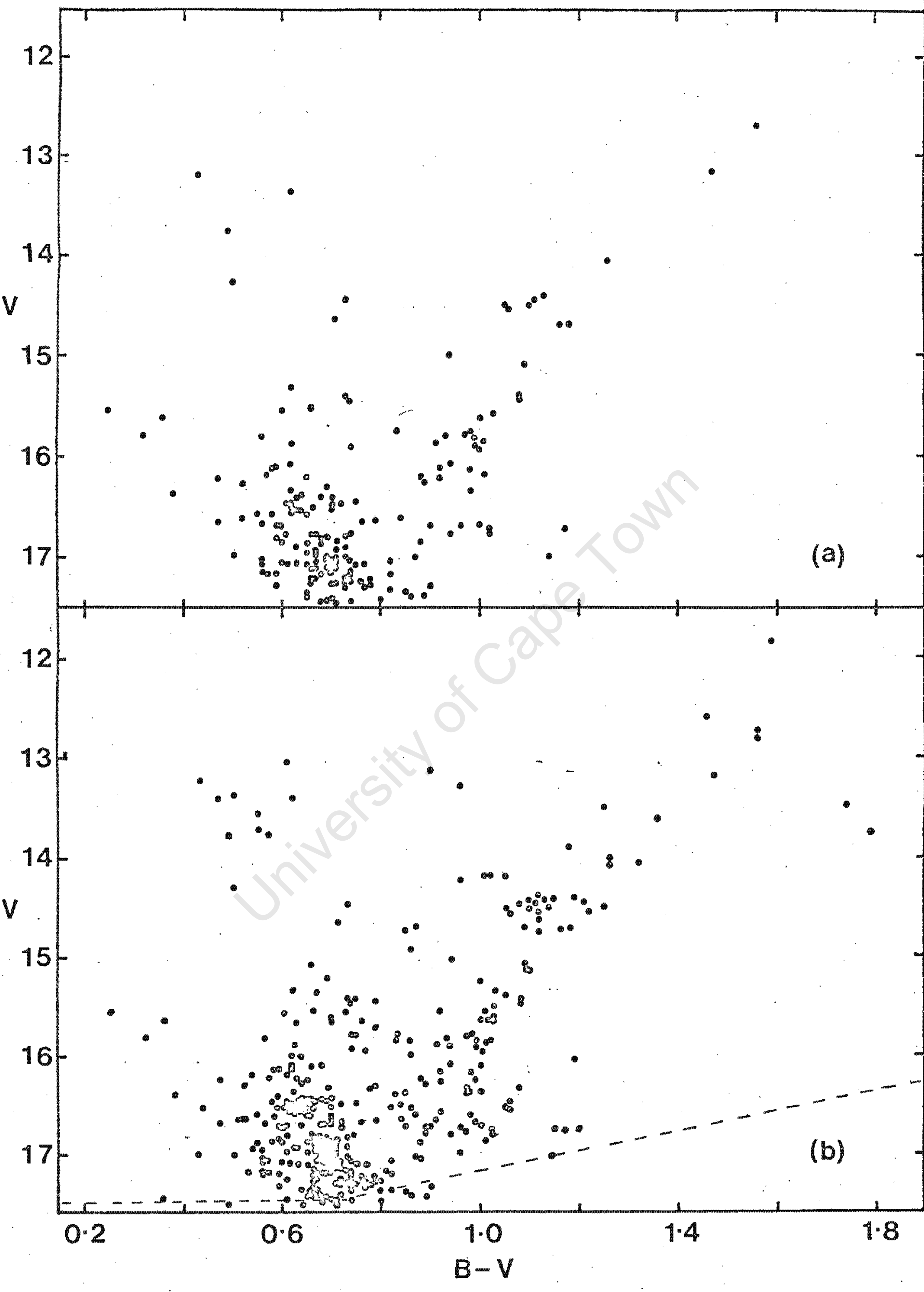

Fig. 2. The Photographic Colour-Magnitude diagram of Melotte 66 showing (a) stars within 3' of the adopted cluster outer, (b) stars within 5' of the centre. The main sequence gap is prominent in both diagrams

4. The Colour-Magnitude Diagram

Figs. 2(a) and (b) show the CM diagrams of the photographic results for stars in zone 1 (0' to 3' from the cluster centre) and zones 1 and 2 (0' to 5') respectively. The principal features of the CM diagram of an old open cluster are clearly outlined. A well populated main sequence terminates at V ~ $16^m.4$ and exhibits a distinct gap, centered at V = $16^m.7$, in both diagrams. There is no evidence of a horizontal subgiant sequence but the rising subgiant branch is very prominent and is most heavily populated at its faint end near V = $16^m.0$. A group of stars near V = $14^m.6$, $\overline{B-V}$ = $1^m.05$ represents the giant branch clump or red horizontal branch (Cannon, 1970). Above this lies a sparse, rather scattered red giant branch which may extend to V = $11^m.8$, (B-V) = $1^m.5$. A scattering of stars to the blue of the main sequence turnoff suggests the presence of a number of blue stragglers. These stars are almost all confined to zone 1 which may be interpreted as supporting the suggestion of McCrea (1964) that they represent close binaries which have undergone mass exchange. Such binaries would be expected to behave as super-massive stars during the dynamic evolution of the cluster, becoming strongly concentrated to the cluster centre. Conversely the members of the giant clump are much less strongly concentrated; indeed, their density in zone 2 is higher than in zone 1.

Fig. 3(a) shows the CM diagram of the stars in zone 3, lying between 3' and 5' from the cluster centre. The CM diagram of stars in the comparison zone (inner radius 10') which were measured in the preliminary study (Hawarden, 1970) is shown in Fig. 3(b) . This outer zone has twice the combined area of zones 1 and 2; zone 3 has almost the same area as the combined inner zones. Comparison of Figs. 3(a) and (b) indicate that the former includes a number of red giants and giant branch clump stars and probably also a substantial number of main sequence cluster members, at least below V = $17^m.0$.

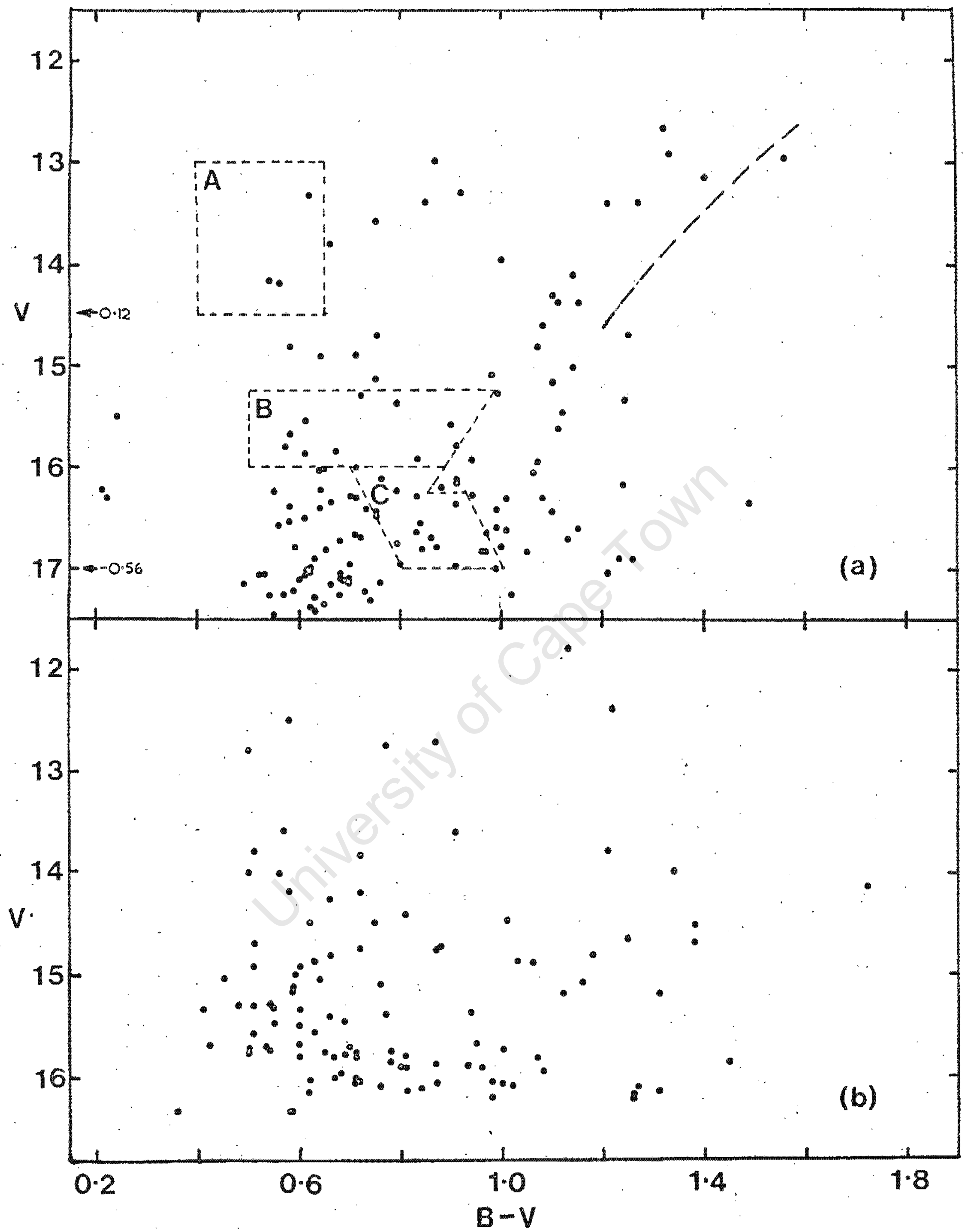

Fig 3. The Photographic CM diagrams (a) of stars between 5' and 7' from the centre of Melotte 66 (b) stars in the annular region between 10' and 12'.24 from the cluster centre. Outlined in Fig. 3(a) are three of the areas in which star counts were carried out. The dashed curve shows the approximate locus of the red giants in Fig. 2(b).

Star counts in a suitably located box in the CM diagram (V between $16^{m}_{.}0$ and $16^{m}_{.}3$, (B-V) between $0^{m}_{.}50$ and the boundary of area C) indicate an excess of 8 ± 4 stars in zones 1 and 2 relative to zone 3. Approximate χ^2 tests indicate about one chance in five that this excess is accidental.

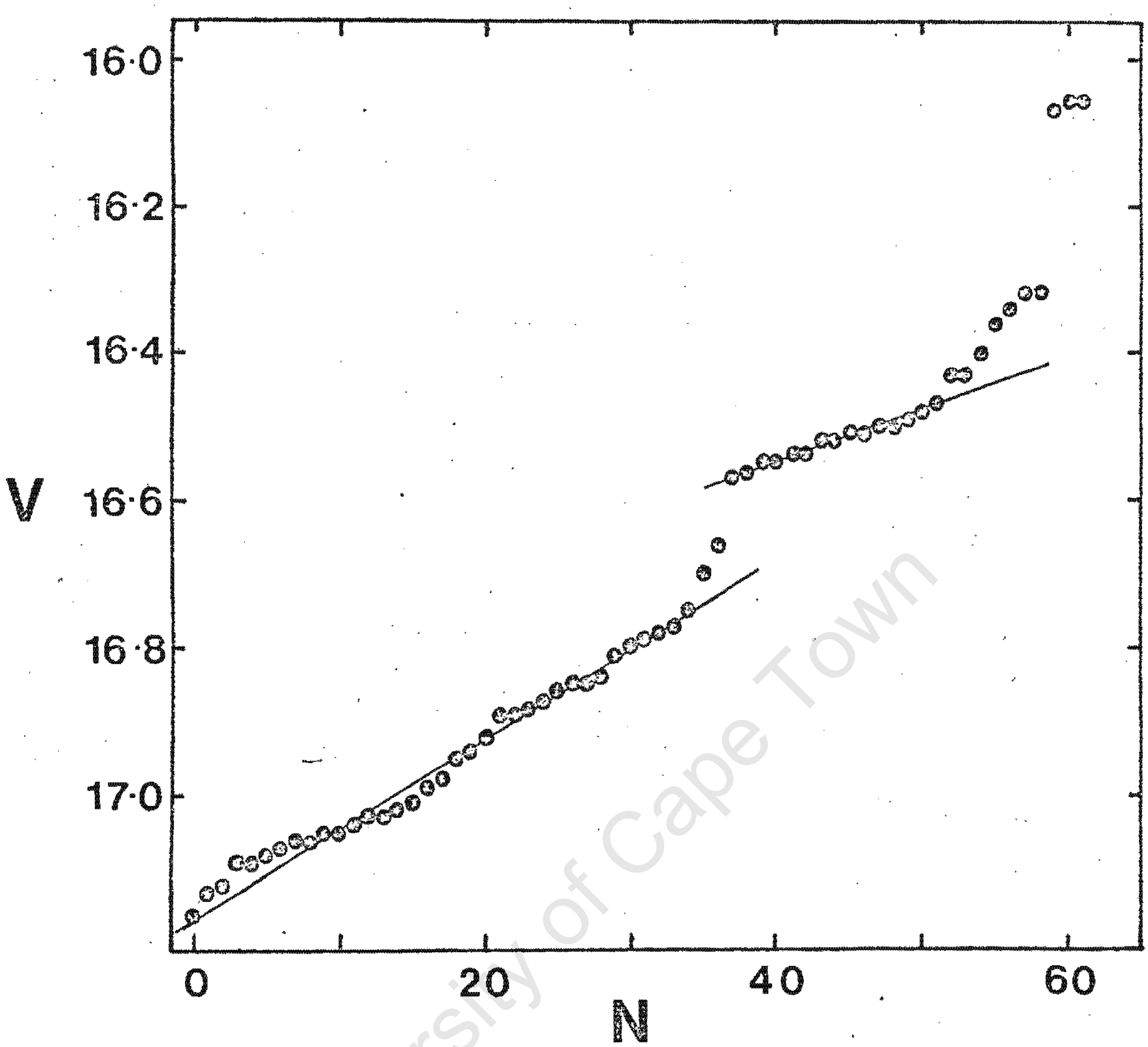

Fig. 4. Integral distribution diagram of stars near the main sequence in Fig. 2, the CM diagram of the central 3' radius region of Melotte 66.

5. Ultraviolet Excess, Age and Distance: Problems of Interpretation

The stars in Table 1 are shown plotted in the 2-colour (U-B, B-V) plane in Fig. 5. Their location in the CM diagram Fig. 2(b) has been used to select those which appear likely to be cluster members. In Fig. 5 probable main sequence members are indicated by open circles, cluster giants by filled circles and non-members by crosses. Two further stars which may be cluster giants are indicated by circled crosses. The continuous curve is the standard relation for Class V stars given by Johnson (1966) and the broken curve is a combination of the relations for Class III and Class V stars from the same source. These have been displaced by amounts appropriate to reddenings $E(B-V) = 0^m.14$ and $0^m.12$ respectively. The derivation of these values is discussed below.

In an investigation of the old, metal-poor open cluster NGC 2243 (Hawarden, 1975b) a method is described whereby the reddening and ultraviolet excess of a cluster may be derived from the 2-colour diagram of giant and main-sequence members. The method resembles that used by Eggen & Sandage (1964) but provision is made for corrections for the guillotine effect in dwarfs (Sandage, 1969) and for the effects of gravity on the (U-B) colours of evolved main sequence stars (Eggen, 1966). A value of the reddening is sought which equates the mean ultraviolet excess of the cluster giants with that observed for the main sequence stars after the abovementioned corrections have been applied. In assigning values of reddening $E(B-V)_m$ and $E(B-V)_g$ respectively to the dwarfs and giants in the same 2-colour diagram the standard trajectory is used together with the empirical relationship $E(B-V)_g = 0.82\ E(B-V)_m$ derived by Hartwick and McClure (1972).

The two circled crosses in Fig. 5 represent stars 2261 ($V=13^m.60$, $B-V=1^m.25$, $U-B=1^m.26$) and 2238 ($V=11^m.84$, $B-V=1^m.58$, $U-B=1^m.84$) which lie somewhat above the mean giant locus in the CM diagram.

