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# PHOTOMETRY OF SOUTHERN GLOBULAR CLUSTERS—I
## Bright Stars in ω Centauri

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SUMMARY

The techniques used for observing globular cluster stars are described, and several sources of error are discussed. Photoelectric *UBV* data are presented for 126 stars brighter than $V = 16{\cdot}5$ in ω Cen. These data are compared with those of previous photoelectric and photographic studies. There are four principal conclusions. (i) In the colour–magnitude (C–M) diagram the ω Cen giant branch has an exceptionally large scatter, of which only a small part can apparently be due to errors, field stars, and differential reddening. There is no obvious bifurcation of the red giant branch into normal and asymptotic branches. The large intrinsic scatter may be caused by the presence of normal and asymptotic branches which are then blurred out by a *small* amount of differential reddening. (ii) The large variation in ultra-violet excess with magnitude which was found by E. H. Geyer seems to be largely due to errors in his ultra-violet calibration; the variation found here is approximately that predicted from expected changes in surface gravity. (iii) Most of the reddest giants are small-amplitude variables; there may be a boundary between variables and non-variables at about $(B-V)_0 = 1{\cdot}5$. (iv) After correction for small ($< 0{\cdot}1$ mag) systematic errors, the extensive Royal Greenwich Observatory photographic photometry has the RGO quoted accuracy for $V < 15{\cdot}5$. Several observational programmes are suggested, particularly with a view to confirming that the giant branch scatter is intrinsic.

## 1. INTRODUCTION

The globular cluster ω Centauri (NGC 5139) is the richest of the nearby clusters, and should offer a good testing ground for stellar evolution theory. A comprehensive study of the cluster, involving photographic photometry and the determination of proper motions for several thousand stars, was made at the Royal Greenwich Observatory (*R. Obs. Ann. No.* **2**, 1966; henceforth referred to as RGO); the resultant C–M diagram was discussed by Dickens & Woolley (1967). Geyer (1967) measured photographic *UBV* magnitudes for a smaller sample of stars. Both of these studies indicated that the giant branch of ω Cen is abnormally wide, and Geyer (1967) suggested that the bluer giants lie on an asymptotic branch which is also clearly separated in the two-colour diagram.

We have undertaken *UBV* photoelectric photometry of bright stars in ω Cen for several reasons. By analogy with other globular clusters, it was expected that accurate photometry would resolve the wide ω Cen giant branch into an asymptotic and a normal branch. Newell, Rodgers & Searle (1969) reported considerable systematic errors in the RGO photometry for some stars, and a more extensive check on the accuracy of the RGO photometry seemed worthwhile. The anomalous ultra-violet excess of the bluer giant branch stars reported by Geyer (1967) was based on photographic photometry; a more accurate determination should be possible photoelectrically.

The data reported here extend to $V \sim 16{\cdot}5$, the limit of the RGO photographic survey. This is also a convenient limit in the photoelectric photometry for two reasons: stars brighter than $V \sim 16{\cdot}5$ can be seen and set directly in the 40-in. telescope on Siding Spring Mountain, and the star signal dominates the sky background signal.

## 2. OBSERVATION AND REDUCTION TECHNIQUES

The majority of the observations were made with a Johnson two-channel photometer (Johnson 1962) at the f18 focus of the 40-in. reflector on Siding Spring Mountain; a few were made using the same photometer on the Mount Stromlo 50-in. reflector, and a few using single-channel photometers on the 40-in. and 16-in. reflectors at Siding Spring. RCA 1P21 cells were used, cooled by dry ice, with the standard Corning filters in the single-channel photometers and equivalent Schott filters in the 2-channel photometer ($V$ = 2 mm GG11, $B$ = 1 mm GG13 + 2 mm BG12, $U$ = 2 mm UG2). The ultra-violet red-leak was always less than 0·5 per cent of the ultra-violet signal and so was negligible compared with other sources of error. Initially, all signals were recorded using d.c. integrators, but latterly pulse counting equipment has been used for the 40-in. observations. The two systems are equivalent for broad band photometry of the bright stars discussed here, since dark currents and other instrumental sources of noise are negligible.

The two-channel observations for stars with $V < 14$ were generally made through apertures of 11 or 17 arcsec, with centre-to-centre spacings of 17 and 25 s respectively, while the fainter stars were mostly observed through 8 s apertures 17 s apart. The programme stars were selected using plates taken on the 74-in. reflector at Mount Stromlo which reached to at least $V = 20$. The star and the sky holes were generally required to contain no star less than 5 mag fainter than the programme star, corresponding to a maximum error of 1 per cent. The normal observing procedure was to measure in sequence $V$, $B$, $U$ with the star in one aperture, followed by $U$, $B$, $V$ with the star in the second aperture. Usually, several $U$ measures were made in an effort to attain comparable accuracy in the three colours. Integration times were between 10 and 50 s.

The observations on each night were tied in to a set of three or four local standards; these local standards were themselves tied to at least 20 *UBV* standards on the best nights. The *UBV* standards were all chosen from the Cape lists, principally in the E-regions (Cousins & Stoy 1962, 1963; Cousins 1967). We have not applied the further very small corrections to put our data on to the original Johnson–Morgan system (Cousins 1963), since neither the Cape nor the Johnson–Morgan system is sufficiently well defined for Population II giants.

The data from the two channels were reduced both separately and together, thus providing a check on gross accidental errors and an estimate of internal accuracy. Any sky measurements which were contaminated by known background stars were corrected to a mean value, taking account of the variation in unresolved background with distance from the cluster centre. Mean atmospheric extinction coefficients were used in reducing the data, since the standards and programme stars were always close together on the sky. The instrumental calibration was determined by a best fit to all of the standards measured during each run.

## 3. ACCURACY

The several sources of error in photoelectric photometry include fluctuations in the star signal itself due to both photon statistics and short-term seeing variations, contamination by neighbouring stars, and calibration errors which comprise both night-to-night variations and systematic errors. For the stars considered here ($V < 16{\cdot}5$), the various instrumental sources of noise were negligible. Also, we were not significantly affected by statistical fluctuations in the sky background, since the background signal was at worst about 25 per cent of the total signal. Integration times were chosen so that fluctuations in the star signal produced errors of no more than 1 per cent, estimated both from the photon counts and the agreement between the two channels. This criterion was relaxed to about 2 per cent for stars with $V \approx 16$, and for the ultra-violet measurements. As mentioned in Section 2, errors due to undetected faint stars in the apertures should also be less than 1 per cent in general. There seems little point in trying to further reduce these first two types of error, since they are already comparable with the errors in calibration. The overall intrinsic errors can be estimated from the scatter in stars measured several times. The mean standard deviations of single measurements are given below as functions of magnitude. These figures are appropriate for red giants which

| Magnitude range | s.d. in $V$ | s.d. in $B$–$V$ | s.d. in $U$–$B$ |
|---|---|---|---|
| $V < 14$ | 0·01 mag | 0·01 mag | 0·02 mag |
| $14 < V < 15$ | 0·02 mag | 0·02 mag | 0·02 mag |
| $15 < V < 16$ | 0·025 mag | 0·025 mag | 0·04: mag |

comprise the majority of the stars measured; somewhat higher errors in $U$–$B$ were found for the brightest $\omega$ Cen giants ($V \lesssim 13$) since many of these measurements were made when the Moon precluded work on fainter stars.

There remains the problem of external errors, since broad band photometry done with different filters, cells and telescopes cannot be matched exactly, particularly in the ultra-violet. This problem is severe for highly evolved globular cluster stars, which have rather different energy distributions from the Population I, luminosity class III and V, stars which comprise the majority of the catalogue standards. From the good agreement between our own measurements with different equipment, and also the small scatter in the curves calibrating our instrumental systems with the Cape standards, we believe that systematic colour-dependent errors, or rather differences, are less than 0·02 mag in $V$ and $B$–$V$. However, the $U$–$B$ calibration is considerably less secure, particularly for the bluest and reddest stars (with $B-V < -0{\cdot}1$ or $B-V > 1{\cdot}5$), and we anticipate systematic differences compared with other observers of up to 0·05 mag.