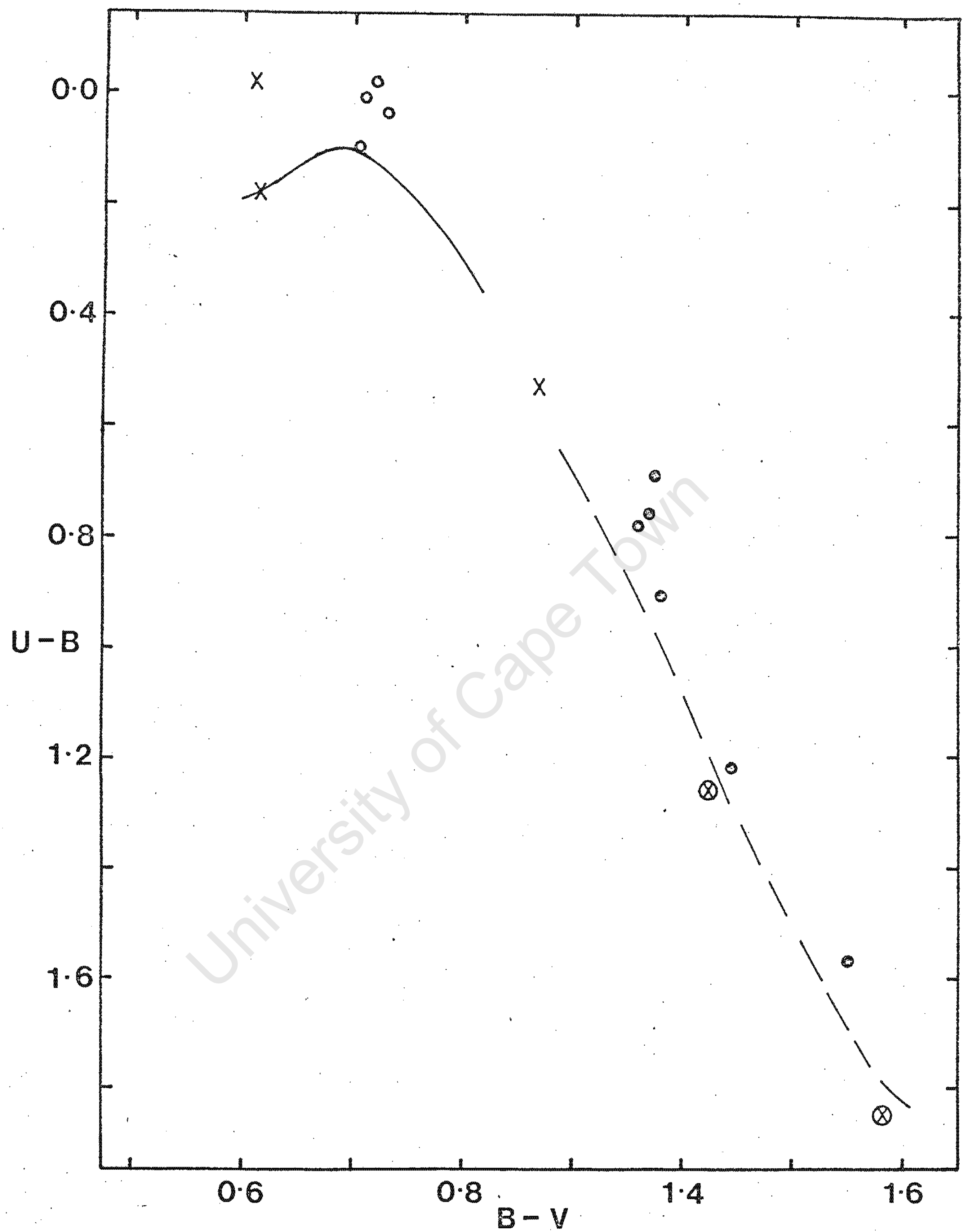

Fig. 5. The 2-colour diagram of the stars in Table I. stars believed to be cluster members are shown as filled circles (normal giants and giant branch clump stars), open circles (main sequence stars) and circled crosses (asymptotic branch or eveolved giant stars). The continuous and dashed curces represent the standard 2-colour relationships reddened by E(B-V)=0$^{m}_{.}$14 and 0$^{m}_{.}$12 respectively.

As is noted below, these may be asymptotic-branch stars or otherwise somewhat peculiar and in Fig. 5 they lie well below the main locus of the other giants.

If they are included in the analysis of Fig.5 the results obtained by the process outlined above are: $\delta(U-B)_{0.6}=0^{m}.13$, $E(B-V)_{m}=0^{m}.10$. If these stars are omitted, $\delta(U-B)_{0.6}=0.14\pm0.03$(s.e.) and $E(B-V)_{m}=0.14$. Thus the exclusion of these stars has little effect on the ultraviolet excess but significantly reduces the reddening estimate.

The calibration of [Fe/H] against $\delta(U-B)$ obtained by Alexander (1967), adjusted for a Hyades abundance [Fe/H] = 0.24 relative to the sun (Hawarden, 1975b) gives an abundance [Fe/H] = -0.4 relative to the sun for Melotte 66.

The bluest point on the main sequence in Fig. 2(a) and (b) lies just above the gap at $V=16^{m}.60$, $B-V=0^{m}.62$. The larger reddening given above implies an unreddened colour $(B-V)_{o}=0^{m}.48$ at the turnoff while the corresponding blanketing correction (Wildey, Burbidge, Sandage & Burbidge, 1962) is $\Delta(B-V)=0^{m}.10$ so that the fully-corrected turnoff colour is $(B-V)_{o,c}=0^{m}.58$. The corresponding turnoff colours of M67 (age 5.5×10^{9} years) and NGC 188 (age $\sim 9\times10^{9}$ years) are $(B-V)_{o,c} = 0^{m}.54$ and $0^{m}.62$ respectively, if the reddening values of Sandage & Eggen (1969) are applied to the normal points for these clusters listed in the same paper. In the investigation of NGC 2243 mentioned above a method is presented whereby cluster ages may be estimated differentially from the effective temperature of the turnoff. Variations of heavy element abundance (and, in principle, of helium abundance) between clusters are allowed for by means of corrections determined from comparisons of the turnoff temperatures of theoretical isochrones calculated under identical conditions from models of different abundances. In general a given turnoff temperature corresponds to a larger age in models with lower heavy element contents (cf, for example, the evolutionary tracks of Aizenman, Demarque & Miller, 1969).

In the process of estimating the age of NGC 2243 abundances [Fe/H] =0.11 and 0.00 relative to the sun were adopted for M67 and NGC 188. Allowance for the differences between these values and those obtained above for Melotte 66, together with the observed differences in turnoff colour yields "turnoff" ages for the present cluster of 11.2×10^{9} years (from M67) and 11.4×10^{9} years (from NGC 188).

Gaps such as that in the main sequence of Melotte 66 are believed to result from a period of rapid evolution during the internal contraction of the stars of the upper main sequence subsequent to the exhaustion of hydrogen in a convective core. Aizenman, Demarque & Miller (1969) and Demarque & Heasely (1971) have shown that the existence of such a core is dependent on the stellar mass, heavy element abundance and helium abundance in such a fashion that all must be high enough if convection is to occur. Recent isochrones by M.J. Prather and P. Demarque (1974, preprint) for models with Z=0.02 show a discontinuity corresponding to the core hydrogen exhaustion phase (HEP) for age 9×10^{9} years with Y=0.25 An isochrone for the same composition but with age 10×10^{9} years shows only a trace of a discontinuity. These isochrones are the first to include allowances for convective over shoot mixing at the core boundary and are the oldest yet derived to show a gap for so low a heavy element content.

The ultraviolet excess derived above implies that Melotte 66 has a heavy element abundance Z less than 0.01. It appears unlikely that a cluster so deficient in heavy elements which exhibits a gap as prominent as that in Fig.2 could be older than the most extreme isochrones for which a gap is predicted by evolution theory.

The lower value of the reddening which results if stars 2261 and 2238 are included in the analysis of Fig.4 only makes matters worse: the unreddened is $[Fe/H]=-0.26$ relative to the sun and the mean age estimated from comparisons with M 67 and NGC 188 is 7×10^9 years. The apparent distance modulus is $12^m\!.9$ giving a clump absolute magnitude $M_V=1^m\!.7$ which is comparable with the faintest listed by Cannon.

It might be assumed that the observed ultraviolet colours of the main sequence stars in Fig. 4 have been affected by an unknown systematic error. If these stars are ignored and the ultraviolet excess of the giants is assumed to be zero the resultant reddening is $E(B-V)_m=0^m\!.27$. The turnoff colour is then $(B-V)_o=0.35$, implying an age $\sim3\times10^9$ years. The determination of this value from the turnoff colour involves considerable extrapolation of the theoretical results and is correspondingly unreliable. The distance modulus, on these assumptions, is $(m-M)=14^m\!.0$ and the clump absolute magnitude is $M_V=0^m\!.6$ which is unusually bright!

6. Empirical Estimates of Age, Composition and Distance

Kinman (1965) pointed out that subgiants and giants in clusters with higher heavy element abundances should have lower effective temperatures and defined a corresponding parameter D(B-V), the colour difference between the main sequence turnoff and the subgiant branch at a point $1^{m}.0$ brighter in V. This parameter is independent of reddening but will be sensitive to differences in age as the turnoff in younger clusters is bluer and brighter.

Table IV lists D and $[Fe/H]_{\odot}$ for several clusters for which reasonably consistent ages are available. For M3, M13, M15 and M92 the values of D were derived ffom the normal curves tabulated by Sandage (1970) and the heavy element abundance for M15 is taken from the same paper. The normal curve by Arp (1962) was used to obtain D for M5. The abundances of M3, M5, M13 and M92 were taken from the results of DDO photometry by Osbourne (1973) and that for 47 Tuc from McClure & Osbourne (1974) using the calibration of the δCN index quoted by these workers but adjusted for a Hyades abundance $[Fe/H]_{\odot}=0.24$ (Hawarden 1975b). The result from the DDO photometry is in excellent agreement with that implied by the ultraviolet excess adopted in compromise by Cannon (1974). The value of D for 47 Tuc was derived from the normal points listed by Tifft (1963). Menzies (1973) gives corrections to Tifft's photographic photometry based on photoelectric measures of brighter stars. These corrections, if extrapolated, suggest that the value of D in Table IV may be $\sim 0^{m}.03$ too large. The value of D for NGC 188 was derived from curves drawn by eye through the CM diagrams of Eggen & Sandage (1969). For M67 this quantity was obtained from the normal points listed by Sandage & Eggen (1969). For NGC 2420 (McClure, Forrester & Gibson, 1974) and NGC 2243 (Hawarden, 1975b) values of D were derived from the appropriate CM diagrams while the heavy element abundances and ages were taken from the latter investigation. The ill defined nature of the lower subgiant branches of NGC 2243 and NGC 188 was remarked upon in the paper on NGC 2243; the values

Table lV

Kinman's (1965) parameter D(B-V) together with composition and age estimates for open and globular clusters

Cluster	D(B-V) (mag)	[Fe/H] $_\odot$	Age (10^9y)
M92	0.22	-1.96	12
M15	0.15	-2.1	"
M13	0.17	-1.69	"
M3	0.25	-1.01	"
M5	0.22	-0.68	"
47 Tuc	0.27	-0.35:	12
NGC 188	0.38:	0.00	9
M67	0.48	0.11	5.5
NGC 2420	0.50:	-0.26	4
NGC 2243	0.44:	-0.46	5.0
Mel 66	0.40	-0.40	11.3
		-0.26	7.0
		0.24	3.0::

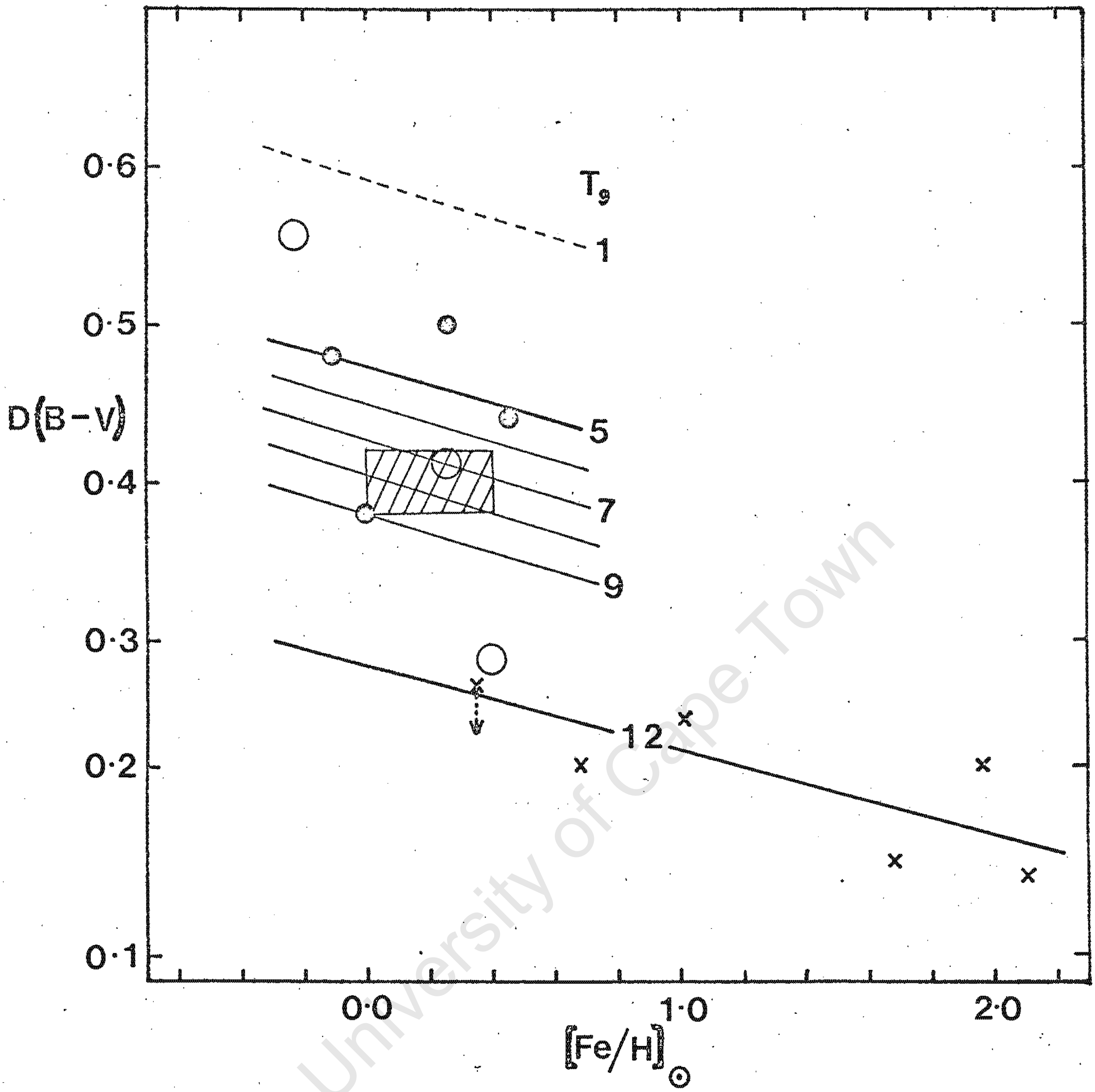

Fig. 6. The variation of the main sequence-subgiant colour difference D(B-V) with composition $[Fe/H]_\odot$ for several globular clusters (crosses) and open clusters (filled cicrles). The dashed arrow shows the effect of applying Menzies' (1973) suggested corrections to the photometry of 47 Tuc. Approximate lines of constant age are shown. The open circles represent possible positions of Melotte 66 for various assumed values of δ(U-B) and age. The shaded area shows the most probable location of Melotte 66 from the observed values of D(B-V) and δ(U-B).

of D for these clusters are correspondingly difficult to determine. The ages of the six globular clusters have been assumed to be 12×10^9 years; the precise value is not critical but consistent independent determinations are lacking.

The resulting values of D and $[Fe/H]_{\odot}$ are shown plotted in Fig. 6 where filled circles and crosses denote open and globular clusters respectively. Tentative loci for constant ages of 12 and 5×10^9 years are shown as heavy lines; fainter lines show even more speculative loci for ages between 5×10^9 years and 9×10^9 years, the latter being defined by the adopted location of NGC 188. The dashed line for 10^9 years is little better than the crudest of approximations.

Notwithstanding the tentativeness with which these loci are specified, the generally strong variation of D with age and the lesser variation with composition appear clear, suggesting that the diagram may provide useable age and abundance information.

In Section 5 three possible values of $[Fe/H]_{\odot}$ and corresponding ages were suggested for Melotte 66. These are listed in Table IV and are plotted as open circles in Fig. 6. The proper locations of the upper and lower points are uncertain owing to the poor definition of the constant age loci in these portions of the diagram.