Finally, there will be errors in the zero points of the tie-in to catalogue standards. Assuming that catalogue errors are negligible, the zero-point errors can be estimated from the scatter between the determinations made on different nights. Typically we observed three local standards on at least six nights, and the resultant standard errors of the zero-points are 0·005 mag, 0·003 mag and 0·008 mag in $V$, $B$–$V$ and $U$–$B$ respectively.

The various systematic effects should affect most of our observations equally, so that *relative* magnitudes for the different clusters we have studied, to be reported in subsequent papers of this series, should be accurate to 0·01 mag.

## 4. OBSERVATIONS OF $\omega$ CEN STARS

We have made photoelectric *UBV* measurements for two main samples of stars in $\omega$ Cen. One consists of all types of stars down to $V \approx 16{\cdot}5$ in a region west of the cluster, chosen to delineate the principal sequences in the C–M diagram, and consequently highly biased. The other consists of a photometrically unbiased sample of bright red giants all round the cluster. We selected all stars which had $11 < V < 13$ and $B-V > 0{\cdot}85$ in the RGO photometry, with proper motions in each coordinate less than 100 units, and at distances greater than about 7 arcmin from the cluster centre. From this list we chose only those stars which could be measured with a clear sky hole on both sides, using apertures of up to 17-arcsec diameter in the two-channel photometer; this gave an eventual total of 47 stars. Further bright stars were added later, mostly stars for which Dickens (private communication) has taken spectra or Brooke (1969) has measured infra-red colours.

The photoelectric data are listed in Table I. Column 1 gives the RGO number, followed by an asterisk if the star is a member of the unbiased sample of bright stars. Columns 2, 3 and 4 give *V*, *B–V* and *U–B*. Column 5 gives *n*, the number of nights on which the star was observed. Column 6 contains notes on membership. An M indicates a star which is a cluster member according to the radial velocity, either from Harding (1965) or from Dickens (private communication). The radial velocity provides a good criterion of membership, since the cluster has the very high mean radial velocity of $+238$ km s$^{-1}$. In the case of the stars observed by Dickens the classification is on the basis of preliminary measurements only, and the stars classed as members certainly have radial velocity $> 150$ km s$^{-1}$. An F in column 6 indicates a star whose radial velocity or proper motion is incompatible with cluster membership, while an f indicates a field star judged from the two-colour diagram. f denotes a star with $\delta(U-B) \leq 0{\cdot}05$ mag measured from the unreddened standard two-colour relation, and f: a star within 0·05 mag of the two-colour relation reddened by $E(B-V) = 0{\cdot}11$ (see below). Note that our M, F and f differ slightly from RGO usuage. ' std ' indicates a local standard, tied in to catalogue standards on *n* nights (column 5); ' var ' indicates a suspected variable star, for which we give mean magnitudes from our observations. Details of the variables are given in Section 8. Column 7 gives alternative star designations used by Arp (1958) and Geyer (1967). Finally, the numbers in parentheses refer to footnotes.

Plate I is an identification chart for the stars we have measured in the region west of the cluster, and includes most of the stars fainter than $V = 13$. All stars with $V \lesssim 13$ (3 digit numbers) are identified on the RGO charts. The few remaining faint stars can be identified from the RGO coordinates.

As noted in Section 3, some of the bright giants have larger measuring errors than usual, particularly in the ultra-violet, since they were measured on moonlit nights. The stars involved are the members of the unbiased sample, which were measured four times on average to give standard deviations of the means of 0·01 mag in *V* and *B–V*, 0·04 mag in *U–B*.

The C–M diagram of the stars in Table I is shown in Fig. 1, and the two-colour diagram in Fig. 2. In each diagram open circles represent stars which are probably not cluster members (F, f or f: in column 6 of Table I), most of the filled circles are cluster members, and members suspected of being variable are represented by a V. Note that most of the possible red horizontal branch stars, with $V \sim 14{\cdot}5$, $B-V \sim 0{\cdot}7$, are classed as probable field stars, although the two-colour diagram

TABLE I

*UBV photometry for stars in ω Cen*

| Star | V | B–V | U–B | n | Notes | | |
|---|---|---|---|---|---|---|---|
| 0003 | 8.57 | 1.29 | 1.44 | 7 | f, std | Arp A | |
| 0004 | 8.80 | 0.00 | -0.10 | 1 | f | Arp B | |
| 0011 | 10.04 | 1.11 | 0.87 | 1 | f | Arp D | |
| 0012 | 10.10 | 1.16 | 1.18 | 1 | F | Arp E | |
| 0015 | 10.55 | 1.62 | 1.98 | 2 | F | | |
| 0024 | 10.80 | 0.36 | 0.33 | 3 | M | G319 | (1) |
| 0036* | 11.16 | 1.60 | 1.90 | 5 | F, std | Arp F | |
| 0040 | 11.37 | 1.50 | 1.41 | 2 | M | | |
| 0043 | 11.64 | 1.71 | 1.84 | 3 | M, var | | |
| 0046 | 11.54 | 1.58 | 1.55 | 2 | M | | |
| 0048 | 11.51 | 1.56 | 1.44 | 2 | M | | |
| 0049 | 11.58 | 1.59 | 1.41 | 2 | M, var | | |
| 0053 | 11.58 | 1.70 | 1.73 | 4 | M, var | Arp G | |
| 0055 | 11.46 | 1.68 | 1.30 | 2 | M | | (2) |
| 0056 | 11.70 | 1.65 | 1.73 | 3 | M, var | | |
| 0058* | 11.64 | 1.42 | 1.18 | 4 | M | | |
| 0061 | 11.54 | 1.65 | 1.68 | 3 | var | G350 | |
| 0062 | 11.50 | 1.65 | 1.71 | 2 | M | | |
| 0070* | 11.61 | 1.80 | 1.68 | 7 | M | | (3) |
| 0074 | 11.74 | 1.36 | 1.14 | 2 | M | | |
| 0084 | 11.87 | 1.66 | 1.79 | 2 | M | | |
| 0085 | 11.84 | 1.61 | 1.62 | 2 | M | | |
| 0090* | 11.66 | 1.64 | 1.66 | 9 | M, var | | |
| 0091* | 11.81 | 1.39 | 1.24 | 5 | M | G299 | |
| 0096* | 11.76 | 1.48 | 1.40 | 5 | M | G242 | |
| 0102* | 11.68 | 1.46 | 1.33 | 5 | M | G200 | |
| 0113 | 11.76 | 0.39 | 0.07 | 6 | F, std | | |
| 0124* | 11.83 | 1.38 | 1.25 | 5 | M | G170 | |
| 0143 | 11.95 | 0.45 | 0.08 | 7 | F, std | Arp J | |
| 0150* | 12.00 | 1.70 | 1.90 | 10 | M | G82 | |
| 0155* | 12.00 | 1.42 | 1.25 | 5 | M | | |
| 0156 | 11.93 | 1.55 | 1.84 | 1 | f | Arp I | |
| 0159* | 12.01 | 1.32 | 1.04 | 6 | M | G381 | |
| 0161* | 11.97 | 1.39 | 1.24 | 4 | | G247 | |
| 0162* | 12.14 | 1.70 | 1.89 | 10 | M, var | | |
| 0171 | 12.07 | 1.48 | 1.46 | 1 | | G28 | |
| 0213* | 12.22 | 1.14 | 0.72 | 5 | M | G324 | |
| 0219* | 12.20 | 1.58 | 1.66 | 5 | M | G220 | |
| 0234* | 12.25 | 1.16 | 0.80 | 3 | M | G283 | |
| 0253* | 12.34 | 1.37 | 1.28 | 8 | M | | |
| 0269* | 12.35 | 1.22 | 0.86 | 4 | | G134 | |
| 0270 | 12.42 | 1.50 | 1.46 | 2 | | G48 | |
| 0272* | 12.38 | 1.36 | 1.19 | 5 | | | |
| 0279* | 12.32 | 1.38 | 1.08 | 4 | | | |
| 0287 | 12.41 | 1.42 | 1.28 | 2 | M | G399 | |
| 0289* | 12.44 | 1.26 | 0.88 | 4 | | | |
| 0297* | 12.44 | 1.31 | 1.02 | 6 | | | |
| 0312* | 12.44 | 1.30 | 0.96 | 5 | | | |
| 0320 | 12.75 | 1.73 | 1.57 | 2 | M, var | | (4) |
| 0331 | 12.54 | 1.65 | 1.94 | 3 | F, var | G244 | |

TABLE I—*continued*

| Star | $V$ | $B–V$ | $U–B$ | $n$ | | Notes | |
|---|---|---|---|---|---|---|---|
| 0364* | 12.50 | 1.11 | 0.63 | 3 | M | | |
| 0371 | 12.68 | 1.60 | 1.76 | 2 | M, var | | |
| 0379* | 12.62 | 1.19 | 0.70 | 3 | | G375 | |
| 0384 | 12.65 | 1.62 | 1.73 | 3 | F, var | | |
| 0394* | 12.66 | 1.35 | 1.19 | 4 | M | | |
| 0399 | 12.67 | 0.43 | 0.00 | 1 | F | Arp K | |
| 0402* | 12.68 | 1.07 | 0.68 | 6 | M | G$\zeta$ | |
| 0415* | 12.66 | 1.10 | 0.60 | 3 | | G289 | |
| 0418* | 12.70 | 1.10 | 0.66 | 3 | | G166 | |
| 0423* | 12.65 | 1.13 | 0.73 | 3 | | G174 | |
| 0434* | 12.76 | 1.16 | 0.84 | 15 | | | (5) |
| 0446* | 12.75 | 1.11 | 0.69 | 4 | | G161 | |
| 0462* | 12.76 | 1.01 | 0.54 | 4 | M | | |
| 0464* | 12.85 | 1.18 | 0.82 | 3 | | | |
| 0370* | 12.82 | 1.02 | 0.48 | 5 | | G108 | |
| 0474* | 12.81 | 1.06 | 0.58 | 3 | | | |
| 0476* | 12.79 | 1.07 | 0.64 | 4 | | | |
| 0481* | 12.88 | 1.11 | 0.66 | 5 | | | |
| 0482* | 12.93 | 1.31 | 1.40 | 6 | f | | |
| 0483* | 12.82 | 1.07 | 0.59 | 4 | | | |
| 0509 | 12.94 | 1.00 | 0.56 | 2 | M | | |
| 0537* | 12.90 | 1.24 | 0.85 | 4 | M | | |
| 0542 | 12.92 | 0.04 | -0.09 | 2 | M | G366 | |
| 0543* | 12.98 | 1.05 | 0.67 | 2 | | G71 | |
| 0575* | 13.04 | 0.98 | 0.51 | 4 | | | |
| 0591* | 13.03 | 1.06 | 0.55 | 4 | | G1 | |
| 0595* | 13.05 | 1.20 | 0.78 | 5 | | G98 | |
| 0601* | 12.98 | 1.04 | 0.51 | 3 | | G128 | |
| 0605* | 13.01 | 1.16 | 0.60 | 3 | | | |
| 2024 | 14.82 | 0.14 | 0.29 | 1 | | | |
| 2379 | 14.88 | 0.18 | 0.21 | 1 | | | |
| 3598 | 14.36 | 0.87 | 0.31 | 2 | M: | G189 | |
| 4135 | 14.05 | 0.60 | 0.00 | 2 | | | |
| 4146 | 14.21 | 0.97 | 0.37 | 1 | | | |
| 4153 | 14.63 | 0.22 | 0.24 | 2 | | | |
| 4373 | 13.96 | 0.76 | 0.25 | 2 | M: | | |
| 4402 | 14.79 | 0.30 | 0.15 | 1 | | | |
| 4403 | 14.67 | 0.97 | 0.37 | 1 | | | |
| 4404 | 14.92 | 0.09 | 0.19 | 2 | | | |
| 4405 | 14.44 | 0.93 | 0.46 | 2 | | | |
| 4407 | 15.41 | 0.93 | 0.61 | 1 | f: | | |
| 4409 | 15.70 | 0.84 | 0.23 | 3 | | | |
| 4415 | 14.02 | 1.15 | 1.08 | 1 | f | | |
| 4419 | 14.73 | 0.18 | 0.24 | 1 | | G387 | |
| 4654 | 14.89 | 0.78 | 0.28 | 1 | f: | | |
| 4655 | 16.14 | 0.62 | 0.01 | 2 | | | |
| 4658 | 16.38 | 0.75 | - | 1 | | | |
| 4659 | 16.27 | 0.95 | - | 1 | | | |
| 4660 | 15.85 | 0.84 | 0.05 | 1 | | | |

TABLE I—*continued*

| Star | $V$ | $B-V$ | $U-B$ | $n$ | | Notes |
|---|---|---|---|---|---|---|
| 4661 | 16.31 | 0.77 | 0.38 | 1 | f | |
| 4663 | 14.94 | 0.86 | 0.24 | 1 | | |
| 4665 | 14.63 | 0.60 | 0.06 | 1 | f: | G382 |
| 5002 | 14.56 | 0.79 | 0.40 | 2 | f | |
| 5003 | 14.29 | 0.63 | 0.07 | 2 | f: | |
| 5005 | 14.91 | 0.17 | 0.23 | 2 | | |
| 5006 | 14.37 | 0.97 | 0.61 | 1 | f: | |
| 5007 | 15.76 | 0.88 | 0.15 | 2 | | |
| 5013 | 15.46 | 0.87 | - | 2 | | |
| 5015 | 14.43 | 0.90 | 0.45 | 2 | f: | |
| 5021 | 14.44 | 0.23 | 0.17 | 1 | | G385 |
| 5022 | 14.41 | 1.01 | 0.53 | 2 | | G386 |
| 5312 | 16.12 | 0.83 | - | 1 | | |
| 5315 | 16.42 | 0.73 | - | 3 | | |
| 5319 | 16.01 | 0.78 | 0.02 | 2 | | |
| 5321 | 15.76 | 0.76 | 0.11 | 1 | | |
| 5324 | 14.79 | 1.06 | 0.55 | 1 | | |
| 5567 | 15.52 | 0.79 | 0.15 | 1 | | |
| 5752 | 14.35 | 0.97 | 0.44 | 1 | | |
| 5759 | 13.10 | 0.93 | 0.47 | 1 | | |
| 5760 | 15.02 | 0.80 | 0.18 | 1 | | |
| 5941 | 13.50 | 0.88 | 0.32 | 1 | | |
| 5952 | 14.79 | 0.92 | 0.26 | 1 | | |
| 6113 | 13.65 | 1.00 | 0.50 | 1 | | |
| 6119 | 13.45 | 0.93 | 0.54 | 1 | f: | G360 |
| 6258 | 14.13 | 0.86 | 0.27 | 1 | | |
| 6400 | 14.24 | 0.86 | 0.27 | 1 | | |

*Notes to Table I.*

(1) Fehrenbach & Duflot (1962).
(2) CH star (Harding 1962).
(3) CH star (Dickens 1972).
(4) TiO variable (Dickens, Feast & Lloyd Evans 1972).
(5) Secondary local standard on some nights.

*Corrections made in proof.*

Star 4402, column $B-V$ for 0.30 read 0.20
Star 6258, column $B-V$ for 0.86 read 0.91
column $U-B$ for 0.27 read 0.35

may not give good discrimination for the bluest stars of the group. The broken line in Fig. 2 represents a standard two-colour relation for Population I stars, obtained by smoothly joining the luminosity class III and V relations of Johnson (1966), while the solid line represents the same relation shifted by a uniform reddening of $E(B-V) = 0{\cdot}11$, $E(U-B) = 0{\cdot}08$. The value $E(B-V) = 0{\cdot}11$ is adopted as the mean reddening of $\omega$ Cen by both Newell, Rodgers & Searle (1969) and by Eggen (1972a). It seems probable that both the size and direction of the reddening line in the two-colour diagram should vary somewhat with the type of star involved (see Hartwick & McClure 1972, and references therein), so that the reddening values adopted may not be quite correct for all of the $\omega$ Cen giants. It is however clear that the two-colour relation provides a good criterion for rejecting several stars as field stars, since the mean cluster ultra-violet excess is between 0·2 and 0·3 mag.