The estimate of $\delta(U-B)_{0.6}$ obtained by direct analysis of Fig. 5 implies $[Fe/H]_{\odot} = -0.4$ while a reduction by 3σ implies $[Fe/H]_{\odot} = 0.0$. The observed value of D(B-V) from Fig. 3 has an uncertainty of about $\pm 0^m.02$ so that it would be expected that Melotte 66 would be properly represented in Fig. 6 by a point lying somewhere within the crosshatched rectangle. Thus, the location within this area of the open circle corresponding to $[Fe/H]_{\odot} = 0.26$ and age $\sim 7 \times 10^9$ years strongly suggests that these estimates are close to the correct values. It may also be tentatively concluded that the ultraviolet excess of the cluster is $\delta(U-B)_{0.6} \simeq 0^m.1$ and that the reddening is in the vicinity of $E(B-V)_m = 0^m.17$. A distance modulus $(m-M)_o = 12^m.4$ is thereby implied, corresponding to a location $\simeq 3$ kpc from the sun. With $b = -14^\circ.3$ the cluster therefore lies some 750 pc from the galactic plane.

7. The Structure of the Giant Branch

It was remarked in section 4 that the density of horizontal branch stars in zone 1 is lower than in zone 2. A further suggestion of a variation in the structure of the giant branch with radial position in the cluster is provided by a comparison of the colours of the bright red giants in the inner and outer zones. In Fig. 3(a) the approximate locus defined by the three red giants in zone 1 is shown as a dashed curve. Most of the red giants in this figure lie well to the blue of this curve. Since the CM Diagram of the field star sample, Fig. 3(b), indicates that this region of the diagram is very little contaminated by non-members it is profitable to examine the situation more closely.

Table II contains 7 stars from zone 1 and 17 stars from zone 2 which have V between $14^{m}.0$ and $15^{m}.0$ with B-V between $0^{m}.95$ and $1^{m}.25$, inclusive. Similarly there are 60 stars in zone 1 and 46 in zone 2 with V between $16^{m}.3$ and $17^{m}.1$ and B-V between $0^{m}.55$ and $0^{m}.75$. This last region of the CM diagram should contain a fairly pure sample of main sequence stars. These counts may be combined in a 2 x 2 contingency table. After Yates corrections are applied a value of $\chi^2 = 4.85$ is obtained. With 1 degree of freedom this implies a probability $P \sim 0.03$ that the observed difference in the distributions of the horizontal branch and main sequence stars in zones 1 and 2 is a chance effect.

Before it is concluded that the clump stars are significantly less concentrated towards the cluster centre than the members of the upper main sequence is should be remarked that the result for χ^2 is critically dependent on the choice of the radius at which the sampling zones are divided. If this be increased until the inner zone contains 13 clump stars the new counts in the two zones give $\chi^2 = 0.186$ and $P \sim 0.7$. Conversely contracting the inner zone until 53 main sequence stars are contained in either sampling area gives $\chi^2 = 2.63$ so that

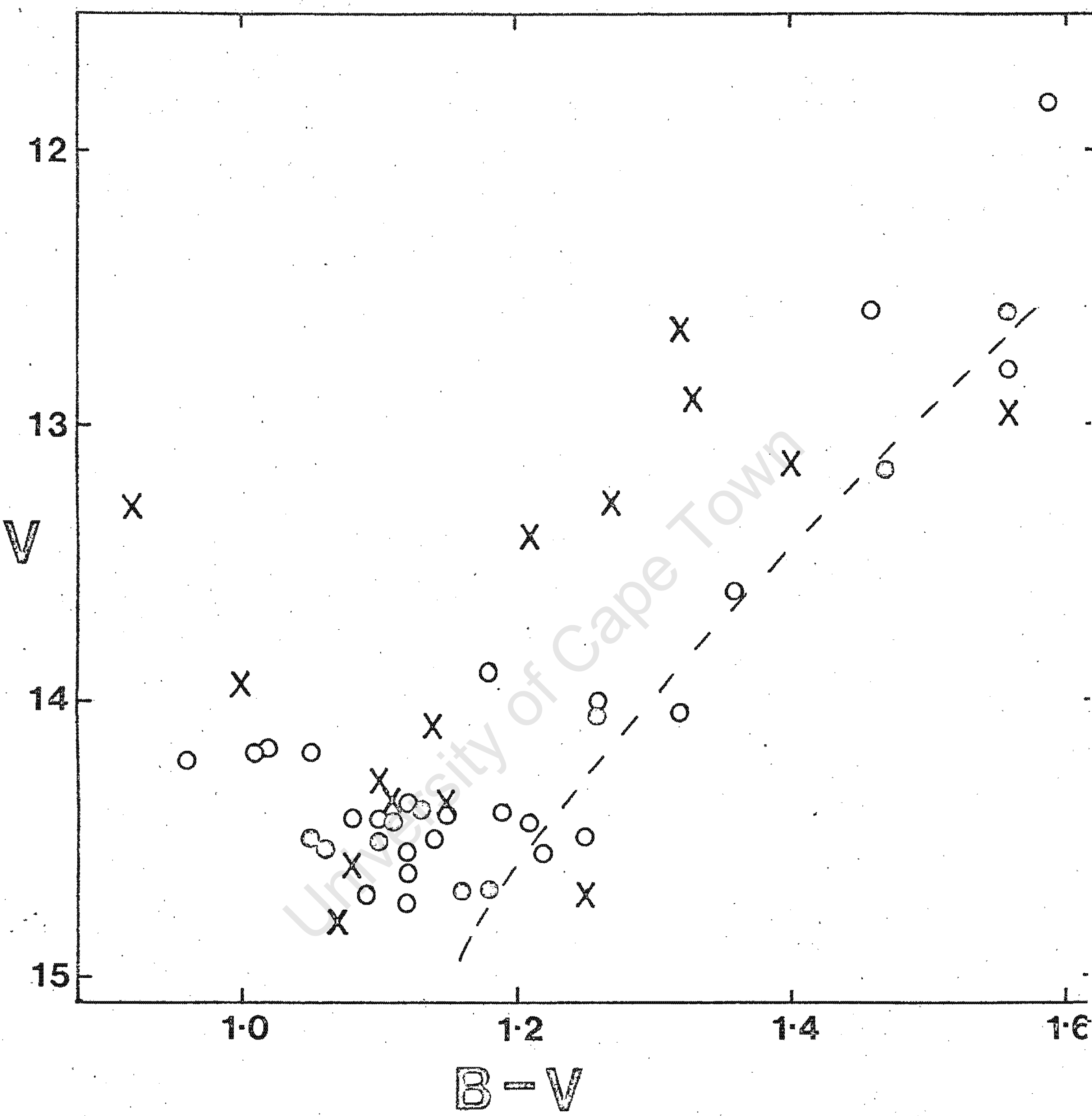

Fig. 7. The CM diagram of the giant branch of Melotte 66. Stars from zones 1, 2 and 3 are represented by filled circles, open circles and crosses, respectively. The dashed curve indicates the approximate locus of the giants in the central region of the cluster.

P ~ 0.11. Evidently the dividing line between zones 1 and 2 in Fig. 1 is so located as to maximise the apparent contrast between the derived distributions of the horizontal branch and main sequence stars. Nonetheless a clear impression remains that the horizontal branch stars in Melotte 66 are less centrally concentrated than the stars of the upper main sequence. A similar effect can be seen in other open clusters older than the Hyades and its presence in NGC 2477 was remarked upon by Eggen & Sandage (1961).

This phenomenon is discussed in more detail in another paper, one of the conclusions of which is anticipated here, namely, the likelihood that the horizontal branch stars in old open clusters have lost mass since leaving the main sequence. If this is the case, any mass dependent process of radial segregation which has operated to produce a detectable outward dispersion of the horizontal branch stars will have had considerably longer to operate on any stars which are in a post-horizontal-branch evolutionary phase such as, for example, the asymptotic branch stage.

The distinct tendency of the red giants in the outer regions of Melotte 66 to be bluer in colour than those in the inner regions is well illustrated in Fig. 7, the combined CM diagram of the giants in zones 1, 2 and 3. Stars from these zones are shown as filled circles, open circles and crosses, respectively. The dashed curve illustrates the approximate locus of the giant branch in zone 1. Four stars from zone 2 and two from zone 3 also lie near this curve but three more stars from zone 2 and four or five from zone 3 appear to lie along a parallel locus some $0^m.15$ to the blue. That this difference is not a product of random photometric errors in zone 2 coupled with systematic errors in the results for the separately-measured stars of zone 3 is strongly indicated by the location of the five horizontal branch stars from zone three, which fall amongst the main concentration of these stars from zone 2 at the blue end of the stubby horizontal branch.

It appears likely, therefore, that the bluer giants of Melotte 66 are in a post horizontal-branch evolutionary phase and may represent a Population 1 analogue of the asymptotic branch of globular clusters. The present chain of supposition is too long to permit profitable speculation as to why these stars in Melotte 66 retain their blueward displacement as they move upward in the CM diagram once again.

In support of the tentative identification of these stars as asymptotic-branch objects it may be recalled that the two members of this group which have been measured photoelectrically lie significantly below the locus of the "normal" giants in the two-colour diagram. It is highly desirable that photoelectric and spectroscopic observations should be obtained for as many as possible of these potentially intriguing stars.

8. Discussion and Summary

The decidedly tentative nature of many of the results of this investigation is unfortunate in view of their potential interest. It is important that further observations of Melotte 66 should be undertaken to clear up the numerous uncertainties and to confirm or refute the suggested interpretations put forward in proceeding sectionsof this paper. Nonetheless, Melotte 66 is evidently an exceptional cluster. If the heavy element abundance has been underestimated here then its distance has been likewise; a heavy element content similar to that of the Hyades would place Melotte 66 more than a kiloparsec from the galactic plane, a remarkable location for an open cluster, especially one with so large a metal abundance. The cluster NGC 6791 (Kinman, 1965) may lie about a kiloparsec from the plane and scanner spectrophotometry by Spinrad & Taylor (1971) indicates an abundance [Fe/H] = 0.7 relative to the sun. Conversely,Kinman's estimate of D(B-V) = $0^{m}.38$ would suggest, from Fig. 6, a value much lower than this, similar to that adopted here for Melotte 66. Further observations of NGC 6791 are urgently needed to confirm or refute the controversial scanner results.

If the heavy element abundance of Melotte 66 has been overestimated here an exceptionally large age would be implied. This would give rise to marked disagreements between observation and theory, chief of which would be the presence of a prominent main sequence gap in a cluster both older and less metal rich than NGC 188. The absolute magnitude of the horizontal branch, too, would then appear to be exceptionally faint.

Further observations of Melotte 66 are, therefore, urgently required. In particular, intermediate-band (DDO) observations of giants should clarify the ambiguities in the present estimate of the heavy element abundance and thus, hopefully, provide a better estimate of the cluster age and distance.

A similar improvement could be obtained from UBV observations of more and fainter main sequence stars by eliminating the necessity for determining the reddening and ultraviolet excess by methods involving comparisons between evolved main sequence stars and (possibly peculiar) giants. Spectroscopic or other radial velocity measurements of the brighter stars would help to confirm or refute the present speculations concerning the structure of the giant branch and would establish whether or not the cluster does in fact possess bluish giants more luminous than the horizontal branch. The kinematic properties of the cluster are also wholly unknown at present.

The present study, then, yields the following results:

(a) Melotte 66 possesses a well-defined gap in the upper main sequence.

(b) The giant branch shows a double structure, the bluer portion of which is populated preferentially by stars from the outer portions of the cluster and may therefore represent a Population I analogue of the asymptotic branch of globular clusters.

(c) The heavy element abundance of Melotte 66 is low, probably corresponding to a value of $[Fe/H] \sim -0.2$ relative to the sun. If so, the age of the cluster is in the vicinity of 7×10^9 years.

(d) The reddening of the cluster is near $E(B-V) = 0\overset{m}{.}17$ and the true distance modulus adopted here, $(m-M)_o = 12\overset{m}{.}4$ indicates that it lies about 3 Kpc from the sun and about 750 pc from the galactic plane.

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NGC 2204 : An Old Open Cluster in the Halo

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Chapter V

Summary

Photographic BV and photoelectric UBV photometry of stars in the open cluster NGC 2204 is presented. The cluster is about 3×10^9 years old. It has a broad giant branch reaching $(B-V)_o \sim 1^{m}.8$ which probably includes a red variable of substantial amplitude. The main sequence exhibits a distinct gap about $0^{m}.4$ below its brightest point.

A reddening $E(B-V) = 0^{m}.08$ and ultraviolet excess $\delta(U-B)_{0.6} = 0^{m}.095 \pm 0^{m}.024$ are derived from the 2-colour (U-B, B-V) diagram of cluster members. This ultraviolet excess implies a logarithmic abundance $[Fe/H]_{\odot} = -0.20$ and the cluster therefore appears to be somewhat poorer in heavy elements than most members of Population I, which is not inappropriate in view of its exceptionally large distance from the galactic plane, $|Z| = 1250$ pc if $(m-M)_o = 13^{m}.25$ as here derived. The blue stragglers present appear to be strongly centrally concentrated; the possible implications thereof are briefly discussed.

1. Introduction

NGC 2204 is a rich, rather diffuse open cluster in Canis Major at $\alpha = 06^h\ 14^m.4$, $\delta = -18°\ 38'$ (1975) with galactic coordinates $l = 226°.0$, $b = -16°.1$. Its appearance on the Palomar Sky Survey charts led King (1964) to list it amongst those clusters which he judged were likely to prove older than the Hyades. It was therefore included in a search for old open clusters (Hawarden, 1975a) which amply confirmed King's suggestion: the resulting pseudo Colour-Magnitude (CM) diagram showed a strong and compact group of reddish stars together with the top of a well-populated main sequence which appeared considerably fainter. The large difference in luminosity between the giant clump, identified by Cannon (1970) as the Population I analogue of the red horizontal branch, with absolute magnitude $M_V \sim 1^m.0$ and the upper extremity of the main sequence is a reliable indication of a substantial age, probably in excess of 10^9 years.

The apparent magnitude of the clump was estimated to be in the vicinity of $V = 13^m.5$ implying a distance modulus of about $12^m.5$ or slightly less; at $b = -16°.1$ this suggested that the cluster lies more than 800 parsecs from the galactic plane. It was therefore included in a program of photographic and photoelectric photometry with the results presented here. I am not aware of any other published or unpublished photometry of this system.

Initial preparations included the selection of a projected cluster center based on star counts in the vicinity. The diffuse nature of the cluster led to the underestimation of its diameter at this stage and the resulting adopted center, shown on the identification chart (Plate I) may be in error by about one arc minute. The angular diameter of the cluster is probably between 14' and 18'.