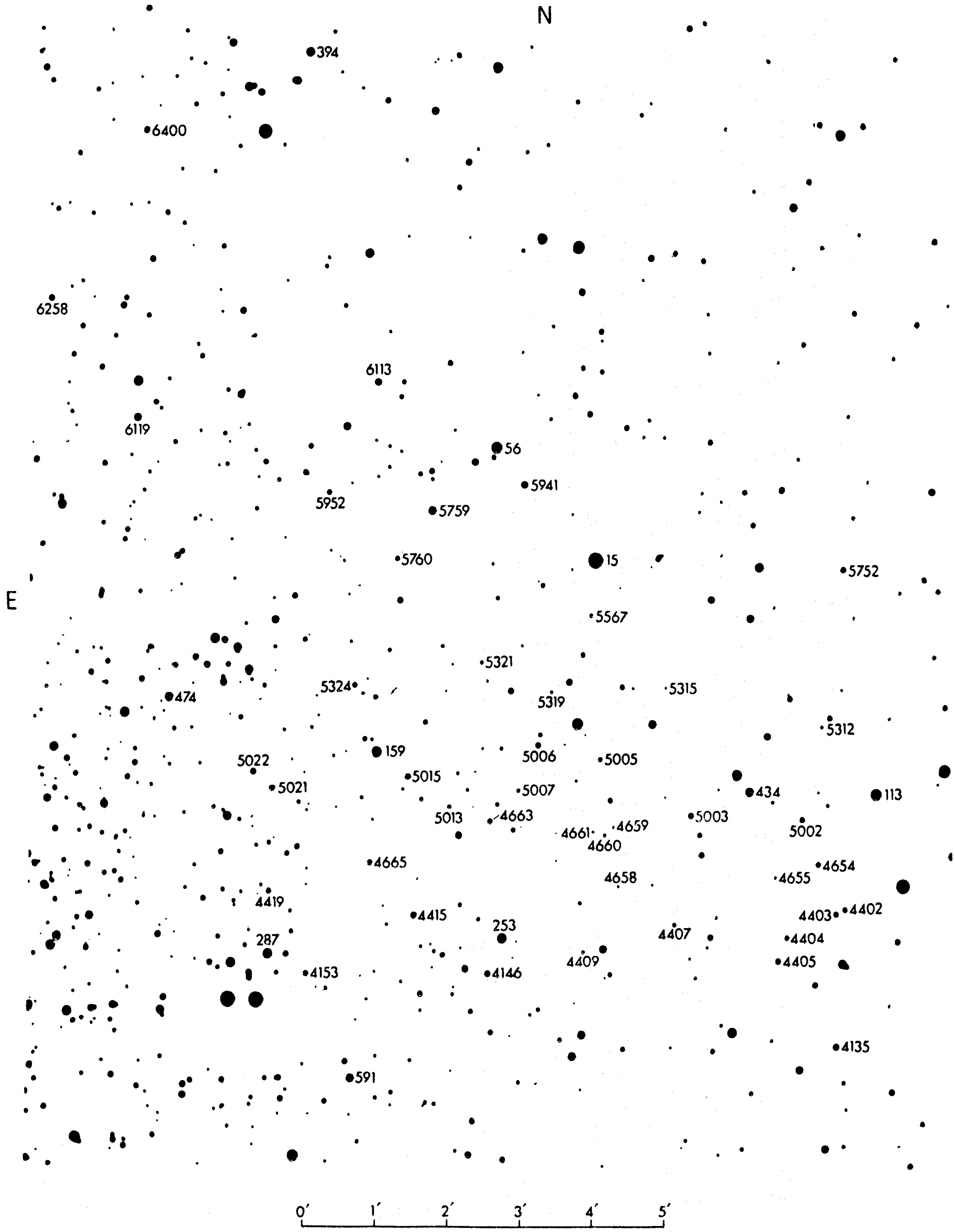


PLATE I. *A V finding chart for the stars measured in a region west of ω Cen, centre approximately* $13^h\ 23^m{\cdot}0$, $-47°\ 12'$ (1970).

It is immediately evident that the giant branch is very broad in the C–M diagram, with no obvious separation into a normal and an asymptotic branch, while the scatter in the corresponding two-colour diagram is small. Fig. 1 does not give a true picture of the cluster C–M diagram since the stars are not a random sample. The unbiased sample of bright red giants, which should be complete to $V = 12{\cdot}9$, gives the C–M diagram shown in Fig. 3. The large scatter of Fig. 1 is still obvious.

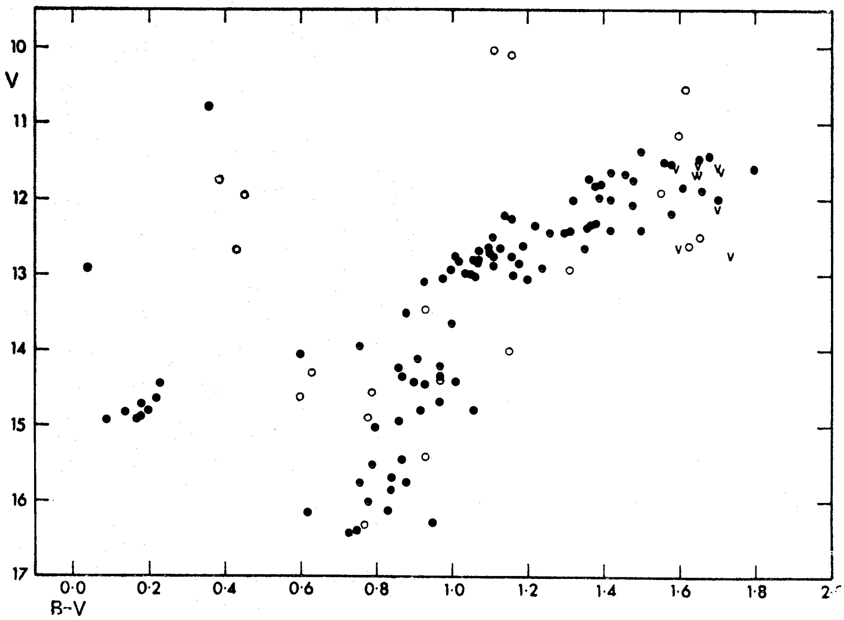


FIG. 1. *The C–M diagram of all stars measured photoelectrically in ω Cen. The majority of the filled circles are cluster members, open circles are believed to be field stars, and V's denote variable stars.*

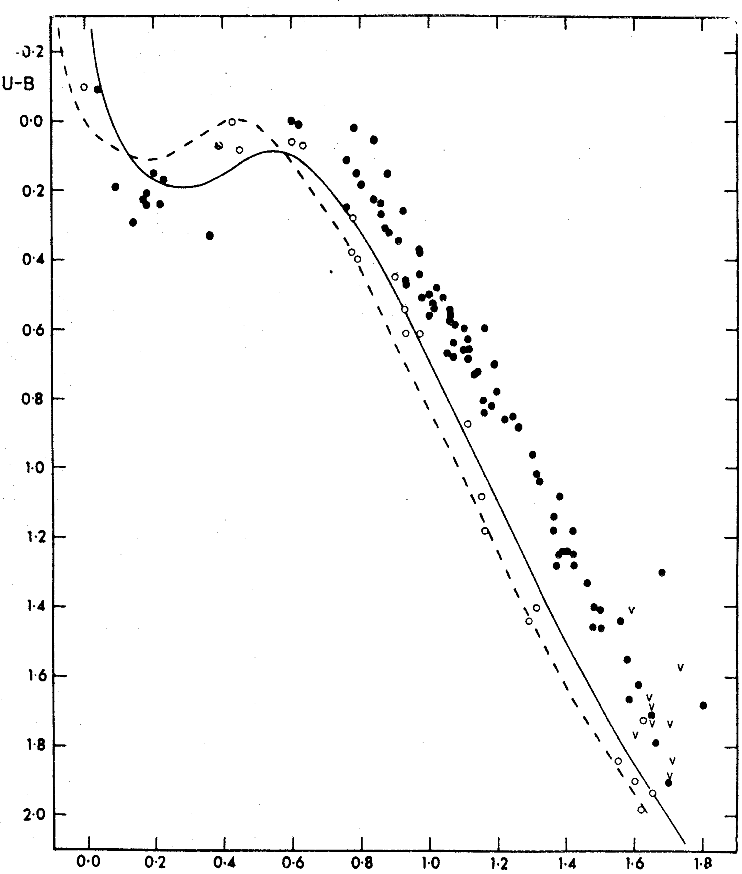


FIG. 2. *The two-colour diagram for ω Cen. The symbols are the same as in Fig. 1. The broken line and solid line represent standard (Population I) two-colour relations, unreddened and reddened by $E(B-V) = 0{\cdot}11$ respectively.*