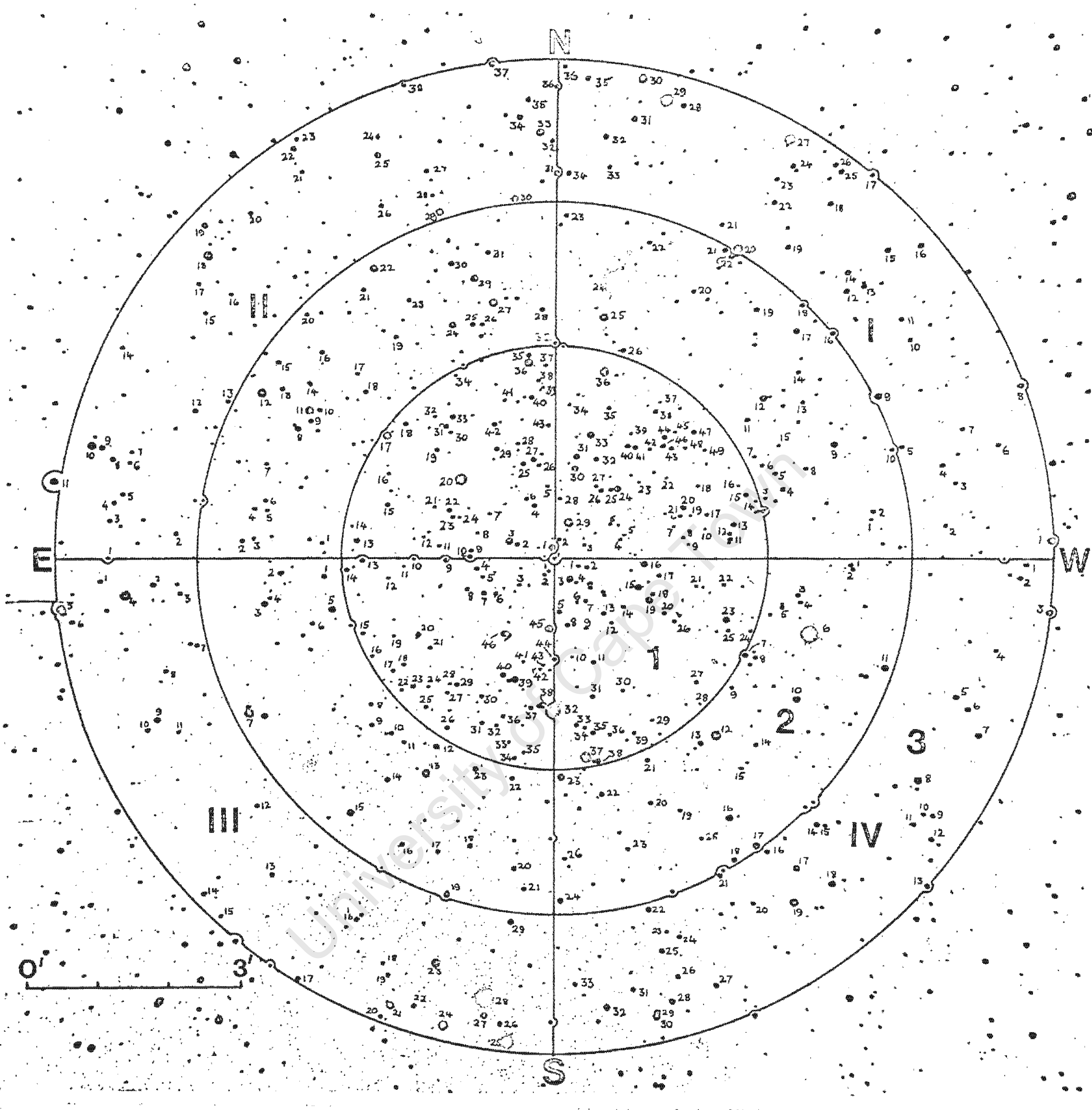

Plate I. Finding chart for stars in NGC 2204, made from a 30 minute V plate taken with the Radcliffe telescope in good seeing.

2. Photoelectric Photometry

Two local standard stars HD 43429 and star 24 in quadrant 1, zone 2 of Plate I were tied to the UBV system by observations of E region stars at equal or symmetric altitudes on 13 and 11 nights respectively. The mean results of these transfer observations are given in Table I and have internal SE's less than $0^{m}.01$ in all cases. No suggestion of variability was encountered and it may be assumed that the zero points of the present photoelectric results are correspondingly well defined.

The fainter sequence stars were observed relative to one or both of the two standards. On most nights these were supplemented by observations of E region stars at equal altitudes. The fainter stars, selected to include a high proportion of cluster members, were checked for the presence of companions on a Radcliffe plate with an estimated limit near $V = 19^{m}.5$.

A general description of the observing program which included NGC 2204 has been given elsewhere (Hawarden, 1975b). Initial observations of brighter stars were made with the 100 cm telescope at the Cape in 1971 and some supplementary observations were made with the Radcliffe 188 cm telescope in 1972 but were not included in the final results. The bulk of the faint stars were observed in 1973 and early 1974 with the 100 cm telescope at the Sutherland observing station of the SAAO. The 1973 observations - which comprise the great majority - were made with a 2-channel "Peoples" photometer used in single channel mode with focal plane diaphragm apertures of $12''.6$ and $19''.0$. The 1974 observations were made with a semiautomatic pulse-counting photometer (van Breda, Carr & Kelly, 1974) using a diaphragm aperture of $11''.0$.

The results are listed in Table I where the stars are identified by a four-digit serial number, the first two digits of which specify respectively the quadrant and radial zone in which the star is to be found on Plate I. The mean results listed have internal SE's reaching about $0^{m}.05$

TABLE I

Results of Photoelectric Photometry of Stars in NGC 2204

Star	V	B-V	U-B	n
HD 43429	5.98	1.06	0.94	13
1224	8.81	0.96	0.67	10
4206	10.01	0.36	0.03	2
1329	11.49	1.17	1.20:	1
2120	11.66	1.29	1.19	2
1227	12.20	0.47	-0.03	1
3304	12.28	1.42	1.46	2
2318	12.50	0.53	0.08	1
2212	12.76	1.21	-	1
3213	13.28	0.38	-	1
2311	13.62	1.04	0.71	2
1309	13.65	1.02	0.73	2
3215	13.72	1.00	0.68	2
4210	13.78	0.98	0.70	2
2222	13.82	1.29	-	1
4223	13.86	1.02	0.58	2
1212	13.93	0.97	-	1
2224	14.19	0.90	0.46	2
3109	14.84	0.16	0.09	2
3223	15.44	0.44	0.03	2
4221	15.53	0.44	0.04	2
3222	15.62	0.37	-0.04:	3
4131	15.63	0.42	0.11	1
4111	15.79:	0.37	0.11	3
2228	15.84	0.50	0.03	1
2143	16.24	0.46	0.02	2
2207	16.43	0.48	0.02	3
1128	16.63	0.44	-	2
2108	16.92	0.58	-	3
2107	17.13:	0.42	-	3
3112	17.25	0.43	-	1
1103	17.42	0.54	-	1
3141	17.52:	0.61:	-	2

in V, B-V and U-B for the faintest stars observed in each colour. A few individual results have larger internal errors and are indicated in Table I by a colon (:). In all, 77 observations of 32 stars were obtained.

The identification chart, Plate I, is a reproduction of a V plate exposed for 30 minutes with the Radcliffe 188 cm telescope at full aperture in good seeing. The boundaries of the radial zones are 3', 5' and 7' from the adopted cluster center. As indicated above, the cluster is believed to extend slightly beyond the outer boundary of zone 3.

3. Photographic Photometry

Details of the photographic material used are given in Table II. The plates were measured on the Askania Iris Photometer at the SAAO. Measures on the Radcliffe plates taken at full aperture were confined to the coma-free field which is slightly larger than zone 1; within this zone all uncrowded stars brighter than $V=17^{m}.5$ were measured. In the two outer zones the measuring limit is in the vicinity of $V=16^{m}.8$.

The reduction procedures used have been described elsewhere (Hawarden, 1975 b,c). Little or no colour dependence of the final (pe-pg) residuals is apparent. The r.m.s. deviation of the measures on the individual plates from the final means average $0^{m}.052$ in V and $0^{m}.043$ in B. The results are listed in Table III where the stars are identified according to the system used in Table I. Those stars which have been measured on only one plate in either or both colours because of crowding or faintness are indicated by a colon (:).

TABLE II

Plates Measured in the Photographic Photometry of NGC 2204

Plate	Telescope	Emulsion & Filter	Exposure (mins)	Date
A 7064	Radcliffe, 188 cm	103aD+GG11 (V)	20	1972 Feb 11
A 7067	Radcliffe, 188 cm	IIaO+GG13 (B)	30	1972 Feb 12
A 7095	Radcliffe, 112 cm	103aD+GG11 (V)	20	1972 Feb 13
A 7096	Radcliffe, 112 cm	IIaO+GG13 (B)	20	1972 Feb 14
47197V	McClean, 46 cm	103aD+Omag 301	80	1971 Dec 21
47197P	McClean, 61 cm	IIaO (B)		

Table III.

Results of Photographic Photometry in NGC 2204.

STAR	V	B-V	STAR	V	B-V	STAR	V	B-V
			RING 1					
1101:	17.49	0.56	1120	15.53	0.50	1136	12.71	1.74
1102	16.25	0.46	1121	16.49	0.52	1138	15.65	0.36
1103:	17.30	0.64	1124:	13.75	1.00	1139	17.52	0.45:
1106:	17.10	0.67	1127:	16.30	0.59	1140	15.33	0.32:
1107:	17.46	0.61	1128	16.65	0.45	1141	15.35	0.43:
1108	17.09	0.57	1129	12.71	1.15	1142	16.68	0.44
1113	15.04	0.33	1130	14.21	0.06	1143	15.95	0.35
1114:	17.25	0.56	1131	14.42	0.60	1144	15.55	0.39
1115	15.44	0.62	1132	15.51	0.23	1145	17.02	0.61:
1116:	17.47	0.71	1133	13.76	1.00	1147	15.64	0.42
1117	16.43	0.41	1134:	17.29	0.64	1148	16.94	0.44
1118:	17.09	0.58	1135	15.36	0.55	1149	17.43	0.68:
2101	13.33	0.58	2115	15.58	0.41	2131	15.51	0.47
2103	13.52	0.09	2116	16.99	0.45	2132	17.41	0.70:
2104	15.34	0.40	2118	15.44	0.70	2133	14.98	0.45
2105	16.63	0.43	2119	15.74	0.63	2136	13.06	1.13
2106	16.27	0.36	2120	11.66	1.28	2137	17.05	0.54
2107	17.09	0.49	2123	16.33	0.43	2138	16.70	0.44
2108	16.92	0.56	2125	14.78	0.60	2140	15.86	0.41
2110:	15.40	0.52	2126:	16.43	0.32	2141	17.12	0.49
2111	16.77	0.33	2127	15.18	0.38	2142	15.42	0.85
2112	17.00	0.40	2128	16.38	0.51	2143	16.23	0.39
2113	15.03	0.51	2129	16.04	0.35			
3103	16.79	0.46	3115	16.13	0.32	3129	15.26	0.48
3104	15.60	0.35	3116	16.79	0.51	3130	16.31	0.46
3105	16.76	0.53	3117	16.47	0.41	3131	16.23	0.44
3106	16.34	0.62	3119:	17.45	0.47	3132	16.72	0.71
3107	15.53	0.35	3120	15.02	0.53	3134	16.41	0.42
3108	16.40	0.39	3121	16.27	0.35	3136	16.28	0.43
3109	14.95	0.03	3122	17.10	0.48	3137	15.63	0.35
3110:	16.83	0.79	3123	15.79	0.40	3140	14.91	0.51
3112	17.24	0.42	3125	16.23	0.37	3144	15.72	0.41
3113	15.39	0.41	3126	15.67	0.40	3145	13.11	1.00
3114	15.51	0.36	3127	17.01	0.46			
4101	16.87	0.40	4115	14.16	0.96	4129	16.98	0.50
4102	15.97	0.40	4116	13.95	0.98	4130	16.86	0.50
4103	13.88	0.92	4117	16.10	0.41	4131	15.65	0.45
4105	15.70	0.37	4119:	13.75	0.87	4132	11.18	1.82
4107	16.13	0.46	4120	16.68	0.37	4133	15.90	0.36
4108	15.84	0.40	4122	16.79	0.43	4134	16.33	0.76
4109	16.92	0.42	4123	13.97	0.96	4135	15.50	0.70
4111	15.32	0.32	4124	16.75	0.87	4136	16.17	0.48
4112	16.65	1.01	4125	16.37	0.48	4137	11.76	1.63
4113	15.99	0.41	4126	16.73	0.44	4139	16.66	0.52
4114	16.12	0.36	4127	16.37	0.81			

Table III (continued)

RING 2

STAR	V	B-V	STAR	V	B-V	STAR	V	B-V
1201:	16.70	0.41:	1210	16.18	0.46	1218	15.66	0.41
1202	15.65	0.41	1211	15.61	0.67	1219	15.54	0.47
1203	16.58	0.43	1212	13.87	0.94	1220	16.27	0.43
1204	15.50	0.45	1213	16.50	0.41	1221	15.33	0.64:
1205	16.17	0.48	1214	16.67	0.44	1223	16.67	0.45
1206	16.41	0.50	1215:	17.03	0.39	1225	13.62	1.26
1207	16.76	0.42	1216	15.54	0.89	1226	15.35	0.40
1208	16.22	0.71	1217	14.62	1.06	1227	16.28	0.41
2201	16.60	0.40	2211:	13.00	0.91	2223	16.73	0.38
2202	15.36	0.49	2212	12.79	1.18	2224	14.18	0.36
2203	16.13	0.52	2213	15.93	0.38	2225	15.76	1.50:
2204	15.90	0.43	2215	16.22	0.38	2226	16.37	0.51:
2205	16.20	0.68	2216	16.04	0.39	2227	13.25	1.53
2206	16.15	0.75	2217	16.47	0.38	2228	15.35	0.51
2207:	16.22	1.31	2218	16.05	0.37	2229	13.81	0.95
2208	14.49	0.09	2219	16.06	0.40	2230	15.52	0.42
2209	15.38	0.45	2221	16.19	0.42	2231	16.16	0.38
2210:	15.42	0.94	2222	13.85	1.23	2232	16.35	0.37
3201	15.19	0.92	3210:	16.07	0.55	3218	15.30	0.40
3202	15.82	0.41	3211	16.69	0.61	3219	15.26	0.55
3203	14.40	0.66	3212	15.09	0.54	3220	15.94	0.51
3205	13.38	0.95	3213	13.22	0.52	3221	16.57	0.93:
3206	16.40	0.68	3214	15.49	0.50	3222	15.59	0.40
3207:	12.69	1.07	3215	13.68	1.08	3223	15.38	0.44
3208	16.26	0.46	3216	15.89	0.45			
3209	15.36	0.40	3217	16.10	0.43			
4203	15.90	0.41	4213	15.16	0.95	4221	15.51	0.44
4204	16.75	0.42	4214	16.35	0.45	4222	15.83	0.43
4207	15.04	0.82	4215:	16.87	0.58	4223	13.87	1.03
4208:	16.34	0.58	4216	13.70	1.05	4224	15.05	0.77
4209:	16.93	0.38	4217	13.73	0.61	4225	16.78	0.45
4210	13.78	0.98	4218	15.31	0.56	4226	17.11	0.35:
4211	13.62	1.04	4219:	16.56	0.87			
4212	12.36	0.98	4220	15.52	0.45			

RING 3

STAR	V	B-V	STAR	V	B-V	STAR	V	B-V
1301	13.07	0.55	1313:	15.74	0.35	1325	15.90	0.59
1302	16.44	0.54	1314	15.04	0.97	1326	16.06	0.48
1303	16.50	0.83	1315	15.51	0.53	1327	12.20	0.47
1304	15.52	0.44	1316	15.36	0.81	1328	16.45	0.47
1305	16.05	0.87	1317:	16.67	0.75	1329	11.49	1.18
1306	16.48	0.59	1318	16.09	0.48	1330	13.70	1.04:
1307	16.54	0.51	1319	15.71	0.86	1331	15.36	0.75
1308	15.04	0.97	1320	12.62	1.09	1332	16.06	0.96
1309	13.64	1.02	1321	16.50	0.44	1334	15.91	0.39
1310:	16.54	0.74	1322	16.06	0.41	1335	16.52	0.61:
1311	15.43	0.48	1323:	16.94	0.36			
1312	15.07	0.49	1324:	15.70	0.44			

Table III (continued).

STAR	V	B-V	STAR	V	B-V	STAR	V	B-V
2301:	17.04	0.47	2313	16.17	0.57	2325	14.35	0.33
2302	15.68	0.41	2314	16.60	0.68	2326	16.10	0.35
2303	16.31	0.42	2315	16.57	0.37	2327	16.88	0.40
2304	16.16	0.32	2316:	16.73	0.65	2329	13.96	0.57
2305	16.39	0.31	2317	16.47	0.51	2330	14.45	1.01
2306:	16.50	0.48	2318	12.53	0.47	2331	15.03	0.47
2307	16.32	0.39	2319	14.99	1.53	2333	13.73	0.94
2308	15.36	0.47	2320	16.01	0.59	2334	15.33	0.39
2309:	14.82	0.51	2321	16.67	0.38	2335	16.32	0.31
2310:	13.05	0.61	2322	15.22	0.82?	2336	16.60	0.44
2311	13.66	0.95	2323	16.78	0.47	2337	14.00	0.79
2312	15.25	0.45	2324	16.69	0.29	2338	16.26	0.92
3301	16.46	0.57	3311	16.58	0.47	3321	13.78	1.04
3302	15.42	0.56	3312	16.25	0.57	3322	16.44	0.48
3303	16.51	0.62	3313	16.37	0.94	3323	13.04	0.77
3304	12.24	1.40	3314	16.15	0.42	3324	12.83	1.30
3306	16.12	0.33	3315:	16.96	0.31	3325	11.44	1.30
3307:	16.36	0.33	3316:	15.99	0.51	3326	16.58	0.44
3308	16.52	0.33	3317	16.04	0.41	3327:	14.98	0.63
3309	15.05	0.50	3319	16.70	0.47	3329:	15.08	0.79
3310	16.03	0.38	3320:	17.09	0.30			
4301	15.84	0.66	4312	15.69	0.45	4323:	16.96	0.33
4302	15.33	0.49	4313	15.76	0.89	4324	16.15	0.45
4303	13.88	0.95	4314	14.93	0.43	4325	15.69	0.46
4305	15.41	0.71	4316	15.82	0.50	4326	16.14	0.38
4306	15.42	0.76	4317	14.35	0.69	4327	15.41	0.42
4307	14.40	0.71	4318	13.93	0.98	4328	15.02	0.57
4308	13.53	0.61	4319	13.04	1.17	4331	16.57	0.48
4309	16.24	0.45	4320	16.53	0.49	4332	14.80	0.67
4310	16.49	0.70	4321	15.61	0.51	4333	16.71	0.48
4311	16.07	0.38	4322	15.41	1.14			

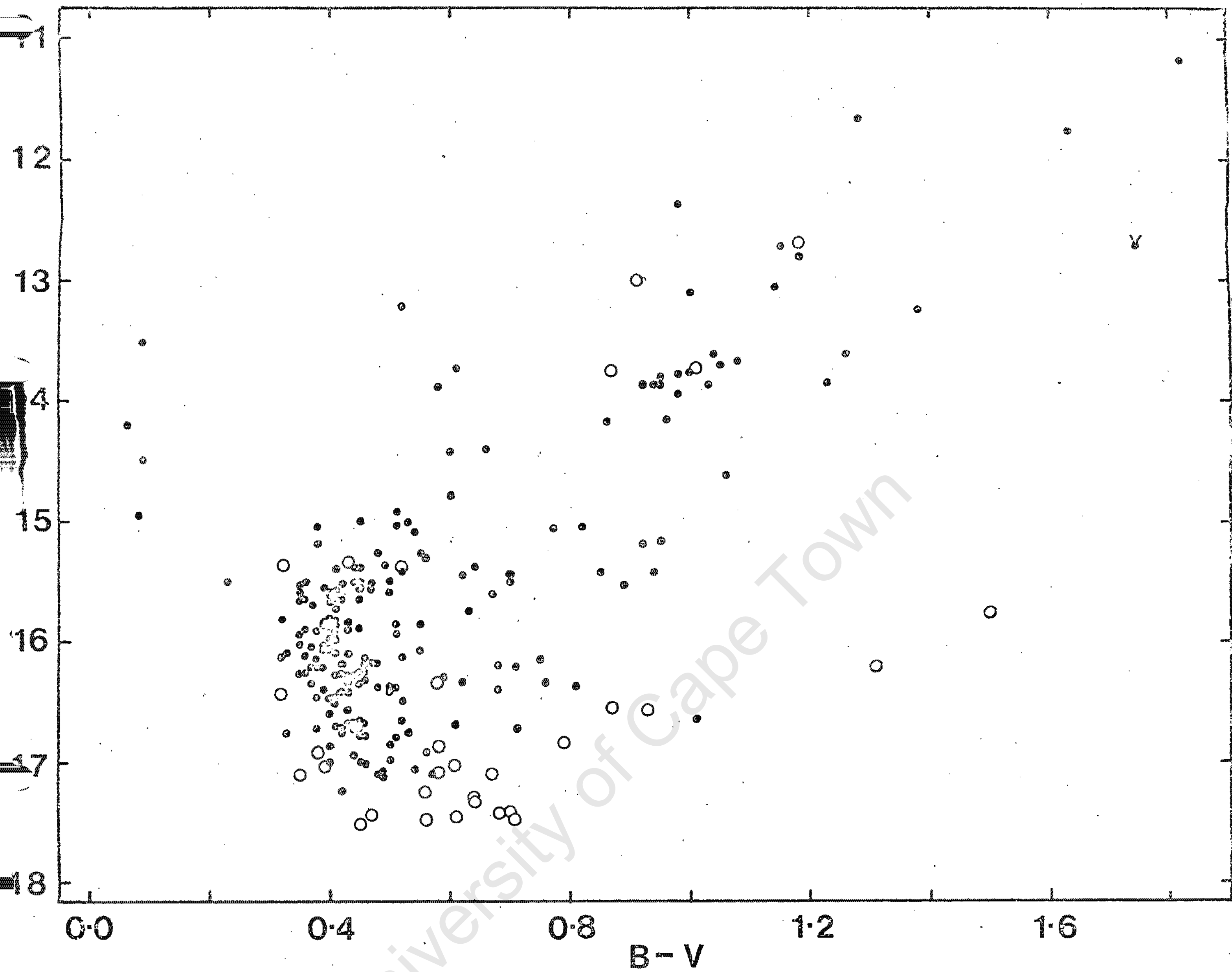

Fig. 1. Photographic CM diagram of stars within 5' of the center of NGC 2204. Open circles represent stars measured on only one plate in either or both colours. The variable 1136 is marked with a V. The suspected gap in the main sequence is at $V=15^{m}.7$.

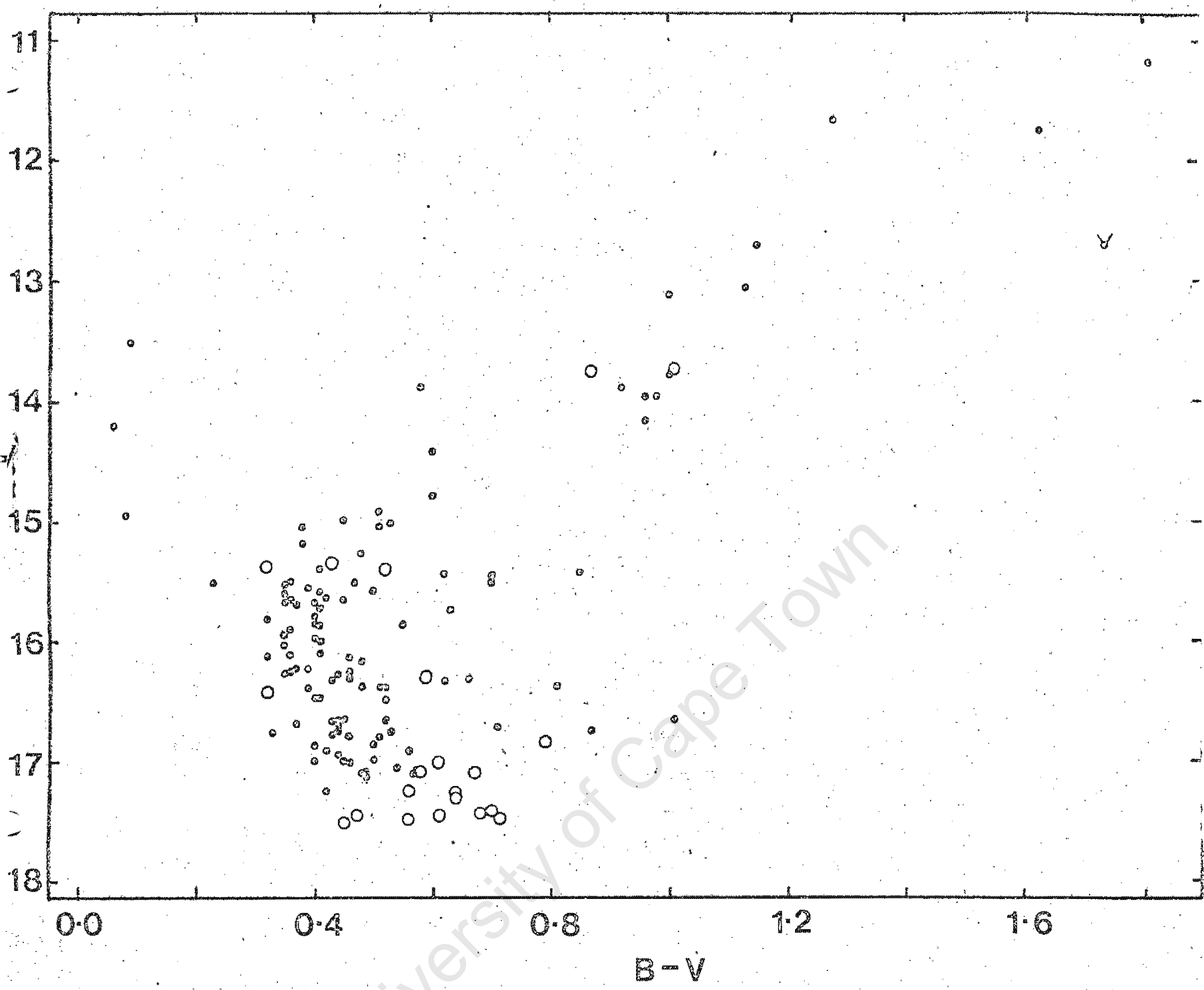

Fig. 2. Photographic CM diagram of stars within 3' of the center of NGC 2204 (zone 1 only). Symbols as for Fig. 1.

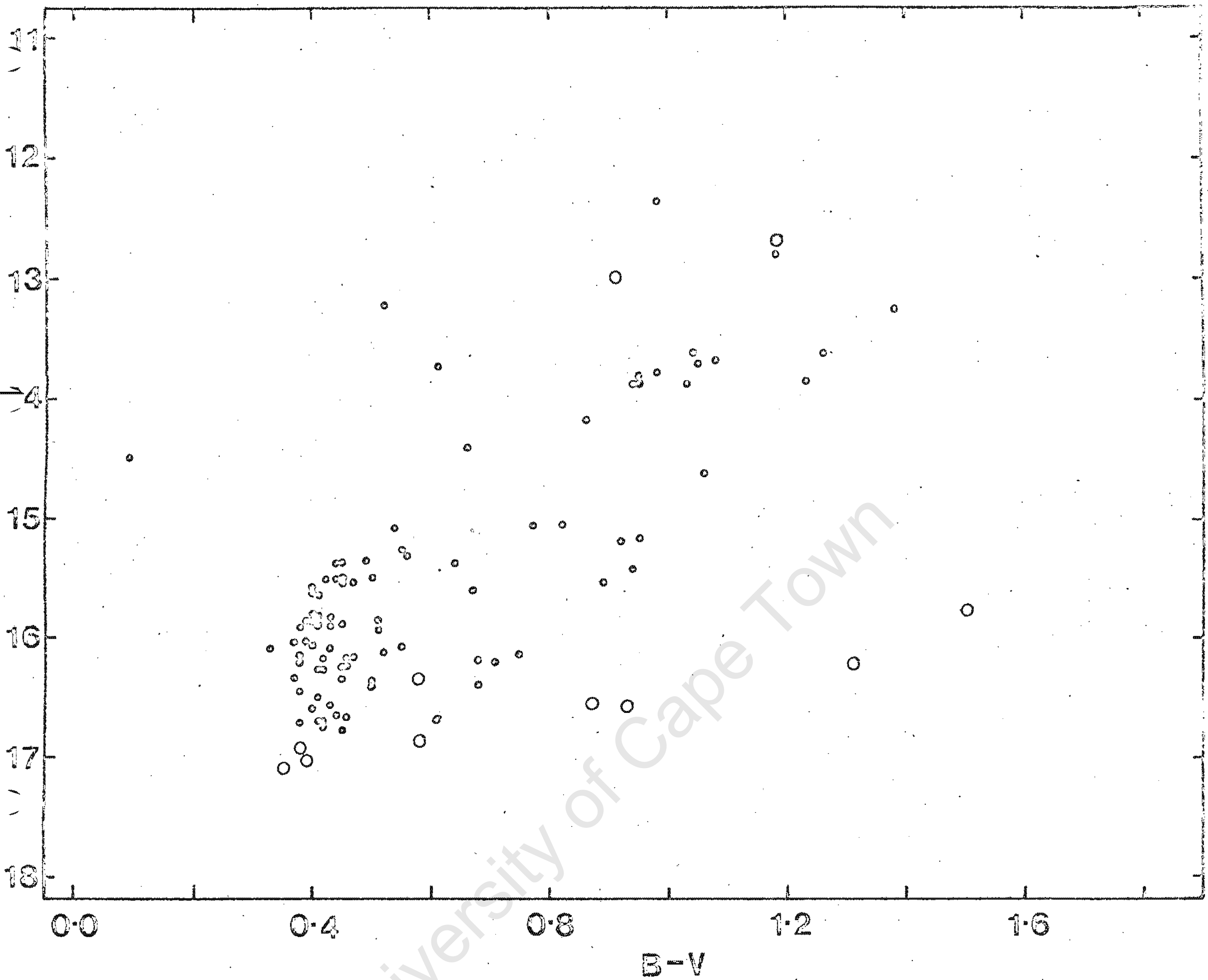

Fig. 3. CM diagram of stars between 3' and 5' from the center of NGC 2204 (zone 2). Symbols as for Fig. 1. The gap near $V=15^{m}.7$ is quite prominent.

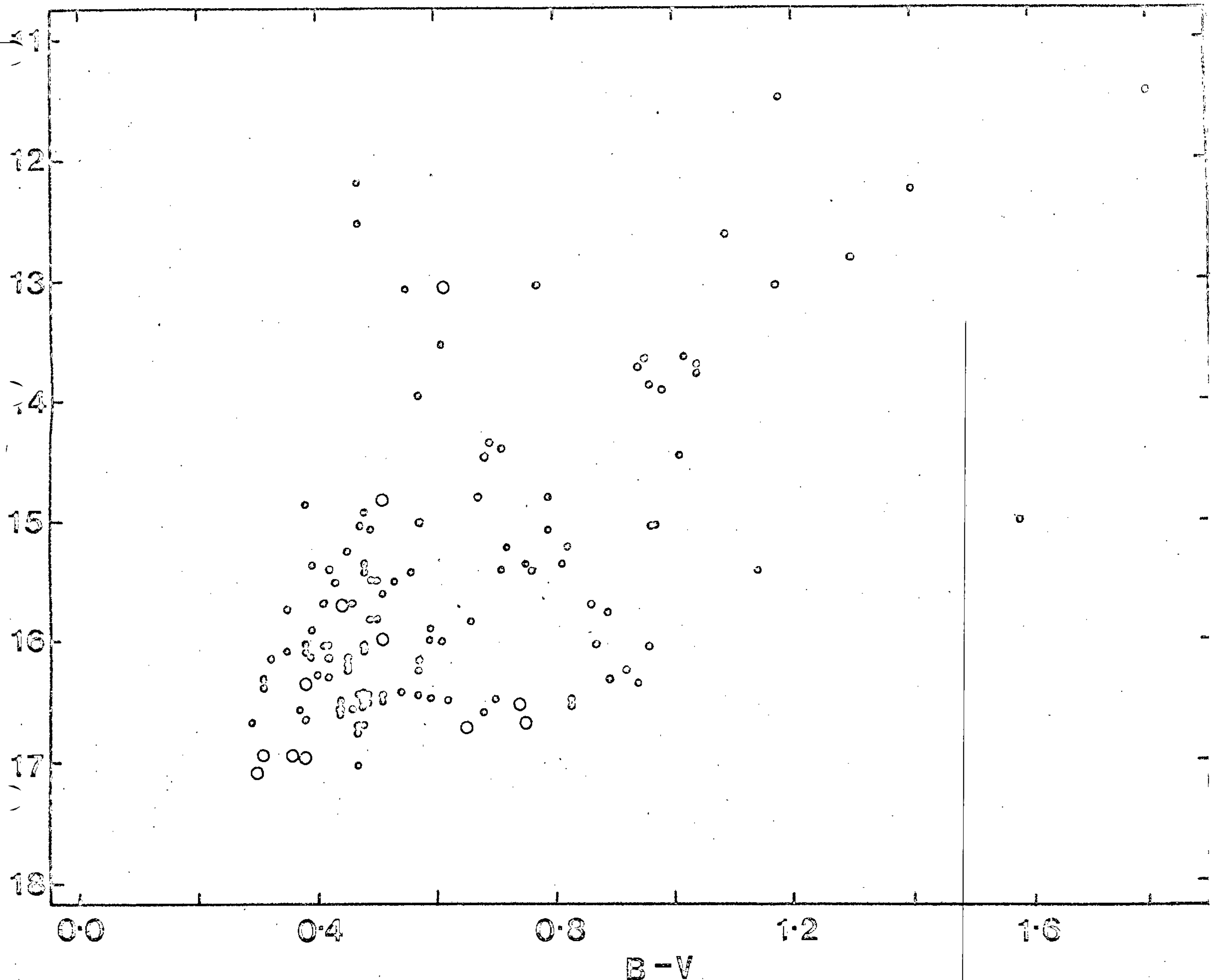

Fig. 4. CM diagram of stars between 5' and 7' from the center of NGC 2204 (zone 3). Symbols as for Fig. 1. Considerable field star contamination is evident at intermediate colours.