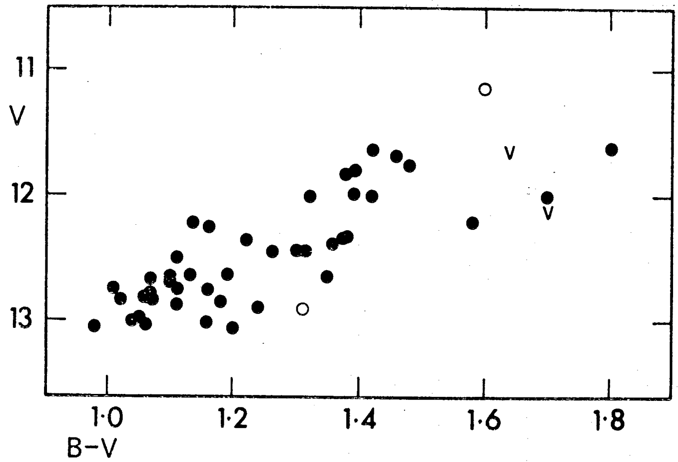


FIG. 3. *The C–M diagram for the unbiased sample of ω Cen red giants, using again the symbols of Fig.* 1.

## 5. COMPARISON WITH PREVIOUS WORK

We have 11 stars in common with the recent work of Eggen (1972a, in which star 364 is apparently wrongly numbered 384 in Table 4). Omitting the suspected variable stars and the still discrepant star 364, the systematic differences (this paper—Eggen) are −0·05, −0·01 and +0·01: mag in $V$, $B-V$ and $U-B$ respectively. The agreement in colour is good, although the discrepancy in $V$ is outside the estimated zero-point uncertainty of the present data.

The new extensive photoelectric data permit a recalibration of the RGO and Geyer (1967) photographic surveys. Considering first the RGO data, the differences $V_{cs}-V_{RGO}$ and $B_{cs}-B_{RGO}$ are plotted against $V_{cs}$ and $B_{cs}$ respectively in Fig. 4. The subscript cs refers to photoelectric data from the present paper. There is

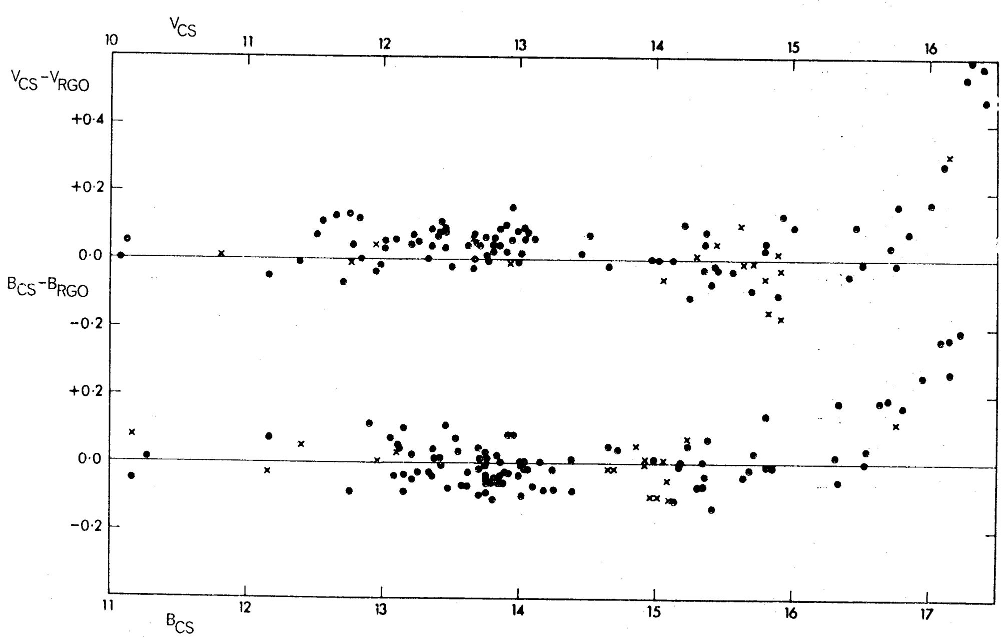


FIG. 4. *The difference between the present photoelectric magnitudes* ($V_{cs}$, $B_{cs}$) *and the RGO photographic magnitudes* ($V_{RGO}$, $B_{RGO}$) *as a function of the photoelectric magnitude. Filled circles denote stars with* $B-V>0·7$ *and crosses denote stars with* $B-V<0·7$.

little evidence for any colour equation in either $V$ or $B$, while the systematic errors in both colours are generally $< 0{\cdot}05$ mag except for the faintest stars. The combined effect of the errors in $V$ and $B$ is that the RGO photometry of the brighter red giants ($V \lesssim 13$) is systematically too bright by 0·04 mag in $V$ and too red by 0·06 to 0·08 mag, while the fainter subgiant photometry is substantially correct down to $V = 15{\cdot}5$. We find no significant systematic errors for the brighter blue horizontal branch stars ($V < 15$), and believe that the apparently very large colour equation found by Newell *et al.* (1969) is probably better regarded as a combination of separate small magnitude equations in $V$ and $B$. The RGO photometry is seriously in error fainter than $V = 15{\cdot}5$. The random errors in the RGO photometry of the giants show no correlation with radius from the cluster centre. After correction for the systematic errors, the mean differences between the present photoelectric data and RGO photographic data are about 0·04 mag in both $V$ and $B$ for all stars with $V < 15{\cdot}5$; these confirm the RGO estimated random errors, which dominate the photoelectric errors.

Geyer (1967) gives photographic data for 40 of the non-variable stars in Table I. Most of these are bright red giants, for which the systematic differences are less than 0·02 mag in $V$ and $B$–$V$. However, Geyer's (1967) ultra-violet measurements seem to be seriously in error; since these form the basis for his often cited conclusion that the subgiants and giants have very different ultra-violet excesses, it is necessary to examine the discrepancy in some detail. A plot of $U_{cs} - U_g$ versus $U_{cs}$ is shown in Fig. 5, where the subscript g denotes the photographic data of Geyer (1967). For $U > 14$ there is an approximate relation $U_g = U_{cs} - 0{\cdot}3(U_{cs} - 14{\cdot}0)$.

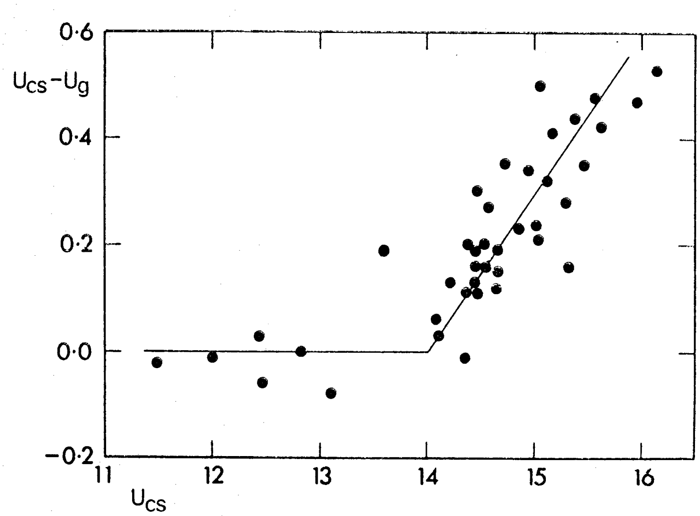


FIG. 5. *The difference between the present photoelectric ultra-violet magnitudes* ($U_{cs}$) *and the photographic magnitudes of Geyer* ($U_g$), *as a function of* $U_{cs}$. *The straight lines give the approximate relation discussed in the text.*

For stars in a narrow range of $B$–$V$ (and consequently of $U$–$B$: see Fig. 2), an error of the form shown in Fig. 5 will produce an apparent large increase in ultra-violet excess with $V$ magnitude, following approximately the relation $\Delta\delta(U{-}B)/\Delta V = 0{\cdot}3$. This is close to the relation found by Geyer (1967) and illustrated in his Fig. 4. We conclude that the anomalous ultra-violet excess found by Geyer (1967) is due almost entirely to an error in the calibration of his photographic magnitudes. Our photoelectric data show a very much smaller effect which is consistent with the expected dependence of ultra-violet excess on surface gravity (see Section 7).