4. The Colour-Magnitude Diagram

Figure 1 shows the CM diagram of the photographic results for stars within 5' of the cluster center (zones 1 and 2). Open circles denote stars which have been measured on only one plate in one or both colours because of crowding or faintness. The features of this CM diagram are those of a cluster of substantial age; a long, sparse giant branch extends from $V=11^{m}.2$, $B-V=1^{m}.8$ to the horizontal branch centered at $V=13^{m}.82$, $B-V=0^{m}.98$ whilst a rich main sequence commences at $V=15^{m}.5$, passes through its bluest point with $B-V=0^{m}.40 \pm 0^{m}.01$ at about $V=16^{m}$ and extends to the calibration limit at $V=17^{m}.5$.

The CM diagrams of field stars near Melotte 66 (Hawarden, 1975c) at $l=260°$, $b=-14°.3$ and near NGC 2420 (McClure, Forrester & Gibson, 1974) at $l=198°$, $b=20°$ include very few stars brighter than $V=14^{m}$ with $B-V > 1^{m}.1$, which suggests that most of the stars in Fig. 1 which are redder and brighter than the horizontal branch are likely to be red giant or asymptotic branch members of NGC 2204. Evidently this cluster has the broad giant branch structure possessed by NGC 188 (Eggen & Sandage, 1969) and Melotte 66 (Hawarden, 1975c). Figs. 2, 3 and 4 show the separate CM diagrams of stars in zones 1 (0' to 3'), 2(3'-5') and 3 (5'-7') respectively. There is no apparent systematic dependance of the colour of the giant branch on radial position such as is shown by Melotte 66. Proper elucidation of the structure of the giant branch in NGC 2204 must await the determination of radial velocities for most of the brighter stars in Figs. 1 and 4.

The giant clump or horizontal branch in Fig. 1 exhibits a distinct downward slope to the blue. This is also shown by the available photoelectric results for clump stars (Table I) which suggests that the phenomenon is not a manifestation of the error distribution resulting from similar, independent random errors in the B and V photographic magnitudes. The members of the clump also show a slight tendency to avoid zone 1 when compared to the stars of the upper main sequence; this fact is discussed elsewhere (Hawarden, 1975d) where it is used in support of the hypothesis that clump stars in old open clusters have lost mass during their post-main-sequence evolution.

Below the giant clump there is little evidence for a rising subgiant branch apart from three suggestively located stars in Fig. 4. However Figs. 1 and 2 convey a distinct impression that a horizontal subgiant branch across the Hertzsprung gap is present, terminating in Fig. 1 near $V=15^{m}.4$, $B-V=0^{m}.9$ in an amorphous group of stars reminiscent of the corresponding portions of the CM diagrams of NGC 188 and NGC 2243 (Hawarden, 1975b).

Centered near $V=15^{m}.73$ in the upper main sequence there appears in Fig. 1 - and, more prominently, in Fig. 3 - a narrow gap. This is well shown in Fig. 5 which is the integral distribution diagram of stars in Fig. 1 with $V > 14^{m}.8$ and with B-V between $0^{m}.30$ and $0^{m}.55$. The diagram was constructed by projecting these stars along lines of slope - 0.5 in the CM diagram, onto the locus with $B-V=0^{m}.43$. This slope is that of the major axis of the error ellipse generated by equal random errors in the B and V magnitudes (Aizenman, Demarque & Miller, 1969). The reality of the gap is supported by the fact that if the projection exercise is omitted the discontinuity in the resulting integral distribution diagram is markedly reduced while projection along a line of slope 0.5 obliterates the discontinuity.

In common with most other main sequence gaps in open clusters, no discontinuity is apparent in the colour of the main sequence on either side of the gap. The presence of this feature is explained by stellar evolution theory as the phase of rapid contraction on a gravitational timescale subsequent to the exhaustion of hydrogen in the central convective core of

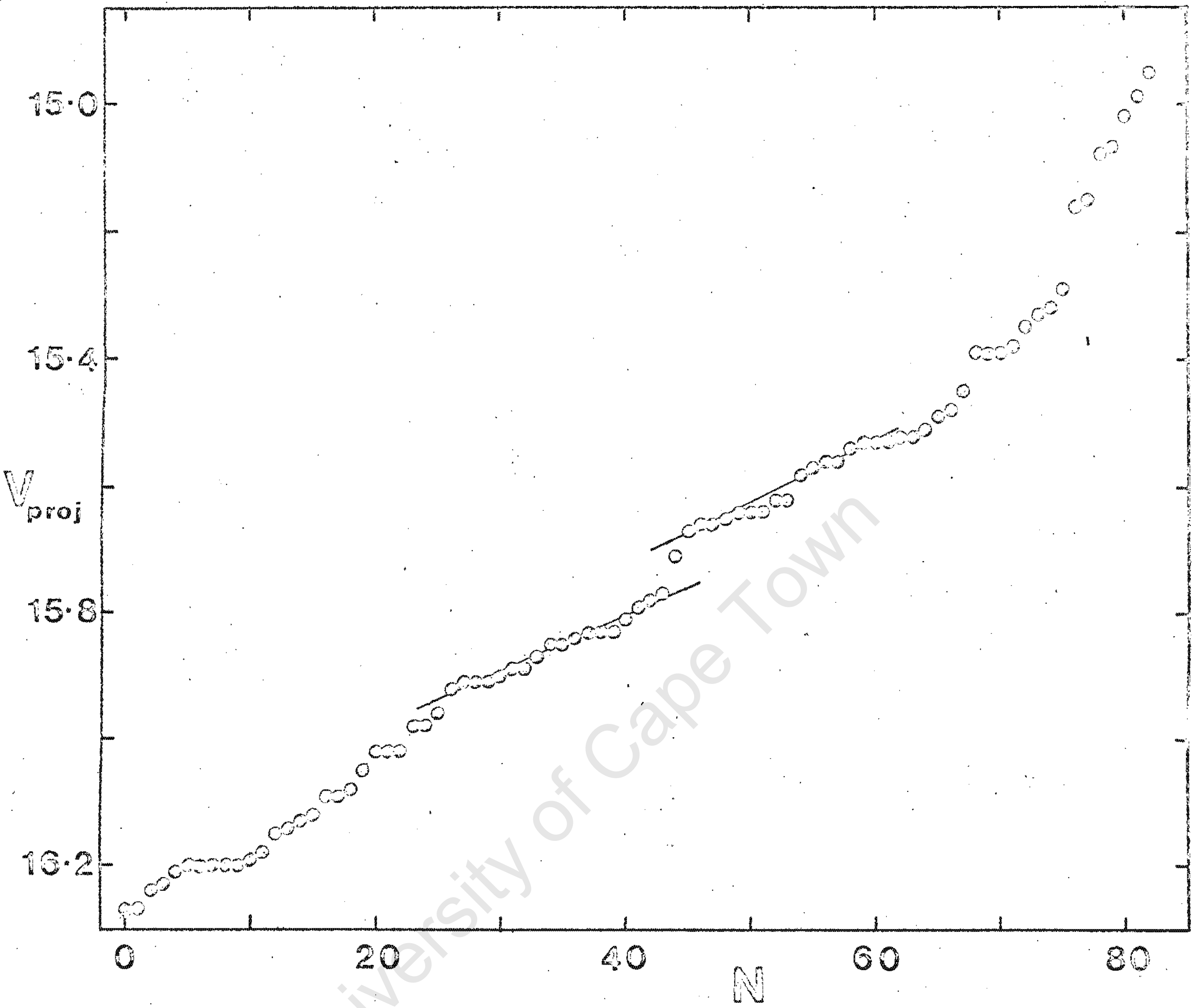

Fig. 5. Integral distribution diagram of stars in Fig. 1. with B-V between $0^m.30$ and $0^m.55$, each projected along a line of slope $\Delta V/\Delta(B-V) = -0.5$ in the CM diagram onto the line $B-V = 0^m.43$. The gap at $15^m.7$ is well shown.

the stars concerned. As has been noted elsewhere (Hawarden, 1975b) theoretical evolutionary calculations uniformly predict that stars on the evolved main sequence above the gap should be appreciably bluer than those below.

In their initial discussion of the uses of integral distribution diagrams such as Fig. 5 Aizenman et al (1969) pointed out that evolutionary theory also predicts that the density of stars per magnitude immediately above the gap should be substantially lower than that below. They note that in both M 67 and NGC 188 the opposite is the case, the star density being distinctly higher in the upper main sequence. Fig. 5 indicates that the star density in the vicinity of and above the gap is noticeably higher than the average for the segment of the main sequence studied. The corresponding diagram for Melotte 66 (Hawarden, 1975c) shows the same effect as M67 and NGC 188.

Returning to the CM diagrams, it may be noted that the region with V between $14^{m}.8$ and $15^{m}.25$ and with B-V between $0^{m}.30$ and $0^{m}.60$ contains, in Fig. 1, a scattered group of 7 stars of which only one is from zone 2. The same area in Fig. 4 contains 6 stars; as the areas of the three zones are in the ratio 9:16:24 there is evidently a density excess of these stars in zone 1 which suggests that the group is a real feature of the cluster CM diagram. While the statistics are scarcely compelling it is of interest to compare this group of stars (which appear in Fig. 5 to be distinctly separate from the main sequence itself) with the "second turnoff" found in NGC 188 by Eggen & Sandage (1969) and with a similar feature in the CM diagram of Melotte 66 (Hawarden, 1975c). Verification of the membership of these stars by radial velocity methods, while difficult, would obviously be of great importance. Their resemblance to the classical "blue stragglers" discussed in the next section was noted by Eggen & Sandage and it may be that the putative blue stragglers studied by Conti, Hensberge, van den Heuvel & Stickland (1974) resemble these stars. The possibility that they represent the progeny of bursts of star formation subsequent to the main formation episode in these clusters cannot be ruled out.

5. The Blue Stragglers - A continuing Puzzle

Five stars in Fig. 1 lie on or above the original main sequence location, substantially bluer and brighter than the unevolved stars remaining. Four of these blue stragglers are from zone 1 while none occur in zone 3. In contrast, main sequence stars with V between $15^m.5$ and $16^m.0$, B-V between $0^m.30$ and $0^m.50$ number 38, 34 and 28 in zones 1, 2 and 3 respectively. It would appear that the blue stragglers are strongly concentrated towards the cluster center, as is the case in M 67 (Murray, Corben & Allchorn, 1965) and in Melotte 66 (Hawarden, 1975c) suggesting that, in these clusters at least, the blue stragglers are considerably more massive than the surviving main sequence stars. In M 67 this has been confirmed by the results of intermediate-band (Strömgren) photometry by Bond & Perry (1971) and by Strom, Strom & Bregman (1971).

McCrea (1964) suggested that the blue stragglers are a consequence of mass exchange in close binaries which would be expected to behave as extra massive stars; these (if the results of calculations by Wielen (1967) and Hénon (1971) are to be believed) would congregate in the center of the cluster over times of the order 10^8 years.

In the paper referred to in connection with the "second turnoff" stars Conti et al (1974) present high-quality radial velocities for blue stragglers in the Hyades, Praesepe and M 7(NGC 6475) which show no signs of the variations to be expected if the stars were close binaries. They obtain a spectroscopic mass similar to that of a main sequence star for the blue straggler in the Hyades (68 Tauri) and attribute the blueward displacement of this star to recent completion of the contraction phase subsequent to core hydrogen exhaustion. This explanation appears unlikely; as was pointed out in the previous section the extent of this blueward evolution across the main sequence gap in open clusters is generally observed to be considerably less than predicted by theory. The density in V of stars which have just passed through this phase is likewise observed to be generally the same as or higher than that of the stars approaching the gap; the postulated presence in the Hyades of a single star above the gap, together with many stars below would seem to be distinctly improbable.

Conti et al obtain rather lower masses for the other two blue stragglers (1.1$M_\odot$ for 40 Caneri in Praesepe and 1.6$M_\odot$ for HD 162374 in M 7) and suggest that these stars may be blue horizontal branch objects which have lost mass while traversing the giant branch. Unfortunately there is no evidence from theoretical studies to suggest that core-helium-burning stars in this mass range attain effective temperatures even remotely high enough to approach the domain of the blue stragglers. Indeed, the recent horizontal branch models of Gross (1973) require masses less than 0.5$M_\odot$ before a model with Z=0.01 approaches log T_e= 4.0. His models with M=1.35 $M_\odot$ have a minimum log T_e corresponding to B-V$\sim 0^m.9$; even this value requires a heavy element abundance an order of magnitude less than is generally accepted for clusters like Praesepe. It is far more likely that Cannon's (1970) identification of the Population I horizontal branch with the giant branch clump is correct and that other explanations must be sought for the results of Conti et al.

If the lack of variation shown by the radial velocities obtained by these authors is taken to rule out the binary theory of McCrea (1964) and the high masses of the blue stragglers in M 67 (and, presumably, in Melotte 66 and NGC 2204) are accepted as generally characteristic of these stars there appears to remain only one explanation for the blue stragglers amongst those suggested heretofore, namely, that these stars were in fact formed much later than the other members of the clusters. The colours of the bluest stragglers in M 67 and in some globular clusters imply, on this hypothesis, that these stars have ages which are essentially negligible compared with those of the parent clusters. It is clear that such a suggestion must be regarded with considerable suspicion in the absence of any other evidence whatsoever that star formation in old clusters of all types is a continuing process.

6. The 2-Colour Diagram : Reddening and Heavy Element Abundance

Comparison of the results in Table I with the CM diagram indicates that essentially all the stars fainter than $V=13^{m}.5$ which have been observed in U are cluster members. Identification of the brighter cluster giants is less certain.

Figure 6 shows the 2-colour (U-B, B-V) diagram of the results in Table I. Obvious non-members are shown as crosses, stars believed to be cluster giants as filled circles and main sequence stars as open circles. The location of the latter stars, which are all somewhat evolved, is affected by their reduced surface gravity. Their positions after application of the appropriate corrections are shown as filled squares.

The circled cross represents the star 1329 which is the bluest and brightest among those in Table I which could be cluster giants. It lies significantly below the other stars in this group, suggesting that it may be a foreground object or in some fashion peculiar. It has been omitted from the subsequent analysis.

The method for the simultaneous determination of the reddening and ultraviolet excess of a cluster from the 2-colour diagram of its giants and main sequence members when the latter occupy a small range in B-V has been discussed in considerable detail elsewhere (Hawarden, 1975b). It is assumed that the ultraviolet excess of main sequence stars with $(B-V)_0 = 0^{m}.6$, inferred from that of the observed, rather bluer, stars by application of gravity corrections derived from Eggen (1966) and guillotine corrections from Sandage (1969) is to be equated with that of the cluster giants. A reddening value is thereby derived, using the result of Hartwick & McClure (1972) relating the reddenings of giants and dwarfs in the same system when the standard reddening trajectory is used for both groups of stars.