## 6. THE INTRINSIC WIDTH OF THE ω CEN GIANT BRANCH

The apparent width of the ω Cen red giant branch is very much greater than in other well-observed clusters such as M15 (Sandage, Katem & Kristian 1968), M5 (Simoda & Tanikawa 1970) and NGC 6752 (Cannon & Stobie 1973). The redder ω Cen giants ($B-V > 1{\cdot}2$) cover a range of at least 0·3 mag in $B-V$ at given $V$, or 1 mag in $V$ at given $B-V$. Since many of the stars with $B-V > 1{\cdot}6$ are known to be variable, and some are CH stars with anomalous positions in the two-colour diagram, we shall consider in detail first the stars with $V \lesssim 13{\cdot}0$ and $B-V \lesssim 1{\cdot}6$. The C–M and two-colour diagrams for these stars are shown in Fig. 6(a) and (b) respectively. The giant branch has been arbitrarily divided into blue, central and red strips in the C–M diagram, and separate symbols used for the three strips.

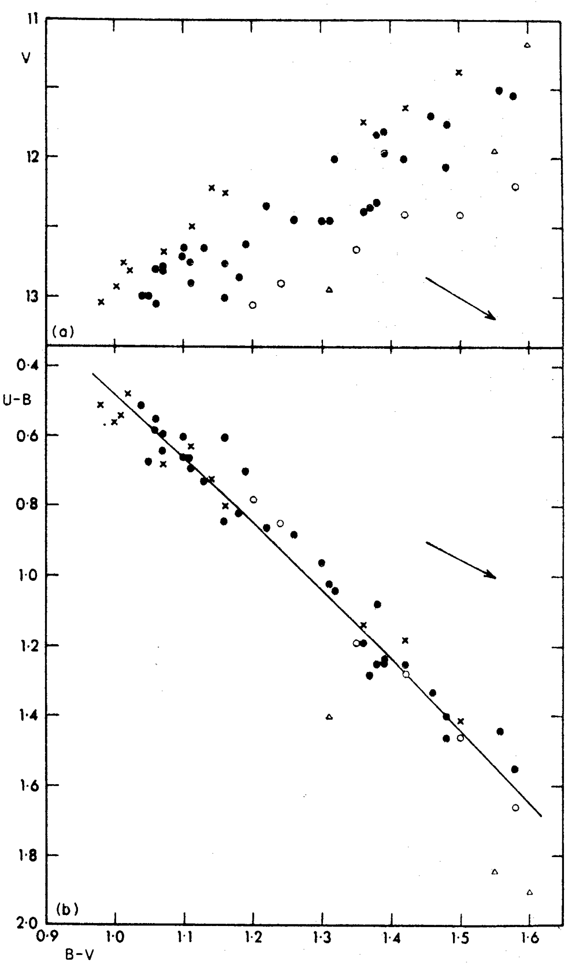


FIG. 6. *A detail of the ω Cen giant branch. The upper panel (a) gives the C–M diagram in which stars on the blue side, centre, and red side of the giant branch have been plotted with different symbols. Triangles represent field stars. The arrow indicates reddening with $E(B-V) = 0{\cdot}1$. The lower panel (b) is the corresponding two-colour diagram (plotted on a compressed U–B scale for clarity). The reddening arrow represents $E(B-V) = E(U-B) = 0{\cdot}1$. The solid line is simply a smooth mean curve drawn through all cluster members.*

Three extrinsic effects may contribute to the dispersion; these are measuring errors, inclusion of non-member stars, and differential interstellar reddening. Our estimated measuring errors (Sections 3 and 4) are negligible compared with the observed scatter in Fig. 6(a). Confirmation that the errors have been estimated correctly comes from the much smaller spread in the two-colour diagram, Fig. 6(b). The dominant measuring error is the mean deviation of 0·04 mag in $U$–$B$. When combined with the smaller error in $B$–$V$, we would expect a scatter in the two-colour diagram with mean deviation 0·05 mag in $U$–$B$. The observed scatter from Fig. 6(b) is 0·06 mag. Consequently measuring errors cannot be contributing significantly to the scatter in the C–M diagram. At the same time, the true scatter in the two-colour diagram must be very small indeed.

The scatter in the C–M diagram is certainly not due to the inclusion of field stars. Three of the stars in Fig. 6 are probably field stars on the basis of radial velocity or the two-colour diagram; these are indicated by open triangles. Many of the remaining stars, including all but two in each of the blue and red strips, are confirmed radial velocity cluster members. The negligible scatter in the two-colour diagram provides independent evidence that most of the stars in Fig. 6 are cluster members, particularly since the cluster stars lie approximately 0·4 mag above the relation for unreddened Population I stars.

A third possibility is that the scatter is due principally to differential reddening. Arrows on Fig. 6 indicate the effect of a reddening $E(B-V) = 0{\cdot}1$, assuming that $A_V = 3.E(B-V)$ and $E(U-B) = E(B-V)$. We have adopted the ratio $E(U-B)/E(B-V) = 1{\cdot}0$ rather than the conventional value of 0·72 since several authors have found that the reddening line is steeper for late type stars (e.g. Fernie 1963; Hartwick & McClure 1972). To reduce the scatter in the C–M diagram to the value typical of globular clusters would require a differential reddening of at least $E(B-V) = 0{\cdot}15$ mag. Such a large effect is precluded by the two-colour diagram, since the stars in the red strip should then lie systematically about 0·15 mag in ($U$–$B$) above those in the blue strip. In fact the stars in the three strips in Fig. 6(a) lie on the same two-colour relation in Fig. 6(b) to within 0·01 mag. The reddening effect cannot be being masked by a surface gravity effect, assuming that only part of the scatter in the C–M diagram is real, since the blue strip stars should have lower surface gravities and again lie below the mean line in the two-colour diagram. We deduce that the scatter in the C–M diagram could be due principally to differential reddening *only if* the ratio $E(U-B)/E(B-V) \approx 2{\cdot}0$ for the $\omega$ Cen giants, a much higher value than has been found for any other stars. Bell (private communication) has calculated synthetic spectra for $\omega$ Cen red giants, and finds that $E(U-B)/E(B-V)$ never exceeds 1·0 for such stars.

As a further check, we note that the blue horizontal branch is much narrower and better defined than is the red giant branch. This is apparent both from the limited photoelectric data available (present data combined with that of Newell *et al.* 1969) and from the complete RGO photographic data. Since the two branches have similar slopes in the C–M diagram, the effects of random differential interstellar reddening should be approximately the same for both branches. The combined blue horizontal branch photoelectric data (29 stars) show a scatter about the mean line in the C–M diagram with 0·03 mag standard deviation in $B$–$V$. A *maximum* differential reddening of 0·05 mag in $B$–$V$ could account for this scatter. However, as the observed scatter is consistent with the photometric errors quoted by Newell *et al.* (1969) it seems that any differential reddening in this sample of stars is small. The sample of stars is distributed around the cluster and coincides with the outer region of our red giant annulus. This implies that differential reddening cannot be the main cause of the scatter in the red giant branch. The only uncertainty in this conclusion is that the photoelectrically measured blue horizontal branch stars do not yet completely cover the region of sky covered by the red giants.

We have looked at the spatial distribution of the red giants, and found little correlation with position in the C–M diagram. There may be a *small* differential reddening effect, in that the C–M diagram for giants within radius $R < 10$ min shows a small bluewards shift relative to that for giants with $R > 16$ min, although both diagrams retain the large scatter of Fig. 6(a). The samples of stars are small, but if the shift is real it can be explained by a mean differential reddening of $E(B-V) \approx 0{\cdot}05$ mag, which is just within the errors in the two-colour diagram.

We conclude that the large scatter in the ω Cen red giant branch is real and an intrinsic property of the stars. We note that this conclusion is different from that of Eggen (1972b), who chose a substantially different sample of stars with $V \approx 12$ and worked principally in the near infra-red; he obtained a large scatter in colour, but suggested that this could mostly be explained by differential reddening. However, we believe that the infra-red data are more compatible with an intrinsic temperature variation than with differential reddening. The $(B-V, R-I)$ relation obtained by Eggen (1972b) is repeated here in Fig. 7. Since the sample of stars was

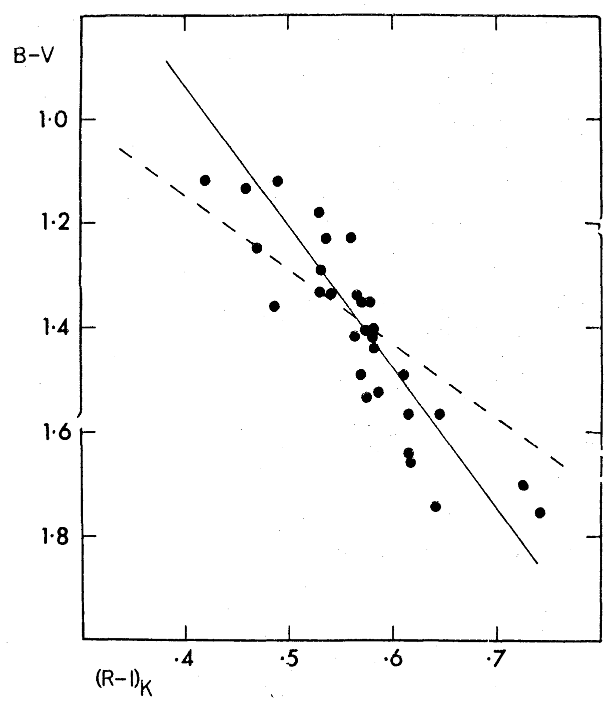


FIG. 7. *The $(B-V, R-I)$ diagram from Eggen's (1972b) data. The solid line is the relation expected if variations in temperature are dominant, while the dashed line is the relation expected from differential reddening.*

selected at virtually constant magnitude this diagram shows the correlation between the scatter in the giant branches in the $(V, B-V)$ and $(R, R-I)$ colour–magnitude diagrams. In Fig. 7 the solid line indicates the relation to be expected when variations in effective temperature are dominant (it is the mean relation for the ω Cen red giants at all magnitudes, derived from the data of Table 4 of Eggen 1972a), and the dashed line is the relation expected from a differential reddening effect, $E(R-I)_K/E(B-V) = 0{\cdot}7$ (Eggen 1972b). Fig. 7 suggests that a range in temperature at a given magnitude is a more important effect than differential reddening.

The correlation in the scatter of the red giant branch in the ($V$, $B$–$V$) and ($R$, $R$–$I$) C–M diagrams is apparent over a wider range of magnitudes ($11{\cdot}5 < V < 13{\cdot}0$) using the $R$, $I$ photometry of Brooke (1969), and is again compatible with variations in temperature. However, the results are not definitive and could be considerably improved if $R$, $I$ photometry existed for the crucial faint red giants whose membership is confirmed by radial velocities.

## 7. THE ULTRA-VIOLET EXCESS OF THE SUBGIANTS

We now investigate the dependence of ultra-violet excess on magnitude, in view of the anomalously large difference in ultra-violet excess between asymptotic, giant and subgiant branches found by Sandage & Walker (1966) in M92 and M3. It has already been shown in Section 5 that a similar effect found in $\omega$ Cen by Geyer (1967) is probably due to an error in his ultra-violet calibration. The failure of accurate photometry to resolve the broad $\omega$ Cen giant branch into a normal and an asymptotic branch makes it impossible to look for the Sandage–Walker effect directly. However, there is no discernable separation of the giants with $V \lesssim 13$ in the two-colour diagram (Fig. 6(b)), and it remains to consider those cluster members fainter than $V = 13$ which lie in the strip $0{\cdot}75 < B{-}V < 1{\cdot}02$. We have measured the ultra-violet excesses $\delta(U{-}B)$ relative to the standard class V two-colour relation of Johnson (1966), after correction for the cluster reddening of $E(B{-}V) = 0{\cdot}11$. The precise forms of the two-colour relation and interstellar reddening law are not important since we are concerned only with relative values of $U$–$B$ over a limited range in $B$–$V$. Fig. 8 shows the plot of $V$ against $\delta(U{-}B)$ for

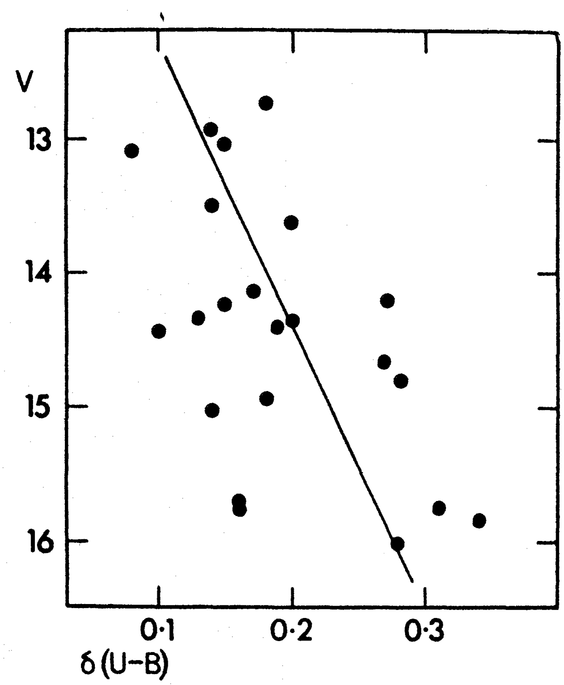


FIG. 8. *The relation between V magnitude and ultra-violet excess* $\delta(U{-}B)$ *for stars with* $0{\cdot}75 < B{-}V < 1{\cdot}02$. *The solid line represents approximately the expected effect of changes in surface gravity.*

these stars; the solid line corresponds to the expected surface gravity effect according to Sandage & Walker (1966). While there is considerable scatter in the observed points, there is a correlation of $\delta(U-B)$ with $V$ which has approximately the predicted slope. The detailed calculations of Bell (1970) lead to approximately the same relation. We conclude that there is no evidence from our data for an anomalous ultra-violet excess amongst the stars of $\omega$ Cen.

## 8. THE RED VARIABLE STARS

In his comprehensive study of variables in $\omega$ Cen, Martin (1938) classified 10 as irregular or long period variables. Eggen (1972a) has observed several of these and some which have been discovered subsequently. Dickens & Woolley (1967) examined the scatter of their photographic magnitudes on 10 plates and deduced that at least 70 per cent of the stars with $B-V_{RGO} > 1{\cdot}53$ were variable. The present study has revealed nine new probable variables with amplitudes greater than 0·06 mag, although only two or three of these can be regarded as certainly variable. The data are not sufficient for a discussion of periods or amplitudes, but it seems likely that all are long period variables. RGO numbers 331 and 384 are field stars and most of the others are members according to their radial