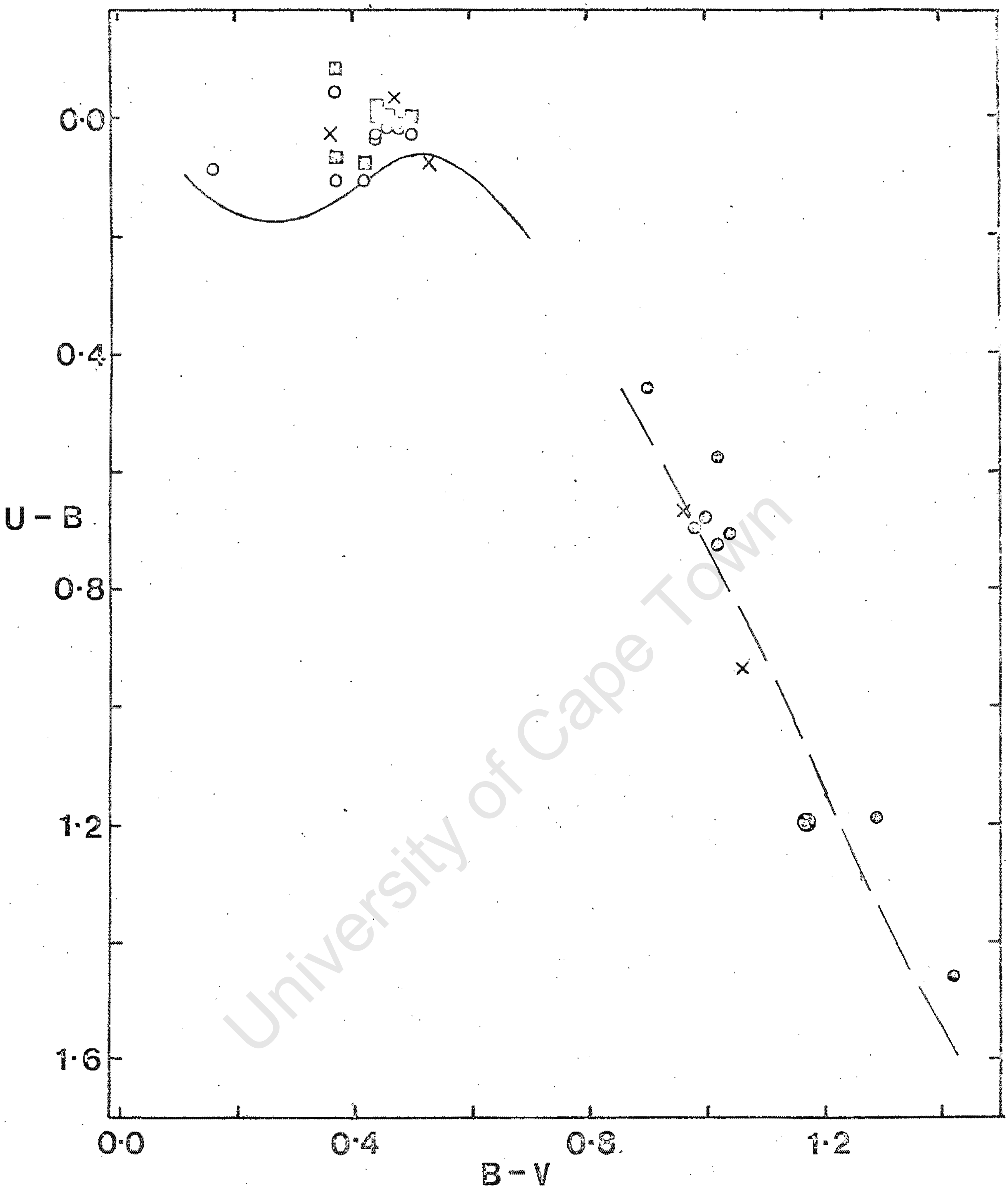

Fig. 6. Photoelectric 2-colour diagram for stars in NGC 2204. Giant and dwarf members are shown by filled and open circles respectively. Filled squares represent the latter after correction for gravity effects. Crosses indicate non members. The standard relatioships for dwarfs (full curve) and giants (dashed curve) are shown reddened by E(B–V) = $0^m_.08$ and $0^m_.065$ respectively.

The standard 2-colour relationships for stars of luminosity Class V and a combination of classes III & V derived from those given by Johnson (1966) are shown in Fig. 6 by a continuous and a dashed curve, respectively. These have been reddened by $E(B-V) = 0^m.08$ and $0^m.065$, the values determined by an analysis of the sort described above. The corresponding ultraviolet excess is $\delta(U-B)_{0.6} = 0^m.095 \pm 0^m.024$ (SE) where the uncertainty chiefly reflects the scatter in the observed ultraviolet excess of the giants. That some of this scatter may be Astrophysical in origin is indicated, firstly by the relatively low internal uncertainties in the observed (U-B)'s, most of which have formal internal SE's less than 0.03, and secondly by the marked vertical separation in Fig.6 between star 4223 and the rest of the clump stars with $0^m.98 < B-V < 1^m.04$. The indicated star appears to be slightly less luminous than the rest of the group,so that their smaller $\delta(U-B)$ values may reflect an intrinsic property of the stars such as reduced surface gravity owing to mass loss. If these four points are omitted, a solution using only the four remaining giants gives a main-sequence reddening $E(B-V)_m = 0^m.10$ with $\delta(U-B)_{0.6} = 0^m.13 \pm 0^m.03$. Conversely, if only the four clump stars with the reddest U-B colours are used, the solution yields $E(B-V)_m = 0^m.06$, $\delta(U-B)_{0.6} = 0^m.07$.

The intermediate solution derived first is to be favoured as involving the fewest assumptions concerning the peculiar natures of the stars included. The ultraviolet excess derived is unusually large but not unique among open clusters. NGC 2420 (McClure, Forrester & Gibson, 1974) also has $\delta(U-B)$ in the vicinity of $0^m.1$ as may Melotte 66 (Hawarden, 1975c). The cluster NGC 2243 probably has a considerably larger excess, in the vicinity of $\delta(U-B)_{0.6} = 0^m.15$.

The calibration of $\delta(U-B)$ against $[Fe/H]$ obtained by Alexander (1967) implies that NGC 2204 has a logarithmic metal abundance $[Fe/H] = -0.20$ relative to the sun or $[Fe/H] = -0.44$ relative to the Hyades if the latter are assumed to have $[Fe/H]_{\odot} = 0.24$ (Hawarden, 1975b).

7. Age, Distance Modulus and Distance from the Galactic Plane

In the paper on NGC 2243 which has been referred to several times in preceding sections, an age determination method, based on the main sequence turnoff colour, was presented and discussed. An expression

$$\Delta \log T_9 = A^{-1} (\Delta \log T_e - B \Delta \log Z) \quad \ldots\ldots \quad (1)$$

is used to derive difference $\Delta \log T_9$ between the ages of two clusters (in units of 10^9 years) in terms of the difference $\Delta \log T_e$ between the effective temperatures of their main sequence turnoffs and the difference $\Delta \log Z$ between their heavy element abundances. The coefficients $A = \partial \log T_e / \partial \log T_9$ and $B = \partial \log T_e / \partial \log Z$ are evaluated from sets of theoretical isochrones calculated under similar conditions. Values of these coefficients are tabulated in the original discussion (Hawarden, 1975b) and may be used to allow for variations in A and B with $\log T_e$ and $\log Z$.

The reddening $E(B-V) = 0^m.08$ adopted for the main sequence implies an unreddened turnoff colour $(B-V)_o = 0^m.32$. The observed (gravity-corrected) ultraviolet excess of the main sequence stars is $0^m.08$ giving blanketing corrections $\Delta(B-V) = 0^m.04$, $\Delta V = -0^m.03$ (Wildey, Burbidge, Sandage & Burbidge, 1962). Thus the blanketing-corrected, reddening free turnoff colour is $(B-V)_{o,c} = 0.36$ whence, from the table by Schlesinger (1969) $\log T_e = 3.849$.

The cluster M 67 appears to have a well-determined age near 5.5×10^9 years (Sandage & Eggen, 1969). The heavy element abundance is probably near $[Fe/H]_\odot = 0.11$ (Barry & Cromwell, 1974; Hawarden 1975b) and the unreddened, blanketing-free turnoff colour is $(B-V)_{o,c} = 0^m.51$. The Tables of A and B referred to above may be used to derive interpolated values of these derivatives appropriate to a comparison of NGC 2204 with M 67, giving $A = -0.17$ $B = -0.051$. Thus, the expression (1) above gives a differentially-determined age of NGC 2204 of 2.8×10^9 years. A similar comparison with NGC 188 gives 3.1×10^9 years if the age of NGC 188 is $\sim 9 \times 10^9$ years (Sandage & Eggen, 1969).

TABLE IV

Normal Points and Evolutionary Deviation of the Main Sequence of NGC 2204

(assuming $E(B-V) = 0^m.08$, $\delta(U-B)_{0.6} = 0^m.095$)

V	B-V	$V_{0,c} - M_v$	M_v
17.48	0.60	12.71	4.50
17.26	0.55	12.81	4.18
17.00	0.50	12.90	3.83
16.69	0.45	12.93	3.49
16.38	0.42	12.75	3.36
16.00	0.40	12.54	3.19
15.80	0.40	12.36	3.19
15.70	0.40	12.24	3.19
15.54	0.42	11.91	3.36
15.45	0.48	11.48	3.70

NGC 2204 is evidently slightly younger than NGC 2420 which it resembles in composition.

Running mean values of V and B-V along the main sequence of NGC 2204 were plotted and smoothed to give normal points in the CM diagram. These are listed in Table lV. After application of reddening and blanketing corrections these were compared with the standard ZAMS listed by Eggen (1965) to give the listed results for $V_{o,c} - M_V$ and M_V; these are shown plotted in Fig. 7. In the above much-quoted study of NGC 2243 (Hawarden, 1975b) an evolutionary deviation curve was derived from an isochrone by Hartwick & van den Berg (1973) for age 5×10^9 years, Y = 0.30, Z = 0.01. This heavy element abundance is also appropriate to NGC 2204 (Z=0.013 if $Z_\odot = 0.02$); the evolutionary deviation curve can be fitted to the points in Fig.7, as shown, by assuming a true distance modulus $(m-M)_o = 13^m.25 \pm 0^m.2$ for NGC 2204.

It is noteworthy that the slope of the lower main sequence in Fig. 2 (from which the points in Fig 7 are derived) is significantly smaller than that of the ZAMS, as is reflected by the divergence of the points in Fig. 7 from the theoretical curve. This introduces most of the internal uncertainty present in the adopted distance modulus. Before this discrepancy in the shape of the main sequence is ascribed to systematic errors in the photometry (which is not unlikely since these points depend on one plate pair only) it may be noted that a very similar effect is shown by the early results in M 67 (cf. Murray et al, 1965).

The distance modulus derivation is almost insensitive to the adopted values of $\delta(U-B)_{0.6}$ and E(B-V); the two alternative solutions given in the previous section alter $(m-M)_o$ by no more than a few hundredths of a magnitude.

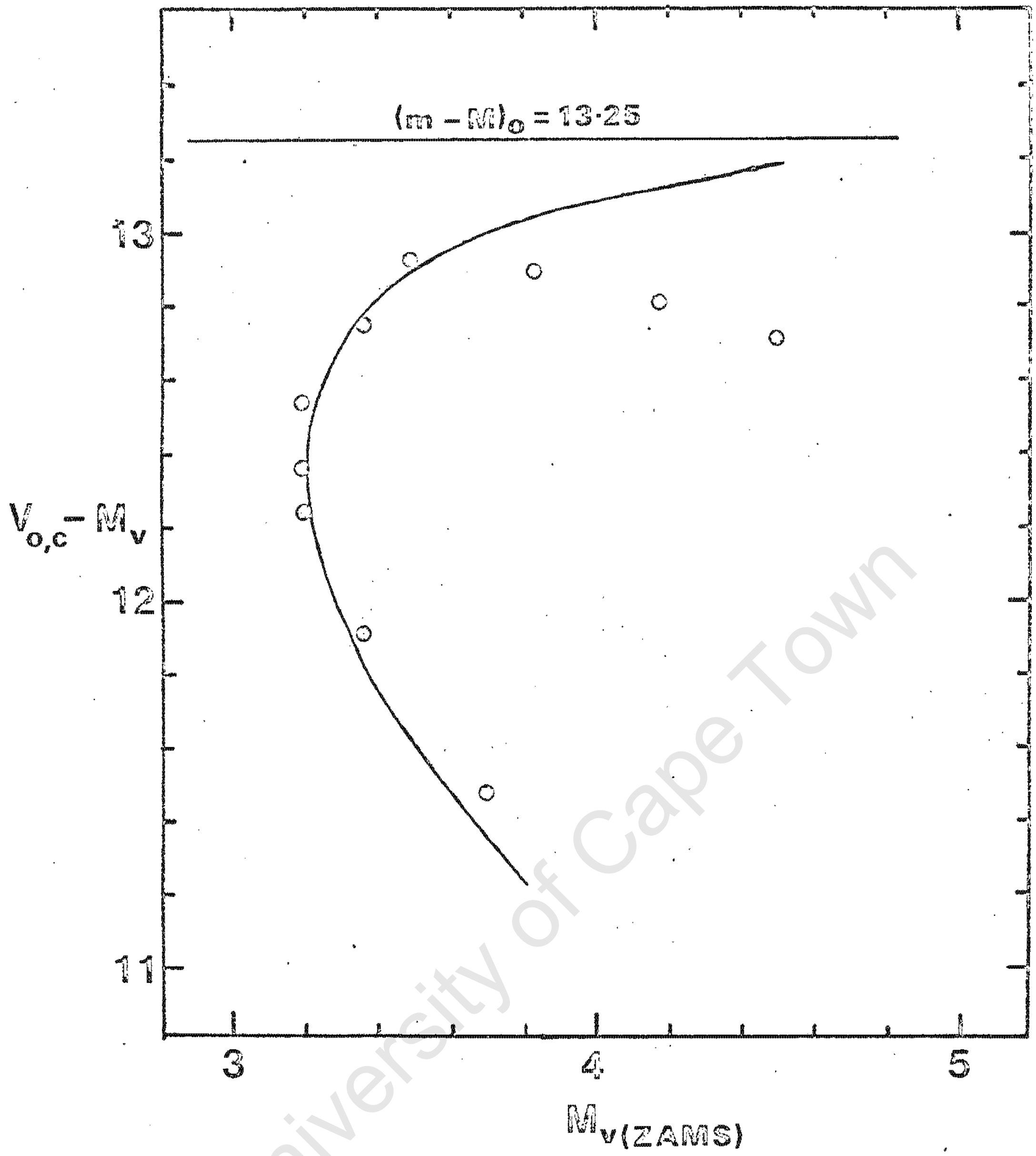

Fig. 7. The evolutionary deviation diagram of the normal points in NGC 2204 (Table IV). A theoretical curve, derived from an isochrone for age 5×10^9 years and Z=0.01, is shown fitted to these points with $(m-M)_o = 13^m.25$.

If $(m-M)_0 = 13.25$ and $R = Av/E(B-V) = 3$ the apparent visual distance modulus is $(m-M)_{A,V} = 13^m.49$. As noted above, the giant clump has its centroid at $V = 13^m.82$ so that the mean absolute magnitude of the horizontal branch of NGC 2204 is $M_V = 0^m.33$, a value reminiscent of that of NGC 2158 ($M_V \sim 0^m.4$ according to Cannon, 1970).

This unusually bright giant clump is not the only exceptional feature of NGC 2204. If $(m-M)_0 = 13^m.25$ the distance of the cluster from the sun is 4.46 kiloparsecs. With a galactic latitude of $-16^\circ.1$ the cluster must therefore lie 1250 parsecs south of the galactic plane. This is significantly further than any other cluster of Population I and is rivalled only by NGC 2243 at about 1100 Kpc and NGC 6891 which is about a kiloparsec from the plane. The combination of large $/Z/$ with an apparently overluminous horizontal branch suggests that the distance modulus has been overestimated. In view of its stability with respect to the reddening and ultraviolet excess, the only obvious source of such error lies in the fitting of the evolutionary deviation curve in Fig. 7. Clearly it will be of importance to investigate further the apparent anomalies in the slope of the lower main sequence.

(8)

A Red Variable in the Giant Branch.

The large distance of the cluster from the galactic plane supports the contention that most of the stars redder and brighter than the giant clump are probably cluster members. In this connection star number 1136 is noteworthy. With a mean V = $12^{m}.82$ (Table III) it lies about 2^{m} below the probable location of the giant branch at its colour, B - V = $1^{m}.7$; stars of this colour are distinctly rare in the halo. If it is regarded as a distant field star, it must lie more than 2.5 kpc from the galactic plane, about 11 kpc from the sun in the approximate direction of the anticenter. Membership of the cluster therefore appears rather likely.

This star is probably variable; on 1971 December 21 it had V = $13^{m}.10$ while on 1972 February 11 and 13 it averaged V = $12^{m}.71$. The B magnitudes show a similar variation. If, at maximum, it lies on the giant branch after the manner of the variables in the Hyades group (Eggen, 1972) it may be a long period variable of substantial amptitude. The luminosity function derived by Eggen for the giants in the Hyades group suggests that M and S type variables are very rare among these stars, although almost all the giants redder than B - V = $1^{m}.5$ appear to vary. Eggen predicts that a Hyades - like cluster should have at least 100 clump stars before the probability of its containing a variable of this type becomes significant. This number will presumably drop when older populations are examined as the rate of evolution along the giant branch may be expected to be lower for stars of lower mass (cf. Cannon, 1970) but it is nonetheless interesting that NGC2204, which contains only 20 or 30 clump members has at least four stars redder than B - V = $1^{m}.5$ which may be presumed to be members of the cluster. Two very red stars below the giant branch are also present in Melotte 66 (Hawarden, 1975c.) It would be interesting to undertake photoelectric photometry of such stars in order to determine (a) whether they are giants, and therefore presumably members of the clusters and (b) whether they are variable, as suggested by Eggen's results.

(9) Comparison With NGC 2243.

NGC 2204 resembles its neighbour NGC 2243 in its large distance from the galactic plane, its considerable age and its significant heavy element deficiency. If the distance moduli of these clusters are even approximately correct there is a very marked difference in the spatial structure of the two systems. As indicated in the introduction NGC 2204 probably has an overall angular diameter of about 18 arc minutes corresponding to a linear diameter of more than 20 parsecs. Conversely, NGC 2243 has an angular diameter which is less than 10 arc minutes so that at a distance of 3.6 kpc its linear diameter is less than 10 parsecs. In addition NGC 2243 is strongly concentrated towards its central region while NGC 2204 shows the looser, relatively ill-defined structure more typical of old open clusters. Clearly the dynamic history of NGC 2243 must be very different from that of its neighbour and it would be of great interest to obtain the radial velocities of these clusters as a first step towards the investigation of their galactic orbits. It is unfortunate that high-quality proper motions of the two systems will not be obtainable for some decades yet!

(10) Conclusions.

NGC 2204 is about 3×10^9 years old. The cluster is moderately deficient in heavy elements, having $\delta(U - B)_{0.6} = 0^m\!.095 \pm 0^m\!.024$ corresponding to a logarithmic abundance $[Fe/H]_\odot = -0.20$. It has a small reddening, believed to be in the vicinity of $E(B-V) = 0^m\!.08$. A distance modulus $(m - M)_0 = 13^m\!.25$ has been derived, which places the cluster 1250 parsecs from the galactic plane, substantially further than any other known open cluster.

The giant branch probably resembles those of NGC188 and Melotte 66 in its loose structure and the cluster contains at least one red variable, star 1136, which is likely to be a member. A very prominent red horizontal branch is centered at $V = 13^m\!.82$, $B-V = 0^m\!.98$. The stars thereof appear to be slightly less centrally concentrated than those of the upper main sequence. The latter feature has a gap centered at $V = 15^m\!.73$, about $0^m\!.3$ below the final turnoff to the red. A scattering of subgiants may be present in the Hertzsprung gap but rising subgiants are probably absent. Several blue stragglers are present and are strongly concentrated to the cluster center, suggesting that they have large masses.

Acknowledgements.

I am indebted to the U.K. Large Telescopes Users Panel for a grant of time on the Radcliffe Telescope which has been essential to the present work. The successful use of this time owes much to the generous assistance and hospitality of Dr. P.J. Andrews and Ms. Beryl Andrews. I am indebted likewise to the Director of the S.A.A.O, Sir Richard Woolley, for generous allocations of time on the Sutherland telescopes. This investigation forms part of a Ph.D. thesis in the Department of Astronomy of the University of Cape Town; I am very grateful to Professor Brian Warner for his advice and supervision.

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Mass Loss From Red Giants in Old Open Clusters

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Chapter VI

Summary

The stars of the giant branch clump or red horizontal branch in all members of a sample of 6 open clusters older than the Hyades are found to be less concentrated towards the cluster centre than the stars of the upper main sequence. In the cluster NGC 2158 the effect is very prominent and is shown to be a real physical property of the cluster. A similar strong effect in NGC 2477 is believed to be largely, but not entirely, a consequence of a systematic variation of reddening with radial position in the cluster. The fact that all six old clusters studied show the deconcentration phenomenon in the same sense is taken as evidence that the phenomenon is a general property of the horizontal branches of Population I systems. It is argued that the phenomenon is a consequence of mass loss during the most luminous phases of red giant evolution, probably by a stellar wind mechanism.

1. Introduction

Dickens & Rolland (1972) have summarised the extensive observational evidence suggesting that horizontal branch stars in several globular clusters are less strongly concentrated to the cluster centre than the red giants and other, less evolved, cluster stars. These differences in radial distribution are commonly interpreted as a result of mass segregation consequent on dynamic relaxation of the clusters concerned although Dickens & Rolland (among others) point out that classical relaxation theory predicts timescales for mass segregation which are, in all but the poorest globulars, far longer than any reasonable estimate of the duration of the horizontal branch stage.

Iben (1972) points out in a review of the present theoretical picture that masses of about $0.5M_{\odot}$ are required if the existence of blue horizontal branch (BHB) stars in globulars is to be explained, notwithstanding that the stars at the main sequence turnoff are believed to have masses near $0.8M_{\odot}$. The results of Stromgren photometry of BHB stars have been summarised by Newell (1972) who concludes that their masses do indeed average about $0.5M_{\odot}$. Further evidence that the horizontal branch stars have lost mass is provided by the intermediate band (DDO) photometry of Osbourne (1973) who finds that red horizontal branch and asymptotic branch stars in M3, M5, M10, M13, and M92 have on average about 0.6 of the mass of giants in the respective clusters.

Numerical models of small clusters with realistic mass spectra studied by Wielen (1967) and by Hénon (1971), who used a different numerical technique, all show marked mass segregation on a timescale $\sim 10^8$ years which is of the same order as the rates of relaxation predicted for small systems from classical relaxation theory by Chandrasekhar (1942). Such segregation effects are indeed observable in the main sequences of M37 (Brosterhus, 1963) and M67 (Murray, Corben & Allchorn, 1965). Their presence in the first of these clusters (which is only a few times 10^8 years old) confirms that the theoretical predictions do give at least an approximation to the actual timescale of this process in open clusters.

Arp & Cuffey (1962) noted that the red giants in NGC 2158 appeared slightly less concentrated to the centre of the cluster than did the main sequence stars, a result which they attributed to selective crowding effects in the inner regions. A similar but much stronger effect was noted in NGC 2477 by Eggen & Stoy (1961). Thus when a preliminary study of the old open cluster Melotte 66 (Hawarden, 1970) suggested that the stars of the horizontal branch of this cluster were also appreciably less concentrated to the cluster centre than the members of the upper main sequencee it appeared profitable to investigate whether this phenomenon is of general occurrence in old open clusters and whether any conclusions could be drawn therefrom concerning the evolution of stars in these systems.

The results are listed in Table I. The two entries for Melotte 66 illustrate the marked effect which small changes in the dividing radius can have on the significance of the results when the sample of clump stars is small.

TABLE I

Radial Distributions of Clump and Main Sequence stars in Old Open Clusters

Cluster	Sample zones	No. Clump stars	No. M/S stars	C	χ^2	P
NGC 2158	Rings 1,2 & 3	22	117	0.27	13.5	0.005
	Rings 4 & 5	24	34			
Mel. 66	0"-180"	7	60	0.32	4.85	0.026
(a)	180"-300"	17	46			
Mel. 66	0"-167"	7	53	0.41	2.63	0.11
(b)	167"-300"	17	53			
NGC 2477	0'-5'	34	57	0.51	3.55	0.06
(a)	5'-10'	36	31			
NGC 2477	0'-5'	34	57	0.81	0.27	0.59
(b)	5'-10'	36	49			
NGC 2264	0'-3'	7	23	0.53	0.87	0.27
	3'-7'	15	26			
NGC 6939	0"-292"	10	74	0.64	0.40	0.53
	292"-423	9	43			
NGC 7789	0"-292"	30	121	0.83	0.17	0.67
	292"-577"	22	74			

3. Radial Variations of Reddening in NGC 2477

The first entry (a) in Table I for NGC 2477 shows the results of a straightforward analysis of Cannon's photometry. The main sequence sample was taken from between $V = 12^{m}.0$ and $V = 13^{m}.0$. Cannon has remarked that the clump stars in the outer zone are systematically redder and fainter than those in the inner region, an effect which is also noticeable in the CM diagram of Eggen & Stoy (1961). He points out that this could be a consequence of systematically larger reddening in the outer portion of the cluster. Photoelectric observations by Hartwick, Hesser and McClure (1972) indicate considerable variations of reddening from star to star, with average reddening values $E(B-V) = 0^{m}.29$ in the inner zone and $0^{m}.34$ in the outer area. This systematic difference implies an average excess visual absorption in the outer zone of about $0^{m}.15$ if $R = A_V/E(B-V) = 3.0$.

The second entry (b) for NGC 2477 in Table I resembles the first except that the main sequence sample from the outer zone includes stars between $V=12^{m}.2$ and $13^{m}.2$. The shift of $0^{m}.2$ represents a slight over correction of the radial reddening variation indicated by the photoelectric results. This correction drastically reduces both the extent and the significance of the observed difference in the radial distributions of the clump and the main sequence samples although the sense of the effect is unchanged in that C remains less than unity despite the fact that the correction applied may be slightly too large.

4. NGC 2158

The analysis in Table I shows a very marked and highly significant difference between the distributions of the clump and main sequence samples in this cluster. The clump sample included all stars listed by Arp & Cuffey (1962) with V between $14^{m}.70$ and $15^{m}.70$ and B-V between $1^{m}.20$ and $1^{m}.50$ while the main sequence sample has V between $16^{m}.50$ and $17^{m}.00$ with B-V between $0^{m}.70$ and $0^{m}.85$.

Before the high significance attributed to the concentration differences by the results in Table I can be accepted it is necessary to consider the remarks made by Arp & Cuffey who suggest that the giant stars, being more luminous, are proportionally more seriously affected by crowding in the central regions and that their consequent omission from the photometry is responsible for their apparent dearth in the inner parts of the cluster.

In order to remove the apparent difference in the distributions of the two groups of stars it would be necessary to postulate that about 60 members of the clump sample in zones 1, 2 and 3 are missing. If any main sequence stars are affected the correction required is higher still. It is likely that at least one star has been omitted from the main sequence sample for each clump star likewise afflicted, especially since the brighter clump stars are likely to be measurable on plates of shorter exposure. If this 1:1 ratio is assumed, it becomes necessary to add 206 stars to both the observed samples if the apparent difference in their radial distributions is to be removed. Since the selected samples include only 139 stars actually measured in the inner region this correction is clearly ludicrously excessive and would make complete nonsense of Arp & Cuffey's attempts to assess the effects of field star contamination, in which they apply crowding corrections of only a few percent to their main sequence sample.

Stars with $V > 16^{m}.0$ and $B-V > 1^{m}.5$ are almost entirely red giant cluster members. They are for the most part brighter than the clump stars and should therefore be even more subject to the selective crowding effects postulated by Arp & Cuffey. The numbers of these stars in the various radial zones, together with the numbers from the clump and main sequence samples, are listed in columns 2, 3 and 4 of Table II, respectively. The projected densities of the respective groups, normalised to a value of 100 in zone 1, are listed in columns 5, 6 and 7. The tabulated densities of the red giants are in close agreement with those of the main sequence sample and show no sign whatever of the large excess in the outer zones exhibited by the clump stars, as would be expected if this excess was a result of crowding rather than a real property of the giant clump sample.

In the absence of significant crowding effects it remains conceivable that NGC 2158 suffers from a radial absorption gradient similar to that found in NGC 2477. Column 8 of Table II contains the mean colours of the main sequence samples in each zone. These means have internal SE's well below $0\overset{m}{.}01$ so that it is likely that the systematic variations shown are not the result of random errors. They are most unlikely to be a result of a reddening gradient, however. Arp & Cuffey were forced to omit from their results all stars fainter than $V=18\overset{m}{.}0$ in zones 1 and 2 (where the significant variations in colour occur) because excessive background fog from scattered light generated intolerable systematic errors in the measures of the fainter stars on the B plates. An enhanced background will produce a spuriously bright magnitude when iris measures of a star thus afflicted are calibrated using standard stars in areas with less background fog. It is thus probable that the slightly bluer mean colours of the main sequence samples in zones 1 and 2 simply reflect in less extreme form the problems encountered by Arp & Cuffey in their reductions of the fainter stars.

The rejection of reddening effects as an explanation for the observed differences in the radial distributions of the main sequence and clump stars is strongly supported by the observed distribution of the red giants.

TABLE II

Radial Distributions of Stars in NGC 2158

Zone	No. Red Giants	No. Clump Stars	No. M/S Stars	Density of Giants	Density of Clump stars	Density of M/s stars	$\overline{(B-V)}_m$ (mag)
1	4	4	36	100	100	100	0.75
2	7	12	53	58	100	49	0.76
3	2	6	28	10	30	16	0.78
4	4	15	24	14	54	9	0.77
5	1	9	10	3	25	3	0.78

If the outer regions of the cluster suffer excess absorption the apparent luminosity function of these regions is displaced towards fainter magnitudes. Thus the main sequence termination point in the central region will appear brighter and the number of stars from the outer regions falling within the main sequence sample interval will be reduced so that the main sequence sample appears to have a higher degree of central concentration than is in fact the case. Since the red giants in NGC 2158 show the same distribution as the main sequence stars it is clear that radial variations in absorption cannot be the reason for the observed concentration of the main sequence sample.

It must be concluded, therefore, that the giant clump stars in NGC 2158 are markedly less centrally concentrated than the brightest stars remaining on the main sequence and that the high significance obtained for this result in Table I is realistic.

5. Clump Concentration as a General Property of Old Open Clusters

With the notable exception of NGC 2158 none of the individual results for the 6 clusters in Table I is statistically significant. However all the cluster listed have clump concentration parameters $C < 1$.

On the null hypothesis that the clump and main sequence samples have the same radial distribution the probability that a given cluster will have $C < 1$ by chance is 1/2. Thus the probability of finding this result in all five remaining clusters is the same as the likelihood of scoring 5 heads on tossing a coin five times, namely 2^{-5} or 0.031. A danger of a'postiori statistics exists here, as NGC 2477 and Melotte 66 were both believed to have $C < 1$ at the start of the investigation. However the fact that C remains less than unity in NGC 2477 even after application of a generous correction for the radial reddening effect, which was unknown at the start of the investigation, coupled with the use of completely new photometry in Melotte 66 serves to restore confidence in the level of significance implied by the probability derived above.

It thus appears likely that the giant branch clump stars in old open clusters are in general less centrally concentrated than the brightest stars remaining on the upper main sequence. Since mass stratification effects are known to be present in the main sequences of similar clusters it may safely be concluded that these stars have lost mass during their intervening evolution.

The contrast between the degree of deconcentration exhibited by the clump stars in NGC 2158 and in NGC 7789 which has a generally similar structure and appearance would seem to indicate that the amount of mass lost varies from cluster to cluster for reasons which are as yet uncertain. Such variation would not be unexpected since it is believed that the amount of mass lost must vary from star to star in the same cluster if the observed width in colour of the globular cluster horizontal branches is to be explained (cf the review article by Iben, referred to earlier). The evident variation from cluster to cluster would also remove the anomaly of Jane's (1974) conclusion that his analysis of DDO photometry of M67 does not reveal any significant mass deficiency in the stars of the giant branch clump. DDO photometry of giants in NGC 2158, while difficult, should prove illuminating.

6. Mass Loss from Luminous Red Giants

The clusters in Table I are all older than the Hyades so that their clump stars may be presumed to have passed through the high-luminosity phases of red giant evolution prior to the helium flash before arriving in the horizontal branch (Cannon, 1970). The identification of the phase of maximum luminosity as that during which mass is lost most rapidly is indicated by the results in the globular clusters, especially those of Osbourne (1973) who used red giants in his mass comparisons but still found that the horizontal branch and asymptotic branch stars were relatively undermassive, thus effectively eliminating the possibility that the mass loss implied by Newell's (1972) results for the blue horizontal branch stars could be generated by ejection of significant amounts of matter well before the stars reach their highest luminosities near the giant branch tip.

This construction is supported also by the fact that the red giants in NGC 2158, most of which are still well below the giant branch tip, still conform closely to the radial distribution of the upper main sequence stars. The only mechanisms known to the writer whereby it has been suggested that rapid mass loss should occur specifically at the most luminous red giant phases are the scaled stellar winds postulated by Heasley & Mengel (1972), the efficiency of which is critically dependent on luminosity in two of their three models. Osbourne's results would appear to eliminate their third model, in which the rate of mass loss is a function of the mass fraction in the convective envelope of the red giants and peaks well before the red giant tip is reached.

If the red giant phases of high luminosity are postulated to be the dominant epochs for mass loss, as in the stellar wind models, it would be expected that red giants of lower luminosity which have not yet passed through such phases would retain their main sequence masses and hence their main sequence

Acknowledgements

I am extremely grateful to Dr Russell D. Cannon for providing, discussing and allowing me to use the results of his unpublished photographic photometry in NGC 2477. I am indebted to several members of the staff of the SAAO and the Royal Greenwich Observatory for a number of stimulating conversations. This investigation forms part of a Ph.D. thesis in the Department of Astronomy at the University of Cape Town. I am grateful to Professor Brian Warner for his valuable advice and supervision.

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