TABLE II

*Suspected variable stars in* $\omega$ *Cen*

| Star | JD (2441000+) | *V* | *B–V* | *U–B* |
|---|---|---|---|---|
| 43 | 387 | 11.56 | 1.71 | 1.84 |
| | 413 | 11.67 | 1.70 | 1.81 |
| | 477 | 11.69 | 1.73 | 1.88 |
| 49 | 387 | 11.48 | 1.57 | 1.35 |
| | 477 | 11.67 | 1.61 | 1.47 |
| 53 | 387 | 11.52 | 1.68 | 1.67 |
| | 413 | 11.60 | 1.71 | 1.73 |
| | 414 | 11.62 | 1.73 | 1.76 |
| | 477 | 11.59 | 1.70 | 1.75 |
| 56 | 387 | 11.67 | 1.64 | 1.68 |
| | 413 | 11.73 | 1.67 | 1.74: |
| | 477 | 11.69 | 1.63 | 1.77 |
| 61 | 387 | 11.55 | 1.67 | 1.74 |
| | 413 | 11.46 | 1.60 | 1.53 |
| | 477 | 11.62 | 1.69 | 1.77 |
| 90 | 029 | 11.75 | 1.74 | - |
| | 045 | 11.74 | 1.68 | - |
| | 047 | 11.76 | 1.68 | - |
| | 113 | 11.62 | 1.62 | - |
| | 115 | 11.58 | 1.63 | - |
| | 154 | 11.60 | 1.59 | 1.64 |
| | 413 | 11.62 | 1.60 | 1.63 |
| | 414 | 11.60 | 1.60 | 1.72 |
| | 477 | 11.66 | 1.61 | 1.66 |

| Star | JD (2441000+) | *V* | *B–V* | *U–B* |
|---|---|---|---|---|
| 162 | 028 | 12.21 | 1.78 | - |
| | 029 | 12.25 | 1.77 | - |
| | 045 | 12.10 | 1.64 | - |
| | 047 | 12.07 | 1.68 | - |
| | 113 | 12.22 | 1.75 | - |
| | 117 | 12.19 | 1.78 | - |
| | 154 | 12.12 | 1.66 | 1.88 |
| | 413 | 11.98 | 1.65 | 1.85 |
| | 414 | 12.00 | 1.65 | 1.85 |
| | 477 | 12.17 | 1.66 | 1.98 |
| 320 | 388 | 12.77 | 1.76 | - |
| | 477 | 12.73 | 1.70 | 1.57 |
| 331 | 387 | 12.49 | 1.68 | 1.97 |
| (field) | 413 | 12.55 | 1.66 | 1.95 |
| | 477 | 12.57 | 1.61 | 1.91 |
| 371 | 388 | 12.73 | 1.60 | - |
| | 413 | 12.66 | 1.58 | 1.67 |
| | 477 | 12.66 | 1.63 | 1.86 |
| 384 | 413 | 12.54 | 1.67 | 2.30: |
| (field) | 414 | 12.61 | 1.58 | 1.55: |
| | 477 | 12.81 | 1.61 | 1.69 |

velocities (Dickens, private communication); all except RGO 331 lie near the cluster two-colour relation.

The data on the variable stars are listed in Table II. Some notes on individual stars follow.

(i) *RGO 53*. Known variable (Eggen 1961, 1972a).
(ii) *RGO 56*. Probably variable. Our observations give range $\Delta V = 0{\cdot}06$ mag, but if Eggen's (1972a) data are included with allowance for the systematic difference of 0·05 mag (Section 5), the range becomes $\Delta V = 0{\cdot}12$ mag.
(iii) *RGO 61*. Almost certainly variable, $\Delta V = 0{\cdot}16$ mag.
(iv) *RGO 90*. Certainly variable, $\Delta V \approx 0{\cdot}18$ mag, possible period $\sim 300^d$.
(v) *RGO 162*. Certainly variable, $\Delta V \approx 0{\cdot}27$ mag, possible period $\sim 110^d$.
(vi) *RGO 320*. TiO variable according to Dickens, Feast & Lloyd Evans (1972).

The variability of the five remaining stars in Table II, including the two field stars, depends on only one discrepant observation each.

All of the suspected red variables, including those of Eggen (1972a), have $B\text{–}V > 1{\cdot}58$. Since the amplitudes are small, the average magnitudes and colours do not differ greatly from the mean values. There are six stars in our sample with $B\text{–}V > 1{\cdot}58$ which are not suspected variables (i.e. range $\Delta V < 0{\cdot}06$ mag), but for four of these we have only two observations, while seven of the 10 observations of RGO 150 were made within 20 days. Consequently it seems probable that all of the reddest giants are variable, and that there is a division between variable and non-variable stars at $B\text{–}V = 1{\cdot}58$, corresponding to $(B\text{–}V)_0 = 1{\cdot}47$ if $E(B\text{–}V) = 0{\cdot}11$ for the giants. However, it may be significant that the redder apparent non-variable stars include the two known CH stars, RGO numbers 55 and 70.

## 9. DISCUSSION AND SUMMARY

We believe that the large spread of the $\omega$ Cen giant branch in the C–M diagram is real, since it can be only slightly reduced by allowing for measuring errors, field stars and differential reddening. For stars with $B\text{–}V < 1{\cdot}4$, the overall scatter is approximately the same as for clusters with well-defined asymptotic giant branches. It may be that there is a *small* amount of differential reddening in $\omega$ Cen, amounting to a few hundredths of a magnitude, which is sufficient to smear out any intrinsic bifurcation of the giant branch. A comparison can be made between the C–M diagram of the unbiased sample of $\omega$ Cen red giants, shown in Fig. 3 of this paper, and the C–M diagram of the NGC 6752 giants, Fig. 1 of Cannon & Stobie (1973). On this interpretation, the many $\omega$ Cen red giants near $V = 12{\cdot}8$, $B\text{–}V = 1{\cdot}06$ constitute a clump of stars on the asymptotic branch. Similar clumps are clearly seen in NGC 6752 and in M5 (Simoda & Tanikawa 1970).

The principal difference between $\omega$ Cen and most other clusters lies in the great scatter amongst the reddest giants, with $B\text{–}V > 1{\cdot}4$. To some extent this difference may be illusory, since $\omega$ Cen contains a much larger sample of stars than the other clusters, and some of the stars in Fig. 1 were measured specifically because they lay far from the usual red giant branch. However, the large scatter is still present in the unbiased sample (Fig. 3).

It is perhaps premature to speculate on possible explanations for the width of the $\omega$ Cen giant branch, before some further obvious observational checks are made.

These are, first, *UBV* photometry for a larger sample of stars with $13 < V < 14$; we have only about six stars in this range, several of which are probably field stars. If there is an asymptotic branch in $\omega$ Cen, it should be more clearly separated in this range than for the brighter stars. Second, one requires *R*, *I* photometry for more of the stars which we have observed, particularly for the reddest and faintest stars, to extend the arguments of Section 6. Third, a detailed study of the variability of the reddest stars could be very profitable, particularly with regard to establishing if there is a clear division between the variable and non-variable members of the cluster. Fourth, a simple control experiment would be to measure a random sample of at least 50 blue horizontal branch stars chosen all round the cluster according to the same criteria as our giant sample. Indications from the available photographic and photoelectric data are that these stars would show a much smaller scatter in the C–M diagram than do the giants, thus removing once and for all the possibility that the main cause of the scatter is differential interstellar reddening.

One possible explanation for the spread can apparently be eliminated, namely that all of the $\omega$ Cen giants are 'CH stars' or 'TiO stars' in varying degree. The known CH and TiO stars suggest that in this case there would be a large spread in the two-colour diagram also.

Apart from confirming the large spread in the $\omega$ Cen giant branch, we can derive several other conclusions from our data.

(i) There is *no* evidence for an anomalous ultra-violet excess amongst the giants and subgiants, analogous to that found by Sandage & Walker (1966) in M92 and M3, although a larger sample of asymptotic branch stars, with $V < 14$, $B-V < 1.0$, would be desirable. The variations in ultra-violet excess which we find are satisfactorily explained by expected changes in surface gravity, and the much larger variations found by Geyer (1967) seem to be a consequence of calibration errors. We note that the original Sandage–Walker result for M92 has been seriously queried (Bell 1970; Strom & Strom 1971), although the effect has not yet been checked directly by new *UBV* observations in M92 itself.

(ii) There is probably a sharp distinction between variable and non-variable red giants occurring at $(B-V)_0 \approx 1.5$; certainly the majority of the redder stars are variable.

(iii) The comprehensive photographic survey done at the Royal Greenwich Observatory (*R. Obs. Ann. No.* **2**, 1966) has only small ($<0.1$ mag) systematic errors for $V < 15.5$, and the RGO estimates of the random errors are confirmed.

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